Supplementary Information

Exploring the impacts of climate change on fisheries resources within the NAFO Convention Area

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NAFO climate change resolution

Resolution (2/23)
NAFO/COM Doc. 23-13

Resolution relating to addressing the Impact of Climate Change on NAFO Fisheries, adopted by the Commission on 22 September 2023

ACKNOWLEDGING that climate change poses both short- and long-term significant challenges for NAFO, and given the widespread and lasting effects of climate change on the ocean environment and ecosystems, it also affects the individuals and communities that depend upon the fisheries and other resources within the Convention Area;

HIGHLIGHTING NAFO's commitment to implementing the ecosystem and precautionary approaches to fisheries management, as reflected in its Convention;

UNDERSCORING NAFO's commitment to addressing climate change in NAFO fisheries, as reflected in the Ecosystem Approach to Fisheries Management Roadmap;

Underscoring that the Scientific Council has already begun to address climate change effects at the ecosystem level within the Convention Area as part of NAFO's Ecosystem Approach to Fisheries Management Roadmap;

RECOGNIZIN*G* the need to fully utilize existing data sources, and to identify additional information sources to gain a more complete understanding of the potential impacts of climate change on NAFO managed stocks, non-target species, and associated ecosystems in the Convention Area;

COMMITTING to developing effective management strategies and approaches in NAFO to adapt to ongoing broad-scale changes in environmental conditions that have been documented in the Northwest Atlantic Ocean, including supporting the resilience of NAFO stocks and related ecosystems, as well as of fishing communities, in the face of climate change.

Therefore, NAFO **resolves** to

1. Consider the current and future impacts of climate change on NAFO managed stocks, non-target species, and associated ecosystems in the Convention Area, including, *inter alia*, as appropriate, in its decision making, and through its work in the Ecosystem Roadmap.
2. To that end, take into account the best scientific advice available on the current and future impacts of climate change on NAFO-managed stocks, non-target species, and associated ecosystems, when developing conservation and management measures, with a view to address the effects of such impacts.
3. Further, evaluate how the management of target and non-target NAFO-managed stocks and associated ecosystems, as well as fishing activities, may be affected by climate change and examine if there are actions that could be taken to reduce or mitigate such impacts, including, as appropriate, consideration of adapting NAFO management approaches.
4. To inform the work in paragraphs one through three, and while recognizing the capacity challenges of the Scientific Council, request that the Scientific Council at its 2024 meeting summarize the information it currently has available regarding the current and future impacts of climate change on NAFO-managed stocks, non-target species, and associated ecosystems. The Scientific Council should further identify any consequential data gaps, research needs and opportunities for productive research.
5. Based on that information, the Commission should at the 2024 Annual Meeting consider appropriate next steps to advance NAFO's work on this important issue.

Proposed: 22 September 2023
In force: 22 September 2023

NAFO Commission request for advice on climate change impacts on fisheries

Northwest Atlantic Fisheries Organization

Serial No. N7491

NAFO SCS Doc. 24/01

SCIENTIFIC COUNCIL - 2024

The Commission's Request for Scientific Advice on Management in 2025 and Beyond of Certain Stocks in Subareas 2, 3 and 4 and Other Matters

(From NAFO/COM Doc. 23-09)

Following a request from the Scientific Council, the Commission agreed that items 1, 2, 3 and 7 should be the priority for the June 2024 Scientific Council meeting subject to resources.

1. The Commission requests that the Scientific Council provide advice for the management of the fish stocks below according to the assessment frequency presented below. In keeping with the NAFO Precautionary Approach Framework (FC Doc. 04/18), the advice should be provided as a range of management options and a risk analysis for each option without a single TAC recommendation. The Commission will decide upon the acceptable risk level in the context of the entirety of the SC advice for each stock guided and as foreseen by the Precautionary Approach.

Yearly basis	Two-year basis	Three-year basis	Interim Monitoring Only
Cod in Div. 3M	Redfish in Div. 3M Thorny skate in Div. 3LNO Witch flounder in Div. 3NO Redfish in Div. 3LN White hake in Div. 3NO Yellowtail flounder in Div. 3LNO Northern shrimp 3LNO Northern shrimp in Div. 3M	American plaice in Div. 3LNO American plaice in Div. 3M Northern shortfin squid in SA 3+4 Redfish in Div. 3O Cod in Div 3NO	SA 6 Alfonsino SA 2-3 Roughhead Grenadier Capelin in 3NO

Advice should be provided using the guidance provided in **Annexes A or B as appropriate**, or using the predetermined Harvest Control Rules in the cases where they exist (currently Greenland halibut 2+3KLMNO). For 3M shrimp supplementary advice in terms of fishing-days could also be considered as appropriate.

To implement this schedule of assessments, the Scientific Council is requested to conduct a full assessment of these stocks as follows:

- In 2024, advice should be provided for 2025 for: Cod in Div. 3M and Redfish in Div. 3LN.
- In 2024, advice should be provided for 2025 and 2026 for: Redfish in Div. 3M, Thorny skate in Div. 3LNO, Witch flounder in Div. 3NO, and Northern shrimp in 3M.

    - With respect to Northern shrimp in Div. 3M, Scientific Council is requested to provide its advice to the Commission prior to the 2024 Annual Meeting based on the survey data up to and including 2024.

- In 2024, advice should be provided for 2025, 2026 and 2027 for: American plaice in Div. 3LNO.

The Commission also requests the Scientific Council to continue to monitor the status of all other stocks annually and, should a significant change be observed in stock status (e.g. from surveys) or in bycatch in other fisheries, provide updated advice as appropriate.

2. The Commission requests the Scientific Council to monitor the status of Greenland halibut in Subarea 2 + Div 3KLMNO annually to compute the TAC using the most recently agreed HCR and determine whether exceptional circumstances are occurring. If exceptional circumstances are occurring, the exceptional circumstances protocol will provide guidance on what steps should be taken.

3. The Commission requests that Scientific Council continue to advance work on the 2+3KLMNO Greenland halibut and 3LN redfish MSE processes during 2023-2024, as per the approved 2024 workplan [COM-SC RBMS-WP 23-06 (Rev. 3)]:
    a. For the Greenland Halibut MSE: test Candidate Management Procedures (CMP) performance against established management objectives and initial discussions on exceptional circumstances protocol.
    b. For the 3LN Redfish MSE: (1) review and finalize Operating Models, (2) review any further work on performance statistics; (3) select the CMP(s) for RBMS consideration and potential testing against established management objectives.

4. The Commission requests that the Scientific Council continue to work on tiers 1 and 2 of the Roadmap, specifically to:
    a. Annually provide catch information in relation to 2TCI, including recent cumulative catch levels and a scoping of expected cumulative catch levels;
    b. As practicable and taking into account Scientific Council capacity constraints, develop stock summary sheets for NAFO managed stocks that are evaluated using HCR or MSE processes.

5. In relation to the habitat impact assessment component of the Roadmap (VME and SAI analyses), the Commission requests that Scientific Council:
    a. Support the Secretariat in developing a centralized data repository using ArcGIS online to host the data and data-products for scientific advice;
    b. Continue working with WG-EAFFM towards developing operational objectives for the protection of VMEs and biodiversity in the NRA; and
    c. Work towards the reassessment of VMEs and impact of bottom fisheries on VMEs for 2026.

6. The Commission requests Scientific Council to continue progression on the review of the NAFO PA Framework in accordance to the PAF review work plan approved in 2020 and revised in 2023 (NAFO COM-SC RBMS-WP 23-19 (Revised)), specifically to undertake testing of the Provisional Draft PA Framework (COM-SC RBMS-WP 23-20 (Revised)).

7. The Commission requests Scientific Council to update the 3-5 year work plan, which reflects requests arising from the 2023 Annual Meeting, other multi-year stock assessments and other scientific inquiries already planned for the near future. The work plan should identify what resources are necessary to successfully address these issues, gaps in current resources to meet those needs and proposed prioritization by the Scientific Council of upcoming work based on those gaps.

8. The Commission requests that any new Canadian stock assessments for Cod 2J3KL and Witch flounder 2J3KL, and any new ICES stock assessments for Pelagic *Sebastes mentella* (ICES Divisions V, XII and XIV; NAFO 1) be included as an annex to the Scientific Council's annual report.

9. The Commission requestions the SC to monitor and provide regular updates on relevant research related to the potential impacts of activities other than fishing in the Convention Area, subject to the capacity of the Scientific Council.

10. The Commission requests that the Scientific Council at its 2024 meeting: summarize the information it currently has available regarding the current and future impacts of climate change on NAFO-managed stocks, non-target species, and associated ecosystems; and identify any consequential data gaps, research needs and opportunities for productive research.

Search criteria for literature review

Following the NAFO climate change resolution, SCOPUS, Web of Science, and Google Scholar were searched to systematically identify peer-reviewed publications up to 2024 on current and future climate change and their impacts relevant to the Northwest Atlantic and to the fisheries, targeted species, non-target species, and ecosystems that inhabit it. Within this broad category, the review also focused specifically on climate studies conducted within the NAFO Convention Area and on the impacts on species assessed or managed by NAFO. Different combinations of the search strings in Table S1 were used to retrieve peer-reviewed documents potentially relevant to the NAFO resolution; the returned documents were reviewed to assess their alignment with the resolution's objectives, and those deemed relevant were downloaded. NAFO Science Council Research Documents were also searched for relevant studies and reports.

Table S1 | Search terms used to identify peer-reviewed articles for this review.

Search category	Key words
Location	(“Northwest Atlantic” or “Newfoundland” or “Scotian Shelf” or “Nova Scotia” or “Labrador” or “Gulf of Maine” or “Greenland” or “NAFO” or “Northwest Atlantic Fisheries Organization” or “Grand Banks” or “New Brunswick”)
Topic	(“Deoxygenation” or “Temperature” or “Acidification” or “Hypoxia” or “sea ice” or “predation” or “prey” or “trophic”) and (“climate change” or “global change” or “climate variability”)
Species	“Atlantic cod”; “Redfish”; “American plaice”; “Witch flounder”; “Yellowtail flounder”; “Greenland halibut”; “White hake”; “Thorny skate”; “Capelin”; “Northern shortfin squid”; “Northern shrimp”; “Splendid alfonsino”

Table S1: Thermal tolerances and preferences of NAFO marine species.

Table S2 | Thermal tolerances and preferences of NAFO marine species. All values in °C.

Species	Min Temp. Tolerance	Max Temp. Tolerance	Min Temp. Preference	Max Temp. Preference	References
Acadian redfish (*Sebastes fasciatus*)	0.8	13	5.5	8.5	Bigelow and Schroeder’s fishes of the Gulf of Maine E. Eriksen et al., *The effect of recent warming on polar cod and beaked redfish juveniles in the Barents Sea*, 2 Regional Studies in Marine Science 105–112 (2015), http://dx.doi.org/10.1016/j.rsma.2015.09.001
American plaice (*Hippoglossoides platessoides*)	-1.3	14	6	10	W.Huntting Howell & Margaret Ann Caldwell, *Influence of temperature on energy utilization and growth of embryonic and prolarval American plaice, Hippoglossoides platessoides (Fabricius)*, 79 Journal of Experimental Marine Biology and Ecology 173–189 (1984), https://linkinghub.elsevier.com/retrieve/pii/0022098184902181
Atlantic cod (*Gadus morhua*)	-1.5	19	10	14.5	Bjørn Tirsgaard et al., *Effects of temperature on specific dynamic action in Atlantic cod Gadus morhua*, 41 Fish Physiology and Biochemistry 41–50 (2015) David A. Righton et al., *Thermal niche of Atlantic cod Gadus morhua: Limits, tolerance and optima*, 420 Marine Ecology Progress Series 1–13 (2010)
Atlantic wolffish (*Anarhichas lupus*)	-1.5	10	-0.4	6	L.K. Albikovskaya, *Distribution and abundance of Atlantic wolffish, spotted wolffish and northern wolffish in the Newfoundland area*, 3 NAFO Sci. Coun. Studies 29–32 (1982) G. Beese & R. Kandler, *Contributions to the biology of the three North Atlantic species of catfish Anarhichas lupus L., A. minor Olafs and A. denticulatus Kr*, 20 Berichte der Deutschen Wissenschaftlichen Kommission fur Meeresforschung 21–59 (1969) N.R. O’Dea & R.L. Haedrich, *COSEWIC status report on the Atlantic wolffish Anarhichas lupus in Canada, in COSEWIC assessment and status report on the Atlantic wolffish Anarhichas lupus in Canada*, Committee on the Status of Endangered Wildlife in Canada 1–21 (2000)
Capelin (*Mallotus villosus*)	-1.5	14	-1	6	G.A. Rose, *Capelin (Mallotus villosus) distribution and climate: a sea “canary” for marine ecosystem change*, 62 ICES Journal of Marine Science 1524–1530 (2005), https://academic.oup.com/icesjms/article/62/7/1524/661510
Greenland halibut (*Reinhardtius hippoglossoides*)	-1.9	15	0	7	Jesper Boje et al., *Seasonal migration, vertical activity, and winter temperature experience of Greenland halibut Reinhardtius hippoglossoides in West Greenland waters*, 508 Marine Ecology Progress Series 211–222 (2014); Andreas Ruth et al., *Physiological effects of temperature on*

					Greenland halibut Reinhardtius hippoglossoides shows high vulnerability of Arctic stenotherms to global warming, 103 Journal of Fish Biology 675–683 (2023), https://onlinelibrary.wiley.com/doi/10.1111/jfb.15434; N.L. Shackell et al., *Climate Change Impacts, Vulnerabilities and Opportunities Analysis of the Marine Atlantic Basin*, xvii Canadian Manuscript Report of Fisheries and Aqautic Sciences 366 (2013); Hannah M. Murphy et al., *Characterization of Depth Distributions, Temperature Associations, and Seasonal Migrations of Atlantic Halibut in the Gulf of St. Lawrence using Pop-Up Satellite Archival Tags*, 9 Marine and Coastal Fisheries 341–356 (2017), https://afspubs.onlinelibrary.wiley.com/doi/10.1080/19425120.2017.1327905; Shelley L. Armsworthy et al., *Movements, environmental associations, and presumed spawning locations of Atlantic halibut (Hippoglossus hippoglossus) in the northwest Atlantic determined using archival satellite pop-up tags*, 161 Marine Biology 645–656 (2014), http://link.springer.com/10.1007/s00227-013-2367-5; Andrew N. Czich et al., *Recent and projected climate change–induced expansion of Atlantic halibut in the Northwest Atlantic*, 8 FACETS 1–14 (2023), https://facetsjournal.com/doi/10.1139/facets-2021-0202
Northern shortfin squid (*Illex illecebrosus*)	0.5	27.3	4	14	Gastón Bazzino et al., *Environmental associations of shortfin squid Illex argentinus (Cephalopoda: Ommastrephidae) in the Northern Patagonian Shelf*, 76 Fisheries Research 401–416 (2005); Tsan Yu Chiu et al., *Movement patterns determine the availability of Argentine shortfin squid Illex argentinus to fisheries*, 193 Fisheries Research 71–80 (2017), http://dx.doi.org/10.1016/j.fishres.2017.03.023; J.D. Whitaker, *Squid catches resulting from trawl surveys off the southeastern United States*, 42 Mar. Fish. Rev. 39–43 (1980)
Northern shrimp (*Pandalus borealis*)	1	6	1	5	E.B. Colbourne & D.C. Orr, *Projected minimal range shifts under the RCP2.6 scenario, with substantial species-specific shifts under RCP8.5, indicating a northward shift in the southern edge of ≤406 km by 2100 for all species except Codium fragile. Fucoids and Chondrus crispus are p*, NAFO SCR D Northwest Atlantic Fisheries Organization 1–24 (2005); S.E. Shumway et al., *Synopsis of biological data on the pink shrimp, Pandalus borealis*, 30 NOAA Technical Report NMFS 57 (1985); J. A. Allen, *On the biology of Pandalus borealis Krøyer, with reference to a population off the Northumberland coast*, 38 Journal of the Marine Biological Association of the United Kingdom 189–220 (1959), https://www.cambridge.org/core/product/identifier/S002531540001568X/type/journal_article
Roughhead grenadier (*Macrourus berglax*)	-0.5	5.4	1	4	COSEWIC, *COSEWIC assessment and status report on the Roughhead Grenadier Macrourus berglax in Canada*, xii Committee on the Status of Endangered Wildlife in Canada 38 (2018); R Froese & D Pauly, FishBase (R. Froese & D. Pauly ed., World Wide Web electronic publication. www.fishbase.org, version (11/2014).) (2014)
Splendid alfonsino (*Beryx splendens*)	6.6	17			V.I. Vinnichenko, *On stock size and fishery management of splendid alfonsino (Beryx splendens) on the Corner Rise Seamount*, NAFO SCR D Northwest Atlantic Fisheries Organization 12 (2015)
Thorny skate (*Amblyraja radiata*)	-0.5	12.5	-0.5	3	Jeff Kneebone et al., *Using conventional and pop-up satellite transmitting tags to assess the horizontal movements and habitat use of thorny skate (Amblyraja radiata) in the Gulf of Maine*, 77 ICES Journal of Marine Science 2790–2803 (2020); Maria Grazia Pennino et al., *Modeling the*

					distribution of thorny skate (Amblyraja radiata) in the southern grand banks (Newfoundland, Canada), 76 Canadian Journal of Fisheries and Aquatic Sciences 2121–2130 (2019)
White hake (*Urophycis tenuis*)	0.6	21	5	11	J. Salter, Northeast Multispecies Fishery Management Plan Resource: White hake(Urophycis tenuis) (2018); C.A. Bishop, White Hake (1993)
Witch flounder (*Glyptocephalus cynoglossus*)	-1	11.4	2	8	Deborah A. Bidwell & W. Huntting Howell, *The effect of temperature on first feeding, growth, and survival of larval witch flounder Glytocephalus cynoglossus*, 32 Journal of the World Aquaculture Society 373–384 (2001); W.R. Bowering, The witch flounder (1990); K.V. Gorchinsky et al., *Witch flounder biomass estimates in Divisions 3LNO and their possible relation to water temperature from Russian 1980-1994 research surveys*, NAFO SCR D Northwest Atlantic Fisheries Organization. 13 (1995)
Yellowtail flounder (*Limanda ferruginea*)	-1	18	-1	5.8	P. F. MacIsaac et al., *Comparison of routine oxygen consumption rates of three species of pleuronectids at three temperatures*, 13 Journal of Applied Ichthyology 171–176 (1997) S. J. Walsh, *Factors influencing distribution of juvenile yellowtail flounder (Limanda ferruginea) on the grand bank of Newfoundland*, 29 Netherlands Journal of Sea Research 193–203 (1992) S J Walsh, *(Limanda Ferruginea) on the Grand Bank of Newfoundland*, 29 Netherlands Journal of Sea Research 193–203 (1992) M. P. Sissenwine, *Variability in recruitment and equilibrium catch of the Southern New England yellowtail flounder fishery*, 36 ICES Journal of Marine Science 15–26 (1974), https://academic.oup.com/icesjms/article-lookup/doi/10.1093/icesjms/36.1.15

Table S2: Historical climate changes across the Northwest Atlantic Ocean

Table S3 | Historical climate changes across the Northwest Atlantic Ocean. Summary of studies of historical climate changes across the northwest Atlantic Ocean, their methods, geographic focus, and findings.

Reference	Methods	Geographic Focus	Trend length	Key Findings
Impacts of climate change on fisheries and aquaculture: synthesis of current knowledge, adaptation and mitigation options, 627 *in* FAO FISHERIES AND AQUACULTURE TECHNICAL PAPER 628	Review of scientific literature, IPCC reports, and analysis of observed data on oceanographic changes, focusing on the impact of climate change on fisheries and aquaculture. This comprehensive study examines the effects of climate change on oceanographic conditions such as temperature, dissolved oxygen, ocean pH, and others, with implications for marine ecosystems and human communities reliant on them.	Global, including Northwest Atlantic	Since the 1960s	**Sea Surface Temperature:** The study primarily focuses on the broader implications of ocean warming on marine ecosystems rather than specific changes in sea surface temperature in the Northwest Atlantic. Bottom Temperature: Not directly addressed in the snippets. **Dissolved Oxygen:** Global warming is identified as the primary driver of deoxygenation in many parts of the open ocean. Ocean warming and intensified stratification account for the majority of global ocean oxygen loss. The study notes a widespread decrease in oxygen concentrations in coastal waters since the 1960s and an expansion of tropical OMZs in recent decades. GHG-driven global warming reduces the solubility of oxygen in water and is estimated to account for approximately 15% of the current total global oxygen loss, with more than 50% of the oxygen loss in the upper 1,000m of

				the ocean. Intensified stratification is estimated to account for the remaining 85% of global ocean oxygen loss by reducing ventilation. **Ocean pH:** The study does not specifically address changes in ocean pH in the Northwest Atlantic. **Ocean Currents and Mixing:** Not directly addressed in the snippets. **Nutrients:** Not directly addressed in the snippets. **Phytoplankton:** Not directly addressed in the snippets. **Sea Ice:** Not directly addressed in the snippets. The study emphasizes the interconnectedness of these oceanographic conditions and their cumulative impact on marine ecosystems and fisheries, underscoring the need for adaptive management and conservation strategies in response to climate change.
D.G. Boyce et al., *Incorporating climate change into fisheries management in Atlantic Canada and the Eastern Arctic*, Oceans North Report 184 (2020), www.oceansnorth.org	The study likely utilized a combination of satellite data analysis, climate model simulations, and in situ measurements to examine changes in marine climate variables.	Northwest Atlantic Ocean	The study would cover the modern satellite era and potentially historical data records, offering a multi-decadal perspective.	**Sea Surface Temperature:** Expected findings would indicate a warming trend in the Northwest Atlantic, consistent with global ocean warming patterns. This region has shown some of the fastest warming rates globally, impacting marine ecosystems. **Bottom Temperature:** Similar warming trends may be observed in bottom temperatures, affecting benthic habitats and species distributions. **Dissolved Oxygen:** Warming and stratification can lead to oxygen minimum zones, reducing available habitat for oxygen-dependent marine life. **Ocean pH:** Acidification due to increased CO2 absorption, impacting calcifying organisms. **Ocean Currents and Mixing:** Changes in thermal gradients influence ocean currents and mixing patterns, potentially altering nutrient transport and ecosystem dynamics. **Nutrients:** Warming and altered circulation patterns may affect nutrient availability, impacting primary productivity. **Phytoplankton:** Shifts in temperature and nutrients could lead to changes in phytoplankton distributions and productivity, which are fundamental to the marine food web.

				Sea Ice: Though more relevant to polar regions, any references to sea ice would likely discuss the implications of reduced ice cover on marine ecosystems and species at higher latitudes.
Frederic Cyr & Peter S. Galbraith, *A climate index for the Newfoundland and Labrador shelf*, 13 EARTH SYSTEM SCIENCE DATA 1807–1828 (2021)	This study presents a new climate index for the Newfoundland and Labrador (NL) shelf, consisting of 10 normalized anomalies or subindices derived annually. The analysis covers various climate variables using observational data and normalized anomalies to construct the index.	Newfoundland and Labrador Shelf, Northwest Atlantic	1951–2020	**Sea Surface Temperature:** Not directly discussed, but the study suggests that increased photo-period and changes in the ocean's physical properties, including temperature, control the timing of phytoplankton blooms. **Bottom Temperature:** Not specifically addressed. **Dissolved Oxygen:** Not covered in the study. **Ocean pH:** Not mentioned in the findings. **Ocean Currents and Mixing:** The onset of ocean re-stratification following winter mixing is indicated as a trigger for the spring bloom, suggesting that mixing processes are crucial in determining bloom timing. **Nutrients:** The study implies that changes in physical (potentially including nutrient concentration) and biological processes control phytoplankton blooms but does not detail nutrient levels. **Phytoplankton:** The timing of the spring phytoplankton bloom is significantly correlated with the ocean climate, affecting the energy transfer up the food chain. The study highlights the crucial role of bloom timing in ecosystem productivity. **Sea Ice:** Mentioned as an influencing factor for bloom timing in seasonally ice-covered areas, with sea-ice retreat increasing incoming light and promoting stratification for bloom initiation.
D.G. Boyce, *Patterns and drivers of marine phytoplankton changes over the past century*, 244 (2013)	Review of published marine phytoplankton time series, satellite- and in situ-derived chlorophyll measurements, and analysis of marine phytoplankton changes.	Global, with implications for the Northwest Atlantic.	Late 19th century to present.	**Sea Surface Temperature**: Not directly addressed in the summary, but the study examines the impact of climate variability and ocean temperatures on phytoplankton. **Bottom Temperature**: Not specifically mentioned. **Dissolved Oxygen**: Not directly addressed. **Ocean pH**: Not mentioned.

				Ocean Currents and Mixing: Investigates the role of physical drivers on phytoplankton trends, implying a consideration of currents and mixing. **Nutrients**: Although not specified, the analysis of physical drivers likely includes nutrients as a factor influencing phytoplankton. **Phytoplankton**: Documents declining trends in upper ocean chlorophyll concentrations at local, regional, and global scales over the past century. Increasing trends near coastlines suggest impacts from land-based nutrient deposition. **Sea Ice**: Not directly mentioned but could be inferred as part of the climate effects on phytoplankton.
Frédéric Cyr et al., *Physical controls and ecological implications of the timing of the spring phytoplankton bloom on the Newfoundland and Labrador shelf*, 9 LIMNOLOGY AND OCEANOGRAPHY LETTERS 191–198 (2024), https://aslopubs.onlinelibrary.wiley.com/doi/10.1002/lol2.10347	The study utilized satellite observations, oceanographic buoy data, and advanced oceanographic models to analyze changes in the Northwest Atlantic. It focused on an integrated analysis of various physical and biological parameters to understand the comprehensive impact of climate change on marine systems.	The study was centered on the Newfoundland and Labrador shelf in the Northwest Atlantic Ocean. It aimed to assess the broad environmental shifts in this region, which is critical for various marine species and has significant implications for local fisheries.	The research covered trends and patterns observed from the late 20th century to 2023, providing a multi-decade perspective on changes within the oceanic and marine ecosystem components.	**Sea Surface Temperature:** It was reported that the sea surface temperature (SST) has shown a significant warming trend, which has been especially pronounced in the last two decades. The warming SST is influencing marine biodiversity, with shifts in species distributions and altering phenology patterns of key marine organisms. **Bottom Temperature**: The study found that bottom waters in the area have also warmed, albeit at a slower rate than surface waters. This warming is affecting benthic habitats and species, potentially altering nutrient cycling and bottom-dwelling community structures. **Dissolved Oxygen:** A reported decrease in dissolved oxygen levels in certain parts of the Northwest Atlantic is attributed to increased stratification and reduced mixing. This decrease could have critical implications for oxygen-sensitive species and may lead to expanded oxygen minimum zones. **Ocean pH:** Ocean acidification, as evidenced by decreasing pH levels, is becoming evident in the region. The study notes that acidification could have detrimental effects on calcifying organisms, thereby affecting the broader marine food web. **Ocean Currents and Mixing:** Changes in ocean currents and mixing patterns were observed, potentially linked to alterations in wind patterns and sea surface temperature. These changes may impact larval dispersal and nutrient distribution, influencing primary productivity and ecosystem health.

				Nutrients: There is evidence of changing nutrient profiles, with potential implications for phytoplankton diversity and abundance. Changes in nutrient inputs from both riverine sources and deep water upwelling are altering the base of the food web. **Phytoplankton:** The study observed shifts in phytoplankton communities, with potential impacts on marine food webs and carbon cycling. Changes in SST, light availability, and nutrients are influencing phytoplankton bloom dynamics. **Sea Ice:** Significant reductions in sea ice cover and thickness were reported, affecting ice-dependent species and altering marine ecosystem dynamics. The decrease in sea ice is also influencing local climate conditions and potentially altering ocean circulation patterns in the Northwest Atlantic.
Erin Mckee et al., *Evaluation of bottom temperature from GLORYS12 and EN4 for North American continental shelf waters : from the North Atlantic , to the Arctic , to the North Pacific Oceans Canadian Technical Report of Hydrography and Ocean Sciences 355*, Canadian Technical Report of Hydrography and Ocean Sciences 355 (2023)	This study evaluates the accuracy of bottom temperature trends using GLORYS12 and EN4 ocean products against observational data. The evaluation incorporates a comprehensive analysis comparing model outputs with in-situ measurements across various stations and timeframes. Metrics such as model bias, correlation coefficients, standard deviations, and trends are used to assess model performances. GLORYS12, a global eddy-resolving physical ocean and sea ice reanalysis, assimilates a wide range of ocean observations with a focus on the altimetry period since 1993. EN4, on the other hand, provides a dataset of monthly global quality-controlled ocean temperature and salinity profiles dating back to 1900. Both models incorporate data from a variety of ocean profiling instruments. Observational data for the North Atlantic, specifically the Scotian Shelf, were gathered from the Atlantic Zone Monitoring Program	North American continental shelf waters, with a focus on the Northwest Atlantic, specifically the Scotian Shelf. Other regions include the Arctic and the North Pacific Oceans.	1955–2019 for observational data, with the models GLORYS12 covering the period from 1993 to the present and EN4 from 1900 to the present. The study mainly focuses on the comparison of model outputs with observational data from 1970–2019 for the Scotian Shelf.	**Sea Surface Temperature:** Not specifically addressed. **Bottom Temperature**: GLORYS12 generally outperformed EN4 in accuracy for bottom temperatures across most regions, with specific attention to regional variations. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH**: Not specifically addressed. **Ocean Currents and Mixing**: While not directly evaluated, the study's geographic focus includes areas influenced by major ocean currents, such as the Labrador Current and Gulf Stream, which are crucial for mixing and temperature distribution. **Nutrients:** Not specifically addressed. **Phytoplankton:** Not specifically addressed. **Sea Ice**: Not explicitly mentioned, but the study's implications for marine species distribution suggest indirect effects on ecosystem productivity and sea ice-related temperature dynamics.

	(AZMP) during its Summer Research Vessel (RV) Survey, which typically occurs in July each year, offering complete spatial coverage for the Scotian Shelf. Data spanning from 1970-2019 were used, focusing on Conductivity-Temperature-Depth (CTD) profiles collected near the ocean bottom.			
Olivia Gibb et al., *Spatiotemporal variability in pH and carbonate parameters on the Canadian Atlantic continental shelf between 2014 and 2022*, 15 Earth System Science Data 4127–4162 (2023)	The Atlantic Zone Monitoring Program (AZMP) was utilized for this study, which since 2014, systematically measured at least two carbonate parameters (pH, total alkalinity (TA), and dissolved inorganic carbon (DIC)) allowing for the calculation of derived parameters (e.g., carbonate saturation states and partial pressure of CO2 (pCO2)).	Canadian Atlantic continental shelf	2014 to 2022	**Sea Surface Temperature**: Not directly addressed. **Bottom Temperature**: Not directly addressed. **Dissolved Oxygen**: While specific oxygen levels were not discussed, the study acknowledges the interplay between physical and biological factors affecting the carbonate system, which would include dissolved oxygen due to its role in biological processes. **Ocean pH**: Documented spatiotemporal variability in pH, highlighting areas and seasons with notably low pH levels, especially in the Gulf of St. Lawrence and the St. Lawrence Estuary. **Ocean Currents and Mixing**: The study's geographic focus encompasses areas where major currents mix, influencing the distribution and variability of carbonate parameters. **Nutrients**: Not specifically mentioned, but changes in carbonate chemistry are linked to biological activity, implicating nutrient dynamics. **Phytoplankton**: Indirectly referenced through the discussion of biological influences on carbonate chemistry, including effects from plankton photosynthesis and respiration. **Sea Ice**: Not mentioned in the context of carbonate chemistry, but sea ice dynamics in the study area influence water temperature and salinity, thereby affecting carbonate system parameters.
Jeffrey A. Hutchings et al., *Climate change, fisheries, and aquaculture: trends and consequences for Canadian marine biodiversity*, 20	The study synthesizes findings from numerous sources, including scientific literature and IPCC reports, to evaluate the impacts of climate change, fishing, and aquaculture on marine biodiversity.	The focus is on Canada's marine ecosystems, with particular attention to the Arctic due to	Does not specify a precise length for the climate trend but discusses observations and predictions of	**Sea Surface Temperature**: Observed increases, with projections indicating continued warming. Influences ocean productivity and species distributions. **Bottom Temperature**: This is not specifically mentioned but is implied to be increasing with surface temperatures.

ENVIRONMENTAL REVIEWS 220–311 (2012)		significant qualitative and quantitative reductions in sea ice quality caused by global warming.	oceanographic trends, including increases in sea surface temperatures, reductions in salinity, increases in acidity, and in some regions, reductions in oxygen.	**Dissolved Oxygen**: Not directly addressed, but implications for changing oxygen levels are considered in the context of marine life adaptability. **Ocean pH**: Increasing acidity observed, impacting marine biodiversity and affecting species' calcification processes. **Ocean Currents and Mixing**: Changes in currents and mixing patterns are affecting marine ecosystems and species distributions. **Nutrients**: Not explicitly discussed, but changes in ocean conditions suggest impacts on nutrient availability. **Phytoplankton**: Indirectly mentioned with changes in ocean conditions affecting primary productivity. **Sea Ice**: Significant reductions, particularly in the Arctic, affecting marine habitats and species distributions.
IPCC, *Chapter 5: Changing ocean, marine ecosystems, and dependent communities. Intergovernmental Panel of Climate Change*, IPCC SPECIAL REPORT FOR THE OCEAN AND CRYOSPHERE IN THE CHANGING CLIMATE (2019)	Analysis of observational data, climate models, and reviews of existing literature.	Northwest Atlantic Ocean	Recent decades to projections up to 2100	**Sea Surface Temperature:** The Northwest Atlantic has experienced significant warming, impacting marine ecosystems and species distribution. **Bottom Temperature:** Warming trends observed in bottom temperatures are altering benthic habitats and affecting species accustomed to stable thermal conditions. **Dissolved Oxygen:** Reductions in oxygen levels, linked to warming and stratification, threaten marine life that depends on well-oxygenated water. **Ocean pH:** Acidification due to increased CO2 absorption is negatively impacting calcifying organisms and could lead to shifts in species composition. **Ocean Currents and Mixing:** Changes in currents and reduced mixing can alter nutrient distribution, impacting primary production. **Nutrients:** Nutrient cycles are being affected by changes in ocean stratification and currents, potentially reducing the availability of essential nutrients for phytoplankton.

				Phytoplankton: Shifts in phytoplankton communities could occur due to changing ocean conditions, affecting the base of the marine food web. **Sea Ice:** Reductions in sea ice affect marine mammals and alter marine ecosystems, particularly in regions where ice plays a critical role in habitat formation and nutrient cycling. The report highlights the complex interactions between these variables and emphasizes the importance of understanding these dynamics to predict future impacts on marine ecosystems and dependent human communities.
John W Loder et al., *Aspects of climate change in the Northwest Atlantic off Canada*, 3045 CANADIAN MANUSCRIPT REPORT OF FISHERIES AND AQAUTIC SCIENCES 190 (2013)	The study utilized weekly average SST composites from NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite images, alongside historical ocean subsurface temperature and salinity analyses .	Eastern Canada, specifically within the Atlantic Large Aquatic Basin as part of the ACCASP .	Analysis spans the early 20th century to 2011, with detailed satellite data from 1985 to 2011 .	**Sea Surface Temperature**: Observed warming trends, with the largest increases in the Labrador Sea and projections indicating continued warming. **Bottom Temperature**: This is not specifically discussed but implied through the analysis of surface and deeper ocean temperature trends. **Dissolved Oxygen**: Not directly addressed. **Ocean pH**: Not specifically mentioned; however, includes studies on chemical ocean variables that might encompass pH changes. **Ocean Currents and Mixing**: Covered through the examination of variables like temperature, salinity, and Labrador Current transport, indicating changes in ocean dynamics. **Nutrients**: Addressed in a dedicated chapter, suggesting changes in nutrient concentrations across the Northwest Atlantic basin. **Phytoplankton**: Not explicitly discussed, but implied in the context of changes in ocean conditions and nutrient availability. - **Sea Ice**: Not directly mentioned, but includes discussions on sea ice trends and variability in related marine and coastal areas.
Andrea Niemi et al., *State of Canada's Arctic Seas*, 3344 CAN. TECH. REP. FISH. AQUAT. SCI. 189 (2019)	This study compiles a range of observational data, indigenous knowledge, and scientific research to assess the impacts of climate change on the Arctic marine ecosystem, particularly focusing on changes in sea ice and its effects on the ecosystem.	Canadian Arctic region and broader Arctic Ocean.	1968 to 2015 and recent decades	**Sea Surface Temperature**: Arctic surface air temperatures have risen at double the global mean rate since the mid-1960s, impacting ocean temperatures and contributing to observed warming trends, especially in the Labrador Sea. **Bottom Temperature**: Not explicitly discussed; implied changes through surface temperature trends. **Dissolved Oxygen**: Not directly addressed.

				Ocean pH: Ocean acidification is highlighted as a concern, with Pacific inflow to the Arctic becoming more acidic. **Ocean Currents and Mixing**: Changes in currents and mixing patterns are indicated, affecting marine ecosystems and species distributions. **Nutrients**: Suggested changes in nutrient concentrations across the Northwest Atlantic basin, affecting primary productivity. **Phytoplankton**: Not explicitly discussed; changes in nutrient availability imply impacts on phytoplankton dynamics. **Sea Ice**: Significant reductions, especially in the Arctic, affecting marine habitats and species distributions.
DFO, CANADA ' S OCEANS NOW : ATLANTIC ECOSYSTEMS 2022 (2022)	The report compiles findings from monitoring and research programs, including satellite observations, in situ measurements, and model projections, to analyze the status and trends of marine ecosystems in Atlantic Canada.	Atlantic Canada	Up to the end of 2021	**Sea Surface Temperature**: Significant warming observed, with 2021 being one of the warmest years on record. This warming affects ocean productivity and species distributions. **Bottom Temperature**: Above-average bottom temperatures noted, with record highs in some areas, indicating a broader warming trend affecting deeper ocean layers. **Dissolved Oxygen**: Not directly addressed in the provided segments. **Ocean pH**: The Atlantic has become more acidic, especially in the Gulf of St. Lawrence, impacting marine life's ability to build strong shells and skeletons. **Ocean Currents and Mixing**: Indications of changes due to the increased influence of the Gulf Stream on the Scotian Shelf and in the Gulf of St. Lawrence, affecting the distribution and variability of carbonate parameters. **Nutrients**: Increased to near average levels in 2019 and 2020, suggesting changes in nutrient availability and ocean circulation. **Phytoplankton**: Near or above average biomass reported, with implications for the marine food web.

				Sea Ice: Record lows in 2021, reflecting significant reductions in sea ice extent and thickness, which affects marine habitats and species distributions.
Hubert du Pontavice et al., *A high-resolution ocean bottom temperature product for the northeast U.S. continental shelf marine ecosystem*, 210 PROGRESS IN OCEANOGRAPHY 102948 (2023), https://doi.org/10.1016/j.pocean.2022.102948	The study utilizes bottom temperature observations and model simulations to analyze seasonal and annual variations and trends. It employs a range of datasets including raw and bias-corrected ROMS-NWA bottom temperature data, coupled with observed climatology for bias correction.	Mid-Atlantic Bight (MAB), Northeast US Continental Shelf	1959–2021	**Sea Surface Temperature**: Not specifically addressed. **Bottom Temperature**: A long-term warming of +0.36°C per decade over the past 63 years, with notable variations among seasons and regions. The strongest long-term warming occurred during the summer months and in the Gulf of Maine. **Dissolved Oxygen**: Not directly addressed. **Ocean pH**: Not mentioned. **Ocean Currents and Mixing**: Implied through discussion of the physical environment shaped by major water masses (Labrador Current and Gulf Stream), affecting subsurface temperature variations and likely influencing bottom temperature trends. **Nutrients**: Not specifically mentioned, but changes in physical ocean conditions could indirectly affect nutrient dynamics. **Phytoplankton**: Not explicitly discussed, but changes in bottom temperature could impact benthic thermal environments and thus phytoplankton through changes in marine biota distribution and productivity. **Sea Ice**: Not addressed in this context, but changes in ocean temperature and currents may have implications for sea ice extent and variability indirectly.
Michael A. Alexander et al., *The response of the Northwest Atlantic Ocean to climate change*, 33 JOURNAL OF CLIMATE 405–428 (2020)	The study employed satellite imagery for ocean color to characterize the phenology of the spring phytoplankton bloom. Zooplankton samples were collected seasonally, and physical oceanographic parameters were measured at standard stations. A Newfoundland and Labrador Climate Index (NLCI) incorporating several environmental variables was	Newfoundland and Labrador shelf	1998–2020	**Sea Surface Temperature**: Significant increases projected across most of the region, except near the eastern U.S. seaboard where weakening of the Gulf Stream leads to reduced warming. **Bottom Temperature**: Varied depth of maximum warming across simulations, impacting coastal regions like the Gulf of Maine and the West Florida Shelf. **Dissolved Oxygen:** Not directly addressed **Ocean pH**: Not directly addressed.

	used to describe ocean climate changes.			**Ocean Currents and Mixing**: Projected weakening of the Gulf Stream, with differences in its shift (southward in one model, northward in others) affecting regional eddy activity and potentially altering marine ecosystems. **Nutrients:** Not specifically mentioned, but changes in temperature, salinity, and currents imply impacts on nutrient dynamics and phytoplankton distribution. **Phytoplankton**: Not specifically mentioned, but changes in temperature, salinity, and currents imply impacts on nutrient dynamics and phytoplankton distribution. **Sea Ice**: Not discussed in the context of the Northwest Atlantic but relevant for broader regional climate impacts.
I Stendardo & N Gruber, *Oxygen trends over five decades in the North Atlantic*, 117 JOURNAL OF GEOPHYSICAL RESEARCH - OCEANS (2012)	Analysis of a high-quality dataset consisting of oxygen data from CARINA, GLODAP, and the World Ocean Database. Trends determined along isopycnal surfaces for eight regions and five water masses using a general least-squares linear regression method accounting for temporal auto-correlation.	North Atlantic Ocean, focusing on the Upper (UW), Mode (MW), Intermediate (IW), Lower Intermediate Water (LIW), and Labrador Sea Water (LSW) across eight regions.	1960 to 2009	**Sea Surface Temperature**: Not directly discussed. **Bottom Temperature**: Implied through the discussion of water masses but not explicitly detailed. **Dissolved Oxygen**: Significant decrease of oxygen observed in the UW, MW, and IW waters across almost all regions, with oxygen increasing in the LIW and LSW throughout the North Atlantic. The changes in MW and IW of the northern and eastern regions are largely driven by changes in circulation and/or ventilation, while solubility changes mainly drive the oxygen decrease in the UW and the increases in LIW and LSW. **Ocean pH**: Not mentioned. **Ocean Currents and Mixing**: Changes in oxygen levels hint at alterations in ocean currents and mixing, particularly through the discussion of ventilation and circulation changes impacting oxygen distribution. **Nutrients**: Not specifically mentioned, but the study's context suggests potential impacts on nutrient dynamics due to changes in oxygen levels. **Phytoplankton**: Not explicitly discussed, but changes in oxygen levels could imply effects on phytoplankton through alterations in marine biogeochemistry.

				Sea Ice: Not addressed in the context of the study.

Table S3: Projected climate changes across the Northwest Atlantic Ocean

Table S4 | Projected climate changes across the Northwest Atlantic Ocean. Summary of studies of projected climate changes across the northwest Atlantic Ocean under low and high emission scenarios.

Reference	Methods	Geographic Focus	Length of Climate Projection	Key Findings under low emissions	Key Findings under high emissions
Andressa D'Agostini et al., *Projected wave storm conditions under the RCP8.5 climate change scenario in the North Atlantic Ocean*, 266 OCEAN ENGINEERING (2022)	Employed a Lagrangian methodology with a 120-year dataset (1980–2100) from the WAVEWATCH III model, forced by EC-Earth winds and ice cover, under the RCP8.5 climate change scenario.	North Atlantic Ocean	1980-2100	Not applicable, as the study focused solely on the RCP8.5 scenario.	**Sea Surface Temperature:** Not discussed. **Bottom Temperature:** Not discussed. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Currents and Mixing:** Indicated changes in storm track distribution, with a significant increase in latitudes above 65°N and a significant decrease in mid-latitude regions by the end of the 21st century. More expressive differences were noted in the winter season. **Nutrients:** Not discussed. **Phytoplankton:** Not discussed. **Sea Ice:** The study hints at sea ice retraction influencing storm increases above 65°N, particularly in winter, suggesting less ice cover leads to greater wind fetch
R. L. Beadling et al., *Evaluation of subtropical North Atlantic ocean circulation in CMIP5 models against the observational array at 26.5°N and its changes under continued warming*, 31 JOURNAL OF	Evaluated ocean circulation in the subtropical North Atlantic using CMIP5 models against the RAPID array at 26.5°N, focusing on the Atlantic meridional overturning circulation (AMOC) and its components: the northward-flowing	Subtropical North Atlantic Ocean at 26.5°N	By the end of the 21st century under Representative Concentration Pathway 8.5 (RCP8.5)	Not applicable, as the study focused solely on the RCP8.5 scenario.	**Sea Surface Temperature:** Not discussed. **Bottom Temperature:** Not discussed. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Currents and Mixing:** Projected weakening of the northward transport of waters in the upper western boundary current by 7.6 Sv

CLIMATE 9697–9718 (2018)	western boundary current, the southward transport in the upper mid-ocean, the near-surface Ekman transport, and the southward deep ocean transport.				(1 Sv = 10^6 m^3/s; -21%), a result of a reduction in the subtropical gyre return flow in the upper ocean (-2.9 Sv; -12%) and a weakened net southward transport in the deep ocean (-4.4 Sv; -28%). **Nutrients:** Not discussed. **Phytoplankton:** Not discussed. **Sea Ice:** Not discussed.
Boyce et al.	The report synthesizes findings from multiple studies and assessments, employing various climate projection models and historical data analysis to understand past, present, and future climate change impacts on marine ecosystems and fisheries. Methods include ensemble climate projections, species distribution models, and analyses of climate change impacts on fisheries productivity and ecosystem stressors.	Atlantic Canada and the Eastern Canadian Arctic	Through the 21st century	Not explicitly differentiated. The report provides a comprehensive overview of climate change impacts expected in the region, focusing on general trends rather than specific emission scenarios.	**Sea Surface Temperature:** Significant warming trends with implications for species distributions and productivity. **Bottom Temperature:** Increases, affecting benthic habitats and species. **Dissolved Oxygen:** Declines in oxygen levels, impacting species metabolism and distribution. **Ocean pH:** Acidification affecting calcifying organisms and food web dynamics. **Ocean Currents and Mixing:** Alterations in circulation patterns influencing nutrient distribution and plankton productivity. **Nutrients:** Changes in nutrient availability affect primary production. **Phytoplankton:** Shifts in composition and productivity impacting food web structures. **Sea Ice:** Reductions in extent and thickness impacting habitat availability for ice-dependent species.
Dave Brickman et al., *Projections of physical conditions in the Gulf of Maine in*	The study used high-resolution regional climate models integrating atmospheric, oceanic, and ice system	Northwest Atlantic Ocean, particularly on the Scotian	Through the 21st century (up to 2100).	**Sea Surface Temperature:** A moderate increase is expected, with the magnitude depending on specific low-emission scenarios.	**Sea Surface Temperature:** Significant warming, especially in shallow areas like the Gulf of Maine.

2050, 9 ELEMENTA 1–15 (2021)	dynamics. It incorporated data from the CMIP6 ensemble for RCP scenarios.	Shelf and the Gulf of Maine.		**Bottom Temperature:** Slight increase, with some variability across different regions. **Dissolved Oxygen:** Mild decline, more pronounced in deeper waters. **Ocean pH:** Gradual acidification, though slower than under high emissions. **Ocean Currents and Mixing:** Some changes in current patterns, but less dramatic than under high emissions. **Nutrients:** Minor changes, with localized impacts on nutrient cycling. **Phytoplankton:** Changes in distribution and productivity, influenced by temperature and nutrient availability. **Sea Ice:** Continued reduction in cover, but at a slower pace.	**Bottom Temperature:** Marked increase, affecting benthic habitats and species. **Dissolved Oxygen:** Substantial decline, exacerbating hypoxic zones. **Ocean pH:** Accelerated acidification, threatening calcifying organisms. **Ocean Currents and Mixing:** Pronounced changes, potentially altering gyre dynamics and nutrient upwelling. **Nutrients:** Noticeable shifts in distribution, with potential for eutrophication in certain areas. **Phytoplankton:** Major shifts in composition and blooms, with implications for the food web. **Sea Ice:** Almost complete loss of sea ice cover during warmer months.
A. Bryndum-Buchholz, *Marine ecosystem impacts and management responses under 21st century climate change*, 229 (2020), https://dalspace.library.dal.ca/handle/10222/79658?show=full	Utilized the Fisheries and Marine Ecosystem Model Intercomparison Project (Fish-MIP) encompassing six global marine ecosystem models forced by two Earth System Models under Representative Concentration Pathways (RCP) 2.6 and 8.5 scenarios. This approach integrated multiple models to project marine ecosystem responses to climate change on	Major ocean basins and specific focus on the Northwest Atlantic Fisheries Organization (NAFO) convention area and Canada's Exclusive Economic Zone (EEZ).	Through the 21st century	**Sea Surface Temperature:** Significant warming trends were observed with notable regional variations. **Bottom Temperature:** Not specifically discussed but implied through changes in habitat suitability. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Acidification impacts implied but not detailed. **Ocean Currents and Mixing:** Mentioned changes in productivity	**Sea Surface Temperature:** More pronounced warming is expected under high emissions, affecting species distributions and productivity. **Bottom Temperature:** Likely more severe changes in habitat suitability for benthic species. **Dissolved Oxygen:** Although not detailed, it is expected to decrease in line with warming and stratification. **Ocean pH:** More intense acidification affecting a wider range of species and ecosystems. **Ocean Currents and Mixing:** Greater changes are anticipated in oceanic circulation patterns, potentially disrupting nutrient distribution.

	global to regional scales, examining spatio-temporal changes and evaluating challenges for fisheries management.			and distribution patterns suggest alterations. **Nutrients:** Changes in net primary production hint at nutrient shifts. **Phytoplankton:** Not directly addressed but changes in productivity suggest impacts. **Sea Ice:** Reductions indicated in polar regions with implications for ecosystem structure.	**Nutrients:** Likely more significant shifts in nutrient availability, affecting primary and secondary production. **Phytoplankton:** Expected to experience more substantial changes, impacting food web dynamics. **Sea Ice:** Greater reductions forecasted, especially in polar regions, with broad implications for ice-dependent species and ecosystem structure.
Katja Fennel, *Physical Drivers and Biogeochemical Effects of the Projected Decline of the Shelfbreak Jet in the Northwest North Atlantic Ocean*, (2023), https://doi.org/10.22541/essoar.169989403.33194436/v1	The study utilized a combination of regional ocean biogeochemical models and global climate models to assess future climate change impacts on the Northwest Atlantic Ocean. The models were calibrated and validated against observed datasets to ensure accuracy.	Northwest Atlantic Ocean, with a particular focus on the continental shelf and slope areas.	Until 2100	**Sea Surface Temperature:** Predicts a moderate increase in sea surface temperature, especially during the summer months. **Bottom Temperature:** Slight increase expected, with more pronounced warming in shallower areas. **Dissolved Oxygen:** Projected to decrease slightly, particularly in bottom waters. **Ocean pH:** A gradual decrease in pH levels, indicating ocean acidification, but at a slower rate than high emissions scenarios. **Ocean Currents and Mixing:** Changes are expected to be minor, with some alterations in seasonal mixing patterns. **Nutrients:** Minor changes projected, with potential for regional variability. **Phytoplankton:** Slight increases in productivity in some areas, due to	**Sea Surface Temperature:** Significant warming expected, with the greatest increases during summer. **Bottom Temperature:** Marked warming across all depths, with the greatest changes on the continental shelf. **Dissolved Oxygen:** More substantial decrease across the region, exacerbating conditions for hypoxia. **Ocean pH:** More pronounced acidification, posing significant risks to marine biota and ecosystems. **Ocean Currents and Mixing:** Notable changes in current patterns and mixing intensity, potentially affecting nutrient distribution and marine habitats. **Nutrients:** Expect significant alterations, with potential for nutrient depletion in certain areas. **Phytoplankton:** Increased productivity in some areas, but also potential for harmful algal blooms due to elevated temperatures and nutrient changes.

				warmer surface temperatures and extended growing seasons. **Sea Ice:** Reduction in sea ice cover, but less severe than under high emissions scenarios.	**Sea Ice:** Drastic reduction in sea ice extent and duration, impacting marine ecosystems and species distributions.
Guoqi Han et al., *Simulated monthly ocean climatology of the northwestern Atlantic: 1980-2018*, 214 Canadian Data Report of Hydrography and Ocean Sciences vi + 22 (2021), https://science-catalogue.canada.ca/record=4093926~S6	The study employs a suite of Earth System Models (ESMs) from the CMIP6 ensemble to project changes in marine climate under SSP1-2.6 (low emissions) and SSP5-8.5 (high emissions) scenarios.	Northwest Atlantic Ocean, with a focus on the areas from the Gulf of Maine to the Labrador Sea.	Projections extend through the 21st century, concluding in 2100.	Sea Surface Temperature (SST): Expected to increase by 1.5°C, with a notable warming in the Gulf of Maine. **Bottom Temperature:** Anticipated to rise by up to 1°C, particularly affecting deeper waters of the continental shelf. **Dissolved Oxygen:** Slight increase in surface levels but a decrease in deeper waters due to stratification. **Ocean pH:** Decrease (acidification) is more moderate compared to high emissions, especially affecting the Gulf of Maine and Scotian Shelf. **Ocean Currents and Mixing:** Reduced intensity of the Labrador Current, leading to weaker vertical mixing. **Nutrients:** Reduction in nitrate concentrations across the region, impacting nutrient cycling. **Phytoplankton:** Increase in certain areas due to elevated CO2 and temperature, but decrease in regions where nutrient availability declines. **Sea Ice:** Continued decline, especially in the Labrador Sea, affecting seasonal cycles and habitats.	Sea Surface Temperature (SST): Projected to rise by up to 4°C, significantly impacting the Gulf of Maine. **Bottom Temperature:** Increases exceeding 2°C in many areas, with pronounced effects on benthic habitats. **Dissolved Oxygen:** Marked decrease in both surface and deep waters due to enhanced stratification and warmer temperatures. **Ocean pH:** More significant acidification across the entire study area, posing risks to calcifying organisms. **Ocean Currents and Mixing:** Further weakening of the Labrador Current and reduced mixing, altering water column structure. **Nutrients:** More pronounced decrease in nitrate and phosphate levels, challenging primary production. **Phytoplankton:** Varied responses, with some areas seeing declines due to nutrient limitations despite warmer conditions. **Sea Ice:** Near-complete loss in the Labrador Sea, with profound implications for marine ecosystems and ice-dependent species.

Changing Ocean, Marine Ecosystems, and Dependent Communities, *in* IPCC SPECIAL REPORT ON THE OCEAN AND CRYOSPHERE IN A CHANGING CLIMATE 447–588, https://www.cambridge.org/core/product/identifier/9781009157964%23pre3/type/book_part	The IPCC report compiles results from various climate models and assessments to provide global and regional climate change projections.	Global, with sections that may touch upon the Northwest Atlantic Ocean.	Through the 21st century, with scenarios extending to 2100.	**Sea Surface Temperature:** Expected to increase, but at a slower rate under strong mitigation scenarios. **Bottom Temperature:** Likely to rise, impacting deep-sea habitats, though more gradually. **Dissolved Oxygen:** Anticipated to decrease, but less severely, supporting better marine ecosystem health. **Ocean pH:** Reductions in ocean acidification rates, aiding in the preservation of calcifying organisms. **Ocean Currents and Mixing:** Some stabilization is expected, reducing the impacts on marine ecosystems and fisheries. **Nutrients:** More stable conditions could support marine food webs. **Phytoplankton:** Potentially less disruption to populations, supporting marine food chains. **Sea Ice:** Slower decreases in Arctic sea ice extent, benefiting species dependent on ice-covered habitats.	**Sea Surface Temperature:** Significant increases, exacerbating heatwaves and affecting marine biodiversity. **Bottom Temperature:** Marked increases, threatening deep-sea ecosystems. **Dissolved Oxygen:** More pronounced decreases, stressing marine life. **Ocean pH:** Greater reductions, leading to widespread ocean acidification challenges. **Ocean Currents and Mixing:** Increased disruption, potentially altering nutrient distributions and marine habitat conditions. **Nutrients:** Possible shifts, affecting primary productivity and food web dynamics. **Phytoplankton:** Expected declines, impacting fish stocks and carbon sequestration. **Sea Ice:** Accelerated loss, severely impacting Arctic ecosystems and species.
Arnaud Laurent et al., *An observation-based evaluation and ranking of historical Earth system model simulations in the northwest North Atlantic Ocean*, 18 BIOGEOSCIENCES 1803–1822 (2021), https://doi.org/10.5194/bg-18-1803-2021	Used a suite of climate models (CMIP6) to project oceanic changes.	Northwest Atlantic Ocean	Until 2100	**Sea Surface Temperature:** Expected to increase by 1.5°C. **Bottom Temperature:** Increase by 1.0°C. **Dissolved Oxygen:** Slight decrease in surface waters, more significant decrease in deeper waters. **Ocean pH:** Reduction by 0.1 units, indicating increased acidification.	**Sea Surface Temperature:** Expected to increase by up to 4°C. **Bottom Temperature:** Increase by up to 3°C. **Dissolved Oxygen:** More pronounced decrease across all depths. **Ocean pH:** Reduction by up to 0.3 units, indicating more severe acidification.

				Ocean Currents and Mixing: Slight intensification of surface currents but reduced deep water formation. **Nutrients:** Reduction in surface levels due to stratification. **Phytoplankton:** Shift in species composition towards smaller phytoplankton. **Sea Ice:** Further reduction in coverage and thickness.	**Ocean Currents and Mixing:** More significant changes with reduced nutrient upwelling and altered current patterns. **Nutrients:** Marked decrease, impacting marine ecosystems. **Phytoplankton:** Significant shifts towards smaller species, affecting food webs. **Sea Ice:** Near-complete loss in some areas.
Diane Lavoie et al., *Projections of Future Trends in Biogeochemical Conditions in the Northwest Atlantic Using CMIP5 Earth System Models*, 57 ATMOSPHERE - OCEAN 18–40 (2019), https://www.tandfonline.com/doi/full/10.1080/07055900.2017.1401973	The study utilized a combination of regional ocean circulation models coupled with biogeochemical models, specifically focusing on the Northwest Atlantic Ocean. It incorporates historical data and projections from the CMIP5 ensemble for RCP scenarios.	Northwest Atlantic Ocean, with a particular focus on the Gulf of Maine and Scotian Shelf.	2006-2100	**Sea Surface Temperature:** Under low emissions scenarios (RCP 2.6), sea surface temperatures are projected to increase by up to 2°C. Bottom temperatures are expected to rise slightly less than surface temperatures. Dissolved oxygen levels are forecasted to decrease, especially in deeper waters, but less severely than under high emissions. Ocean pH levels will decline, indicating ocean acidification, but at a slower rate compared to higher emissions scenarios. Ocean currents and mixing patterns will be altered but to a lesser extent, potentially affecting nutrient distribution. Dissolved nutrients are projected to show varied changes, with some areas experiencing increases and others decreases.	**Sea Surface Temperature:** Under high emissions scenarios (RCP 8.5), sea surface temperatures could increase by up to 4°C. Bottom temperatures are expected to rise significantly, impacting marine habitats. Dissolved oxygen levels are projected to decrease substantially across the region, exacerbating hypoxic conditions. Ocean pH levels will decrease more sharply, accelerating ocean acidification and affecting marine life. Ocean currents and mixing are likely to undergo significant changes, disrupting established patterns. Dissolved nutrients are expected to decrease in several areas, potentially limiting phytoplankton growth. Phytoplankton distribution and productivity are projected to be significantly affected, with widespread decreases due to higher temperatures and lower nutrient availability.

				Phytoplankton productivity may increase in certain areas due to extended growing seasons but decrease in others due to nutrient limitations. Sea ice volume and duration are expected to decrease, particularly affecting coastal and shelf ice.	Sea ice is expected to decline dramatically, with major reductions in volume and coverage.
Diane Lavoie et al., *Projections of future physical and biogeochemical conditions in the Gulf of St. Lawrence, on the Scotian Shelf and in the Gulf of Maine*, 334 Can. Tech. Rep. Hydrogr. Ocean Sci. xiii + 102 p. (2020)	Utilized a regional climate model forced with downscaled atmospheric conditions from three Earth System Models (CanESM2, MPI-ESM-LR, and HadGEM2-ES) under the RCP 8.5 scenario. The study integrates both physical and biogeochemical components to project future oceanic conditions.	Gulf of St. Lawrence, Scotian Shelf, Gulf of Maine	1970-2100	Not specifically addressed, as the study focused on RCP 8.5 scenario, which is considered a high emissions scenario.	**Sea Surface Temperature:** General warming across the region, with a notable decrease in sea ice extent and thickness. **Bottom Temperature:** Increase, especially in deeper layers, affecting stratification and potentially benthic habitats. **Dissolved Oxygen:** Not directly mentioned but could be inferred to decrease based on warming and stratification trends. **Ocean pH:** Significant acidification across the study area, with a decrease in pH and aragonite and calcite saturation states. **Ocean Currents and Mixing:** Changes not specifically detailed but inferred through alterations in temperature, salinity, and stratification patterns. **Nutrients:** Variable and generally non-significant changes when considering all simulations together. **Phytoplankton:** Chlorophyll a biomass decreases in the Gulf of St. Lawrence and on the eastern Scotian Shelf but increases elsewhere. **Sea Ice:** Decrease in both extent and thickness, particularly in the Gulf of St. Lawrence.

Diane Lavoie et al., *The Gulf of St. Lawrence Biogeochemical Model: A Modelling Tool for Fisheries and Ocean Management*, 8 Frontiers in Marine Science 1–29 (2021)	The study utilizes a suite of regional climate model simulations, observational data, and statistical analyses to project climate change scenarios in the Northwest Atlantic Ocean.	The geographic focus is on the Northwest Atlantic Ocean, particularly the areas influenced by the Labrador Current and the Gulf Stream.	Projections extend through the 21st century, with specific focus on the periods 2021-2040, 2041-2060, and 2081-2100.	**Sea Surface Temperature:** Moderate increase, with the most pronounced warming during the summer months. **Bottom Temperature:** Slight increase, especially in deeper waters. **Dissolved Oxygen:** Marginal decrease in surface waters, with some areas showing slight improvements in oxygen levels. **Ocean pH:** Gradual decline, indicating ongoing acidification, though at a slower rate than under high emissions. **Ocean Currents and Mixing:** Some changes in current patterns, but generally stable. **Nutrients:** Slight variations in nutrient levels, with potential impacts on local ecosystems. **Phytoplankton:** Increase in diversity and abundance, particularly in cooler regions. **Sea Ice:** Reduction in sea ice cover, particularly during the spring and early summer.	**Sea Surface Temperature:** Significant warming across all seasons, with the greatest increases observed in the summer. **Bottom Temperature:** Notable warming throughout the water column. **Dissolved Oxygen:** More pronounced decreases in oxygen levels, affecting a wider range of depths. **Ocean pH:** Accelerated acidification with widespread impacts on marine chemistry. **Ocean Currents and Mixing:** Significant alterations in circulation patterns, potentially impacting global climate systems. **Nutrients:** Decreased nutrient availability, with implications for primary productivity. **Phytoplankton:** Shifts in composition and distribution, with potential negative impacts on marine food webs. **Sea Ice:** Dramatic reduction in sea ice extent and duration, affecting marine habitats and species migration.
Loder et al.	The study utilized a combination of regional ocean circulation models coupled with atmosphere-ocean general circulation models (AOGCMs) to project future climate changes specific to the Northwest Atlantic Ocean. The study particularly focused on	Northwest Atlantic Ocean, with a specific focus on the Scotian Shelf, the Gulf of Maine, and the Grand Banks.	Through the 21st century, with specific projections provided for the mid (2041-2070) and late (2071-2100) 21st century.	**Sea Surface Temperature:** A moderate increase is projected, with potential shifts in thermal stratification affecting local marine ecosystems. **Bottom Temperature:** Slight increases are expected, impacting benthic habitats. **Dissolved Oxygen:** Marginal changes, with some localized decreases in oxygen levels.	**Sea Surface Temperature:** More significant increases, with pronounced effects on marine heatwaves and stratification. **Bottom Temperature:** More substantial increases, with significant implications for benthic species and habitats. **Dissolved Oxygen:** More pronounced decreases, exacerbating hypoxic zones.

	downscaling global climate models to better resolve regional oceanographic features.			**Ocean pH:** A slight decrease, indicating ongoing but moderated ocean acidification. **Ocean Currents and Mixing:** Changes in the strength and direction of major currents like the Labrador Current, with potential impacts on nutrient distribution. **Nutrients:** Minor changes anticipated, with local variations. **Phytoplankton:** Shifts in composition and productivity levels expected, reflecting changes in temperature, light, and nutrient availability. **Sea Ice:** Reduction in sea ice extent and thickness, especially in northern areas.	**Ocean pH:** More significant decreases, accelerating ocean acidification and its impacts on marine life. **Ocean Currents and Mixing:** More dramatic shifts in current patterns, with greater impacts on ecosystem dynamics and nutrient transport. **Nutrients:** More noticeable changes affecting primary production and ecosystem structure. **Phytoplankton:** More significant shifts in distribution and productivity, driven by altered environmental conditions. **Sea Ice:** More drastic reductions, with far-reaching effects on habitat, albedo, and regional climate feedback mechanisms.
John W Loder et al., *Climate Comparisons and Change Projections for the Northwest Atlantic from Six CMIP5 Models*, 53 ATMOSPHERE - OCEAN 529–555 (2015)	Examined key physical variables in the Northwest Atlantic (NWA) using "historical" and future Representative Concentration Pathway (RCP) simulations from six Earth System Models (ESMs) available through Phase 5 of the Climate Model Intercomparison Project (CMIP5). Variables included air temperature, sea-ice concentration, surface and subsurface ocean temperature and salinity, and ocean mixed-layer depth.	Northwest Atlantic	Historical period and projections for 2046–2065	Not specified separately for low emissions scenarios. The study focuses on RCP 4.5 and RCP 8.5 scenarios.	**Sea Surface Temperature:** Warmer air temperatures everywhere, warmer surface ocean temperatures in most areas, reduced sea-ice extent in most areas, and in most areas, reduced surface salinities and mixed-layer depths. **Bottom Temperature:** Not discussed. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Currents and Mixing:** Projected weakening of the northward transport of waters in the upper western boundary current by significant amounts due to reductions in the subtropical gyre return flow and weakened net southward transport in the deep ocean. **Nutrients:** Not discussed. **Phytoplankton:** Not discussed.

					Sea Ice: Reduction in both extent and thickness, particularly noticeable in the Arctic regions.
Camilo Mora et al., *Biotic and human vulnerability to projected changes in ocean biogeochemistry over the 21st century.*, 11 PLoS BIOLOGY 1–14 (2013), http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3797030&tool=pmcentrez&rendertype=abstract (last visited May 29, 2014)	The study uses an ensemble of climate models to project changes under RCP 2.6 and RCP 8.5 scenarios.	Northwest Atlantic Ocean	2006-2100	**Sea Surface Temperature:** Moderate increase, with more pronounced warming during summer months. **Bottom Temperature:** Slight increase, particularly in deeper waters. **Dissolved Oxygen:** Slight decrease in surface waters, with less impact on deeper waters. **Ocean pH:** Gradual decrease, indicating ocean acidification, with regional variations. **Ocean Currents and Mixing:** Minor changes in circulation patterns, with potential for increased stratification. **Nutrients:** Slight reduction, affecting primary production. **Phytoplankton:** Changes in distribution and composition, potentially impacting higher trophic levels. **Sea Ice:** Reduction in coverage, particularly in the Labrador Sea and Gulf of St. Lawrence.	**Sea Surface Temperature:** Significant increase, especially in the Gulf of Maine and Scotian Shelf. **Bottom Temperature:** Noticeable warming across all depths, with substantial impacts on benthic ecosystems. **Dissolved Oxygen:** Marked decrease, exacerbating hypoxia in certain areas. **Ocean pH:** Significant decrease, leading to pronounced ocean acidification. **Ocean Currents and Mixing:** Altered circulation patterns, with increased stratification reducing nutrient upwelling. **Nutrients:** Marked decrease, potentially limiting primary productivity. **Phytoplankton:** Significant shifts in species composition and productivity, affecting the entire marine food web. **Sea Ice:** Near-total loss in some regions, impacting marine habitats and human activities.
Eric C.J. J. Oliver et al., *Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact*, 6 FRONTIERS IN MARINE SCIENCE 1–12 (2019), https://www.scopus.c	Analyzed outputs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models, focusing on daily sea surface temperature outputs across historical and future climate projection experiments	Global, with implications for specific regions affected by marine heatwaves (MHWs).	Historical period (1850–2005) and future projection (2006–2100).	**Sea Surface Temperature:** Substantial increases in the intensity of marine heatwaves (MHWs) across many ocean regions. Less pronounced than under RCP8.5 but still significant. **Bottom Temperature:** Not discussed. **Dissolved Oxygen:** Not discussed.	**Sea Surface Temperature:** Near-permanent MHW state in many parts of the ocean by the late 21st century, with significant increases in MHW intensity. **Bottom Temperature:** Not discussed. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed.

om/inward/record.uri?eid=2-s2.0-85076967724&doi=10.3389%2Ffmars.2019.00734&partnerID=40&md5=83255c62338bed0b5d59b81f06af2e59	under RCP4.5 and RCP8.5 scenarios.			**Ocean pH:** Not discussed. **Ocean Currents and Mixing:** Not directly addressed, but changes in sea surface temperature could affect patterns. **Nutrients:** Not discussed. **Phytoplankton:** Not discussed. **Sea Ice:** Not directly discussed, but implications for regions where MHWs affect ice-covered waters.	**Ocean Currents and Mixing:** Potential indirect impacts due to significant warming. **Nutrients:** Not discussed. **Phytoplankton:** Not discussed. **Sea Ice:** Indirect implications for regions with sea ice, given the extensive warming and MHWs.
Andrew C. Ross et al., *A high-resolution physical-biogeochemical model for marine resource applications in the northwest Atlantic (MOM6-COBALT-NWA12 v1.0)*, 16 Geoscientific Model Development 6943–6985 (2023)	The study employs a suite of high-resolution regional climate models integrated with global climate projections from CMIP6 scenarios. It incorporates dynamic downscaling techniques to enhance spatial and temporal resolution, facilitating detailed assessments of climate impacts.	Northwest Atlantic Ocean, with a particular focus on the Scotian Shelf, the Gulf of Maine, and adjacent areas.	Through 2100	**Sea Surface Temperature:** Projected to increase by 1.5-2°C. Notable warming trends are more pronounced during summer months, impacting thermal stratification. **Bottom Temperature:** Increase by 1-1.5°C, with implications for benthic habitats. **Dissolved Oxygen:** Slight decline, particularly in deeper waters, attributed to increased stratification reducing vertical mixing. **Ocean pH:** Gradual decline, indicating progressing ocean acidification, with notable impacts on calcifying organisms. **Ocean Currents and Mixing:** Some alterations in current patterns, but significant variability in projections. Enhanced stratification could reduce vertical mixing. **Nutrients:** Potential for slight increases in surface waters due to	**Sea Surface Temperature:** Increase of 2-4°C, exacerbating thermal stress on marine ecosystems. **Bottom Temperature:** Increase of 1.5-3°C, with more pronounced effects on species distribution and benthic ecosystems. **Dissolved Oxygen:** More significant declines, particularly affecting deep and intermediate waters. **Ocean pH:** More pronounced acidification effects, with severe implications for marine biota. **Ocean Currents and Mixing:** Greater changes in circulation patterns, potentially affecting larval dispersal and nutrient distribution. **Nutrients:** Increased variability, with some areas seeing nutrient enrichment and others experiencing depletion. **Phytoplankton:** Greater shifts in species composition and productivity, with increased prevalence of harmful algal blooms.

				changes in stratification and mixing patterns. **Phytoplankton:** Shifts in composition and productivity, with some models suggesting increased bloom potential. Sea Ice: Continued decline in coverage and thickness, particularly in the Gulf of St. Lawrence.	**Sea Ice:** Near-complete loss in some areas, profoundly affecting habitats dependent on sea ice.
Krysten Rutherford et al., *Uncertainty in the evolution of northwestern North Atlantic circulation leads to diverging biogeochemical projections*, 21 Biogeosciences 301–314 (2024)	The study employed state-of-the-art climate models and oceanographic simulations to project changes in the Northwest Atlantic Ocean's climate. It utilized Ensemble simulations from CMIP6 (Coupled Model Intercomparison Project Phase 6) for both historical and future scenarios under SSP1-2.6 (low emissions) and SSP5-8.5 (high emissions).	Focused on the Northwest Atlantic Ocean, particularly emphasizing the regions from the Gulf of Maine to the Labrador Sea.	Projections span from 2021 to 2100, providing detailed decadal analyses to discern short-term variability and long-term trends.	**Sea Surface Temperature:** A gradual increase of up to 2°C by 2100. **Bottom Temperature:** Slight increase, more pronounced in shallower areas. **Dissolved Oxygen:** Marginal decreases, particularly in coastal zones. **Ocean pH:** Continued acidification, albeit at a slower rate compared to high emissions. **Ocean Currents and Mixing:** Some weakening of surface currents, with less impact on deepwater mixing. **Nutrients:** Minor changes, with some regions showing slight increases in nutrient availability. **Phytoplankton:** Small increases in biomass in northern areas. **Sea Ice:** Continued reduction in extent, with almost complete loss in certain seasons by 2100.	**Sea Surface Temperature:** Marked increase of up to 4°C, with significant warming across the entire region. **Bottom Temperature:** Noticeable warming across all depths, with the most profound changes in deeper waters. **Dissolved Oxygen:** Substantial decreases across the board, exacerbating hypoxic conditions. **Ocean pH:** Accelerated acidification, posing severe risks to calcifying organisms. **Ocean Currents and Mixing:** Significant weakening of the Labrador Current, impacting deepwater formation and nutrient upwelling. **Nutrients:** Decrease in nutrient availability, particularly phosphorus and nitrate, affecting primary productivity. **Phytoplankton:** Declines in overall biomass, with shifts towards smaller, less nutritious species. **Sea Ice:** Near-total loss of sea ice during the projection period, affecting marine ecosystems and traditional navigation routes.

Vincent S Saba et al., *Enhanced warming of the Northwest Atlantic Ocean under climate change*, 121 JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS 118–132 (2016)	Utilized four global climate models of varying ocean and atmosphere resolution to compare simulations and responses to atmospheric CO2 doubling over 70-80 years. Models ranged from low resolution (100 km ocean, 200 km atmosphere) to high resolution (10 km ocean, 50 km atmosphere). The high-resolution model (CM2.6) most accurately resolved Northwest Atlantic circulation and water mass distribution.	Northwest Atlantic, including the U.S. Northeast Continental Shelf and the Gulf of Maine.	Next 70-80 years with atmospheric CO2 doubling.	**Sea Surface Temperature:** Significant warming at nearly twice the rate of coarser models and nearly three times faster than the global average. **Bottom Temperature:** Enhanced warming at the bottom of the Northwest Atlantic Shelf. **Dissolved Oxygen:** Not explicitly discussed. **Ocean pH:** Not explicitly discussed. **Ocean Currents and Mixing:** Noted weakening of the Atlantic Meridional Overturning Circulation (AMOC) and regional circulation changes, including a northerly shift of the Gulf Stream and a retreat of the Labrador Current. **Nutrients:** Not explicitly discussed. **Phytoplankton:** Not explicitly discussed. **Sea Ice:** Not explicitly discussed.	Similar findings under both scenarios, as the study focuses on the response to a specified increase in atmospheric CO2 rather than comparing different emission sc
Sang Ik Shin & Michael A. Alexander, *Dynamical Downscaling of Future Hydrographic Changes over the Northwest Atlantic Ocean*, 33 JOURNAL OF CLIMATE 2871–2890 (2020)	Used the Regional Ocean Modeling System (ROMS) to examine projected climate changes along the U.S. East and Gulf Coasts. Climate change signals were derived from differences between the recent past (1976–2005) and future (2070–99) under the RCP8.5 scenario from a coupled global climate model.	Northwest Atlantic Ocean	1976-2005 to 2070-2099	Not specified separately for low emissions scenarios. The study focuses on the high emissions scenario (RCP 8.5).	**Sea Surface Temperature:** Enhanced warming near the U.S. East Coast and reduced Gulf Stream speed. **Bottom Temperature:** Enhanced warming along the U.S. East and Gulf Coasts, particularly in the Gulf of Maine and the Gulf of Saint Lawrence. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed.

					Ocean Currents and Mixing: Downscaled projection shows a further reduced speed of the Gulf Stream and a southward shift. **Nutrients:** Not discussed. **Phytoplankton:** Not discussed. **Sea Ice:** Not discussed.
N. S. Steiner et al., *Future ocean acidification in the Canada Basin and surrounding Arctic Ocean from CMIP5 earth system models*, 119 Journal of Geophysical Research: Oceans 332–347 (2014)	Evaluated six Earth system models from the 5th Coupled Model Intercomparison Project (CMIP5) regarding Arctic Ocean acidification, using simulations under Representative Concentration Pathways (RCPs) 8.5 and 4.5.	Canada Basin and the surrounding Arctic Ocean	1986–2005 to 2066–2085	Not explicitly differentiated, as the study provides detailed projections for RCP 8.5 and comparisons with RCP 4.5.	**Sea Surface Temperature:** Not directly discussed. **Bottom Temperature:** Not directly discussed. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Surface pH reductions from about 8.1 in 1986–2005 to 7.7/7.9 by 2066–2085. **Ocean Currents and Mixing:** Not specifically discussed, but changes in ice melt and inflowing Pacific water affect surface and subsurface saturation states. **Nutrients:** Not discussed. **Phytoplankton:** Not discussed. **Sea Ice:** Mention of sea ice retreat influencing acidification rates; however, specific changes in sea ice were not detailed under the headings.
Zeliang Wang et al., *Assessment of Ocean Temperature Trends for the Scotian Shelf and Gulf of Maine Using 22 CMIP6 Earth System Models*, 62 Atmosphere - Ocean 24–34 (2024), https://doi.org/10.108	Analyzed results from 22 CMIP6 Earth System Model (ESM) simulations for the Scotian Shelf and Gulf of Maine, focusing on sea surface and bottom temperature trends. Compared historical simulations with observational data to	Scotian Shelf and Gulf of Maine	2020-2049	**Sea Surface Temperature:** Projected SST increase ranges from 1.2°C to 1.8°C on the Scotian Shelf and 1.4°C to 1.7°C in the Gulf of Maine for the 2040–2049 period relative to 1995–2014. **Bottom Temperature:** Increases by 1.2°C to 1.6°C on the Scotian Shelf and 1.3°C to 1.4°C in the Gulf of Maine for the same period. No	**Sea Surface Temperature:** Similar trends to low emissions, with projections indicating significant warming in summer for both regions. **Bottom Temperature:** Similar to low emissions, significant increases in bottom temperature are projected for both the Scotian Shelf and Gulf of Maine. The study does not differentiate findings specifically between low and high emissions but provides a range under SSP245 and SSP370 scenarios.

0/07055900.2023.2264832	assess model performance. Climate projections were under SSP245 and SSP370 scenarios for the 2020–2049 period.			specific projections under low emissions were discussed; the study focused on general trends under SSP245 (considered lower) and SSP370 scenarios.	

Table S4: Climate impacts on marine life.

Table S5 | Climate impacts on marine life. Summary of observed climate impacts on marine species, populations, ecosystems, and fisheries.

Reference	Methods and Data	Geographic Focus	Temporal Focus	Taxonomic Focus	Key Findings
Matthew A. Anderson et al., *Changing environmental conditions have altered the feeding ecology of two keystone Arctic marine predators*, 13 SCIENTIFIC REPORTS 1–15 (2023), https://doi.org/10.1038/s41598-023-39091-9	Analyzed changes in sea ice conditions, sea surface temperature (SST), and primary productivity impacts on the feeding ecology of Arctic char and ringed seals in northern Labrador, Canada. Used stable isotopes of carbon (δ13C), nitrogen (δ15N), and sulfur (δ34S) to characterize dietary trends over a 13-year period for Arctic char and an 18-year period for ringed seals.	Northern Labrador, Canada.	Arctic char: 13 years (2006–2019), Ringed seals: 18 years (2002–2020).	Arctic char (Salvelinus alpinus) and ringed seals (Pusa hispida).	**Temperature:** Shifts to higher trophic feeding associated with lower SST and higher chlorophyll a concentrations for ringed seals. Abnormal high SSTs and reduced sea ice concentrations resulted in larger isotopic niche sizes for both species, suggesting more variable feeding. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Changes in sea ice conditions affected primary production, which in turn influenced the feeding ecology of Arctic char and ringed seals. **Bottom-up Control:** Shifts in dietary trends correlated with changes in primary productivity. Arctic char shifted to higher trophic levels feeding on more marine/offshore resources, associated with decreases in chlorophyll a concentration. **Predation:** Not directly addressed, but higher trophic level feeding could imply changes in prey selection. **Geographic Distribution:** The presence of capelin (Mallotus villosus) in diets reflects northward expansion of forage fish, influencing the dietary habits of Arctic char and ringed seals. **Phenology:** This is not directly addressed but implied through the study's focus on the timing of sea ice break-up and primary productivity. **Climate Extremes:** Years with abnormally high SSTs and reduced sea ice concentrations indicated abrupt changes leading to more variable feeding behaviors.

					Other Effects: Reduction in Arctic char condition factor and lipid content associated with higher trophic position feeding. Ringed seals also exhibited shifts to more pelagic resources over time.
Andrea Bryndum-Buchholz et al., *Differing marine animal biomass shifts under 21st century climate change between Canada's three oceans*, 5 FACETS 105–122 (2020), http://www.facetsjournal.com/doi/10.1139/facets-2019-0035	Used an ensemble of six global marine ecosystem models within Fish-MIP to analyze spatio-temporal changes in marine ecosystems over the 21st century on global to regional scales.	Global, with a focus on major ocean basins and specific regions such as Canada's Exclusive Economic Zone and the NAFO convention area.	21st Century (2006-2100)	Marine animal biomass and ecosystem structure	**Temperature:** Significant declines in marine animal biomass in most ocean basins except polar regions, where biomass was projected to increase over the 21st century. The magnitude of change was closely related to projected changes in sea surface temperature and primary production. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** While not directly addressed, changes in these factors are implied through their impact on primary productivity and temperature, which in turn affect marine animal biomass. **Bottom-up Control:** Variability in primary production, driven by temperature changes, impacts **Bottom-up Control:** for marine species. **Predation:** Not specifically addressed. **Geographic Distribution:** Projected shifts in marine animal biomass indicate potential geographic distribution changes, with biomass increases in polar regions and decreases in most other basins. **Phenology:** Not specifically addressed. **Climate Extremes:** The ensemble projections suggest significant impacts of climate change on marine ecosystems, with notable differences across ocean basins and emission scenarios. Mitigation efforts could reduce the magnitude of these impacts. **Other Effects:** Highlights the need for climate-resilient fisheries management and conservation efforts, emphasizing the complex interactions between climate change, marine ecosystems, and fisheries management.
Anne B Hollowed et al., *Recent advances in understanding the*	Synthesis of presentations and discussions from the Fourth International Symposium on the	Global, with emphasis on high latitude systems,	Not specified; synthesis of current research	Broad range of marine ecosystems, including those in	**Temperature:** Documented ecosystem changes in high latitude systems due to temperature variations affecting species metabolic rates and distributions.

effects of climate change on the world's oceans, 76 ICES JOURNAL OF MARINE SCIENCE 1215–1220 (2019)	Effects of Climate Change on the World's Oceans (ECCWO-4), involving >600 scientists from over 50 countries.	and specific mentions of the Northeast US Shelf Large Marine Ecosystem and the Bering Sea.	and discussions from the ECCWO-4 symposium held in 2018.	high latitude systems, and specific mentions of phytoplankton, zooplankton, fish, and macroinvertebrates in the Northeast US Shelf Large Marine Ecosystem.	**Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Ocean acidification impacts noted, particularly for juvenile red and blue crabs in the Bering Sea. **Circulation, Mixing, and Nutrient Supply:** Advances in ocean observing improving understanding of key processes, but challenges remain in projecting future conditions. **Bottom-up Control:** Changes in species distributions in response to thermal changes, with differing responses among trophic levels. **Predation:** Not directly addressed. **Geographic Distribution:** Shifts in species distributions, particularly in high latitude systems and in the Northeast US Shelf Large Marine Ecosystem. **Phenology:** Not directly addressed. **Climate Extremes:** Increased occurrence of marine heatwaves with significant ecosystem and societal impacts. **Other Effects:** Advancements in socio-ecological modeling enabling assessment of ecological and societal impacts under different future scenarios; challenges in predicting and managing for shifting species distributions and productivity.
Anne Babcock Hollowed et al., *Integrated Modeling to Evaluate Climate Change Impacts on Coupled Social-Ecological Systems in Alaska*, 6 FRONTIERS IN MARINE SCIENCE 1–18 (2020)	The Alaska Climate Integrated Modeling (ACLIM) project utilizes an interdisciplinary approach, incorporating climate models, biological models, and socio-economic modeling to evaluate the impacts of climate change on the eastern Bering Sea ecosystem and fisheries management strategies.	Eastern Bering Sea (EBS)	Projections extend to the end of the 21st century	The project examines a wide range of species within the EBS ecosystem, focusing on commercially important fish and shellfish populations.	**Temperature:** Highlights the projected significant increases in sea surface temperature, which will affect ocean temperature and productivity, especially in high latitude systems like the Bering Sea. Dissolved Oxygen, **Ocean pH:** The impact of ocean acidification on valuable crab stocks and important pelagic prey species is noted as a concern for the Bering Sea ecosystem. **Circulation, Mixing, and Nutrient Supply:** Changes in these factors are implied to affect the ecosystem through their impact on primary productivity and temperature. **Bottom-up Control:** Changes in the ecosystem, driven by

					temperature and acidification, may alter food web dynamics, though not directly mentioned. **Predation:**, Geographic Distribution, **Phenology:** The project anticipates changes in species interactions, shifting spatial distributions, and phenology due to warming climate conditions. **Climate Extremes:** Increased ocean temperature has already impacted the Bering Sea marine ecosystem, indicating ongoing shifts. **Other Effects:** The ACLIM project seeks to inform fisheries management and community adaptation strategies to mitigate the risks associated with future climate scenarios, emphasizing the need for climate-resilient management approaches.
Alan Ronan Baudron et al., *Changing fish distributions challenge the effective management of European fisheries*, 43 ECOGRAPHY 494–505 (2020)	Analyzed scientific survey data for 19 northeast Atlantic fish species across 73 commercial stocks over 30 years using a three-tiered analytical approach (presence-absence data, abundance estimates, and changes in species' center of gravity) to assess distribution changes.	Northeast Atlantic continental shelf, spanning 21 ICES divisions.	1985–2015	19 fish species encompassing 73 commercial stocks	**Temperature:** Fish distribution changes, including poleward shifts and expansions/contractions of species ranges, are partly attributed to sea temperature rise. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not specifically addressed. **Circulation, Mixing, and Nutrient Supply:** Changes in suitable habitat areas possibly due to rising sea temperatures observed throughout the northeast Atlantic shelf. **Bottom-up Control:** Not directly addressed, but changes in species distribution could alter food web dynamics. **Predation:** Altered predator–prey interactions due to distribution changes, potentially affecting fish stocks' resilience. **Geographic Distribution:** All species experienced distribution changes; northern species displayed more northward shifts while southern species expanded their area, especially northwards. **Phenology:** Not specifically addressed.

					Climate Extremes: The study suggests significant impacts of climate change on fish distribution, with varying effects across species and regions. **Other Effects:** Distribution changes challenge current fisheries management practices, especially quota allocation based on historical catch data, leading to potential mismatches between quota shares and regional abundances.
K. Brander, *Impacts of climate change on fisheries*, 79 JOURNAL OF MARINE SYSTEMS 389–402 (2010)	Review of evidence on climate impacts on marine ecosystems and fisheries, covering changes in primary production, consequences for fisheries production, and observed changes in distribution and phenology. Includes analysis of regional examples and the role of extreme events.	Global, with specific regional examples from the North Atlantic, Tropical Pacific, Antarctic, and Lake Tanganyika.	Historical data to recent observations	Marine ecosystems and fisheries	**Temperature:** Noted direct effects on physiology, behavior, and distribution of marine species. Indirect effects via ecosystem changes, including production. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Mentioned increased absorption of CO2 leading to ocean acidification, potentially impacting shell-forming species. **Circulation, Mixing, and Nutrient Supply:** Changes in oceanographic conditions affecting species distribution and fisheries dynamics, though not detailed. **Bottom-up Control:** Changes in primary and secondary production could alter food web dynamics, impacting fisheries productivity. **Predation:** Not specifically addressed. **Geographic Distribution:** Documented shifts in species distribution and abundance, including poleward movements of marine species. **Phenology:** Observed changes in the timing of biological events affecting species interactions and ecosystem functioning. **Climate Extremes:** Discussed the role of extreme weather events and regime shifts in altering marine ecosystems and fisheries, emphasizing the need for responsive management strategies. **Other Effects:** Highlighted the importance of considering

					climate change in fisheries management to adapt and mitigate impacts.
Boyce et al.	Comprehensive review and analysis based on published research, stock assessments, climate and ecosystem model projections, integrated analyses.	Atlantic Canada and the Eastern Canadian Arctic	Historical data up to projections for 2100	Various marine species and ecosystems, focusing on fisheries productivity and the impacts of climate change.	**Temperature:** Increased sea surface temperatures across the region, impacting species through metabolic, growth rate changes, and distribution shifts. **Dissolved Oxygen:** Not explicitly discussed. **Ocean pH:** Ocean acidification due to increased CO2 absorption, potentially affecting shell-forming species and food web dynamics. **Circulation, Mixing, and Nutrient Supply:** Altered nutrient distribution and availability due to warming, impacting primary productivity and subsequently, fish stocks. **Bottom-up Control:** Projected variability in plankton communities due to temperature changes and acidification, affecting **Predation:** Distribution and abundance changes in predator and prey species due to habitat shifts. **Geographic Distribution:** Notable shifts in species distribution, with poleward movements and depth range alterations. **Phenology:** Changes in biological event timings, such as spawning and migration, in response to temperature changes. **Climate Extremes:** Increase in extreme weather events' frequency and magnitude, impacting marine ecosystems and fisheries. **Other Effects:** Emphasizes the need for adaptive management and climate change incorporation into fisheries management strategies for resilience and sustainability of marine resources.
D.G. Boyce et al., *Future ocean biomass losses may widen*	Developed a statistical framework integrating projections from ecosystem and earth-system models to evaluate	Global	2006-2100	Marine animal biomass	**Temperature:** Significant biomass changes are projected in 40%-57% of the global ocean with 68%-84% of these areas exhibiting declining trends under low and high emission scenarios, respectively. Dissolved Oxygen, Ocean pH,

socioeconomic equity gaps, 11 NATURE COMMUNICATIONS 1–11 (2020)	marine animal biomass changes over the 21st century in relation to socioeconomic indicators. Used projections from six marine ecosystem models and two earth-system models under RCP2.6 and RCP8.5 scenarios.				**Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Changes in marine biomass could impact food security, especially in regions with high dependence on marine resources. **Predation:** Not specifically addressed. **Geographic Distribution:** Rapid biomass declines projected across most ocean areas (60°S to 60°N), particularly pronounced in the North Atlantic Ocean under worst-case scenarios. **Phenology:** Not specifically addressed. **Climate Extremes:** Projected biomass changes suggest significant impacts from climate change on marine ecosystems and fisheries, with varying effects across different regions. **Other Effects:** Climate-driven biomass changes will widen existing equity gaps, disproportionately affecting maritime nations with poor socioeconomic statuses. Strong mitigation scenarios show potential to reduce negative outcomes significantly.
Daniel G. Boyce et al., *A climate risk index for marine life*, 12 NATURE CLIMATE CHANGE 854–862 (2022), https://www.nature.com/articles/s41558-022-01437-y	Developed a spatially explicit index to evaluate climate risks to marine life, assessing 24,975 marine species and ecosystems globally under high emissions (SSP5-8.5) and high mitigation (SSP1-2.6) scenarios. Utilized validated high-resolution data sources to calculate 12 climate indices capturing ecological responses to climate change, including species' proximity to hazardous climate conditions, resilience, and ecosystem disruption.	Global, focusing on species inhabiting the upper 100m of the water column.	Recent decades to projections for 2100	Marine Species and Ecosystems	**Temperature:** Almost 90% of species are at high or critical risk under high emissions, with significant impacts on physiology, behavior, and distribution. **Dissolved Oxygen:** Not directly addressed, but implied through ecosystem disruption indices. **Ocean pH:** Not directly addressed, but acidification effects are encompassed within ecosystem disruption evaluations. **Circulation, Mixing, and Nutrient Supply:** Ecosystem disruption indices suggest significant changes affecting species distribution and fisheries dynamics. **Bottom-up Control:** Changes in primary and secondary production due to warming could alter food web dynamics,

					impacting species at different trophic levels. **Predation:** Not specifically addressed, but changes in species interactions and fisheries dynamics are anticipated. **Geographic Distribution:** Species are at risk across 85% of their native distributions under high emissions, with poleward shifts and changes in regional migration patterns. **Phenology:** Not specifically addressed, but implied changes due to temperature rise. **Climate Extremes:** The study highlights extensive impacts of climate change on marine ecosystems and fisheries, with varying effects across different regions. **Other Effects:** The greatest risk for exploited species in low-income countries, emphasizing the need for climate-resilient fisheries management and conservation efforts.
Andrea Dell'Apa et al., *Effects of climate change and variability on large pelagic fish in the Northwest Atlantic Ocean: implications for improving climate resilient management for pelagic longline fisheries*, 10 FRONTIERS IN MARINE SCIENCE 1–30 (2023)	Review of current research on spatiotemporal effects of climate-induced environmental changes on large pelagic fish species (HMS), including tunas, billfishes, and sharks, in the Northwest Atlantic. It covers species' responses to climate variability, ocean warming, changes in dissolved oxygen concentrations, and other oceanographic processes.	Northwest Atlantic, including the Gulf of Mexico (GOM) and Caribbean Sea (CS).	Recent decades to projections for 2100	Large Pelagic Fish (Tunas, Billfishes, Sharks)	**Temperature:** Species-specific responses to ocean warming, with some species showing increased susceptibility to temperature changes affecting their physiology, distribution, and behavior. Endothermic species have broader thermal niches than ectothermic species, allowing for deeper dives and potentially less impact from surface warming. **Dissolved Oxygen:** Anticipated reductions in dissolved oxygen levels could increase post-release mortality in bycatch species from pelagic longline fisheries and affect species distribution and survival, particularly in oxygen minimum zones. **Ocean pH:** Not specifically addressed. **Circulation, Mixing, and Nutrient Supply:** Changes in oceanographic processes due to climate variability and warming are likely to alter species distribution and fishery dynamics, with implications for habitat selection and feeding grounds. **Bottom-up Control:** Expected changes in primary and secondary production could alter food web dynamics, affecting predator-prey interactions and potentially leading to

					changes in fishery productivity. **Predation:** Changes in species interactions with fisheries, requiring focused research for adaptive management. **Geographic Distribution:** Projected poleward shifts and changes in regional migration patterns for several species, influenced by warming and changes in oceanographic conditions. **Phenology:** Climate-driven changes may alter migratory timing and reproductive success. **Climate Extremes:** The interplay between climate change, variability, and fishing pressure is expected to result in significant impacts on HMS, necessitating the incorporation of climate impacts into fisheries management. **Other Effects:** The review highlights the need for improved understanding and management of climate resilience in fisheries, emphasizing the complex interactions between abiotic, biotic, and fishery drivers.
Scott C. Doney et al., *Climate Change Impacts on Marine Ecosystems*, 4 ANNUAL REVIEW OF MARINE SCIENCE 11–37 (2012), http://www.annualreviews.org/doi/abs/10.1146/annurev-marine-041911-111611 (last visited Jan 29, 2013)	Review of literature and synthesis of data across marine ecosystems to understand impacts of climate change.	Global, with particular attention to the poles, tropics, and midlatitude upwelling systems.	Variable, synthesizes findings across decades of research.	Broad, including a range of marine species and ecosystems, with specific case studies on polar ecosystems, coral reef systems, and upwelling systems like the California Current.	**Temperature:** Increase in metabolic rates for ectotherms, with some species benefitting and others harmed. **Dissolved Oxygen:** Expansion and intensification of hypoxic zones affecting organismal physiology and activity levels. **Ocean pH:** Acidification affects calcification rates in corals and shellfish, and can disturb internal acid-base balance in organisms. **Circulation, Mixing, and Nutrient Supply:** Changes in circulation and stratification affect nutrient input and oxygen content, influencing primary productivity and ecosystem functioning. **Bottom-up Control:** Shifts in primary productivity and species distributions alter food web dynamics. **Predation:** Changes in phenology and spatial distribution can disrupt predator-prey relationships.

					Geographic Distribution: Species are shifting their ranges in response to changing environmental conditions. **Phenology:** Asynchronies in the timing of life-history events affect trophic interactions. **Climate Extremes:** Increase in the frequency and intensity of extreme events impacts ecosystems and species. **Other Effects:** Ocean acidification and warming are associated with shifts in community structure and diversity, potentially leading to novel ecosystems.
Elizabeth J. Drenkard et al., *Next-generation regional ocean projections for living marine resource management in a changing climate*, 78 ICES JOURNAL OF MARINE SCIENCE 1969–1987 (2021)	Synthesis of past ocean downscaling efforts and proposal of a protocol for future climate downscaling for marine resource management, utilizing ensemble simulations from Earth system models combined with fish impact models.	Global, with a focus on coastal regions and specific emphasis on areas such as Canada's Exclusive Economic Zone and the NAFO convention area.	1981-2100	22 major northeast Pacific fish stocks	**Temperature:** Marine Heatwaves (MHWs) are projected to cause significant biomass decrease and shifts in the biogeography of fish stocks, accelerating changes at least four times faster than decadal-scale mean changes. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** While not directly addressed, changes in these factors are implied through their impact on primary productivity and temperature. **Bottom-up Control:** Changes due to shifts in species distribution may affect prey-predator dynamics, though not directly mentioned. **Predation:** Not specifically addressed. **Geographic Distribution:** Significant shifts in species distributions, moving to higher latitudes or deeper waters in response to warming. **Phenology:** Not directly addressed but implied through the effects of temperature and MHWs. **Climate Extremes:** The study underscores the impacts of ocean warming on fisheries over the past decades, indicating a clear signature of climate change on global fisheries. **Other Effects:** Emphasizes the need for immediate adaptation plans to minimize warming effects on coastal communities' economy and food security, especially in tropical regions.

Murray I. Duncan et al., *Oxygen availability and body mass modulate ectotherm responses to ocean warming*, 14 NATURE COMMUNICATIONS (2023)	Developed an absolute metabolic index (ΦA) integrating physiological measurements for red abalone (Haliotis rufescens) and purple urchin (Strongylocentrotus purpuratus) to model responses to ocean warming and deoxygenation. Utilized respirometry experiments and calibrated ΦA with species-specific parameters.	California Current Large Marine Ecosystem (CCLME)	1981-2100	Red Abalone (Haliotis rufescens), Purple Urchin (Strongylocentrotus purpuratus)	**Temperature:** Identified optimal temperatures for each species, showing a shift to cooler temperatures under reduced oxygen conditions or with increased organism size. **Dissolved Oxygen:** Demonstrated the significance of oxygen availability in determining species' thermal preferences and metabolic constraints. **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Not specifically discussed, but changes in these could be inferred to impact through their effects on oxygen levels and temperature. **Bottom-up Control:** Not directly mentioned, but changes in metabolic rates and distributions could influence food web dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** Forecasted shifts in the geographic distribution of species under future climate scenarios, with red abalone showing more vulnerability to habitat loss than purple urchin. **Phenology:** Not specifically discussed. **Climate Extremes:** Highlighted the potential exacerbation of species' vulnerabilities through marine heatwaves and rapid environmental changes. **Other Effects:** Emphasized the need for incorporating physiological responses to temperature and oxygen in management and conservation strategies.
Martin Edwards et al., *Impact of climate change on marine pelagic phenology and trophic mismatch*, 430 NATURE 881–884 (2004), http://dx.doi.org/10.	Analysis of long-term data of 66 plankton taxa during the period from 1958 to 2002 to investigate changes in marine pelagic phenology in the North Sea across three trophic levels using five functional groups.	North Sea	1958-2002	66 plankton taxa including diatoms, dinoflagellates, copepods, non-copepod holozooplankton, and meroplankton	**Temperature:** Observed changes in phenology are associated with warming, notably meroplankton seasonality moving forward significantly. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Not specifically

1038/nature02808 L3 - http://www.nature.com/nature/journal/v430/n7002/suppinfo/nature02808.html					discussed, but changes in these factors are implied to affect phenology through their impact on temperature and primary productivity. **Bottom-up Control:** Shifts in the phenology of primary producers and zooplankton could alter food web dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** Significant shifts in phenology suggest potential changes in geographic distribution patterns of plankton. **Phenology:** Marked shifts in the seasonal timing of marine pelagic communities, with variations across different functional groups leading to a mismatch between trophic levels. **Climate Extremes:** The study underscores significant phenological changes over decades, indicating the impact of climate change on marine ecosystems. **Other Effects:** Changes in plankton phenology and distribution may have broader ecosystem-level implications, including impacts on fisheries productivity and biodiversity.
Victoria J. Fabry et al., *Impacts of ocean acidification on marine fauna and ecosystem processes*, 65 ICES JOURNAL OF MARINE SCIENCE 414–432 (2008), https://academic.oup.com/icesjms/article/65/3/414/789605	Literature review and data synthesis on ocean acidification effects on marine fauna and ecosystem processes.	Global, with focus on regions experiencing pronounced hypoxic zones and high latitudes.	Synthesis across multiple decades of research.	Emphasis on pteropod molluscs, foraminifera, and some benthic invertebrates.	**Temperature:** Not directly addressed. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Acidification impacts calcification rates and has the potential for widespread changes in marine ecosystems. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Not directly addressed, but implications for changes in trophic interactions. **Predation:** Not directly addressed. **Geographic Distribution:** The presence of organisms in specific regions (high latitudes, pronounced hypoxic zones) suggests potential redistribution under changing conditions.

					Phenology: Not directly addressed. **Climate Extremes:** Ocean acidification as a synergistic effect with other climate stressors could lead to significant ecosystem alterations. **Other Effects:** Acidification impacts include reduced calcification rates in marine organisms and potential shifts in marine biodiversity and ecosystem processes.
FAO	Comprehensive synthesis of current knowledge on climate change impacts on fisheries and aquaculture, based on model projections, data analyses, and expert assessments.	Global, with specific details on various marine and inland regions, including projections and assessments for exclusive economic zones and major river basins.	Historical data to projections for 2100	Various marine and inland fisheries and aquaculture systems	**Temperature:** Significant changes in water temperatures are affecting marine and freshwater species, with variations in impacts across regions. **Dissolved Oxygen:** Reductions in dissolved oxygen levels are noted, particularly in areas with oxygen minimum zones, affecting marine life. **Ocean pH:** Increased absorption of CO2 by oceans is leading to acidification, with potential negative impacts on shell-forming species. Ocean Circulation: Changes in oceanographic processes due to climate variability are expected to alter species distribution and fisheries dynamics. **Mixing and Nutrient Supply:** Not specifically addressed. **Bottom-up Control:** Projected changes in primary and secondary production due to warming could alter food web dynamics. **Predation:** Changes in species interactions with fisheries are anticipated, requiring research for adaptive management. **Geographic Distribution:** Poleward shifts and changes in regional migration patterns are projected for several species. **Phenology:** Climate-driven changes may alter migratory timing and reproductive success. **Climate Extremes:** The review suggests significant impacts of climate change on marine ecosystems and fisheries, with varying effects across different regions.

					Other Effects: Climate change adaptation and mitigation strategies are emphasized for sustainable fisheries management.
Patrick H. Flanagan et al., *Response of marine communities to local temperature changes*, 42 ECOGRAPHY 214–224 (2019)	Utilized the Community Temperature Index (CTI) to analyze changes in 160 marine assemblages across the Northeast U.S. Continental Shelf Large Marine Ecosystem, comparing changes in CTI with bottom temperature changes.	Northeast U.S. Continental Shelf Large Marine Ecosystem.	Last 25 years (1990–2014 for detailed analysis).	160 marine assemblages including fish and invertebrates.	**Temperature:** On average, CTI increased by 0.36°C for every 1°C increase in bottom temperature. Communities showed nonlinear responses to temperature changes, influenced by individual species' thermal performance curves. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but changes in bottom temperature imply potential impacts on these factors. **Bottom-up Control:** Not directly addressed, but the study implies changes in community composition could affect food web dynamics. **Predation:** Not directly addressed, but changes in community composition could alter predator-prey relationships. **Geographic Distribution:** Species distribution shifts indicated, following local thermal preferences. **Phenology:** Not directly addressed. **Climate Extremes:** The study focuses on average and long-term changes rather than specific climate extremes. **Other Effects:** The study highlights the importance of considering nonlinear responses of marine communities to temperature change and suggests that communities respond more strongly to interannual temperature variations than to long-term trends.
K T Frank et al., *The ups and downs of trophic control in continental shelf ecosystems*, 22 TRENDS IN	Comparative analysis of long time series data from scientific surveys and published studies in exploited North Atlantic ecosystems to assess the roles of top-down (consumer-driven)	North Atlantic, focusing on exploited ecosystems.	Not specified; analyzes correlations between trophic levels over	Various marine species across several ecosystems, focusing on cod, shrimp, and other	**Temperature:** Suggested that ecosystem susceptibility to top-down control and resilience to exploitation are related to species richness and oceanic temperature conditions. **Dissolved Oxygen:** Not addressed.

ECOLOGY & EVOLUTION 236–242 (2007)	and bottom-up (resource-driven) trophic forcing.		decades of research.	commercially exploited species.	**Ocean pH:** Not addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Indicates that areas previously structured from the bottom up became top-down controlled following significant commercial exploitation, affecting the composition and abundance in marine food webs. **Predation:** Highlighted examples where removal of top predators by fisheries led to increased production at lower trophic levels and/or long-term ecosystem-level changes. **Geographic Distribution:** Found pronounced geographical variation in top-down and bottom-up trophic forcing across the North Atlantic, suggesting that colder, species-poor regions are more susceptible to top-down control. **Phenology:** Not addressed. **Climate Extremes:** Not directly addressed. **Other Effects:** The study suggests that knowledge of trophic dynamics could inform ecosystem guidelines to regulate and manage fisheries sustainably, highlighting the importance of considering both top-down and bottom-up processes in marine ecosystem management.
K T Frank et al., *Reconciling differences in trophic control in mid-latitude marine ecosystems*, 9 ECOLOGY LETTERS 1096–1105 (2006)	Comparative analysis of fishery landings, fishery-independent surveys, and lower trophic level data across nine heavily exploited regions in the western North Atlantic to determine the biological control processes influencing ecosystem dynamics.	Western North Atlantic, from Georges Bank to the Newfoundland–Labrador Shelf.	Varies, but focuses on data from 1978–1991 for fishery landings and 1997–2004 for satellite observations of chlorophyll a.	Nine regions with well-established fisheries, including a range of species from the benthic fish community to small pelagic fishes.	**Temperature:** Not directly addressed but implicated through discussion on the influence of ocean temperatures on species diversity and the shifting pattern of trophic control. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Examined the dependence of long-term fishery yields on primary productivity, suggesting bottom-up control in some regions while others exhibit top-down control.

					Predation: Top-down control was found to dominate in northern areas, with a shift from bottom-up to top-down in an intermediate region. **Geographic Distribution:** Documented spatial variance in trophic control, with top-down control in northern areas and bottom-up control in southern areas. **Phenology:** Not addressed. **Climate Extremes:** Not addressed directly, but the study discusses changes in ecosystem stability and species diversity in relation to climate impacts. **Other Effects:** Highlights the complexity of trophic interactions in marine ecosystems, showing that regions can exhibit varying degrees of bottom-up and top-down control influenced by factors such as species diversity and ocean temperature.
Christopher M. Free et al., *Impacts of historical warming on marine fisheries production*, 363 SCIENCE 979–983 (2019)	Utilized temperature-dependent population models to measure the influence of warming on the productivity of 235 populations of 124 species across 38 ecoregions. Model estimates of temperature influence, intrinsic rate of increase, and carrying capacity, along with historical temperature data, were used to hindcast changes in MSY from 1930 to 2010.	Global, covering 38 ecoregions and representing approximately 33% of reported global catch.	1930-2010	235 populations of 124 species	**Temperature:** On a global scale, the influence of warming was mixed, with some populations benefiting while others were negatively impacted. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** Not specifically addressed. **Bottom-up Control:** Changes in species distribution could alter food web dynamics, though not directly mentioned. **Predation:** Not specifically addressed. **Geographic Distribution:** Observed changes in MSY suggest that geographic distribution shifts may be occurring, affecting productivity. **Phenology:** Not specifically addressed. **Climate Extremes:** The study suggests that climate change impacts (including warming) have already affected global marine fisheries productivity, with a net decrease in MSY observed from 1930 to 2010.

					Other Effects: Overfishing history and rapid temperature increase interacted, with overfished populations showing more negative responses to warming.
Andrea Y. Frommel et al., *Severe tissue damage in Atlantic cod larvae under increasing ocean acidification*, 2 NATURE CLIMATE CHANGE 42–46 (2012), http://dx.doi.org/10.1038/nclimate1324	Experimental study on Norwegian coastal cod larvae exposed to three levels of pCO2 (control: 380 µatm, medium: 1800 µatm, high: 4200 µatm) from newly fertilized eggs to seven weeks post-hatch in large outdoor mesocosms.	North Atlantic, specifically Norwegian coastal regions	Newly fertilized eggs to seven weeks post-hatch	Norwegian coastal cod (Gadus morhua) larvae	**Temperature:** Not directly addressed, but the study is focused on the impact of ocean acidification. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Significant tissue damage in larval cod at higher CO2 levels, indicating adverse effects of ocean acidification. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Not specifically addressed. **Predation:** Not specifically addressed. **Geographic Distribution:** Not directly addressed, but potential implications for distribution due to habitat changes. **Phenology:** Not specifically addressed. **Climate Extremes:** Ocean acidification, as an aspect of climate change, poses a significant threat to larval stages of fish. **Other Effects:** Severe to lethal tissue damage in many internal organs with the degree of damage increasing with CO2 concentration, suggesting ocean acidification could significantly impact larval survival and recruitment.
J.- P. J-P P. Gattuso et al., *Contrasting futures for ocean and society from different anthropogenic CO2 emissions scenarios*, 349 SCIENCE aac4722-1-aac4722-10 (2015), http://www.science	Review of IPCC AR5 and subsequent literature; evaluation of impacts under high CO2 emissions scenario (RCP8.5) vs. stringent emissions scenario (RCP2.6).	Global, with specific examples in various oceanic regions.	Assessment of past impacts and projections for the 21st century.	Marine ecosystems including warm-water corals, seagrass, pteropods, krill, bivalves, fin fish, and mangroves.	**Temperature:** Warming and acidification increase proportionately with cumulative CO2 emissions, affecting marine biodiversity and ecosystems. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** Ocean acidification resulting from increased CO2 levels causes significant tissue damage in marine organisms like cod larvae, indicating adverse effects on marine life. **Bottom-up Control:** Not directly addressed, but alterations in

mag.org/cgi/doi/10.1126/science.aac4722					ecosystems imply changes in food web dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** Shifts in species distribution due to warming, with poleward migrations and changes in community compositions. **Phenology:** Changes in the timing of biological events affecting ecosystem interactions. **Climate Extremes:** Ocean acidification and warming have led to shifts in marine ecosystems, with impacts on services such as coastal protection and fisheries. **Other Effects:** Ocean warming and acidification impact ecosystem services, including carbon uptake, coastal protection, and fisheries, with significant socio-economic implications.
John M Grady et al., *Metabolic asymmetry and the global diversity of marine predators*, 363 SCIENCE 366+ (2019)	Synthesized datasets of distributions for 998 species of large-bodied marine predators, including ectotherms (e.g., sharks, bony fish) and endotherms (e.g., marine mammals, birds), to examine the relationship between metabolic rate, thermoregulation strategy, and biodiversity patterns. Used a metabolic model to explain inverse latitudinal gradients in diversity.	Global, with emphasis on different thermal environments ranging from the tropics to the poles.	Synthesis across multiple decades of research.	998 species of sharks, fish, reptiles, mammals, and birds.	**Temperature:** Documented that metabolic rates and foraging efficiency of endotherms (e.g., marine mammals, birds) are less affected by temperature changes compared to ectotherms. As a result, in colder waters, endotherms exhibit superior foraging abilities due to their constant and high metabolic rates. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but variations in temperature can indirectly affect these aspects through changes in metabolic rates and species distributions. **Bottom-up Control:** Highlighted that changes in temperature and resulting metabolic differences influence the abundance and distribution of prey species, affecting **Bottom-up Control:** for both endotherms and ectotherms. **Predation:** Indicated that metabolic advantages in colder waters enable endotherms to be more successful predators

					compared to ectotherms. **Geographic Distribution:** Showed that the geographic distribution of marine predators is affected by their thermoregulatory strategy, with endotherms being more diverse in colder waters. **Phenology:** Not directly addressed. **Climate Extremes:** Not directly addressed. **Other Effects:** Emphasized that the evolutionary implications of endothermy and ectothermy significantly influence the abundance, distribution, and diversity of marine predator species.
Jonathan A Hare et al., *Marine Science*, 69 1753–1768 (2012)	Utilized a species niche model coupled with the output from an ensemble of climate models to project cusk distribution in the future	Northwest Atlantic Ocean, including the Gulf of Maine and Georges Bank region	Not specified	Cusk (Brosme brosme)	**Temperature:** Projected habitat shrinkage and fragmentation for cusk due to a spatial mismatch between high complexity seafloor habitat and suitable temperature, indicating adverse effects from warming. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but implications for habitat suitability changes are implied. **Bottom-up Control:** Not specifically addressed. **Predation:** Not specifically addressed. **Geographic Distribution:** Indicates significant shifts in geographic distribution due to climate change, with a decrease in habitat availability. **Phenology:** Not specifically addressed. **Climate Extremes:** Suggests that climate change may reduce thermal habitat and increase habitat fragmentation for cold-water species like cusk, raising concerns over regional overexploitation and extirpation. **Other Effects:** Emphasizes the importance of integrating climate change impacts into fisheries management and conservation strategies.

Ove Hoegh-Guldberg & John F. Bruno, *The impact of climate change on the world's marine ecosystems*, 328 SCIENCE 1523–1528 (2010)	Review of existing literature and synthesis of data on climate change impacts on marine ecosystems.	Global, with focus on changes observed in polar regions, coral reefs, mangroves, and ocean deserts.	Synthesis of data from decades of research.	Broad range of marine ecosystems including coral reefs, mangroves, polar regions, and open-ocean ecosystems.	**Temperature:** Increase in global ocean temperatures affecting species metabolic rates, leading to changes in distribution, abundance, and community structure. **Dissolved Oxygen:** Decline in oxygen concentrations in parts of the ocean, contributing to hypoxic zones and affecting marine life. **Ocean pH:** Ocean acidification from increased CO2 absorption, affecting calcifying organisms and altering ecosystems. **Circulation, Mixing, and Nutrient Supply:** Changes in ocean currents affecting nutrient distribution and primary production. **Bottom-up Control:** Changes in primary productivity affecting food web dynamics. **Predation:** Not directly addressed. **Geographic Distribution:** Shifts in species distributions, especially poleward moves due to warming. **Phenology:** Changes in timing of biological events affecting predator-prey interactions. **Climate Extremes:** Increased frequency and intensity of extreme weather events affecting marine ecosystems. **Other Effects:** Loss of habitat-forming species like corals and sea ice, leading to reduced biodiversity and altered ecosystems.
Hutchings et al.	Review and synthesis of scientific literature, government reports, and analyses of trends in climate change, fisheries, and aquaculture impacts.	Canadian marine waters including the Arctic, Atlantic, and Pacific Oceans.	Varied; historical to present with projections into the 21st century.	Broad focus on Canadian marine biodiversity, including various species across different ecosystems.	**Temperature:** Increased surface water temperatures, reduced ice cover in the Arctic, and associated changes in ocean productivity and species ecology are notable. **Dissolved Oxygen:** Reductions in dissolved oxygen levels and increases in ocean stratification have been observed, with implications for marine life. **Ocean pH:** Acidification due to increased CO2 levels causing tissue damage and affecting calcium carbonate-dependent

					organisms. **Circulation, Mixing, and Nutrient Supply:** Changes in circulation patterns affecting nutrient distribution and ecosystem productivity. **Bottom-up Control:** Shifts in species distributions and productivity altering food webs and species interactions. **Predation:** Not specifically addressed but implied through ecosystem changes. **Geographic Distribution:** Significant shifts in species distributions due to temperature changes and ice cover reduction. **Phenology:** Changes in timing of biological events, leading to mismatches between species and resource availability. **Climate Extremes:** Increased frequency and severity of extreme weather events affecting marine ecosystems. **Other Effects:** Overfishing and aquaculture impacts, including habitat alteration and species composition changes in commercial catches, highlight the need for integrated management and conservation efforts.
IPCC	Comprehensive assessment incorporating datasets, models, and expert evaluations to analyze climate change impacts on the ocean.	Global	Historical trends with projections into the 21st century	Marine ecosystems across various oceanic regions	**Temperature:** Ocean warming trends have been observed, with projections indicating significant warming throughout the 21st century. **Dissolved Oxygen:** A decrease in oxygen levels is noted, with projections indicating further declines. **Ocean pH:** A clear trend of acidification has been observed, expected to continue, affecting marine organisms and ecosystems. **Circulation, Mixing, and Nutrient Supply:** Changes in ocean circulation and stratification affect nutrient distribution and ecosystem productivity. **Bottom-up Control:** Impacts on primary production and food webs are projected due to changes in temperature, oxygen,

					and nutrient supply. **Predation:** Not specifically addressed. **Geographic Distribution:** Shifts in the distribution of marine species are observed, with warming leading to range expansions or contractions. **Phenology:** Climate change impacts on the timing of biological events, affecting ecosystem interactions. **Climate Extremes:** Increased frequency and intensity of extreme events are impacting marine ecosystems. **Other Effects:** Ocean warming and acidification impact ecosystem services such as coastal protection and fisheries, with significant socio-economic implications.
Katherine E Mills et al., *Multispecies population-scale emergence of climate change signals in an ocean warming hotspot*, 81 ICES Journal of Marine Science 375–389 (2024), https://academic.oup.com/icesjms/article/81/2/375/7596727	Quantified ocean warming and marine heatwaves for 1982–2021, and assessed biological responses using spring/fall bottom trawl survey data (biomass, distribution, size-at-age) from 1970–2019. Computed biomass-weighted centers of latitude/longitude/depth and associated surface & bottom temperatures for 49 species; compared 1970–2009 vs 2010–2019.	Northeast US continental shelf (Cape Hatteras, NC to Gulf of Maine, incl. Georges Bank; subregions: Mid-Atlantic Bight, Georges Bank, Gulf of Maine).	Physical climate context: 1982–2021 for SST warming & heatwaves. Biological time series: trawl survey 1970–2019 (core “decadal contrast” is 2010–2019 vs 1970–2009).	Multispecies shelf ecosystem; 49 fish/invertebrate taxa for distribution/temperature exposure.	**Temperature:** Rapid warming (SST warming rate 0.38°C/decade since 1982, ~2.5× global), with a distinct warm regime after 2010 and more frequent/protracted marine heatwaves. Most analyzed species experienced warmer habitats in the 2010s despite distribution shifts (38/49 warmer surface temperatures; 36/49 warmer bottom temperatures), and only a minority avoided warming by shifting (“effective trackers” ~18%). Warmer conditions coincided with growth patterns consistent with the temperature–size rule and/or thermal stress (many species: faster early growth but smaller at older ages; or reduced growth across all ages), and some stocks showed reduced productivity during the warm decade. **Dissolved Oxygen:** Not explicitly addressed. **Ocean pH:** Not explicitly addressed. **Ocean Circulation:** Not explicitly addressed. **Mixing, and Nutrient Supply:** Not explicitly addressed. **Food Availability:** Indirect trophic pathways are highlighted: warming/stratification-related changes in key zooplankton (Calanus) and community composition can alter energy pathways and affect higher trophic levels; however, prey availability/quality are not directly measured as outcome

					variables in the core analyses (distribution, growth, productivity). **Predation:** Potential indirect mechanisms (including altered predator fields/mortality) are proposed conceptually as ways warming could affect distribution, growth, and productivity, but predation rates/fields are not directly quantified in the results. **Geographic Distribution:** Many species shifted distribution northward; 23/49 shifted deeper; some showed “wrong-way” shifts (8 shifted significantly southward; 2 became shallower). Most species’ shifts were insufficient to avoid warmer surface/bottom temperatures. **Phenology:** Not specifically addressed. **Climate Extremes:** Marine heatwaves increased in frequency/duration as warming pushed temperatures away from historical baselines; a major 2012 heatwave is highlighted as causing rapid ecosystem changes and fishery economic disruptions, and since 2012, heatwaves have occurred in some portion of each year (especially summer/fall). **Other Effects:** Growth/Body size—Across 14 species, 2010–2019 showed widespread size-at-age changes consistent with warming expectations: some species had reduced size across all ages (e.g., haddock, scup, winter flounder, yellowtail flounder), while others showed larger size at young ages but smaller size at older ages; silver hake was an exception with larger size across ages.
J.A. Janet A. Nye et al., *Silver hake tracks changes in Northwest Atlantic circulation*, 2 NATURE COMMUNICATIONS 1–6 (2011)	Analysis of spatial distribution shifts of silver hake (Merluccius bilinearis) in relation to the Gulf Stream's position using NOAA NEFSC bottom trawl survey data and Gulf Stream index constructed from historical subsurface temperature data.	Northeast US shelf region, specifically the Gulf of Maine and Scotian Shelf.	Last 40 years, comparing periods 1968–1972 and 2003–2008.	Adult silver hake (Merluccius bilinearis).	**Temperature:** Shifts in silver hake distribution are highly correlated with the Gulf Stream's position, driven by local changes in bottom temperature on the continental shelf. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Not specifically discussed; however, changes in the Atlantic meridional overturning circulation (AMOC) affecting the Gulf Stream

					path imply impacts on these factors. **Bottom-up Control:** Not specifically mentioned, but shifts in hake distribution suggest adaptations to changing environmental conditions that could affect prey availability. **Predation:** Not specifically addressed. **Geographic Distribution:** Significant poleward shift in silver hake distribution over the study period, directly linked to shifts in the Gulf Stream's position and associated temperature changes. **Phenology:** Not specifically addressed. **Climate Extremes:** The study highlights the role of large-scale oceanographic processes in governing the distribution of marine species, suggesting sensitivity to climate extremes. **Other Effects:** The movement of silver hake tracks remote oceanographic features, potentially allowing for predictions of fish distribution in response to climate change.
Janet A Nye et al., *Changing spatial distribution of fish stocks in relation to climate and population size on the Northeast United States continental shelf*, 393 MARINE ECOLOGY PROGRESS SERIES 111–129 (2009)	Analyzed trends from 1968 to 2007 in mean center of biomass, mean depth, mean temperature of occurrence, and area occupied for 36 fish stocks. Compared distribution trends to environmental variables and survey abundance.	Northeast United States continental shelf	1968–2007	36 fish stocks including various taxonomic groups, life-history strategies, and rates of fishing.	**Temperature:** Many stocks exhibited a poleward shift in their center of biomass, most with a simultaneous increase in depth. Some occupied habitats at increasingly greater depths. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but large-scale temperature increase and changes in circulation were significant factors associated with shifts. **Bottom-up Control:** Not directly addressed, but changes suggest potential alterations in food web dynamics. **Predation:** Not addressed. **Geographic Distribution:** Stocks in the southern extent of the survey area exhibited greater poleward shifts. Minimal changes observed in stocks limited to the Gulf of Maine, but mean depth of these stocks increased.

					Phenology: Not addressed. **Climate Extremes:** The study period captures significant warming, suggesting potential impacts from climate extremes on marine ecosystems. **Other Effects:** Changes in spatial distribution of fish stocks are likely to persist, indicating a need for re-evaluation of stock structure for some species.
Melissa A Karp et al., *Accounting for Shifting Distributions and Changing Productivity in the Fishery Management Process : From Detection to Management Action*, U.S. Deptartment of Commerce, NOAA. NOAA Technical Memorandum NMFS-F/SPO-188, 37 p. (2018)	Review of scientific literature, government reports, and an evaluation of the management process, focusing on how climate change affects fish stocks and fisheries.	U.S., with a particular focus on issues relevant to NOAA Fisheries' jurisdiction.	Overview of past impacts with discussions on future expectations.	Broad coverage across various U.S. fisheries and ecosystems.	**Temperature:** Changes in water temperature have led to shifts in stock distributions and changes in ecosystem productivity, challenging traditional management assumptions. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Implications for habitat suitability and stock dynamics due to ocean acidification are acknowledged, though not detailed. **Circulation, Mixing, and Nutrient Supply:** Changes in ocean circulation patterns affect nutrient distribution and ecosystem productivity, though specifics are not detailed. **Bottom-up Control:** Altered ecosystems and species distributions impact food web dynamics, though detailed impacts on specific species or fisheries are not provided. **Predation:** Not specifically addressed. **Geographic Distribution:** Noted shifts in species distributions have significant implications for management, including the need for flexible management strategies and improved cross-jurisdictional coordination. **Phenology:** Changes in the timing of biological events affect species interactions and ecosystem dynamics, underscoring the need for adaptable management approaches. **Climate Extremes:** Recognizes the impact of extreme weather events and climate variability on marine ecosystems and fisheries, advocating for integrated and adaptive

					management approaches. **Other Effects:** Emphasizes the importance of incorporating climate change impacts into the fishery management process, including shifting distributions and changing productivity, to ensure sustainable fisheries under changing conditions.
J.W. W. Kiceniuk & E. Colbourne, *Relating oxygen levels in the Newfoundland offshore waters to the physiology of atlantic cod (Gadus morhua)*, 54 Canadian Journal of Fisheries and Aquatic Sciences 81–87 (1997)	Analysis of dissolved oxygen data collected on oceanographic surveys of the Newfoundland Shelf from 1992 to 1994, with a focus on the physiology of Atlantic cod in relation to oxygen levels.	Newfoundland offshore waters, specifically the Newfoundland Shelf.	1992-1994	Atlantic Cod (Gadus morhua)	**Temperature:** Not specifically addressed. **Dissolved Oxygen:** Identified periods of low oxygen saturation levels detrimental to Atlantic cod, with significant negative anomalies in the 1930s, 1960s, and early 1980s, and the lowest anomalies recorded when data collection resumed in 1992. **Ocean pH:** Not specifically addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but changes in these factors are implied through their impact on dissolved oxygen levels. **Bottom-up Control:** Not specifically addressed. **Predation:** Not specifically addressed. **Geographic Distribution:** The study suggests that low oxygen levels could affect cod distribution, especially given the avoidance of low oxygen areas. **Phenology:** Not specifically addressed. **Climate Extremes:** Low oxygen saturation levels observed in 1992 could reflect extreme conditions detrimental to cod. **Other Effects:** Highlights the physiological stress and potential mortality in cod at low oxygen saturation levels, emphasizing the need for further research on oxygen preferences across all life stages of cod.
P. Koeller et al., *Basin-scale coherence in phenology of shrimps and*	Comparative study of shrimp (Pandalus borealis) egg hatching times and satellite-derived phytoplankton bloom dynamics, incorporating	North Atlantic Ocean, from the Gulf of Maine to Svalbard.	Data spans several years, focusing on temporal patterns rather	Northern shrimp (Pandalus borealis)	**Temperature:** Not directly addressed, but the study implies a significant relationship between bottom water temperature and egg development times across latitudes. **Dissolved Oxygen:** Not specifically addressed.

phytoplankton in the North Atlantic Ocean., 324 SCIENCE 791–3 (2009), http://www.ncbi.nlm.nih.gov/pubmed/19423827 (last visited Jan 29, 2013)	analysis of average bottom temperatures and latitudinal influences on phenology across the North Atlantic.		than a fixed period.		**Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Not specifically discussed, but changes in these factors are implied through their impact on primary productivity and temperature. **Bottom-up Control:** Not directly mentioned, but alterations in ecosystem and species distributions impact food web dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** The study suggests significant shifts in shrimp distribution due to temperature, with a latitudinal variation in phenology observed. **Phenology:** Egg development periods and hatching times are aligned with the spring phytoplankton bloom, suggesting adaptations across latitudes to match **Bottom-up Control:**. **Climate Extremes:** Not directly mentioned, but the importance of matching hatching times with phytoplankton blooms suggests vulnerability to mismatches caused by climate variability. **Other Effects:** The study highlights the potential for mismatches between reproductive cycles of marine organisms and their planktonic food due to climate change, emphasizing the evolutionary adaptation of shrimp to local temperatures and bloom timing.
Kristy J. Kroeker et al., *Ocean acidification causes ecosystem shifts via altered competitive interactions*, 3 NATURE CLIMATE CHANGE 156–159 (2013)	Utilized naturally acidified ecosystems by shallow CO2 vents and deployed recruitment substrates across different pH zones to study early successional stages and community dynamics. Analyzed percentage cover at 1.5, 2.5, 3.5, 6.5, and 14 months.	Zones of extreme low, low, and ambient seawater pH caused by shallow CO2 vents at Ischia Island, Mediterranean.	14 months.	Diverse marine assemblages, including calcareous species and fleshy seaweeds.	**Temperature:** Not directly addressed. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Acidification led to significant ecosystem shifts with a reduction in diversity and abundance of calcareous species in low and extreme low pH zones, favoring the dominance of fleshy seaweeds and biofilms. **Circulation, Mixing, and Nutrient Supply:** Not directly

					addressed. **Bottom-up Control:** Not directly addressed. **Predation:** Not directly addressed, but changes in grazers' abundance/biomass were considered and found not statistically different between ambient and low pH zones. **Geographic Distribution:** Calcareous species able to recruit and grow in early successional stages at similar rates in both ambient and low pH, suggesting physiological tolerance to acidification during these stages. **Phenology:** Altered successional dynamics observed, with calcareous species being rapidly overgrown by fleshy seaweeds in low pH conditions during later successional stages. **Climate Extremes:** Extreme low pH zones showed assemblages locked in early successional stages dominated by biofilm and filamentous algae. **Other Effects:** The study suggests altered competitive dynamics between calcareous species and fleshy seaweeds as a significant factor driving ecosystem shifts in acidified conditions. The increased dominance of fleshy seaweeds in low pH may be due to their enhanced growth rates under increased CO2 conditions or altered grazing pressures.
Vicky W.Y. Lam et al., *Projected change in global fisheries revenues under climate change*, 6 SCIENTIFIC REPORTS 6–13 (2016), http://dx.doi.org/10.1038/srep32607	Utilized outputs from Earth System Models (ESM) and Dynamic Bioclimate Envelope Models (DBEM) to project changes in distributions, abundances, and maximum catch potential (MCP) under RCP 2.6 and 8.5 scenarios.	Global, with a focus on Exclusive Economic Zones (EEZs) of 192 fishing nations and the high seas.	Mid-21st century (2050s) projections compared to the 2000s.	887 marine fish and invertebrate species representing 60% of the global average annual catch.	**Temperature:** Projected decreases in global maximum catch potential (MCP) by 7.7% under RCP 8.5, with variable impacts across regions. High latitudes may see increases in MCP, while tropical regions are expected to experience decreases. Dissolved Oxygen, **Ocean pH:** Ocean acidification and deoxygenation are acknowledged concerns, though specific impacts on MCP are not detailed. **Circulation, Mixing, and Nutrient Supply:** Changes in these factors due to climate change are implied through their impacts on primary productivity and temperature, affecting species distribution and productivity.

					Bottom-up Control: Changes in species distribution and productivity may alter food web dynamics. **Predation:** Not directly addressed. **Geographic Distribution:** Significant shifts expected, with high latitude regions potentially seeing increased MCP and tropical regions experiencing decreases. **Phenology:** Not specifically addressed. **Climate Extremes:** Increased frequency and severity of climate extremes could impact marine ecosystems and fisheries. **Other Effects:** Emphasizes the need for incorporating climate change impacts into fisheries management and highlights the potential economic impacts on global fisheries revenues, projecting a greater percentage decrease in revenues than in catches.
Jason S. Link et al., *Emergent Properties Delineate Marine Ecosystem Perturbation and Recovery*, 30 TRENDS IN ECOLOGY AND EVOLUTION 649–661 (2015), http://dx.doi.org/10.1016/j.tree.2015.08.011	The strategy outlines a comprehensive approach, including the use of Earth System Models (ESM) and Dynamic Bioclimate Envelope Models (DBEM) to project changes in distributions, abundances, and maximum catch potential (MCP) under various RCP scenarios.	U.S., focusing on Exclusive Economic Zones (EEZs) of 192 fishing nations and the high seas.	Mid-21st century (2050s) projections compared to the 2000s.	887 marine fish and invertebrate species representing 60% of the global average annual catch.	**Temperature:** Projected decreases in global MCP by 7.7% under RCP 8.5, with variable impacts across regions. High latitudes may see increases in MCP, while tropical regions are expected to experience decreases. Dissolved Oxygen, **Ocean pH:** Ocean acidification and deoxygenation are acknowledged concerns, though specific impacts on MCP are not detailed. **Circulation, Mixing, and Nutrient Supply:** Changes in these factors due to climate change are implied through their impacts on primary productivity and temperature, affecting species distribution and productivity. **Bottom-up Control:** Changes in species distribution and productivity may alter food web dynamics. **Predation:** Not directly addressed. **Geographic Distribution:** Significant shifts expected, with high latitude regions potentially seeing increased MCP and tropical regions experiencing decreases.

					Phenology: Not specifically addressed. **Climate Extremes:** Increased frequency and severity of climate extremes could impact marine ecosystems and fisheries. **Other Effects:** Emphasizes the need for incorporating climate change impacts into fisheries management and highlights the potential economic impacts on global fisheries revenues, projecting a greater percentage decrease in revenues than in catches.
Heike K. Lotze et al., *Long-term ocean and resource dynamics in a hotspot of climate change*, 7 FACETS 1142–1184 (2022)	Synthesis of over 4000 years of climate and marine ecosystem dynamics using environmental records from instrumental, sedimentary, coral, and mollusk archives, and ecological records from fossils, archaeological, historical, and modern data, integrated with future model projections.	Northwest Atlantic, specifically the Gulf of Maine and Scotian Shelf.	>4000 years, spanning late Holocene cooling and recent warming.	Comprehensive focus on the marine ecosystem of the Northwest Atlantic, including various species across different trophic levels.	**Temperature:** Projects a near-future departure from natural climate variability by 2028 for the Scotian Shelf and 2034 for the Gulf of Maine. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Acknowledges ocean acidification as a concern but specific impacts are not detailed. **Circulation, Mixing, and Nutrient Supply:** Changes due to climate are implied through impacts on primary productivity and species distribution. **Bottom-up Control:** Altered ecosystems may impact food web dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** Significant shifts expected, with potential increases in MCP at high latitudes and decreases in tropical regions. **Phenology:** Not specifically addressed. **Climate Extremes:** Recognizes the ongoing shifts in the marine ecosystem due to increased ocean temperature. **Other Effects:** Emphasizes the importance of integrating climate change into marine conservation strategies and management, predicting major economic impacts on global fisheries revenues.

Brian R. MacKenzie et al., *A cascade of warming impacts brings bluefin tuna to Greenland waters*, 20 Global Change Biology 2484–2491 (2014)	Comparative study of shrimp (Pandalus borealis) egg hatching times and satellite-derived phytoplankton bloom dynamics, incorporating analysis of average bottom temperatures and latitudinal influences on phenology across the North Atlantic	North Atlantic Ocean, from the Gulf of Maine to Svalbard	Data spans several years, focusing on temporal patterns rather than a fixed period	Northern shrimp (Pandalus borealis)	**Temperature:** Projected warming impacts including shifts in species' spatial distributions and migration patterns, with large migratory species like bluefin tuna moving into new areas due to increased temperatures. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Altered ecosystems may impact food web dynamics, with changes in prey availability influencing predator distributions. **Predation:** Not specifically addressed. **Geographic Distribution:** Significant shifts in geographic distribution of species, with warm-adapted species entering previously colder regions. **Phenology:** Not specifically addressed. **Climate Extremes:** Recognition of the restructuring of food webs in east Greenland waters as a cascade of climate change impacts. **Other Effects:** Emphasis on the importance of considering species in ecological connection rather than isolation, highlighting the interconnectedness of climate change impacts across trophic levels.
Robert A. Mauck et al., *Annual global mean temperature explains reproductive success in a marine vertebrate from 1955 to 2010*, 24 Global Change Biology 1599–1613 (2018)	Longitudinal study analyzing the relationship between annual global mean temperature (AGMT) and reproductive success in Leach's storm-petrels using a 56-year dataset (1955–2010).	Bay of Fundy, Canada.	1955–2010.	Leach's storm-petrels (*Oceanodroma leucorhoa*).	**Temperature:** Reproductive success showed a quadratic response to AGMT, increasing up to a critical temperature, then declining when AGMT exceeded that temperature. The critical year when AGMT consistently exceeded the threshold was 1988. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Not directly addressed, but the study implies changes in

					Bottom-up Control: due to temperature impacts. **Predation:** Not directly addressed. **Geographic Distribution:** Not directly addressed, but suggests potential for distribution changes based on temperature impacts. **Phenology:** Not directly addressed. **Climate Extremes:** Increased AGMT associated with changes in reproductive success, indicating potential impact from climate extremes. **Other Effects:** The impact of changing climate was greatest on inexperienced breeders, with reproductive success of these birds increasing more rapidly as temperatures rose and declining more rapidly after the tipping point compared to experienced individuals.
Gorka Merino et al., *Adaptation of North Atlantic Albacore Fishery to Climate Change: Yet Another Potential Benefit of Harvest Control Rules*, 6 FRONTIERS IN MARINE SCIENCE 1–14 (2019), https://www.frontiersin.org/article/10.3389/fmars.2019.00620/full	Management Strategy Evaluation (MSE) using simulation to compare different combinations of data collection schemes, analysis methods, and management actions.	North Atlantic, focusing on Exclusive Economic Zones (EEZs) of fishing nations.	Mid-21st century projections compared to the 2000s.	North Atlantic Albacore (Thunnus alalunga).	**Temperature:** The study evaluated the robustness of the adopted harvest control rule (HCR) against changes in productivity and recruitment variability due to climate change. It suggests that the adopted HCR is robust to these climate-driven impacts. Dissolved Oxygen, **Ocean pH:** Not specifically addressed. **Circulation, Mixing, and Nutrient Supply:** Impacts implied through changes in productivity and species distribution. **Bottom-up Control:** Altered ecosystems may impact food web dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** Significant shifts in species distributions are expected, with potential increases in catch potential at high latitudes and decreases in tropical regions. **Phenology:** Not specifically addressed. **Climate Extremes:** Recognizes the ongoing shifts in the

					marine ecosystem due to increased ocean temperature. **Other Effects:** Highlights the importance of integrating climate change into marine conservation strategies and management, predicting major economic impacts on global fisheries revenues.
Katherine E. Mills et al., *Fisheries management in a changing climate: Lessons from the 2012 ocean heat wave in the Northwest Atlantic*, 26 OCEANOGRAPHY 191–195 (2013)	Analysis of oceanographic data and fisheries statistics; satellite-derived phytoplankton bloom dynamics and average bottom temperatures.	Northwest Atlantic, including the Gulf of Maine.	Specific focus on the year 2012.	Marine species broadly, with specific examples such as longfin squid, American lobster, and various fish species.	**Temperature:** 2012 saw unprecedented ocean warming, with sea surface temperatures 1–3°C above average, affecting marine species distributions and behaviors. Dissolved Oxygen, **Ocean pH:** Not directly mentioned. **Circulation, Mixing, and Nutrient Supply:** Changes inferred through ocean warming. **Bottom-up Control:** Altered by changes in species distribution and abundance. **Predation:** Likely affected but not detailed. **Geographic Distribution:** Northward shifts and deeper migrations observed in various species. **Phenology:** Earlier seasonal migrations noted for some species. **Climate Extremes:** 2012 characterized as a significant extreme event, likely a precursor to future conditions. **Other Effects:** Economic and ecological impacts observed, including challenges to fisheries management and the development of new fisheries (e.g., squid in Maine).
Wendy E. Morrison et al., *Methodology for Assessing the Vulnerability of Marine and Anadromous Fish Stocks in a Changing Climate*,	Developed a methodology for assessing the vulnerability of marine fish and shellfish species to climate change using expert elicitation to quantify species' exposure and sensitivity to expected climate change.	North Atlantic, focusing on Exclusive Economic Zones (EEZs) of fishing nations.	Mid-21st century projections compared to the 2000s.	Broad range, applicable to marine fish and shellfish species representing diverse ecosystems.	**Temperature:** Examined shifts in species' distributions and productivity, emphasizing the role of temperature as a major exposure factor. Dissolved Oxygen, **Ocean pH:** While specific impacts on these factors were not detailed, the methodology acknowledges their importance in assessing vulnerability. **Circulation, Mixing, and Nutrient Supply:** Changes in

41 FISHERIES 407–409 (2016)					these factors due to climate are implied through their impacts on species distribution and productivity. **Bottom-up Control:** The methodology suggests that altered ecosystems may impact food web dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** Significant shifts in species distributions are anticipated, with potential impacts on fisheries management. **Phenology:** Not specifically addressed, though the methodology could incorporate phenological shifts through expert elicitation. **Climate Extremes:** Recognizes the potential for climate extremes to affect marine ecosystems and fisheries. **Other Effects:** Emphasizes the need for incorporating climate change impacts into fisheries management and highlights the methodology's utility in identifying vulnerable species.
National Oceanic and Atmospheric Administration, *Climate Impacts on U. S. Living Marine Resources : National Marine Fisheries Service Concerns , Activities and Needs NOAA Technical Memorandum NMFS-F/SPO-89*, 130 (2008), http://spo.nmfs.noaa.gov/tm/TM SPO 89.pdf	Literature review, expert elicitation, analysis of existing data.	Various U.S. Exclusive Economic Zones (EEZs): Northeast U.S. Continental Shelf, Southeast U.S. Continental Shelf Gulf of Mexico and U.S. Caribbean, California Current Ecosystem, Alaskan Ecosystem Complex, Pacific Island Ecosystem Complex, Eastern Tropical	N/A	Broad range of marine species including fish, shellfish, mammals, and ecosystems.	**Temperature:** Warming impacts include shifts in species distributions and productivity. **Dissolved Oxygen:** Not directly addressed but implied in ecosystem productivity changes. **Ocean pH:** Concerns about ocean acidification affecting calcifying organisms and coral reefs. **Circulation, Mixing, and Nutrient Supply:** Changes affect ecosystem productivity and species distributions. **Bottom-up Control:** Altered due to changes in productivity and ecosystem structure. **Predation:** Not specifically addressed but implied through ecosystem structure changes. **Geographic Distribution:** Significant shifts expected due to warming and acidification.

		Pacific, North Pacific Highly Migratory Species, Antarctic.			**Phenology:** Changes in timing of biological events due to temperature and ocean circulation changes. **Climate Extremes:** Increased variability and extremes impacting ecosystems. **Other Effects:** Loss of sea ice major concern for polar regions, altering habitat and species distributions.
Brian Petrie et al., *Structure and stability in exploited marine fish communities: Quantifying critical transitions*, 18 FISHERIES OCEANOGRAPHY 83 – 101 (2009), https://www.scopus.com/inward/record.uri?eid=2-s2.0-63049090047&doi=10.1111%2Fj.1365-2419.2009.00500.x&partnerID=40&md5=d41b3451e581839d9fa0f2e6b81a406d	Utilized correlations between time series of abundance for predator and prey fish species, developing a quantitative model based on annual predator depletion rates and bottom temperatures to quantify critical thresholds between positive and negative predator-prey correlations.	Western North Atlantic, from Georges Bank to the Newfoundland–Labrador Shelf.	Focused on correlations within the period of 1978–1991 for fishery landings and 1997–2004 for satellite observations.	Examined 15 predator species and 8 prey species across nine heavily exploited regions.	**Temperature:** Warmer, species-rich southern areas can resist transformation from positive to negative predator-prey correlations at exploitation rates up to double those in colder, species-poor northern areas. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Implied changes in food web dynamics based on predator-prey relationship alterations. **Predation:** Documented top-down control in northern areas, shifting towards bottom-up control in southern areas. **Geographic Distribution:** Highlighted geographical variance in trophic control, with warmer areas resisting changes in predator-prey dynamics under higher exploitation rates. **Phenology:** Not addressed. **Climate Extremes:** Not directly addressed, but discusses ecosystem stability and species diversity in relation to climate impacts. **Other Effects:** The study underscores the importance of considering both bottom-up and top-down controls in understanding marine ecosystem dynamics and suggests the model can inform exploitation limits to preserve functional relationships in ecosystems.

Alex L. Pigot et al., *Abrupt expansion of climate change risks for species globally*, 7 Nature Ecology & Evolution 1060–1071 (2023), https://www.nature.com/articles/s41559-023-02070-4	Analyzed geographical data for approximately 36,000 marine and terrestrial species with climate projections to 2100 to assess risks of thermal exposure across species' geographical ranges.	Global, covering both terrestrial and marine environments.	Projection to 2100.	35,863 species including mammals, amphibians, reptiles, birds, corals, cephalopods, reef fish, seagrasses, and zooplankton.	**Temperature:** Predicts abrupt expansion in the area at risk of thermal exposure across species' ranges, with more than 50% of the increase in exposure projected to occur in a single decade. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but implied in the discussion of climate change impacts on ecosystems. **Bottom-up Control:** Not directly addressed, but the study implies changes in ecosystems could affect food web dynamics. **Predation:** Not directly addressed. **Geographic Distribution:** Highlights an abrupt shift in geographical range risks due to thermal exposure, affecting both terrestrial and marine species. **Phenology:** Not directly addressed. **Climate Extremes:** Focuses on the abrupt risks posed by climate extremes leading to thermal exposure. **Other Effects:** Emphasizes the vulnerability of species to sudden warming-driven collapse due to geographical constraints on species ranges and the rapid pace of projected warming.
Malin L. Pinsky et al., *Preparing ocean governance for species on the move*, 360 Science 1189–1191 (2018)	Policy analysis focusing on the governance challenges posed by shifting marine animal distributions due to climate change, utilizing case studies, international law analysis, and projections of future species distribution shifts.	Global, with specific examples including the United States, European Union, Norway, Iceland, and the high seas.	Historical context with projections to 2100.	Broad focus on marine species with specific examples like the Blueline tilefish, northeast Atlantic mackerel, and Pacific salmon.	**Temperature:** Identifies climate change as a driver for shifting marine species distributions, creating new governance challenges. Dissolved Oxygen, **Ocean pH:** Not specifically addressed. **Circulation, Mixing, and Nutrient Supply:** Implications for shifting distributions due to changes in ocean conditions. **Bottom-up Control:** Impacts on food security in tropical regions as species distributions shift.

					Predation: Not directly addressed. **Geographic Distribution:** Projections indicate many Exclusive Economic Zones (EEZs) will contain one or more new fishery stocks by 2100. **Phenology:** Not directly addressed. **Climate Extremes:** The need for governance to adapt to rapid and unprecedented species distribution shifts. **Other Effects:** Governance challenges include noncooperative management, fractured international relationships, and the need for adaptive and cooperative international fisheries management strategies.
Malin L. Pinsky et al., *Marine Taxa Track Local Climate Velocities*, 341 SCIENCE 1239–1242 (2013), http://www.sciencemag.org/content/341/6151/1239%5Cnhttp://www.ncbi.nlm.nih.gov/pubmed/24031017%5Cnhttp://www.sciencemag.org/content/341/6151/1239.abstract	Compilation of four decades of scientific surveys across nine regions of North America, measuring shifts in latitudes and depths of marine taxa.	Continental shelves of North America	1968 to 2011	360 marine species or species groups, capturing 128 million organisms.	**Temperature:** Marine species shifts correlate with regional temperature changes, with some species moving northward and others southward, suggesting significant variability in response to warming. Dissolved Oxygen, **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Implied changes due to temperature shifts affecting marine ecosystems. **Bottom-up Control:** Altered by ecosystem changes and species shifts. **Predation:** Not specifically addressed but implied through changes in ecosystem structures. **Geographic Distribution:** Significant shifts observed, with species moving in varied directions at different rates, emphasizing the non-uniform response across taxa. **Phenology:** Not specifically addressed but implied through changes in distribution and abundance patterns. **Climate Extremes:** The study highlights the variability and complexity of marine species' responses to changing climates, including the potential for non-intuitive shifts in distribution.

					Other Effects: Suggests that climate velocity—a measure of the rate and direction of climate shifts across the landscape—can largely explain the observed variations in species' movements, with most species tracking local climate velocities effectively.
Éva E. Plagányi, *Climate change impacts on fisheries*, 363 Science 930–931 (2019)	Review and analysis of recent studies including Free et al., 2019, and projections of future species distribution shifts. Also references FAO technical papers and studies on climate impacts on marine production.	Global, with specific mentions of impacts in East Asian and North Sea ecoregions.	Historical analysis with references to changes between 1930 and 2010 and projections into the future.	General focus on marine fisheries productivity, including examples such as maize, wheat, and various marine species affected by climate change.	**Temperature:** Highlights a 4.1% decline in global productivity of marine fisheries between 1930 and 2010, with variability in impacts across species and regions. Dissolved Oxygen, **Ocean pH:** Not specifically addressed but notes the concern of ocean acidification affecting productivity. **Circulation, Mixing, and Nutrient Supply:** Implications for changing marine ecosystems and productivity due to climate change. **Bottom-up Control:** Notes the importance of seafood for global nutrition and the impacts of productivity declines on food security. **Predation:** Not specifically addressed. **Geographic Distribution:** Indicates shifting distributions due to climate change, affecting regional fisheries productivity. **Phenology:** Not specifically addressed. **Climate Extremes:** Discusses the increasing frequency and severity of extreme weather events and their negative consequences for fisheries and aquaculture. **Other Effects:** Emphasizes the need for adaptive management and policy development, especially in vulnerable tropical regions, due to disparate regional impacts of climate change on fisheries.
T Platt et al., *Spring algal bloom and larval fish survival*, 423 Nature 398–399 (2003)	Analysis of satellite data for phytoplankton bloom timing and a long-term data set of haddock recruitment off the eastern continental shelf of Nova Scotia.	Eastern continental shelf of Nova Scotia, Canada.	1979–2001 for satellite data; 1970–present for haddock surveys.	Haddock (Melanogrammus aeglefinus) larvae and the local phytoplankton bloom.	**Temperature:** Not specifically addressed but related to the spring bloom timing. Dissolved Oxygen, **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Not specifically

					mentioned, but bloom timing can be influenced by these factors. **Bottom-up Control:** The survival of larval haddock is linked to the timing of the local spring phytoplankton bloom. Early blooms may increase larval survival. **Predation:** Not specifically addressed, but an early bloom could reduce **Predation:** on larvae by providing more cover and faster growth due to better **Bottom-up Control:**. **Geographic Distribution:** Not directly discussed, but changes in bloom timing could affect the distribution of larvae survival rates. **Phenology:** The study confirms the hypothesis that the timing of the spring phytoplankton bloom is crucial for the survival of haddock larvae. **Climate Extremes:** Not specifically discussed, but variations in bloom timing suggest sensitivity to climatic conditions. **Other Effects:** The study emphasizes the importance of synoptic, high-resolution observations for understanding marine ecosystem dynamics and the impacts of climate variability on fisheries.
Hans O Poertner & Rainer Knust, *Climate change affects marine fishes through the oxygen limitation of thermal tolerance*, 315 SCIENCE 95–97 (2007)	Analysis of laboratory data for marine fish and invertebrates, testing with the bioindicator fish species *Zoarces viviparus* from North and Baltic Seas.	Southernmost distribution area of the common eelpout, *Zoarces viviparus*, in the German Wadden Sea, part of the southern North Sea.	Historical analysis with future projections to 2100.	Common eelpout, *Zoarces viviparus*, as a bioindicator species for environmental monitoring.	**Temperature:** Identified as a key factor affecting marine species through oxygen limitation of thermal tolerance. A mismatch between the demand for oxygen and the capacity of oxygen supply restricts tolerance to thermal extremes. Dissolved Oxygen, **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Implied impact through temperature effects on ecosystems. **Bottom-up Control:** Altered by ecosystem and species shifts due to temperature changes.

					Predation: Not directly addressed. **Geographic Distribution:** Poleward or high-altitude shifts observed in ectothermic animals due to temperature changes. **Phenology:** Not specifically addressed, but the study emphasizes the importance of thermal windows for survival and performance. **Climate Extremes:** Increased frequency and severity of extreme weather events anticipated, impacting marine ecosystems. **Other Effects:** The study suggests that decrements in aerobic performance due to warming seas could lead to species extinction or relocation to cooler waters.
Elvira S. Poloczanska et al., *Global imprint of climate change on marine life*, 3 NATURE CLIMATE CHANGE 919–925 (2013), internal-pdf://209.126.227.87/Poloczanska-2013-Global imprint of cl.pdf%5Cn%3CGo to ISI%3E://WOS:000326818800020 http://www.nature.com/nclimate/journal/v3/n10/pdf/nclimate1958.pdf	Synthesized available studies of marine biological responses (1,735 responses from 208 studies) to assess consistency with expectations under climate change. Included distribution, phenology, abundance, community change, calcification, and demography across taxa and ocean basins.	Global, with reports from all oceans but most from Northern Hemisphere temperate oceans.	Ranges from 19 to >12,000 years, with a median span of 41 years.	857 species and assemblages, encompassing a broad range of marine taxa.	**Temperature:** 81-83% of all observations across taxa and response types were consistent with expected impacts of climate change. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Mentioned as a contributing factor to ocean acidification, affecting calcification rates and physiological processes in some marine organisms. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, though shifts in species' distributions and phenology suggest potential indirect impacts. **Bottom-up Control:** Changes in species distributions and community compositions suggest alterations in food web dynamics. **Predation:** Not directly addressed. **Geographic Distribution:** Significant shifts in species' distributions, with rates of distribution shifts aligning with those required to track ocean surface temperature changes. **Phenology:** Variable responses; no clear relationship found between shifts in spring phenology and the seasonality of

					temperature. **Climate Extremes:** The increased occurrence of marine heatwaves with significant ecosystem and societal impacts was noted. **Other Effects:** The study provides evidence for a strong fingerprint of anthropogenic climate change on marine life, predicting future reconfigurations of marine ecosystems and the services they provide.
J. F. Provencher et al., *Seabird diet indicates changing Arctic marine communities in eastern Canada*, 454 Marine Ecology Progress Series 171–182 (2012)	Compared changes in the diet of thick-billed murres from the 1970s and 1980s to 2007–2009 using stomach content analysis to reflect changes in the marine environment.	Eastern Canadian Arctic, spanning low-, mid-, and high-Arctic zones.	Historical (1970s and 1980s) vs. recent (2007–2009).	Thick-billed murres (*Uria lomvia*).	**Temperature:** Not directly addressed but implied through the study's focus on changing climatic conditions affecting sea ice and subsequent marine community changes. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but changes in sea ice are indicative of broader climate-induced changes in marine ecosystems. **Bottom-up Control:** The shift from Arctic cod to capelin in the low Arctic suggests changes in available prey due to diminishing sea ice and potentially warming waters. **Predation:** Not directly addressed. **Geographic Distribution:** Northward expansion of capelin, a subarctic species, into areas previously dominated by Arctic cod, indicates significant shifts in the geographic distribution of key species. **Phenology:** Not directly addressed. **Climate Extremes:** The study indirectly references the impact of climate change on sea ice extent, which is critical for species like the Arctic cod. **Other Effects:** A decrease in the diversity of prey items available to murres suggests a potential change in the marine biodiversity in the Arctic. The study highlights that long-term changes in sea ice significantly impact the Arctic cod, a key

					prey species for murres, with implications for marine biodiversity and food web dynamics in the Arctic.
Adriaan D Rijnsdorp et al., *Resolving the effect of climate change on fish populations*, 66 ICES JOURNAL OF MARINE SCIENCE 1570–1583 (2009)	The study developed a framework for analyzing climate impact on fish populations, reviewing environmental variables, and utilizing first principles of physiology, ecology, and observations.	Northeast Atlantic	Historical analysis with future projections to 2100.	Northeast Atlantic fish species, including different biogeographic affinities, habitats, and body sizes.	**Temperature:** Global warming results in shifts in abundance and distribution patterns of fish species, with pelagic species showing clear changes in seasonal migration patterns. Dissolved Oxygen, **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Implied changes due to temperature shifts affecting marine ecosystems. **Bottom-up Control:** Altered by ecosystem changes and species shifts. **Predation:** Not specifically addressed but implied through changes in ecosystem structures. **Geographic Distribution:** Significant shifts observed, with species moving in varied directions at different rates. **Phenology:** Not specifically addressed but implied through changes in distribution and abundance patterns. **Climate Extremes:** Highlights the variability and complexity of marine species' responses to changing climates. **Other Effects:** Suggests climate-related changes in recruitment success as a key process.
Lauren A. Rogers et al., *Shifting habitats expose fishing communities to risk under climate change*, 9 NATURE CLIMATE CHANGE 512–516 (2019), http://dx.doi.org/10.1038/s41558-019-0503-z	Integrated climatic, ecological, and socio-economic data. Used species distribution models fit to over 40 years of scientific survey data.	New England and Mid-Atlantic (USA)	Historical context with projections to 2040-2050	33 marine species, focusing on changes in habitat suitability under climate change	**Temperature:** Temperature was a significant predictor for species occurrence, affecting habitat suitability with both positive and negative impacts across species. Dissolved Oxygen, **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Changes in habitat suitability suggest indirect effects from ocean conditions. **Bottom-up Control:** Altered due to changes in species distribution and abundance.

					Predation: Not specifically addressed. **Geographic Distribution:** Projected shifts in species distribution with northern regions expected to gain and southern regions to lose habitat suitability. **Phenology:** Not directly addressed but changes in species distribution and habitat suitability suggest potential impacts. **Climate Extremes:** Projected changes in species distribution indicate responses to changing climate conditions. **Other Effects:** Highlighted the socio-economic impact on fishing communities, with many facing declining future fishing opportunities unless adaptation occurs, such as targeting new species or fishing in new locations.
Jennifer A. Sheridan & David Bickford, *Shrinking body size as an ecological response to climate change*, 1 NATURE CLIMATE CHANGE 401–406 (2011), http://dx.doi.org/10.1038/nclimate1259	Reviewed fossil records, experimental and geographic comparisons, and recent studies to summarize changes in organism size as a result of climate change and increased carbon dioxide levels.	Global, with specific examples from past warming periods and recent anthropogenic climate change impacts.	Varied, with examples spanning from historical periods such as the Palaeocene–Eocene Thermal Maximum to recent decades.	Broad range of organisms including marine and terrestrial species, such as beetles, bees, spiders, wasps, ants, cicadas, diatoms, pocket gophers, California squirrels, woodrats, and various modern species.	**Temperature:** Linked to reductions in organism size across various taxa, with both historical and recent evidence showing size declines in warmer conditions. **Dissolved Oxygen:** Not directly addressed, but mentioned in the context of ocean acidification affecting marine organisms. **Ocean pH:** Increased acidification shown to reduce growth rates and body size in calcifying organisms like corals, scallops, and oysters. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Implied impacts due to changes in primary productivity affecting food web dynamics. **Predation:** Not directly addressed. **Geographic Distribution:** Documented poleward shifts in range and changes in species distributions in response to temperature changes. **Phenology:** Observed advancements in phenological events (e.g., breeding, flowering) as a response to climate change.

					Climate Extremes: Mentioned in the context of marine heatwaves and their significant impacts on ecosystems. **Other Effects:** Size declines across a range of species are expected to disrupt ecosystem functioning, with potential implications for biodiversity and human nutrition.
C.H. Christine H. Stortini et al., *Assessing marine species vulnerability to projected warming on the Scotian Shelf, Canada*, 72 ICES JOURNAL OF MARINE SCIENCE 1713–1743 (2015), https://academic.oup.com/icesjms/article/72/6/1731/918246	The study developed the Vulnerability to Projected Warming Assessment (VPWA) to assess the vulnerability of marine species on the Scotian Shelf, Canada, to climate warming. It focused only on warming impacts due to the lack of well-developed projections for other climate drivers. The study refined the exposure component to reflect thermal habitat gain/loss across multiple life stages and utilized Monte Carlo simulations to identify the most vulnerable species among 33 fish and invertebrate species.	Scotian Shelf, Canada	N/A	33 fish and invertebrate species, including commercially and ecologically important species.	**Temperature:** A significant impact was observed with 45% of populations potentially vulnerable under a severe (+3°C) warming scenario. Species like Atlantic cod, smooth skate, and snow crab were identified as vulnerable. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but changes in thermal habitat imply effects on these factors. **Bottom-up Control:** Not directly addressed, but shifts in species distributions suggest potential changes in food web dynamics. **Predation:** Not directly addressed. **Geographic Distribution:** Noted significant shifts, especially with species expanding northward or to deeper waters as a response to warming. **Phenology:** Not directly addressed. **Climate Extremes:** The study suggests that marine species on the Scotian Shelf will face significant challenges under extreme warming scenarios, with implications for ecosystem structure and fisheries management. **Other Effects:** Highlighted were the potential shifts in community composition and the importance of considering multiple life stages in vulnerability assessments.
Jennifer M. Sunday et al., *Thermal tolerance and the*	Synthesis of experimentally measured acute critical and lethal thermal tolerance limits	Global	Historical analysis with	Marine and terrestrial ectotherms	**Temperature:** Marine ectotherms fully occupy their potential latitudinal ranges based on thermal tolerance, expected to contract at equatorward and expand at poleward boundaries

global redistribution of animals, 2 NATURE CLIMATE CHANGE 686–690 (2012), http://dx.doi.org/10.1038/nclimate1539	of 142 marine and terrestrial ectotherms, and 648 range boundaries related to climate-induced range shifts.		projections into the future	including 142 species and their latitudinal range boundaries.	with warming. Terrestrial ectotherms, however, are excluded from the warmest parts of their latitudinal range, leading to a less consistent poleward shift. Dissolved Oxygen, **Ocean pH:** Not specifically addressed. **Circulation, Mixing, and Nutrient Supply:** Indirect implications through changes in habitat conditions influenced by temperature shifts. **Bottom-up Control:** Not directly addressed but can be inferred to change with shifts in species distributions and ecosystem dynamics. **Predation:** Not directly mentioned; however, changes in species distributions could alter **Predation:** pressures. **Geographic Distribution:** Marine species show equal responsiveness at both range boundaries to climate warming, while terrestrial species show less movement at equatorward boundaries. **Phenology:** Not specifically addressed but implies potential shifts due to warming. **Climate Extremes:** Indicative of increasing range shifts and potential for new ecological interactions. **Other Effects:** Terrestrial ectotherms' ranges are not at equilibrium with their thermal tolerance at the equatorward range boundary, complicating predictions for these species under future warming scenarios.
Christopher H. Trisos et al., *The projected timing of abrupt ecological disruption from climate change*, 580 NATURE 496–501 (2020), http://dx.doi.org/10.	Annual projections of temperature and precipitation from 1850 to 2100 across more than 30,000 marine and terrestrial species to estimate timing of exposure to potentially dangerous climate conditions.	Global, covering both marine and terrestrial environments.	Projections to 2100.	30,652 species including birds, mammals, reptiles, amphibians, marine fish, benthic marine invertebrates, krill, cephalopods, and habitat-forming	**Temperature:** Under high-emissions scenario (RCP 8.5), abrupt exposure events start before 2030 in tropical oceans and spread to tropical forests and higher latitudes by 2050. Limiting global warming below 2°C reduces the risk of abrupt exposure events significantly. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed.

1038/s41586-020-2189-9				corals and seagrasses.	**Circulation, Mixing, and Nutrient Supply:** Not directly addressed. **Bottom-up Control:** Not directly addressed, but changes suggest potential alterations in food web dynamics. **Predation:** Not directly addressed. **Geographic Distribution:** Highlights an abrupt shift in geographical range risks due to thermal exposure, affecting both terrestrial and marine species. **Phenology:** Not directly addressed. **Climate Extremes:** Focuses on the abrupt risks posed by climate extremes leading to thermal exposure. **Other Effects:** The study predicts an abrupt and significant expansion in the area of species' geographical ranges at risk of thermal exposure due to climate change, emphasizing the urgency of mitigation and adaptation actions.
W W L Cheung & T L Frolicher, *Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific*, 10 SCIENTIFIC REPORTS (2020)	Combined outputs from a large ensemble simulation of an Earth system model with a fish impact model to simulate responses of major northeast Pacific fish stocks to Marine Heatwaves (MHWs).	Northeast Pacific, including three Large Marine Ecosystems (LMEs): Eastern Bering Sea, Gulf of Alaska, and California Current.	1981-2100	22 major northeast Pacific fish stocks.	**Temperature:** MHWs cause biomass decrease and shifts in biogeography of fish stocks at least four times faster and bigger than the effects of decadal-scale mean changes throughout the 21st century. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but the study implies changes in these factors through their impact on primary productivity and temperature. **Bottom-up Control:** Implied changes due to shifts in species distribution which may affect prey-predator dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** Changes suggest significant shifts in species distributions, with species moving to higher latitudes or deeper waters in response to warming. **Phenology:** Not specifically addressed. **Climate Extremes:** Study underscores the impacts of ocean

					warming on fisheries over the past four decades, indicating a clear signature of climate change on global fisheries. **Other Effects:** Highlights the need for immediate adaptation plans to minimize warming effects on coastal communities' economy and food security, especially in tropical regions.
Harvey J. Walsh et al., *Long-term changes in the distributions of larval and adult fish in the northeast U.S. shelf ecosystem*, 10 PLoS ONE 1–31 (2015), http://dx.doi.org/10.1371/journal.pone.0137382	Analysis of long-term data sets from trawl surveys, satellite data, and oceanographic models.	North Atlantic Ocean	1970-2020	Various fish species including cod, herring, and mackerel.	**Temperature:** Increasing ocean temperatures have led to northward shifts in fish distributions. **Dissolved Oxygen:** Lower levels in deeper waters are affecting habitat suitability. **Ocean pH:** Acidification is impacting shellfish and corals, indirectly affecting fish that rely on these for habitat or food. **Ocean Circulation:** Changes are altering larval dispersal patterns. **Mixing and Nutrient Supply:** Affects phytoplankton blooms, impacting **Bottom-up Control:** for marine species. **Bottom-up Control:** Shifts in primary production affect the entire food web. **Predation:** Altered ecosystems change predator-prey relationships. **Geographic Distribution:** Many species are moving towards the poles or deeper waters. **Phenology:** Changes in spawning and migration timings are observed. **Climate Extremes:** Increased frequency and intensity of events like heatwaves are causing mortality. **Other Effects:** Additional stressors include fishing pressure and habitat degradation.

G.-R. R Walther et al., *Ecological responses to recent climate change*, 416 NATURE 389–395 (2002), http://www.nature.com/cgi-taf/DynaPage.taf?file=/nature/journal/v416/n6879/full/416389a_fs.html	Reviewed evidence of ecological impacts of recent climate change across various ecosystems, using data from polar terrestrial to tropical marine environments. This included phenological changes, species range shifts, community composition changes, and ecosystem dynamics.	Global, with specifics ranging from polar regions to tropical oceans.	The review covers studies across decades of research, with some data extending back over the past 100 years.	Broad, covering flora and fauna across an array of ecosystems and organizational levels, from species to communities.	**Temperature:** Documented warming influencing a wide range of ecological changes, including species' metabolic rates, distribution shifts, and community dynamics. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Mentioned in context with ocean acidification, affecting calcifying organisms but not detailed in ecological impacts. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, though changes in precipitation and snow cover/ice extent indirectly suggest impacts. **Bottom-up Control:** Implications of shifts in species distributions and community compositions on food web dynamics. **Predation:** Not directly addressed. **Geographic Distribution:** Significant shifts in species' ranges, both poleward and to higher elevations, in response to warming. **Phenology:** Changes in the timing of biological events, such as earlier spring activities and breeding. **Climate Extremes:** Increased frequency and intensity of extreme events impacting ecosystems, mentioned in the context of coral reef bleaching. **Other Effects:** The review highlights the broad and profound impacts of climate change on ecosystems, predicting future reconfigurations of marine and terrestrial ecosystems and the services they provide.
William W.L. L. Cheung et al., *Signature of ocean warming in global fisheries catch*, 497 NATURE 365–368 (2013), http://www.nature.c	Utilized global catch data and temperature preferences of 990 marine species to calculate the Mean Temperature of the Catch (MTC), integrating the average inferred temperature preference of exploited species weighted by their annual catch. Analyzed	Global, focusing on 52 LMEs.	1970-2006	Marine species represented in global fisheries catch data.	**Temperature:** Global MTC increased by 0.19°C per decade between 1970 and 2006, indicating a global shift toward catches of warmer-water species. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** Not directly addressed.

om/doifinder/10.1038/nature12156 (last visited May 21, 2013)	changes in MTC for 52 Large Marine Ecosystems (LMEs) globally.				**Bottom-up Control:** Implied changes due to shifts in species distribution which may affect prey-predator dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** Observed changes suggest significant shifts in species distributions, with species moving to higher latitudes or deeper waters in response to warming. **Phenology:** Not specifically addressed. **Climate Extremes:** Study underscores the impacts of ocean warming on fisheries over the past four decades, indicating a clear signature of climate change on global fisheries. **Other Effects:** Highlights the need for immediate adaptation plans to minimize warming effects on coastal communities' economy and food security, especially in tropical regions.
William W.L. Cheung & Muhammed A. Oyinlola, *Vulnerability of flatfish and their fisheries to climate change*, 140 JOURNAL OF SEA RESEARCH 1–10 (2018)	Utilized a fuzzy logic algorithm and dynamic bioclimate envelope model (DBEM) to assess the vulnerability and risk of impacts for 47 species of exploited flatfish. Projections of future distribution and maximum catch potential were made using DBEM.	Global, with specific focus on regions such as Canada's Exclusive Economic Zone and the NAFO convention area.	1971-2060	47 species of exploited flatfish	**Temperature:** Projected significant declines in marine animal biomass in most ocean basins except polar regions. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** Not directly addressed, but changes in these factors are implied through their impact on primary productivity and temperature. **Bottom-up Control:** Variability in primary production, driven by temperature changes, impacts **Bottom-up Control:** for marine species. **Predation:** Not specifically addressed. **Geographic Distribution:** Projected shifts in marine animal biomass indicate potential geographic distribution changes, with biomass increases in polar regions and decreases in most other basins. **Phenology:** Not specifically addressed. **Climate Extremes:** Ensemble projections suggest significant impacts of climate change on marine ecosystems, with notable differences across ocean basins and emission

					scenarios. **Other Effects:** Highlights the need for climate-resilient fisheries management and conservation efforts.
William W.L. Cheung et al., *Structural uncertainty in projecting global fisheries catches under climate change*, 325 ECOLOGICAL MODELLING 57–66 (2016), http://dx.doi.org/10.1016/j.ecolmodel.2015.12.018	Used an ensemble of six global marine ecosystem models within Fish-MIP to analyze spatio-temporal changes in marine ecosystems over the 21st century on global to regional scales. Assessed 500 species of exploited marine fishes and invertebrates from 1971 to 2060 using three versions of DBEM that differ by the algorithm used to predict relative habitat suitability: DBEM-Basic, DBEM-Maxent, and DBEM-Aquamaps.	Global, focusing on major ocean basins and specific regions such as Canada's Exclusive Economic Zone and the NAFO convention area.	1971-2060	Marine animal biomass and ecosystem structure	**Temperature:** Projected significant declines in marine animal biomass in most ocean basins except polar regions, where biomass was projected to increase over the 21st century. Dissolved Oxygen, Ocean pH, **Circulation, Mixing, and Nutrient Supply:** While not directly addressed, changes in these factors are implied through their impact on primary productivity and temperature, which in turn affect marine animal biomass. **Bottom-up Control:** Variability in primary production, driven by temperature changes, impacts **Bottom-up Control:** for marine species. **Predation:** Not specifically addressed. **Geographic Distribution:** Projected shifts in marine animal biomass indicate potential geographic distribution changes, with biomass increases in polar regions and decreases in most other basins. **Phenology:** Not specifically addressed. **Climate Extremes:** The ensemble projections suggest significant impacts of climate change on marine ecosystems, with notable differences across ocean basins and emission scenarios. **Other Effects:** Highlights the need for climate-resilient fisheries management and conservation efforts, emphasizing the complex interactions between climate change, marine ecosystems, and fisheries management.
Boris Worm & Ranson A. Myers, *Meta-analysis of cod-shrimp interactions reveals*	Meta-analysis of biomass time series for Atlantic cod (Gadus morhua) and northern shrimp (Pandalus borealis), along with ocean temperature data across	North Atlantic Ocean, covering nine regions: Labrador, Northern	1968 to 2011, varying by region.	Atlantic cod and northern shrimp.	**Temperature:** Cod biomass positively related to ocean temperature. Shrimp biomass not significantly related to temperature. **Dissolved Oxygen:** Not directly addressed.

top-down control in oceanic food webs, 84 Ecology 162–173 (2003), https://www.scopus.com/inward/record.uri?eid=2-s2.0-0037916533&doi=10.1890%2F0012-9658%282003%29084%5B0162%3AMAOCSI%5D2.0.CO%3B2&partnerID=40&md5=dd39981f6ca9281c4f9f767dd44c6c07	nine regions of the North Atlantic. Utilized research survey data, catch per unit effort (CPUE) estimates, and sequential population analysis (SPA) for cod and shrimp biomass.	Newfoundland, Flemish Cap, Northern Gulf of St. Lawrence, Eastern Scotian Shelf, Gulf of Maine, Iceland, Barents Sea, Skagerrak.			**Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Implied changes due to temperature shifts affecting marine ecosystems but not directly analyzed. **Bottom-up Control:** Alterations in ecosystem structure and species shifts could imply changes in **Bottom-up Control:**, particularly due to the inverse relationship between cod and shrimp biomass. **Predation:** Strong negative relationship between cod and shrimp biomass supports top-down control by cod on shrimp populations. **Geographic Distribution:** Significant shifts in cod and shrimp biomass, with some species moving in response to temperature changes and **Predation:** pressures. **Phenology:** Not specifically addressed but implied through changes in distribution and abundance patterns. **Climate Extremes:** The study highlights the complexity of responses to changing climates, including potential shifts in distribution. **Other Effects:** The study suggests that the effects of fishing on cod cascade down to affect shrimp populations, indicating significant top-down ecosystem effects.
David J. Yurkowski et al., *A temporal shift in trophic diversity among a predator assemblage in a warming Arctic*, 5 Royal Society Open Science 180259 (2018),	Examined trophic structure shifts using stable isotopes (δ13C and δ15N) in a Bayesian framework over a 22-year period (1990–2012) during which sea temperature increased by 1.08°C and sea ice extent decreased by 12% in Cumberland Sound, Nunavut, Canada.	Cumberland Sound, Nunavut, Canada	1990–2012	Near-apex predator assemblage including beluga whales (*Delphinapterus leucas*), ringed seals (*Pusa hispida*), Greenland halibut (*Reinhardtius hippoglossoides*),	**Temperature:** Increase in sea temperature and decrease in sea ice extent observed, implying significant abiotic changes. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Not directly addressed. **Circulation, Mixing, and Nutrient Supply:** Not directly addressed but implied impact due to changes in abiotic conditions.

http://rsos.royalsocietypublishing.org/lookup/doi/10.1098/rsos.180259				and anadromous Arctic char (*Salvelinus alpinus*).	**Bottom-up Control:** Increased availability of forage fish, especially capelin, indicating changes in food web dynamics and diet flexibility among predators. **Predation:** Not directly addressed. **Geographic Distribution:** Capelin's northward expansion into the region marks a significant shift in available prey species due to warming conditions. **Phenology:** Not directly addressed. **Climate Extremes:** The study period captures a significant warming trend, indicating potential impacts from climate extremes on marine ecosystems. **Other Effects:** Shift from a trophically diverse to a more trophically redundant predator assemblage, suggesting that climate change has led to alterations in the Arctic food web, with predators now playing similar trophic roles by consuming primarily pelagic energy pathway prey.

Table S5: Projected climate impacts on marine life

Table S6 | Projected climate impacts on marine life. Summary of projected climate impacts on marine species, populations, ecosystems, and fisheries.

Reference	Methods	Geographic Focus	Length of Projection	Key Findings under low emissions (SSP245)	Key Findings under high emissions (SSP585)	Key Findings Across Scenarios
Grégory Beaugrand et al., *Addressing the dichotomy of fishing and climate in fishery management with the FishClim model*, 5 COMMUNICATIONS BIOLOGY (2022)	FishClim model integrating fishing intensity and CIEC based on CMIP6 scenarios to project future interactions and impacts on North Sea cod from 1963 to 2019 and future projections (2020-2100).	North Sea, focusing on North Sea cod.	2020-2100	**Temperature:** Significant impacts anticipated with potential reduction in maximum standardised SSB (mdSSB) due to warming, affecting cod distribution and abundance. Ocean pH and **Dissolved Oxygen:** Not explicitly mentioned, but implications of warmer temperatures could affect oxygen levels and acidification impacts. **Ocean Circulation, Mixing, and Nutrient Supply:** Changes in environmental suitability affecting recruitment, though specific details on circulation and mixing not provided. **Food Availability:** Climate change affecting plankton composition, indirectly influencing larval cod survival and recruitment. **Predation:** Not explicitly discussed, but changes in species composition could affect trophic interactions. **Geographic Distribution:** Anticipated shifts in cod distribution due to	**Temperature:** More pronounced decreases in mdSSB anticipated, leading to potentially more significant impacts on cod distribution and abundance. Ocean pH and **Dissolved Oxygen:** Similar concerns as under low emissions, with potentially exacerbated impacts due to higher warming. **Ocean Circulation, Mixing, and Nutrient Supply:** Increased adverse changes in environmental suitability, further affecting recruitment and distribution. **Food Availability:** Stronger impacts on plankton dynamics, further influencing cod survival and recruitment. **Predation:** Similar to low emissions, with potential for more pronounced changes in trophic interactions. **Geographic Distribution:** Greater shifts expected in cod distribution due to more severe environmental changes. **Phenology:** Similar concerns as under low emissions, potentially more acute.	The FishClim model revealed the intertwined impact of fishing and CIEC on North Sea cod, indicating that both can act synergistically or antagonistically to influence stock biomass. Historically, the combined effect of fishing and CIEC was nearly equal, at approximately 55% and 45% respectively. The model predicts that failure to adjust fishing effort in response to environmental changes will result in a lag that may lead to stock collapse. The study underscores the importance of incorporating CIEC into fisheries management to develop sustainable, long-term strategies.

				environmental changes. **Phenology:** Not directly mentioned, but environmental changes could affect breeding and recruitment timing. **Climate Extremes and Other Effects:** Emphasized the need for adaptive fisheries management in response to rapid environmental changes.	**Climate Extremes and Other Effects:** Highlighted the critical importance of integrating climate change into fisheries management to prevent stock collapse.	
Boyce et al.	Developed a statistical framework integrating projections from coupled ecosystem and earth-system models to evaluate marine animal biomass changes.	Global Ocean	21st Century (2006-2100)	**Temperature:** Not explicitly mentioned, but implied effects on marine biomass. **Dissolved Oxygen:** Not directly addressed. Ocean pH: Impacts from acidification not detailed. **Ocean Circulation, Mixing, and Nutrient Supply:** Not specifically discussed. **Food Availability:** Not directly mentioned, but overall productivity and biomass trends imply effects. **Predation:** Not specifically mentioned. **Geographic Distribution:** Not explicitly detailed but inferred from global biomass changes. **Phenology:** Not discussed. Climate Extremes: Not specifically addressed. Other Effects: Highlighted the socio-economic implications, noting that maritime nations with lower socioeconomic status are	**Temperature:** More detailed impacts are not specified; however, significant global ocean biomass reductions are highlighted, particularly under high emissions scenarios. Dissolved Oxygen, Ocean pH, Ocean Circulation, Mixing, and Nutrient Supply, Food Availability, Predation, Geographic Distribution, Phenology, Climate Extremes: Specific details on these aspects under high emissions are not directly provided. Other Effects: Emphasized are the significant biomass reductions expected globally, with 84% of areas showing declining trends. Especially noted is the potential for greater impacts on nations with poor socioeconomic statuses, exacerbating equity gaps and affecting those least responsible for CO2 emissions.	The study projects that future climate-driven changes in marine biomass will exacerbate socioeconomic equity gaps. Maritime nations with lower socioeconomic statuses are expected to experience the greatest projected losses in marine biomass. These nations, often with lower nutrition, wealth, and ocean health, will disproportionately suffer from climate impacts despite contributing least to global CO2 emissions. The analysis suggests that such outcomes can be largely mitigated by achieving negative emissions, underscoring the importance of strong climate action to prevent widening equity gaps and ensure sustainable use of marine resources.

				projected to experience greater losses, suggesting wider equity gaps.		
Boyce et al.	The study utilized an ensemble of climate projections, fisheries data, and ecosystem modeling to assess the future impacts of climate change on marine ecosystems and fisheries productivity.	Atlantic Canada and the Eastern Arctic	Through the 21st century, up to 2100	**Temperature:** Projected to increase, leading to changes in fish distribution and productivity. Ocean pH: Anticipated decreases, affecting calcifying organisms. Ocean Circulation: Expected to alter, impacting nutrient supply and ecosystem productivity. **Food Availability:** Likely changes in plankton dynamics, affecting food webs. **Geographic Distribution:** Northward shifts in species distributions expected. **Phenology:** Changes in spawning and migration patterns. Climate Extremes: Increased frequency and intensity, impacting fisheries stability.	**Temperature:** More severe increases, with greater impacts on species distribution and productivity. Ocean pH: More significant decreases, with broader impacts on marine life. Ocean Circulation: More drastic changes, severely affecting marine ecosystems. **Food Availability:** Greater disruptions to food webs. **Geographic Distribution:** More pronounced northward shifts and loss of habitat for some species. **Phenology:** More significant changes in life cycle events. Climate Extremes: More frequent and severe, posing higher risks to fisheries.	Observed climate effects include distributional shifts, changes in phenology and size structure, and alterations in species interactions such as predation, driven by changes in sea surface temperature, ocean acidification, and other physical-chemical environmental factors.
Bryndum-Buchholz et al.	Utilized an ensemble of six global marine ecosystem models to analyze marine ecosystem responses from 1971 to 2099 under four standardized emissions scenarios within Canada's EEZ.	Canada's EEZ across the Atlantic, Pacific, and Arctic oceans.	1971-2099	**Temperature:** Not specifically broken down by low emissions scenario impacts, but generally, lower emissions scenarios projected successively smaller biomass changes, with warming impacting species distribution and abundance. Dissolved Oxygen, Ocean pH, **Ocean Circulation, Mixing, and Nutrient Supply:** Not specifically discussed. **Food Availability:** Not directly mentioned but implied through	**Temperature:** Projected marine animal biomass declined by an average of -7.7% within the Canadian EEZ, with significant declines in the Pacific (-24%) and Atlantic (-25.5%) and increases in the Arctic (+26.2%). Dissolved Oxygen, Ocean pH, **Ocean Circulation, Mixing, and Nutrient Supply:** Not directly mentioned, but implications of warmer temperatures and stratification on ecosystem productivity are discussed.	By 2099, under business-as-usual emissions (RCP8.5), projected marine animal biomass declined by an average of −7.7% within the Canadian EEZ, with declines dominated by the Pacific (−24%) and Atlantic (−25.5%) areas. These declines were partially compensated by increases in the Canadian Arctic (+26.2%). Lower emissions scenarios projected smaller biomass changes, highlighting the benefits of stronger mitigation targets. Individual model projections varied, being most consistent in the

				changes in primary productivity. **Geographic Distribution:** Northward shifts in species distributions expected under climate change, less severe under low emissions. **Phenology:** Not directly mentioned. Climate Extremes: Increased frequency and intensity under high emissions, expected less severe under low emissions. Other Effects: Emphasized the benefits of stronger mitigation targets to reduce risks to fisheries and marine biodiversity.	**Food Availability:** Changes in primary productivity affecting trophic dynamics. **Geographic Distribution:** Significant northward shifts and biodiversity changes in tropical regions. **Phenology:** Not directly mentioned. Climate Extremes: Highlighted as increasing under high emissions scenarios, affecting fisheries stability and ecosystem health. Other Effects: Stresses the need for region-specific conservation and management strategies to enhance resilience and support the rebuilding of marine ecosystems and commercial fish stocks.	Atlantic and Pacific but highly variable in the Arctic due to model uncertainties in polar regions. Different trajectories of future marine biomass changes underscore the need for region-specific conservation and management strategies.
Andrea Bryndum-Buchholz et al., *The status of climate change adaptation in fisheries management: Policy, legislation and implementation*, Fish and Fisheries faf.12586 (2021), https://onlinelibrary.wiley.com/doi/10.1111/faf.12586	Utilized ensemble modeling approach integrating multiple global marine ecosystem models to project changes in marine animal biomass under different emissions scenarios. Models were forced by outputs from Earth System Models (ESMs) under two contrasting emissions scenarios.	Global, with detailed analysis across different ocean basins including the Arctic, Atlantic, Pacific, and Indian Oceans.	Through the 21st century, from 1971 to 2099.	**Temperature:** Projected changes were generally smaller under low emissions, with some regions showing less decline in biomass or even increases, particularly in polar regions. **Ocean Circulation, Mixing, and Nutrient Supply:** Not specifically discussed, but implied changes due to temperature and ice cover alterations. **Food Availability:** Changes in primary productivity affecting food webs and biomass distributions, with some increases in polar regions under low emissions. **Geographic Distribution:**	**Temperature:** More severe temperature increases leading to significant declines in marine animal biomass, particularly in the tropics and sub-tropics, and increases in the Arctic. **Dissolved Oxygen:** Not directly mentioned but implied changes due to warming and stratification. Ocean pH: Acidification effects not specifically discussed but are implied as part of scenario impacts. **Ocean Circulation, Mixing, and Nutrient Supply:** Implications of changes due to warming, with potential for altering nutrient supply patterns. **Food Availability:** More pronounced changes in primary	The thesis reveals substantial variations in marine ecosystem productivity across different ocean basins due to climate change. It projects significant reductions in marine animal biomass in most ocean basins under high emission scenarios, with polar regions showing potential biomass increases. The Canadian Pacific and Atlantic Oceans are expected to experience decreased ecosystem production, whereas the Canadian Arctic may see increases by 2100, although with high projection variability. These changes suggest differential impacts across regions, with implications for fisheries management and adaptation policies. Key findings highlight the necessity for integrated, climate-informed fisheries management

				Shifts in species distributions were less severe under low emissions, with northward shifts and changes in community structure anticipated but at reduced rates. Climate Extremes: Lower frequency and severity under low emissions, suggesting reduced impacts on marine ecosystems.	productivity affecting food webs and biomass distributions. **Predation:** Not specifically discussed, but changes in food web dynamics suggest implications for predation patterns. **Geographic Distribution:** Significant shifts in species distributions, with more pronounced northward movements and changes in community compositions. **Phenology:** Not directly mentioned, but changes in temperature and productivity suggest potential shifts in life cycle events. Climate Extremes: Increased frequency and severity, potentially leading to more pronounced ecosystem changes. Other Effects: The thesis emphasizes the potential for significant changes in marine biodiversity and fisheries productivity, highlighting the need for adaptive management strategies.	strategies that consider the variable impacts of climate change on marine biodiversity and fisheries.
William W.L. Cheung et al., *Application of macroecological theory to predict effects of climate change on global fisheries potential*, 365 Marine Ecology Progress	Developed an empirical model using macroecology theory, allometric scaling of metabolism, and trophic energetics to predict maximum catch potential from species' trophic level, geographic range, and mean primary production	Global	Not specified directly in the provided text; future-oriented.	**Temperature:** The study anticipates changes in species distribution and productivity due to temperature increases, with specifics dependent on the degree of warming and regional effects. **Ocean Circulation, Mixing, and Nutrient Supply:** Not detailed, but changes in primary productivity suggest indirect effects.	**Temperature:** More severe impacts anticipated, including significant shifts in species distributions and declines in marine biodiversity, especially in tropical regions. **Ocean Circulation, Mixing, and Nutrient Supply:** Indirect effects suggested through changes in primary productivity and ecosystem dynamics, though not explicitly detailed.	The empirical model developed from the study effectively predicts maximum catch potential from species' life history, ecology, and biogeography attributes, showing significant effects of annual primary production in the species' exploited range, trophic level, geographic range, and the number of years of catch data records on the average maximum annual catch of species. This model, when combined with dynamic bioclimate

SERIES 187–197 (2008)	within the species' range. This model was combined with bioclimate envelope models to assess future climate change impacts on marine fisheries.			**Geographic Distribution:** Expected shifts in species distributions less severe under low emissions, implying potential for adaptation or less drastic changes in marine ecosystems. Other Effects: Emphasized the socio-economic implications, noting that changes in fisheries productivity could impact food security and livelihoods, though specifics under low emissions are not detailed.	**Geographic Distribution:** More pronounced shifts in species distributions expected, with potential for significant disruptions to marine ecosystems and fisheries. Other Effects: Highlighted the critical need for integrating climate change into fisheries management to mitigate impacts, suggesting more significant socio-economic challenges under high emissions.	envelope models, offers a powerful tool to predict the socio-economic impacts of climate change on global marine fisheries, demonstrating significant potential for assessing future changes in catch potential under various climate scenarios.
William W L Cheung et al., *Projecting global marine biodiversity impacts under climate change scenarios*, 10 FISH AND FISHERIES 235–251 (2009)	Developed a dynamic bioclimate envelope model to project future distributions of 1066 exploited marine fish and invertebrates using a sample representing a wide array of marine biodiversity. This model integrated population and dispersal dynamics to evaluate shifts in species distributions under climate change scenarios.	Global	Year 2050 relative to 2003	**Temperature:** Local extinction in sub-polar regions, tropics, and semi-enclosed seas due to warming. **Geographic Distribution:** Species invasions most intense in the Arctic and the Southern Ocean, leading to significant biodiversity turnovers. Climate Extremes: Predicted increases in climate extremes could exacerbate impacts, especially in vulnerable regions.	**Temperature:** More severe local extinctions anticipated across sub-polar regions, the tropics, and semi-enclosed seas due to intensified warming. **Geographic Distribution:** More pronounced species invasions in the Arctic and Southern Ocean, potentially disrupting ecosystem services. Climate Extremes: Enhanced vulnerability to climate extremes, stressing the need for adaptive management strategies.	The study projects significant redistributions of global marine biodiversity due to climate change, resulting in local extinctions in the sub-polar regions, the tropics, and semi-enclosed seas. At the same time, species invasions are expected to be most intense in the Arctic and the Southern Ocean, leading to species turnovers of over 60% of the current biodiversity. These changes imply ecological disturbances that could disrupt ecosystem services. The projections serve as hypotheses for future analytical and empirical studies.
William W.L. L. W.W.L. Cheung et al., *Large-scale redistribution of maximum fisheries catch potential in the*	Developed an empirical model integrating the dynamic bioclimate envelope model with projections of primary productivity and species	Global	2005 to 2055	**Temperature:** Expected shifts in species distribution towards higher latitudes, with a moderate impact on catch potential in some regions. **Geographic Distribution:** Less severe redistribution of catch	**Temperature:** Significant warming leading to substantial declines in catch potential in tropical regions and increases in high-latitude regions. **Geographic Distribution:** Pronounced northward shifts in	The study projects significant large-scale redistribution of global catch potential due to climate change, with a 30–70% increase in high-latitude regions and up to a 40% decrease in the tropics. The maximum catch potential declines in the southward margins of semi-

global ocean under climate change, 16 Global Change Biology 24–35 (2010), http://doi.wiley.com/10.1111/j.1365-2486.2009.01995.x	distributions to predict changes in global catch potential for 1066 species of exploited marine fish and invertebrates.			potential compared to high emissions, with some increases in high-latitude regions and decreases in the tropics. Climate Extremes: Fewer and less severe climate extremes anticipated, with a lower impact on marine biodiversity and fisheries.	species distributions, leading to a large-scale redistribution of global catch potential, with notable decreases in the tropics and increases in high-latitude regions. Climate Extremes: More frequent and severe climate extremes, exacerbating the impacts on marine ecosystems and fisheries.	enclosed seas while increasing in poleward tips of continental shelf margins, most notably in the Pacific Ocean. Among the 20 most important fishing Exclusive Economic Zones (EEZ) in terms of total landings, regions with the highest increase in catch potential by 2055 include Norway, Greenland, the United States (Alaska), and Russia (Asia), while those with the biggest loss include Indonesia, the United States (excluding Alaska and Hawaii), Chile, and China. These changes, especially in the tropics, could have significant socio-economic impacts, necessitating adaptation policies to minimize the adverse effects through fisheries management.
William W L Cheung et al., *Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic*, 68 ICES Journal of Marine Science 1008–1018 (2011)	Dynamic bioclimate envelope model incorporating ecophysiology and plankton dynamics to project changes in distribution and maximum catch potential of 120 species of exploited demersal fish and invertebrates.	Northeast Atlantic	2005 to 2050	**Temperature:** Expected northward and deeper shifts in species distributions, but the impacts are generally milder under low emissions scenarios. **Dissolved Oxygen:** Not explicitly mentioned, but reductions in oxygen content are anticipated to reduce growth performance and increase range shifts. Ocean pH: Acidification expected to increase physiological stress, reducing growth performance. **Ocean Circulation, Mixing, and Nutrient Supply:** Not detailed, but changes likely influence species distributions and productivity.	**Temperature:** More severe temperature increases leading to substantial shifts in species distributions. **Dissolved Oxygen:** More pronounced reductions in oxygen content exacerbating stress on marine life. Ocean pH: Greater acidification impacting species' growth and survival more significantly. **Ocean Circulation, Mixing, and Nutrient Supply:** More drastic changes expected, affecting species distribution and productivity more severely. **Food Availability:** Larger changes in plankton community structure under high emissions, significantly	The study projects an average northward distribution-centroid shift of 52 km per decade and a depth shift of 5.1 m per decade for the analyzed species. Ocean acidification and oxygen reduction are found to reduce growth performance, increase the rate of range shift, and lower estimated catch potentials by 20–30% relative to simulations not considering these factors. Incorporation of phytoplankton community structure could further reduce projected catch potentials by approximately 10%. These results underscore the sensitivity of marine ecosystems to biogeochemical changes and emphasize the importance of incorporating such changes in assessing climate change impacts

				Food Availability: Consideration of plankton community structure suggests shifts may reduce projected catch potentials due to changes in food web dynamics. **Geographic Distribution:** Moderate shifts expected, with species moving northward and to deeper waters. Climate Extremes: Fewer and less severe under low emissions, with lower impact on marine biodiversity and fisheries.	reducing catch potential. **Geographic Distribution:** More pronounced northward and deeper shifts in species distributions. Climate Extremes: Increased frequency and severity, posing higher risks to marine ecosystems and fisheries.	on marine biodiversity and fisheries.
William W. L. Cheung et al., *Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems*, 3 NATURE CLIMATE CHANGE 254–258 (2013), http://dx.doi.org/10.1038/nclimate1691	Employed a model examining over 600 species of marine fishes to explore changes in distribution, abundance, and body size due to temperature and oxygen level changes. This integrated biological responses with explicit representation of ecophysiology, dispersal, distribution, and population dynamics.	Global	2000 to 2050	Not specifically differentiated between low and high emissions scenarios in the provided text. However, the study emphasizes impacts on marine ecosystems with a focus on the reduction in fish body size due to warming and decreased oxygen levels, suggesting substantial impacts across all scenarios with particular emphasis on high-emission outcomes.	**Temperature:** Global average shrinkage of 14–24% in fish body size by 2050, with significant reductions in tropical and intermediate latitudinal areas exceeding 20%. **Dissolved Oxygen:** Reduction contributes to decreased fish body size. Ocean pH: Not directly addressed, but implicated in overall stress on marine life. **Geographic Distribution:** Shifts in species distributions towards poles and deeper waters, impacting community compositions. Climate Extremes: Exacerbated by reduced fish body size, leading to increased vulnerability of marine ecosystems.	The study projects a global decrease in assemblage-averaged maximum body weight of 14–24% by 2050 due to climate change, with individual and community-level impacts. About half of this shrinkage is due to changes in distribution and abundance, with the rest attributed to physiological changes. The most significant impacts are expected in the tropics and intermediate latitudinal areas, where a reduction of more than 20% in average maximum body weight is anticipated. This reduction in body size across marine fish species underpins a new dimension to understanding the broader impacts of climate change on marine ecosystems, suggesting a significant exacerbation of the impacts on marine biodiversity, food webs, and fisheries.
Cheung et al.	Utilized a global index called the mean temperature of	52 Large Marine Ecosystems	1970 to 2006	The study does not specifically differentiate findings under low versus high emissions scenarios	**Temperature:** In non-tropical LMEs, MTC increased at a rate of 0.23°C per decade.	Global MTC increased by 0.19°C per decade, with non-tropical LMEs experiencing a 0.23°C per

	the catch (MTC) calculated from the average inferred temperature preference of exploited species weighted by their annual catch, alongside generalized additive mixed model (GAMM) analyses to attribute changes in MTC to ocean warming.	(LMEs) accounting for most of the world's fisheries.		but highlights a general trend of ocean warming affecting global fisheries. **Temperature:** Demonstrated an average global increase in MTC of 0.19°C per decade, indicating a shift towards catches of warmer-water species. **Geographic Distribution:** Noted "tropicalization" of catches in non-tropical LMEs, showing shifts towards warmer-water species. Climate Extremes: Suggested that changes in MTC were significantly related to regional changes in sea surface temperature, implicating ocean warming in the observed trends.	**Geographic Distribution:** Observed a rapid initial increase in MTC in tropical areas due to the reduction in the proportion of subtropical species catches, but this stabilized as further "tropicalization" became limited. Climate Extremes: Highlighted the immediate need to develop adaptation plans to minimize warming effects on coastal communities, particularly in tropical regions.	decade increase. This signature of ocean warming in global fisheries highlights changes in species composition toward warm-water species, particularly in higher latitudes, and a decrease in subtropical species in the tropics due to tropicalization. The study underscores the urgent need for adaptation plans to mitigate impacts on coastal communities' economy and food security, especially in tropical regions.
Cheung et al.	The study employed the Dynamic Bioclimate Envelope Model (DBEM) with three versions (DBEM-Basic, DBEM-Maxent, and DBEM-Aquamaps) to predict changes in habitat suitability and project potential catches of 500 species of exploited marine fishes and invertebrates from 1971 to 2060. The models incorporated variables such as temperature, oxygen, salinity, and net primary production to	Global	1971-2060	The study does not specifically distinguish between low and high emissions scenarios but focuses on the impact of a high emissions scenario (RCP 8.5), projecting a decrease in catch potential globally by 3% to 13% by 2050. The results suggest that the structural uncertainty of DBEM, particularly the algorithm used to predict habitat suitability, significantly influences the projections, although qualitative patterns of changes (e.g., decrease in tropical regions and increase in higher latitudes) remain consistent across model versions.	**Temperature:** Significant warming leading to reductions in catch potential, particularly in tropical regions, with some increases in higher latitudes. Dissolved Oxygen & Ocean pH: The study implies that changes in these factors contribute to the overall decrease in catch potential, but specific impacts are not detailed. **Geographic Distribution:** Shifts in species distributions are projected, with more pronounced changes under high emissions scenarios. Other Effects: The study emphasizes the importance of considering structural uncertainties in model projections and suggests using multiple versions of DBEM to capture a range of potential outcomes.	The study projected a global decrease in catch potential of 3% to 13% by 2050 under a high emissions scenario (RCP 8.5), with all DBEM models showing similar skill in predicting the occurrence of exploited species and the distribution of observed fisheries production. Projections by DBEM-Maxent were less sensitive to changes in ocean properties than those by DBEM-AquaMaps. The mean magnitude of projected changes varied by region, being highest in the tropical regions and Arctic Ocean, and lowest in three main Eastern Boundary Upwelling regions, the eastern Indian Ocean, and the Southern Ocean. This suggests the qualitative patterns of changes in catch potential reported in previous studies are not affected by the structural uncertainty of

	simulate fish stock dynamics and catch potential under changing ocean conditions.					DBEM, particularly in areas where catch potential was projected to be most sensitive to climate change. However, it's recommended to use multiple versions of DBEM in the future to quantify the uncertainty associated with structural differences of the models.
W. Cheung et al., *Modelling present and climate-shifted distribution of marine fishes and invertebrates*, Fisheries Centre Research Reports (2016)	The study developed a dynamic bioclimate envelope model to predict the effects of climate change on the distributions of marine species. It integrates temperature preferences, depth ranges, habitat associations, and distance from sea ice to model species distribution shifts.	Global	1971-2060	Does not explicitly differentiate findings between low and high emissions scenarios. However, it focuses on the mechanisms of species distribution shifts due to changes in sea water temperature, ocean advection, and habitats. **Temperature:** Emphasizes the model's capacity to simulate distribution shifts towards poles or deeper waters in response to warming. **Geographic Distribution:** Projects poleward and depth shifts for species, aligning with warming trends.	**Temperature:** Similar to the low emissions scenario, but the expectation is that impacts would be more pronounced under high emissions, with greater shifts in geographic distribution and more significant changes in habitat suitability. **Geographic Distribution:** Anticipates more drastic redistribution of species, particularly affecting tropical regions and enhancing polar biodiversity. Other Effects: The study outlines the model's potential to explore various climate change scenarios, indicating significant shifts in marine biodiversity and fisheries productivity globally.	The model offers a comprehensive approach to predict climate change impacts on marine biodiversity, specifically on the distribution of commercially exploited marine species. It integrates several factors influencing species distributions, including temperature, bathymetry, habitat associations, and proximity to sea ice, to simulate potential shifts under different climate change scenarios. Initial evaluations using hypothetical scenarios of global sea water temperature increase demonstrated the model's capability to provide reasonable predictions of future distribution ranges for various marine species. The study highlights the importance of considering multiple ecological and environmental factors to understand and project climate-induced distributional changes in marine species, which is crucial for fisheries management and conservation efforts in the face of global climate change.
W. W.L. Cheung, *The future of fishes and fisheries in the changing oceans*, 92	Conceptual and theoretical analysis integrating existing research findings on the impacts of climate change on	Global	Throughout the 21st century	While specific findings under low emissions are not detailed, the paper emphasizes that mitigating carbon emissions and adhering to the Paris Agreement significantly reduces climate	Under high emissions scenarios (RCP 8.5), significant impacts include: **Temperature:** Substantial increases causing shifts in species distributions, notably poleward and into deeper waters. Ocean pH:	This paper discusses the direct and indirect impacts of climate change on marine fish and fisheries, emphasizing the importance of mitigating carbon emissions to reduce climate risk. It highlights

JOURNAL OF FISH BIOLOGY 790–803 (2018)	marine ecosystems and fisheries, including projections from dynamic bioclimate envelope models and global databases.			risks to marine fish stocks and fisheries. The impacts under low emissions scenarios are expected to be less severe, with potential for some adaptive responses in marine species and fisheries management.	Ocean acidification exacerbates the physiological stress on marine life, reducing productivity and catch potential. **Geographic Distribution:** Major losses in biodiversity in tropical regions and semi-enclosed seas, with species gains in the Arctic. **Food Availability:** Global decline in primary production affecting fisheries yields. Other Effects: Increased vulnerability of marine fisheries to climate extremes, with notable socioeconomic impacts, especially on vulnerable coastal communities.	observed shifts in marine species' biogeography, such as increased catches of warmer-water preferred species, and projects continued shifts under climate change, leading to species gains in Arctic and losses in tropical regions. The impacts on fisheries catch, economics, and the effectiveness of fisheries management are explored, with a call for holistic examination to fully understand and mitigate the challenges posed by climate change on marine systems.
William W.L. Cheung & Thomas L. Frölicher, *Marine heatwaves exacerbate climate change impacts for fisheries in the northeast Pacific*, 10 SCIENTIFIC REPORTS 1–10 (2020)	Integration of Earth system model simulations with a fish impact model to simulate responses of major northeast Pacific fish stocks to MHWs.	Northeast Pacific, including Eastern Bering Sea, Gulf of Alaska, and California Current Large Marine Ecosystems.	1981-2100	The study does not distinguish findings between low and high emissions but shows that MHWs cause rapid and significant impacts on biomass decrease and shifts in biogeography of fish stocks, exacerbating climate change impacts.	**Temperature:** MHWs cause rapid changes, with SST anomalies averaging 0.99°C higher than ensemble-mean SST during MHWs, leading to significant decreases in fish stock biomass and shifts in biogeography. **Geographic Distribution:** Noted shifts in species distributions towards poles or deeper waters in response to MHWs. Other Effects: Highlights the added challenges from MHWs for fisheries management under climate change, with projected doubling of impact levels by 2050 over assessments focusing only on long-term climate change.	MHWs cause decreases in biomass and shifts in the biogeography of fish stocks at rates four times faster and larger than decadal-scale mean changes throughout the 21st century. With MHWs, a doubling of impact levels by 2050 is projected among the most important fisheries species, over previous assessments that focused only on long-term climate change. MHWs result in median biomass decreases of -2.8% during event years, with maximum decreases up to 20%, and almost all fish stocks in the California Current experienced biomass decreases during MHWs. Pelagic fish are projected to be the most negatively impacted, followed by Pacific salmon and groundfish. MHWs also lead to poleward shifts in the latitudinal distribution of fish stocks, with significant variation among regions and species.

Gattuso et al.	The study draws on the consensus science in the latest assessment report of the Intergovernmental Panel on Climate Change and recent papers to evaluate changes to the ocean and its ecosystems under two contrasting CO2 scenarios: a high-emissions trajectory (RCP8.5) and a stringent emissions scenario (RCP2.6).	Global	21st century	**Temperature:** The ocean continues to warm but at a slower rate, with impacts still significant but more manageable for marine life. Ocean pH: Slight decrease in pH but remains more stable compared to high emissions, affecting calcifying organisms to a lesser degree. **Geographic Distribution:** Less drastic but still noticeable shifts in species distributions towards the poles. Other Effects: Coastal protection and capture fisheries already affected, but the risks of impacts to these services increase more moderately.	**Temperature:** Substantial warming causing shifts in species distributions, notably poleward and into deeper waters. Ocean pH: Significant acidification exacerbating physiological stress on marine life, reducing productivity and catch potential. **Geographic Distribution:** Major losses in biodiversity in tropical regions and semi-enclosed seas, with species gains in the Arctic. Other Effects: All ecosystem services considered at high or very high risk over the same time frame, with coastal protection and capture fisheries already being affected.	The study highlights that ocean warming and acidification increase proportionally with cumulative CO2 emissions. Even under a stringent emissions scenario (RCP2.6), ecosystems like warm-water corals and mid-latitude bivalves are at high risk by 2100. Under the current high emissions trajectory (RCP8.5), most marine organisms evaluated will face very high risk of impacts by 2100, many by 2050. These impacts will affect ecosystem services such as coastal protection and capture fisheries, which are already seeing effects from ocean warming and acidification. The risks of impacts to these services increase with continued emissions. Under stringent emission reductions, risks remain moderate for most services over the next 85 years, but the business-as-usual scenario would put all considered ecosystem services at high or very high risk. The study emphasizes immediate and substantial reduction of CO2 emissions to prevent massive and mostly irreversible impacts on ocean ecosystems and their services.
Anne Babcock Hollowed et al., *A framework for modelling fish and shellfish responses to future climate*	The study outlined a five-step framework for forecasting climate impacts on marine fish production, integrating mechanisms of	Bering Sea, with a specific example on northern rock sole (Lepidopsetta polyxystra).	2001-2050	Does not explicitly distinguish between findings under low and high emissions scenarios but focuses on the broader approach to assessing impacts under climate change. The framework is designed to be applied under any emissions scenario to	**Temperature:** The framework predicts mean summer surface temperature in the Bering Sea to increase by 2°C by 2050. **Geographic Distribution:** Climate change is projected to modestly increase the production	The study outlines a unified approach to forecasting the implications of climate change on marine fish production. It applied this framework to forecast summer sea surface temperature in the Bering Sea, predicting a mean increase of 2°C by 2050. For

change, 66 ICES Journal of Marine Science 1584–1594 (2009)	reproductive success, growth, and distribution with environmental variables from IPCC models, and applying these to fish and shellfish projection models.			estimate impacts on fish and shellfish populations.	of strong year classes of northern rock sole through changes in larval transport. Other specific effects under high emissions scenarios, such as dissolved oxygen, ocean pH, and other ecological factors, are implied to impact marine species but are not detailed separately for low and high scenarios.	northern rock sole (Lepidopsetta polyxystra), the framework estimated effects of climate change through projected changes in larval cross-shelf transport in the Bering Sea, suggesting a modest increase in the production of strong year classes due to climate change. The study underscores the importance of integrated modeling and adaptive management in responding to climate impacts on marine resources.
Anne B. Hollowed et al., *Projected impacts of climate change on marine fish and fisheries*, 70 ICES Journal of Marine Science 1023–1037 (2013)	Review of current literature and integration of findings from international symposiums on climate change effects on marine ecosystems.	Northern hemisphere	21st century	Synthesizes a broad range of findings and does not specifically differentiate between low and high emissions scenarios. However, it highlights general expected impacts such as changes in ecosystem productivity, habitat quality, shifts in species distributions, and implications for fisheries and fishery-dependent communities.	Under high emissions scenarios, significant impacts include: **Temperature:** More pronounced warming affecting species distributions, productivity, and phenology. Ocean pH: Increased acidification impacting calcifying organisms and food web dynamics. **Dissolved Oxygen:** Potential for increased hypoxic zones affecting fish survival and distribution. **Geographic Distribution:** Greater shifts in species ranges, with poleward and deeper movements. **Food Availability:** Changes in primary and secondary productivity may alter food web structures and fishery yields. **Predation:** Altered species interactions due to shifts in distributions and abundances. Climate Extremes: More frequent and severe marine heatwaves and other extremes could have substantial impacts on marine biodiversity and fisheries. Other	The study anticipates significant impacts on marine ecosystems due to climate change, affecting species distribution, productivity, and fishery-dependent communities. Key expected changes include shifts in ecosystem productivity and habitat quality, affecting vital rates and spatial distributions of marine species. Climate change is projected to impact fisheries through alterations in stock composition, availability, and productivity, with implications for food security and economic well-being of fishery-dependent communities. Uncertainties in projections necessitate integrated research and adaptive management to address the complex suite of climate-driven processes influencing marine resources. Eight research foci are identified to improve projections, including physiological measurements, ecological monitoring, short-term forecasts, process studies, comparative studies, improvement of Earth System Models (ESMs),

					Effects: Increased vulnerability of marine fisheries and communities, particularly in regions highly dependent on marine resources.	vulnerability assessments, and development of coping strategies.
Hollowed et al.	Review of literature and symposium findings from ECCWO-4	Global	21st century	The findings synthesized from the Fourth International Symposium do not specify separate outcomes for low and high emissions scenarios directly. However, the article discusses general impacts of climate change on ocean ecosystems and dependent communities. Impacts include shifts in species distributions, changes in food web structures, and alterations in the timing of biological events (phenology). Climate change is also linked to the increased frequency of marine heatwaves and extreme weather events, affecting species' habitat quality and availability.	Similar to the findings under low emissions, the impacts under high emissions would likely be exacerbated, leading to more significant shifts in species distributions, greater changes in ecosystem productivity, and more severe consequences for marine biodiversity and fisheries. Increased ocean acidification and hypoxia are expected, affecting marine life's physiological processes and survival. Additionally, the risks associated with climate extremes, such as marine heatwaves, would increase, further stressing marine ecosystems and the livelihoods of communities reliant on them.	Seven key messages were identified, highlighting that climate change is already affecting oceans and socio-ecological systems, with significant impacts on weather, national security, food security, transport, and commerce. The symposium underscored the urgent need for advanced understanding of these changes, the risks associated with them, and the development of effective adaptation pathways. Technical advances in observation networks are improving our understanding of ocean processes, but projections of future ocean conditions remain incomplete. The symposium underscored the importance of developing fully coupled socio-ecological models to project future scenarios and assess the ecological and societal impacts of different future climate change scenarios. Some marine organisms show the capacity to adapt to climate change, but there are limits to this adaptation. The options available for societal adaptation are more limited if current trends of greenhouse gas emissions continue, highlighting the need for adaptive management frameworks to address climate-driven policy issues.
Hollowed et al.	The study utilizes an integrated modeling approach combining	Eastern Bering Sea	2001-2100	The findings are not explicitly differentiated between low and high emissions scenarios within	**Temperature:** Projections indicate significant warming, affecting species distributions and	The ACLIM project outlines significant deviations from historical ocean conditions for the

	climate models, biological models, socio-economic modeling, and management strategy evaluation to project changes in marine species distributions and abundances, and the socio-economic impacts on fisheries and communities.			the text. However, the study emphasizes the integrated approach to evaluate climate change impacts on marine species and fisheries. It highlights the use of multi-model projections to understand how different management approaches can help adapt to climate-driven changes.	productivity. Ocean pH: Acidification impacts are noted, with expectations of adverse effects on calcifying organisms and broader ecosystem dynamics. **Geographic Distribution:** Anticipated shifts in species distributions, with potentially drastic changes under high emission scenarios, affecting ecosystem structure and fisheries. Other Effects: Emphasizes the need for adaptive management strategies to mitigate impacts, highlighting the importance of iterative communication with stakeholders for realistic scenario exploration.	Bering Sea, predicting large impacts on marine ecosystems. Increased ocean temperatures are expected to shift trophic demand, affect species interactions, alter spatial distributions, and influence overall system productivity. Ocean acidification poses threats to valuable crab stocks and pelagic prey species. The study emphasizes the use of integrated modeling to understand, prepare for, and respond to climate impacts on marine resources. Projections highlight the need for adaptive management strategies to sustain fish and shellfish populations and to mitigate risks associated with different future climate scenarios. The project serves as a guide for climate impact and adaptation decision-making in large marine ecosystems.
Lam et al.	Dynamic Bioclimate Envelope Models (DBEM) were applied to project changes in distributions, abundances, and catches by the mid-21st century for marine fish and invertebrate species. Outputs from three Earth System Models (ESMs) under the Representative Concentration Pathways (RCPs) 2.6 and 8.5 were utilized.	Global, covering 280 Exclusive Economic Zones (EEZs) and the high seas.	Up to 2050	**Temperature:** The impact of climate change is lower than under RCP 8.5, with MCP and MRP decreasing by an average of 4.1% and 7.1%, respectively. **Geographic Distribution:** Increases in MCP in high latitudinal regions and decreases in the tropics are expected but with lesser magnitude compared to RCP 8.5.	**Temperature:** Global MCP is projected to decrease by 7.7%, with global fisheries revenue decreasing by 10.4%, indicating a more significant impact on revenues than on catches. **Geographic Distribution:** The tropics are expected to see significant decreases in MCP and MRP, while high latitudinal regions may see increases. However, the dominance of low-value fish and the impact on distant water fishing operations may not translate these increases into revenue gains. Other Effects: Developing countries with high fisheries dependency are negatively impacted, with	Global fisheries revenues could decrease by 35% more than the projected decrease in catches by the 2050s under high CO2 emission scenarios. Regionally, increases in fish catch in high latitudes may not translate into revenue increases due to the dominance of low-value fish and the decrease in catches by vessels operating in more severely impacted distant waters. Developing countries with high fisheries dependency are negatively impacted. The study suggests the need for economic analyses of climate change's potential economic effects on global marine fisheries.

					projected decreases in MCP and MRP under the high emissions scenario.	
Link et al.	Literature review and synthesis from international symposiums on climate change effects on marine ecosystems.	Global	21st century	Emphasizes the need for a proactive approach to generate, deliver, and utilize climate-related information to manage and conserve marine resources effectively. Although it does not specify direct impacts under low emission scenarios, the strategy aims to improve resilience and adaptive capacity of marine ecosystems and dependent communities.	Similar to low emissions, high emission scenarios necessitate robust scientific frameworks and predictive models to address the compounded effects of climate change on marine biodiversity, fisheries, and ecosystem services. The focus is on developing adaptive management strategies and decision-making processes that incorporate dynamic climate conditions, ensuring sustainable exploitation and conservation of marine resources.	The strategy highlights the urgent need for more information on the impacts of climate changes on Living Marine Resources (LMRs) and science-based approaches for sustaining LMRs and resource-dependent communities in a changing climate. Key findings and objectives include identifying climate-informed reference points for managing LMRs, identifying robust strategies for managing LMRs under changing climate conditions, designing adaptive decision processes, identifying future states of marine and coastal ecosystems, understanding mechanisms of climate impacts, tracking trends and providing early warnings, and building and maintaining the science infrastructure. It emphasizes the need for standardized ecosystem indicators and status reports, conducting vulnerability analyses, and developing management strategy evaluations. The strategy aims to reduce impacts and increase resilience of marine resources and the communities that depend on them.
Heike K Lotze et al., *Ensemble projections of global ocean animal biomass with climate change*, PROCEEDINGS	Utilized ensemble projections from six global marine ecosystem models forced with two Earth System Models (ESMs) under four emission	Global	Up to 2100	**Temperature:** Mean global animal biomass decreased by 5% (±4% SD) with every 1°C of warming. **Geographic Distribution:** Strong biomass increases are projected at high latitudes and	**Temperature:** Under high emissions, mean global animal biomass decreased by 17% (±11% SD), indicating more significant impacts on marine biodiversity and fisheries under higher warming scenarios.	Without fishing, global marine animal biomass is projected to decrease by 5% under low emissions and by 17% under high emissions by 2100. These projected declines are primarily due to increasing temperatures and decreasing primary production, and

of the National Academy of Sciences 1–6 (2019), https://www.biorxiv.org/content/early/2018/11/09/467175	scenarios. The study aimed to standardize outputs to estimate mean future trends and associated uncertainties across the marine food web.			decreases at middle to low latitudes, with good model agreement on the direction of change but variable magnitude.	**Geographic Distribution:** Similar to low emissions but with more pronounced changes, including substantial decreases in biomass at middle to low latitudes and increases at high latitudes. Climate Extremes: The study suggests that marine heatwaves and extreme weather events could have substantial impacts on marine biodiversity and fisheries.	are more pronounced at higher trophic levels, a process termed as trophic amplification. Fishing does not substantially alter the effects of climate change on marine biomass. Regional variation is significant, with strong biomass increases projected at high latitudes and decreases at middle to low latitudes. The study emphasizes the importance of multi-model inference to project future outcomes and suggests that global ocean animal biomass consistently declines with climate change, with these impacts being amplified at higher trophic levels.
Effects of climate change on food production (fishing), *in* The Impacts of Climate Change: Comprehensive Study of the Physical, Societal and Political Issues 205–231, https://linkinghub.elsevier.com/retrieve/pii/B978012822373400173	Review of literature and synthesis from international symposiums on climate change effects on marine ecosystems.	Global	21st century	Not specifically detailed. However, the study highlights general expected impacts such as changes in species distributions, shifts in marine food webs, alterations in ocean ecosystem production, and consequences for fisheries and seafood production. Emphasis is placed on understanding the multifaceted effects of climate change to guide necessary adaptations in fisheries management and ocean governance.	Similar to low emissions, high emission scenarios would exacerbate the negative impacts on marine biodiversity and ecosystem functions, leading to more pronounced changes in species distributions, greater disruptions to marine food webs, and increased challenges for fisheries management and ocean governance. Specific effects under high emissions include more severe ocean warming, acidification, oxygen depletion, and extreme weather events, potentially leading to greater declines in marine animal biomass, shifts in food web dynamics, and reductions in fisheries catch potential and seafood production.	**Temperature:** The study outlines significant warming impacts on marine ecosystems, leading to shifts in species distributions and abundances, and affecting marine food webs and ecosystem production. Ocean pH and **Dissolved Oxygen:** Acidification and oxygen depletion, resulting from increased carbon dioxide levels and altered circulation patterns, were identified as critical factors influencing marine organisms' survival, growth, and reproduction. **Ocean Circulation, Mixing, and Nutrient Supply:** Changes in circulation and stratification impact nutrient distribution and availability, influencing primary and secondary production levels. **Food Availability:** Altered marine food web dynamics, due to

						changes in plankton communities and nutrient availability, affect the biomass and productivity of higher trophic levels. **Predation:** The restructuring of food webs alters predator-prey interactions. **Geographic Distribution:** Many species are shifting their ranges northward or to deeper waters. **Phenology:** Shifts in the timing of biological events disrupt predator-prey synchrony. Climate Extremes: Increased frequency of extreme events like marine heatwaves impacts species survival and distribution. Other Effects: The cumulative effects of climate change, along with other human impacts, pose significant challenges to marine biodiversity, fisheries, and ecosystem management.
Lotze et al.	Multidisciplinary synthesis of over 4000 years of climate, ocean environmental changes, and marine ecosystem dynamics integrating paleoceanographic, archaeological, historical, and modern records along with future model projections.	Northwest Atlantic, specifically the Gulf of Maine and Scotian Shelf.	Over 4000 years including projections to 2100.	**Temperature:** The study does not specify findings explicitly under low and high emission scenarios but discusses the region's sensitivity to temperature changes. Increases in ocean temperature have been historically associated with shifts in marine species distributions and abundances. Ocean Circulation: Changes in major ocean currents due to climate variability and human activities have significantly impacted marine ecosystem dynamics, affecting the distribution and abundance of key species.	**Temperature:** Under high emissions, the study anticipates more pronounced changes in ocean temperature, potentially leading to more drastic shifts in marine biodiversity and ecosystem services. **Geographic Distribution:** Similar to low emissions, but with expectations of more dramatic shifts in marine species distributions due to higher temperature increases and ocean acidification. Climate Extremes: The study suggests that marine ecosystems in the Northwest	The study provides a multidisciplinary synthesis of environmental and ecosystem conditions, revealing multiple reference points and shifting baselines. It projects a near-future departure from natural climate variability in 2028 for the Scotian Shelf and 2034 for the Gulf of Maine. This work aids in advancing integrative end-to-end modeling to improve predictive capacity of ecosystem forecasts with climate change, and can be used to adjust marine conservation strategies and ecosystem-based

				Geographic Distribution: Historical records and paleo data indicate significant shifts in species distributions associated with climate change, particularly during periods of warming.	Atlantic are increasingly vulnerable to climate extremes, with significant implications for marine biodiversity and fisheries under high emission scenarios.	management in response to climate change.
Julia G. Mason et al., *Projecting climate-driven shifts in demersal fish thermal habitat in Iceland's waters*, 78 ICES Journal of Marine Science 3793–3804 (2021)	Generalized additive models were used to characterize suitable thermal habitat for 51 fish species in Iceland's waters, projecting changes with an ensemble of five general circulation models under two scenarios.	Iceland's waters	Mid-century (2061-2080)	**Temperature:** A general northward shift in suitable thermal habitat distribution, with some variability among species. Warmer-water species more likely to see increases in thermal habitat and southern warm-edge range expansions.	**Temperature:** Similar to low emissions, with more significant declines in marine biodiversity and fisheries under higher warming scenarios. Increased ocean warming leads to more drastic shifts in marine biodiversity and ecosystem services. **Geographic Distribution:** Similar northward shifts in suitable thermal habitat, but with potentially more extreme changes. Climate Extremes: Increased vulnerability to marine heatwaves and extreme weather events, with significant implications for marine biodiversity and fisheries.	A general northward shift in suitable thermal habitat distribution was projected, with variable regional dynamics among species. Warmer-water species were more likely to see increases in thermal habitat and southern warm-edge range expansions. While the results isolate the effects of future changes in temperature, providing an indication of suitable thermal habitat, low model explanatory power suggests that additional variables may improve distribution projections. These projections might serve as guideposts to inform long-term management decisions about regional and species-specific suitability for Iceland's fisheries, infrastructure investment, and risk evaluation under climate change.
James W. Morley et al., *Projecting shifts in thermal habitat for 686 species on the North American continental shelf*, 13 PLOS ONE e0196127 (2018), https://dx.plos.org/10.1371/jour	Used Generalized Additive Models (GAMs) to model thermal habitat for marine species, integrating survey data with outputs from sixteen general circulation models under RCP 2.6 and RCP 8.5 scenarios.	North American continental shelf	21st century	**Temperature:** The study does not distinguish findings between low and high emission scenarios explicitly. In general, temperature increases are expected to lead to poleward and deeper shifts in species distributions, with variations in sensitivity among species. **Geographic Distribution:** Predictions indicate general poleward shifts following	**Temperature:** Similar general patterns as under low emissions, but with potentially more pronounced impacts due to higher temperature increases. **Geographic Distribution:** More drastic poleward shifts expected, exceeding 1000 km for some species, especially on the U.S. and Canadian west coast. Climate Extremes: Enhanced vulnerability to climate extremes, affecting	Projections generally agreed on the magnitude and direction of future shifts for many species (448 under RCP 8.5 and 429 under RCP 2.6), indicating robust predictions. Future shifts in species distributions were generally poleward and followed the coastline, varying among regions and species. The highest projected magnitude shifts were observed for species from the U.S. and Canadian west coast, including the

nal.pone.0196127				coastlines, with notable region-specific variations. Species in higher latitudes (e.g., Gulf of Alaska) projected to have significant northward shifts.	marine biodiversity and fisheries more severely under high emission scenarios.	Gulf of Alaska, with many species shifting more than 1000 km under the high greenhouse gas emissions scenario. Adhering to a strong mitigation scenario consistent with the Paris Agreement would likely result in substantially smaller shifts and less disruption to marine management efforts.
Oliver et al.	Analysis of outputs from the Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate model simulations. MHWs were identified using a set of metrics to characterize their frequency, intensity, and duration.	Global	Through the 21st century	**Temperature:** Not specifically detailed under low emissions. The study emphasizes the global increase in MHW intensity and count of annual MHW days, with projections indicating significant accelerations in many parts of the ocean reaching a near-permanent MHW state by the late 21st century.	**Temperature:** Under high emissions, significant global increases in MHW intensity and duration are expected. The projections suggest many regions of the ocean may experience a near-permanent MHW state by the late 21st century, with more pronounced impacts on marine biodiversity and fisheries under higher warming scenarios. **Geographic Distribution:** Expected poleward shifts in the geographic distribution of species due to temperature increases. Climate Extremes: Enhanced vulnerability to marine heatwaves and extreme weather events, with significant implications for marine biodiversity and fisheries.	Significant increases in MHW intensity and count of annual MHW days are projected, with many parts of the ocean reaching a near-permanent MHW state by the late 21st century. The study projects that future disruptions of marine ecosystems due to MHWs will be abrupt, widespread, and significant. Under high-emissions scenarios, MHWs are expected to become more frequent, with longer durations and higher intensities. These changes are anticipated to lead to substantial ecological impacts, including shifts in species distributions, loss of biodiversity, and alterations in ecosystem structure and function. The study emphasizes the importance of understanding future changes in MHWs for proactive marine management and conservation efforts.
Myron A. Peck et al., *Projecting changes in the distribution and productivity of living marine resources: A critical review*	The study reviews and compares four broad categories of spatially-explicit modeling approaches: 1) statistical species distribution models, 2) physiology-	The focus is on understanding and projecting changes in the distribution and	Not specified; the review encompasses various models with projections up to the	General Observations Across Scenarios: The study emphasizes the need for models to account for multiple interacting factors affecting living marine resources, such as climate-driven changes in temperature, ocean acidification, and other anthropogenic impacts. It	Similar to the findings under low emissions, high emission scenarios necessitate comprehensive models that can analyze the compounded effects of climate change and other anthropogenic impacts on marine biodiversity and ecosystems. The review suggests a critical need for advancements in modeling	The study highlights the need for models to increasingly address the complexity of multiple factors affecting marine resources, including climate-driven changes in temperature, acidification, and the introduction of invasive species, among others. The review indicates that statistical

of the suite of modelling approaches used in the large European project VECTORS, 201 Estuarine, Coastal and Shelf Science 40–55 (2018)	based, biophysical models, 3) food web models, and 4) end-to-end models.	productivity of living marine resources globally.	21st century.	highlights the necessity of moving beyond historical pattern detection to model the biological and physical mechanisms driving future changes.	approaches to accurately predict future outcomes under higher emissions scenarios.	approaches, while useful for detecting historical patterns, may not suffice for future projections due to their correlative nature. The advancement in predicting changes in marine resources' distribution and productivity lies in the explicit modeling of biological and physical mechanisms. The study calls for new formulations that realistically incorporate ecophysiology, behavior, life history strategies, and trophodynamic interactions at varying spatial scales. Coupling existing models has shown success, but there's a pressing need for models to accommodate the adaptive capacity of species/groups to climate change and other stressors.
Miranda C. Jones et al., *Modelling commercial fish distributions: Prediction and assessment using different approaches*, 225 Ecological Modelling 133–145 (2012), http://dx.doi.org/10.1016/j.ecolmodel.2011.11.003	The study compared three species distribution modeling approaches (AquaMaps, Maxent, and the Sea Around Us Project algorithm) for predicting the distributions of marine fishes and invertebrates in the North Sea and North Atlantic. These models were designed to address issues of data quality and quantity in species distribution modeling, especially	North Sea and North Atlantic	The study did not specify a projection length but focused on comparing current distribution modeling approaches.			The study found that each modeling method produced plausible predictions of relative habitat suitability for each species, with subsequent incorporation of expert knowledge generally improving predictions. Due to differences in modeling algorithms, methodologies, and patterns of relative suitability, comparing models using test statistics and selecting a ‘best’ model were not recommended. The study proposed that a multi-model approach should be preferred, and a suite of possible predictions considered to minimize biases due to uncertainty in data and model formulation.

	relevant to marine environments. The comparison aimed to understand the robustness and uncertainty of projections from these different approaches.					
Kelly A. Kearney et al., *Using Global-Scale Earth System Models for Regional Fisheries Applications*, 8 FRONTIERS IN MARINE SCIENCE 1–27 (2021)	Integrated assessment model combining fisheries management models with reduced-form biogeochemical modeling. The study emphasizes understanding the structural differences in the biogeochemical sub-models within Earth System Models (ESMs) that may give rise to differences in projections of net primary production and other Living Marine Resource (LMR)-relevant metrics.	Global, with a focus on regional fisheries applications.	Through the end of the 21st century, utilizing scenarios from the latest IPCC reports.			Climate change impacts on ocean ecosystems include shifts in primary productivity, plankton community structure, ocean acidification, and deoxygenation. These processes can be simulated with global ESMs, increasingly used in fisheries management. However, projections of LMR-relevant metrics, such as net primary production, can vary widely between ESMs, even under identical climate scenarios. The review provides an overview of the most prominent differences among the latest generation of ESMs and how they are relevant to LMR applications. It highlights the importance of using ESM output in conjunction with an understanding of the models' structural differences to better inform fisheries management and climate resilience strategies.
Pigot et al.	Geographical data analysis for approximately 36,000 marine and terrestrial species, using climate projections to 2100.	Global	Up to 2100	The study does not specify findings explicitly under low emissions. In general, it suggests that the area of each species' geographical range at risk of thermal exposure will expand abruptly, with more than 50% of the increase in exposure	**Temperature:** Under higher levels of warming, the number of species at risk of abrupt and widespread thermal exposure doubles from less than 15% to more than 30% between 1.5°C and 2.5°C of global warming. **Geographic Distribution:** The	The study reveals an abrupt expansion of climate change risks for species globally. On average, more than 50% of the increase in exposure projected for a species will occur in a single decade, indicating an abrupt risk expansion across species' geographical ranges. This abruptness results

				projected for a species to occur in a single decade.	abruptness in the expansion of thermal exposure risks is projected to occur for both terrestrial and marine species across all studied organism groups, with similar levels of abruptness under both higher and lower greenhouse gas emission pathways.	from the rapid pace of future projected warming and the fact that species disproportionately occupy sites close to their upper thermal limit. With higher levels of global warming, the number of species at risk of abrupt and widespread thermal exposure increases, emphasizing the urgent need for mitigation and adaptation actions. The study underlines that climate threats to thousands of species are expected to expand abruptly in the coming decades, highlighting the critical importance of understanding spatial and temporal dynamics of thermal exposure.
Jennie E. Rheuban et al., *Projected impacts of future climate change, ocean acidification, and management on the US Atlantic sea scallop (Placopecten magellanicus) fishery*, 13 PLOS ONE 1–21 (2018)	Integrated assessment model combining elements of fisheries management models, socio-economic models, and biogeochemical modeling.	US Atlantic	Through the 21st century	**Temperature:** Not specifically addressed. Ocean Acidification: Potentially reduces sea scallop biomass by approximately 13% by end of century under the highest impact and management scenario. **Geographic Distribution:** Not specifically addressed. Management: Management-set catch limits improve outcomes under both climate scenarios; a 10% area closure increases future biomass by more than 25% under the highest ocean acidification impacts.	**Temperature:** Not specifically addressed. Ocean Acidification: May decline sea scallop biomass by more than 50%, leading to subsequent declines in industry landings and revenue. **Geographic Distribution:** Not specifically addressed. Management: Despite increased management efforts, projected long-term decline of the fishery under ocean acidification scenarios.	Under RCP4.5 with the highest impact and management scenario, ocean acidification could reduce sea scallop biomass by approximately 13% by century's end; however, lesser impact scenarios show little change. Under RCP8.5, sea scallop biomass may decline by more than 50% by the century's end, leading to declines in industry landings and revenue. Management strategies, including set catch limits and a 10% area closure, improve outcomes under both climate scenarios. The study emphasizes that while increased management can mitigate some impacts, it does not prevent long-term decline due to ocean acidification. These projections underscore the need for further research on acidification impacts on P. magellanicus, given the industry's high value.

Nancy L. Shackell et al., *Thermal Habitat Index of Many Northwest Atlantic Temperate Species Stays Neutral under Warming Projected for 2030 but Changes Radically by 2060*, 9 PLOS ONE (2014)	Generalized Additive Models (GAMs) were used to quantify the realized habitat of 46 temperate/boreal marine species using over 41 years of survey data from 35°N–48°N in the Northwest Atlantic. Changes in a "realized thermal habitat index" under short-term (2030) and long-term (2060) warming scenarios were estimated.	Northwest Atlantic from Cape Hatteras, North Carolina to Cape Breton Island, Nova Scotia, Canada	Short-term (2030) and Long-term (2060)	**Temperature:** By 2030, less than 10% of species will lose realized thermal habitat at the national scale (USA and Canada), but planktivores are expected to lose significantly in both countries, possibly leading to indirect changes in predator distribution. **Geographic Distribution:** The study suggests moderate shifts by 2030, mainly affecting planktivores.	**Temperature:** By 2060, the realized habitat of a majority of species will change significantly (76% in Canada, 85% in the USA), with more species expected to lose (55% in Canada, 65% in the USA) than gain. The projection affirms the need for research on the effects of extreme "weather" and gradual warming. **Geographic Distribution:** Major shifts in species distribution are expected by 2060, with a greater loss at lower latitudes (~40°N), indicating significant ecosystem changes based on thermal habitat alone.	2030 Scenario: Less than 10% of species are projected to lose realized thermal habitat at a national scale (USA and Canada), with planktivores expected to experience significant habitat loss in both countries. This may indirectly affect the distribution of their predators. 2060 Scenario: In Canada, 76% of species' realized habitat will change (55% loss, 21% gain), while in the USA, 85% of species' realized habitat will change (65% loss, 20% gain). The ecosystem is expected to undergo radical changes based on thermal habitat alone, emphasizing the importance of climate change mitigation to preserve marine biodiversity and ecosystem functions. The magnitude of projected warming by 2060 (approximately 1.5–3°C) highlights the need for research on the effects of extreme weather events and increasing mean temperature on marine species. The study suggests incorporating a "realized thermal habitat index" into stock assessment processes to help manage fisheries in light of gradual or extreme warming.
Craig A. Stow et al., *Skill assessment for coupled biological/physical models of marine systems*, 76 Journal of Marine Systems 4–15 (2009),	The study reviews several metrics and approaches for evaluating model skill, including goodness-of-fit measures and various statistical analyses to assess the accuracy and uncertainty of	Not specified.	Not applicable, as the focus is on the assessment of model skill rather than on projecting climate impacts over a specific time frame.			Emphasizes the complexity of accurately predicting marine system behaviors due to various factors such as temperature, dissolved oxygen, and ocean circulation. It suggests that no single metric can fully reveal model skill, recommending the use of multiple metrics in concert for a thorough appraisal. The study highlights the importance of

http://dx.doi.org/10.1016/j.jmarsys.2008.03.011	marine system models. It discusses the importance of using multiple metrics for a comprehensive skill assessment and highlights the need for rigorous model skill assessment in decision-making applications.					understanding model limitations and uncertainties in both model development and application, particularly for high-stakes decision-making. It calls for the routine application and presentation of rigorous skill assessment metrics to improve forecasting abilities and acknowledge our limitations in modeling marine systems.
Patrick L. Thompson et al., *Groundfish biodiversity change in northeastern Pacific waters under projected warming and deoxygenation*, 378 Philosophical Transactions of the Royal Society B: Biological Sciences (2023)	Combined fisheries-independent trawl survey data with high-resolution regional ocean models to make projections on how 34 groundfish species will be impacted by changes in temperature and oxygen in British Columbia (BC) and Washington.	Northeastern Pacific waters, specifically BC and Washington.	Mid-21st century (2046–2065)	General Observations Across Scenarios: Projected shifts in groundfish species distributions due to warming and deoxygenation are expected to lead to considerable compositional turnover. Species may move to deeper depths as conditions warm, but low oxygen levels will limit the depth they can occupy. Biodiversity is expected to decrease in shallow waters (<100 m) due to significant warming, increase at mid-depths (100–600m) as shallow species move deeper, and decrease at depths where oxygen is limited (>600 m).	Similar to the findings under low emissions, with an emphasis on the significant role of both temperature and oxygen in shaping future groundfish distributions. The study underscores the complexity of predicting exact outcomes due to the intertwined effects of warming, oxygen levels, and species' depth preferences.	Temperature & **Dissolved Oxygen:** Projected shifts in distribution and abundance of groundfish due to warming and deoxygenation, with species moving to deeper depths but limited by low oxygen levels. Biodiversity is expected to decrease in shallow waters (<100 m) due to significant warming, increase at mid-depths (100–600 m) as species shift deeper, and decrease in areas where oxygen is limited (>600 m). This indicates significant compositional turnover, highlighting the joint role of temperature, oxygen, and depth in determining the impacts of climate change on marine biodiversity.
Derek P. Tittensor et al., *Next-generation ensemble projections reveal higher climate risks for marine ecosystems*, 11 Nature	The study uses an ensemble approach, integrating outputs from different global marine ecosystem models, which are in turn driven by climate projections from the latest CMIP6 Earth	Global	Mid-21st century (2046–2065)	**Temperature:** The study shows a greater decline in mean global ocean animal biomass under strong mitigation scenarios due to elevated warming, despite greater uncertainty in net primary production in the high-emissions scenario. Dissolved Oxygen & Ocean pH: Not specifically addressed in the	Similar to the findings under low emissions, with a greater emphasis on the significant decline in mean global ocean animal biomass due to elevated warming, despite greater uncertainty in net primary production in the high-emissions scenario. The study underscores the complexity of predicting outcomes due to the intertwined	The new ensemble ecosystem simulations under CMIP6 indicate a greater decline in mean global ocean animal biomass under both strong-mitigation and high-emissions scenarios, attributed to elevated warming. Despite greater uncertainty in net primary production in high-emission scenarios, there is a consensus on

CLIMATE CHANGE 973–981 (2021), https://www.nature.com/articles/s41558-021-01173-9	system models. The analysis focused on the effects of climate change on ocean ecosystems under strong-mitigation and high-emissions scenarios.			summary. **Geographic Distribution:** Regional shifts in biomass are highlighted, pointing to the need to reduce uncertainty in projected responses of marine ecosystems to climate change to support adaptation planning.	effects of warming, oxygen levels, and species' depth preferences.	the decline in marine biodiversity. Regional shifts in biomass changes accentuate the urgency to reduce uncertainty in marine ecosystem projections to aid adaptation planning. The study emphasizes the pronounced climate risks marine ecosystems face under future climate change scenarios, underscoring the significant need for mitigation efforts to preserve marine biodiversity and ecosystem services.
Bryony L Townhill et al., *Harmful algal blooms and climate change: exploring future distribution changes*, 75 ICES JOURNAL OF MARINE SCIENCE 1882–1893 (2018)	Species distribution modelling using high-resolution, downscaled shelf seas climate projections nested within global projections. Considered environmental preferences and shifts for harmful algal species.	North-west European shelf	Mid to end of 21st century	**Temperature:** Most species' habitat will shift north this century, with suitability increasing in the central and northern North Sea. **Geographic Distribution:** The habitat of most species will shift north, with significant increases in suitability in the central and northern North Sea, indicating potential for more frequent detrimental blooms if wind, irradiance, and nutrient levels are also suitable.	Similar to low emissions, but the study focuses on changes expected by the mid to end of the century without differentiating findings explicitly between low and high emissions scenarios.	Temperature, Salinity, Depth, and Stratification: Most harmful algal species' habitats will shift north this century, with suitability increasing in the central and northern North Sea. The habitat defined by temperature, salinity, depth, and stratification is predicted to become more favorable for these species in northern regions. Other Effects: Increased occurrence in the central and northern North Sea might lead to more frequent detrimental blooms if conditions such as wind, irradiance, and nutrient levels are also suitable. Prioritizing monitoring in these areas could help establish early-warning systems for aquaculture and health protection.
Trisos et al.	Annual projections (1850 to 2100) of temperature and precipitation across the ranges of over 30,000 marine and terrestrial species to estimate exposure to	Global	Through the 21st century	Under a scenario keeping global warming below 2°C, less than 2% of assemblages globally are projected to undergo abrupt exposure events affecting more than 20% of their constituent species. This indicates a relatively low risk of sudden	Under a high-emissions scenario (RCP 8.5), abrupt exposure events to beyond-niche climate conditions are projected to begin before 2030 in tropical oceans and spread to tropical forests and higher latitudes by 2050. This could lead to catastrophic biodiversity losses,	The study projects that future disruption of ecological assemblages due to climate change will be abrupt, with most species within any given assemblage being exposed to climate conditions beyond their realized niche limits almost simultaneously. Under a

	potentially dangerous climate conditions.			biodiversity losses under strong mitigation efforts.	affecting both protected and unprotected areas similarly.	high-emissions scenario (RCP 8.5), such abrupt exposure events begin before 2030 in tropical oceans and spread to tropical forests and higher latitudes by 2050. If global warming is kept below 2°C, less than 2% of assemblages globally are projected to undergo abrupt exposure events of more than 20% of their constituent species. However, the risk accelerates with the magnitude of warming, threatening 15% of assemblages at 4°C, with similar levels of risk in protected and unprotected areas.
Clive N. Trueman et al., *Thermal sensitivity of field metabolic rate predicts differential futures for bluefin tuna juveniles across the Atlantic Ocean*, 14 NATURE COMMUNICATIONS (2023)	Used natural chemical tracers to determine the individual experienced temperatures and expressed field metabolic rates (FMR) of Atlantic bluefin tuna during their first year of life.	Atlantic Ocean, focusing on historically-important spawning and nursery grounds for bluefin tuna.	Next 50 years	**Temperature:** Preference for temperatures 2–4 °C lower than those maximizing FMR to avoid temperatures warm enough to limit metabolic performance. **Geographic Distribution:** Limiting global warming to below 2 °C would preserve habitat conditions in the Mediterranean Sea for bluefin tuna.	Similar to the findings under low emissions, indicating that warming within the next 50 years under high emissions scenarios would make historically important spawning and nursery grounds thermally limiting.	**Temperature:** The study found that bluefin tuna exhibit a preference for temperatures 2–4°C lower than those that maximize field metabolic rates, thereby avoiding temperatures warm enough to limit metabolic performance. Historically important spawning and nursery grounds for bluefin tuna in the Atlantic Ocean will become thermally limiting due to warming within the next 50 years. However, limiting global warming to below 2°C could preserve habitat conditions in the Mediterranean Sea for this species. The approach used provides a mechanistic understanding of the linkages between experienced temperature and physiological response, offering greater potential for predicting responses of fish populations to climate change.
John J. Wiens & Joseph Zelinka, *How*	Review of SDMs, new analyses of SDM studies,	Global	Next ~50 years	**Temperature:** Projected impacts suggest a potential extinction of 14%-32% of	Similar to low emissions due to the study's focus on synthesizing across scenarios. The highest risks	Overall impact projections suggest a loss of 14%–32% of macroscopic species under intermediate climate

many species will Earth lose to climate change?, 30 Global Change Biology (2024)	discussion of biases in SDMs, examination of species' ability to shift climatic niches, and integration of taxon-specific forecasts of species loss with projections of global biodiversity.			macroscopic species due to climate-related factors even under intermediate climate change scenarios. **Geographic Distribution:** Anticipates a broad range of species losses across different taxa, with significant shifts in species distributions expected. Climate Extremes: Emphasizes the importance of considering the rate of niche changes relative to the pace of projected climate change.	are associated with scenarios exceeding a 2.5°C increase, with extreme scenarios potentially leading to the loss of millions of species due to inability of many species to adapt or migrate fast enough.	change scenarios, potentially including 3–6 million animal and plant species. This review underscores the variability in species' vulnerability to climate change, highlighting that many SDM studies may underestimate global species loss by excluding species with limited locality data, thus biasing against the most vulnerable species. Conversely, the study points out that the fundamental assumption of SDMs, that species' climatic niches do not change over time, may often be violated. **Temperature:** The review finds mean rates of positive thermal niche change across species of ~0.02°C/year, indicating that rates of niche evolution may still lag behind projected climate warming by ~3–4 fold. Other Effects: Emphasizes the potential for considerable underestimation of species extinction risks due to methodological biases in current approaches.
Kristen L. Wilson et al., *Projected 21st-century distribution of canopy-forming seaweeds in the Northwest Atlantic with climate change*, 25 Diversity and Distributions 582–602 (2019)	Used occurrence records and the Maxent species distribution model. Present-day distributions were projected to mid-century (2040–2050) and end-century (2090–2100) using RCP2.6 and RCP8.5 scenarios.	Northwest Atlantic	Mid-century (2040–2050) and end-century (2090–2100)	**Temperature:** Minimal projected range shifts. Most species except C. fragile predicted to experience northward shifts in their southern range of ≤406 km by 2100. **Geographic Distribution:** Northward expansions outweighed southern extirpations for fucoids and C. crispus, leading to overall range expansions. Kelps and C. fragile projected for range contractions.	**Temperature:** Substantial species-specific range shifts, with significant northward shifts in the southern range for all species except C. fragile. **Geographic Distribution:** Major range shifts and seaweed community reorganization south of Newfoundland by 2100.	Projected minimal range shifts under the RCP2.6 scenario, with substantial species-specific shifts under RCP8.5, indicating a northward shift in the southern edge of ≤406 km by 2100 for all species except Codium fragile. Fucoids and Chondrus crispus are predicted to expand their range, while kelps and C. fragile are expected to contract. These shifts highlight the critical role of climate change mitigation in limiting alterations to rocky shore community composition and underscore the potential for

						significant seaweed community reorganization under a business-as-usual scenario.
FAO	Synthesis of current knowledge, modeling projections, and expert assessments.	Global, with emphasis on specific regions for detailed analyses.	Through the 21st century	**Temperature:** Increases expected globally with significant regional variability. Polar regions may experience the most warming, affecting ice-dependent species and leading to shifts in species distributions northwards. **Dissolved Oxygen:** Reductions in oxygen levels expected to be less severe under low emissions, but still impactful in creating and expanding hypoxic zones, affecting fish metabolism and habitat suitability. Ocean pH: Acidification less severe under RCP2.6, but still impacts calcium carbonate-dependent organisms, potentially affecting food webs and fisheries. Ocean Circulation: Changes in circulation patterns may be less pronounced, possibly mitigating some impacts on nutrient distribution and upwelling areas. Mixing and Nutrient Supply: Potential for less disruption to vertical mixing processes, maintaining more stable nutrient supply patterns. **Food Availability:** Changes in primary productivity may be less drastic, affecting food availability for marine organisms differently across regions. **Predation:** Altered predator-prey relationships due to shifts in	**Temperature:** More pronounced warming, especially in tropical regions, exacerbating heat stress on marine species and leading to coral bleaching and loss of biodiversity. **Dissolved Oxygen:** Greater reductions in oxygen levels, expanding hypoxic zones and negatively affecting fish growth, reproduction, and survival. Ocean pH: More severe acidification, undermining the structure of coral reefs and affecting shell-forming organisms, with cascading effects on marine food webs. Ocean Circulation: More significant changes could alter nutrient distribution and disrupt major fisheries, particularly in upwelling zones. Mixing and Nutrient Supply: Increased stratification may reduce nutrient upwelling, impacting primary productivity and food availability for higher trophic levels. **Food Availability:** Declines in primary productivity could severely impact marine food webs, reducing fish stocks and fisheries yields. **Predation:** Enhanced mismatches in predator-prey dynamics due to more rapid shifts in distributions and abundances, affecting fisheries. **Geographic Distribution:** More	Model projections suggest global decreases in maximum catch potential in exclusive economic zones of 2.8% to 5.3% by 2050 under RCP2.6, and 7.0% to 12.1% under RCP8.5. Regional impacts vary, with significant decreases expected in the tropics and some increases in high latitude regions. - Inland fisheries face competition for water resources, often under-recognized, impacting water quantity and quality. Specific countries like Pakistan and Iraq are highlighted for high current and future stresses, while others like Myanmar and Colombia are expected to face low stress. - Climate change will significantly change the availability and trade of fish products, with geopolitical and economic consequences, especially for countries highly dependent on the sector. Adaptations must consider the multifaceted context of fisheries, complementing overall governance for sustainable use.

				species distributions and abundances. **Geographic Distribution:** Shifts in species distributions may be less extreme, reducing the rate of change in community composition. **Phenology:** Changes in timing of biological events like spawning may still occur but could be less pronounced. Climate Extremes: Less frequent and severe extreme weather events may reduce direct impacts on marine and coastal ecosystems. Other Effects: Ecosystem changes are expected to be less severe than under high emissions, potentially allowing more time for adaptation.	extensive shifts in species distributions leading to new community assemblages, loss of endemic species, and increased invasion by non-native species. **Phenology:** Greater changes in the timing of life-cycle events, affecting reproductive success and species interactions. Climate Extremes: Increased frequency and severity of storms, heatwaves, and other extreme events could cause more direct damage to marine ecosystems and infrastructure. Other Effects: Greater overall impact on marine biodiversity, fisheries, and ecosystem services, challenging management and conservation efforts.	

Table S6: NAFO Stock assessment data and methods

Table S7 | NAFO Stock assessment data and methods. Overview of the data, methods, and results of NAFO stock assessments.

Reference	Species Assessed	Data Sources Used	Assessment Methods	Climate Inclusion	Key Findings
R. Alpoim, *An Assessment of American Plaice (Hippoglossoides platessoides) in NAFO Division 3M*, NAFO SCR D NORTHWEST ATLANTIC FISHERIES ORGANIZATION 1–20 (2023), https://www.nafo.int/Portals/0/PDFs/sc/2023/scr23-024.pdf	American Plaice (Hippoglossoides platessoides) in NAFO Division 3M	- NAFO statistical database (NAFO STATLANT 21A Extraction Tool). - EU-Spain/Portugal bottom trawl surveys (1988-2022). - Catch data from Portugal and Russia (2020-2022).	The assessment did not utilize age-length keys (ALKs) due to their absence for recent years, thus relying on catches and survey data. Main methods: - Evaluation of year-class strengths from 1991 to 2005. - Analysis of recruitment pulses from 2008-2012 and 2015-2018. - Trend examination in stock biomass and abundance using EU survey data. - Fishing mortality indexed by the catch/biomass (C/B) ratio.	The assessment did not directly address climate change or variability effects on the fish stock.	- Year-classes from 1991 to 2005 were weak. - Observed recruitment pulses in 2008-2012 and 2015-2018 had less strength than those before the mid-90s. - EU survey data showed increases in stock biomass and abundance from 2007 to 2017, with a stable trend or slight drop in abundance thereafter. - Fishing mortality index has been at or below 0.1 since the mid-2000s. - The stock is at levels similar to the mid-1990s when the fishery was closed.
R. Nygaard, *Assessment of Demersal Redfish in NAFO Subarea 1*, NAFO SCR D NORTHWEST ATLANTIC FISHERIES ORGANIZATION 1–14 (2023)	Demersal Redfish in West Greenland (Golden redfish - *Sebastes norvegicus*, Deep-sea redfish - *Sebastes mentella*) in NAFO Subarea 1	- Commercial catch data (1952-2022) with uncertainties in landings especially in 1977-1979 and the 1980s-1990s. - Survey data from EU-Germany, Greenland deep-water, and Greenland Shrimp and Fish (SFW) surveys. - Sampling of EU-German commercial catches of golden redfish during 1962-90. - Gillnet and trawl surveys in Nuuk fjord and Uummannaq fjord (for species distribution).	- No analytical assessment due to lack of adequate commercial data. - Utilized survey indices from several ongoing and historic surveys to estimate stock biomass and abundance trends. - Noted issues with differentiation between species and stocks, as well as challenges in estimating catch sizes due to practices in shrimp fishery and the introduction of sorting grids in 2002. - Observed a lack of new incoming year classes in recent decades, suggesting limited recruitment.	Climate change or variability effects were not directly discussed in the assessment. However, the potential migration of redfish into Subarea 1 from nearby areas such as East Greenland could be influenced by environmental changes.	- Golden redfish showed a slightly increasing biomass from 2005 to 2015, with current biomass still below the 1980s level due to poor recruitment before 2020. - Deep-sea redfish biomass indices indicated an increase from 2008 to 2013/2017 but have been slowly decreasing since then. - Recent surveys (2020-2022) suggest unusually good recruitment, with observed increases in juvenile redfish abundance. - The assessment concludes that while there has been some recovery, the biomass of both species remains low, and initiating a directed fishery is not advisable at the moment.

Irene Garrido et al., *Analysis of the Flemish Cap cod fishery: monitoring of the consequences of the management decisions*, 23 36 (2023), https://www.nafo.int/Portals/0/PDFs/sc/2023/scr23-011.pdf	Cod in NAFO Division 3M	- STACFIS catch estimates (1960-2022). - EU bottom trawl survey indices (1988-2022). - Commercial catch data from multiple countries (2010-2022). - Length distributions from commercial catches (2022). - Catch-at-age data (1988-2022). - EU survey data (abundance indices, total biomass, and weight-at-age in stock).	- Bayesian Statistical Catch-at-Age (SCAA) model used to assess stock status based on commercial catch data and survey indices. - Model fitted with JAGS, incorporating prior distributions for natural mortality by age, recruitment, catch numbers-at-age, and survey index variability. - Catch-at-age derived from EU survey age-length keys (ALKs) applied to commercial catch length distributions. - Analysis included total biomass, Spawning Stock Biomass (SSB), recruitment, and fishing mortality estimates. - Retrospective analysis and short-term projections performed to evaluate stock dynamics and fishing impact.	Climate change or variability was not directly addressed or integrated into the assessment methodology or results.	- SSB declined rapidly since 2017 but remained stable in the last 3 years and is above Blim. - Recruitment oscillated around intermediate levels since 2013, significantly lower than in 2011-2012. - Fishing mortality has been below Flim since the fishery reopened in 2010, decreasing since 2019. - Total biomass increased sharply during 2006-2012, then followed a decreasing trend, stabilizing below the series' beginning level since 2020. - Projections under various fishing mortality scenarios indicate that total biomass is expected to increase under most scenarios, with SSB projected to increase by 2025 except under the highest fishing mortality scenario.
N. Cadigan et al., *A State-Space Assessment Model for 3NO Cod*, NAFO SCR D NORTHWEST ATLANTIC FISHERIES ORGANIZATION 1–55 (2022)	Atlantic Cod (Gadus morhua) in NAFO Division 3NO	- Total fishery landings (1960-2019). - Survey indices from Canadian RV surveys and the EU-Spain survey. - Length and age-composition data of catches. - Stock weights and maturity data. - Natural mortality rates estimated using the Lorenzen method.	- Developed a state-space stock assessment model (SSAM) to address concerns about catch statistics reliability, inclusion of a plus group, stock productivity changes, and the inclusion of EU-Spain survey indices. - The model includes uncertainty in total fishery catch estimates, the age composition of catches, variable productivity, and indices from both Canadian and EU-Spain surveys. - Utilizes process errors in population dynamics and a censored likelihood approach for landings. - Estimation of natural mortality rates (M) based on the Lorenzen method.	Climate change or variability effects were not explicitly included.	- SSAM and traditional ADAPT estimates of Spawning Stock Biomass (SSB) and fishing mortality (F) are broadly similar, with some discrepancies in estimates of SSB during 1960-1990 due to different assumptions about natural mortality and the use of a plus group. - The model suggests poor recruitment below approximately 150,000 tonnes of SSB, a conclusion that could have significant implications for stock management. - Notes the importance of further research on time-varying natural mortality and recommends simulation testing before the SSAM is considered for stock advice.

			- SSAM includes a plus group at age 10 and accounts for process error in population dynamics.		
Nygaard	Golden Redfish (Sebastes norvegicus) and Deep-sea Redfish (Sebastes mentella) in NAFO Subarea 1	- Commercial catch data and uncertainties in landings, particularly during 1977-1979 and the 1980s-1990s. - Survey data from EU-Germany, Greenland deep-water, and Greenland Shrimp and Fish surveys. - Historical length composition data from sampling of EU-German commercial catches of golden redfish during 1962-1990.	- Lack of adequate commercial data prevented an analytical assessment; assessment was based on survey indices. - Survey indices from several ongoing and historic surveys used to estimate stock biomass and abundance trends. - Challenges in differentiating between species and stocks in official statistics noted. - The introduction of sorting grids in 2002 in shrimp fishery trawls noted as a factor potentially affecting redfish survival. - Lack of new incoming year classes in recent decades suggested limited recruitment.	Climate change or variability effects were not directly discussed in the assessment. Potential migration of redfish into Subarea 1 from nearby areas such as East Greenland could be influenced by environmental changes.	- Golden redfish showed a slightly increasing biomass from 2005 to 2015, with current biomass still below the 1980s level due to poor recruitment before 2020. - Deep-sea redfish biomass indices indicated an increase from 2008 to 2013/2017 but have been slowly decreasing since then. - Recent surveys (2020-2022) suggest unusually good recruitment, with observed increases in juvenile redfish abundance. - The assessment concludes that while there has been some recovery, the biomass of both species remains low, and initiating a directed fishery is not advisable at the moment.
R.A. Rademeyer & D.S. Butterworth, *Updated SCAA Base Case Assessment and sensitivities for Greenland Halibut*, NAFO SCR D Northwest Atlantic Fisheries Organization 1–25 (2023)	Greenland Halibut	- Updated data from 2017 to 2021. - Landings data for Greenland Halibut in Sub-area 2 and Div. 3KLMNO. - Commercial catch at age and catch weights-at-age. - Proportion mature-at-age. - Survey catch-at-age data and biomass indices.	- Statistical Catch-at-Age (SCAA) model identical to that applied in 2017. - Base Case and sensitivity tests including variations in recruitment variability and survey series selection. - Estimation of selectivities for commercial and survey data, with selectivity modeled by double-normal shape for certain surveys. - Recruitment assumed to be related to spawning stock size via Beverton-Holt stock-recruitment relationship, with annual fluctuation.	Climate change or variability effects were not directly addressed or integrated into the assessment methodology or results.	- Essentially unchanged results from 2017, apart from a slight downward shift in overall biomass scale. - Recent slight downward trend in exploitable biomass, but incoming recruitment of above recent average strength likely to reverse this trend. - Sensitivity runs showed little difference from the Base Case. - New data and trends are consistent with predictions made in 2017 when a revised management procedure was adopted.

B. Rogers et al., *Assessment of 3LN redfish using the ASPIC model in 2022 (Sebastes mentella and S. fasciatus)*, NAFO SCR D Northwest Atlantic Fisheries Organization 1–31 (2022)	Deep-sea Redfish (Sebastes mentella) and Acadian Redfish (Sebastes fasciatus) in NAFO Division 3LN	- Commercial fishery data and Total Allowable Catches (TACs). - Canadian and EU-Spain survey data. - Commercial Catch Per Unit Effort (CPUE) data. - Commercial length frequencies and research survey data.	- The ASPIC (a non-equilibrium surplus production model) was initially used but ultimately rejected due to mismatches between observed survey indices and model biomass estimates. - A lack of recent survey indices (since 2019) limits understanding of current stock status. - The assessment included examination of commercial length frequencies and research survey data for biomass estimation and trends. - Recruitment analysis focused on redfish between 15 and 20 cm and pre-recruitment indices (less than 15 cm).	Climate change or variability effects were not explicitly included in the assessment.	- The stock appears to be above the interim limit reference point (Blim). - Biomass is at or below the long-term mean, with recent declines from mid-2010s highs to long-term mean levels. - Recruitment has been below the long-term average since the mid-2010s. - The rejection of the ASPIC model and absence of Canadian spring survey data in recent years limit detailed analysis of stock status and trends.
A. Burmeister & T. Buch, *A Provisional Assessment of the Shrimp Stock off West Greenland in 2023*, NAFO SCR D Northwest Atlantic Fisheries Organization 1–23 (2023)	Northern Shrimp (Pandalus borealis) off West Greenland	- Catch and effort data from fishing fleets. - Biomass and stock-composition from a research trawl survey. - Catch data. - Information on stock distribution from fishery logbooks.	- Logistic stock-recruitment model fitted by Bayesian methods. - CPUE and survey series used as biomass indicators. - Model includes catch data and a term for predation by Atlantic cod, using available cod biomass series. - CPUE standardized by linearized multiplicative models. - Adjustments made for poor survey coverage due to abnormal sea ice distribution, using a five-year average for un-surveyed areas.	- Mean survey bottom temperature data from 1990–96 to 2022. - Shift in shrimp distribution correlated with temperature changes. - Mention of cod biomass estimation and its distribution affecting shrimp stock, suggesting a link to climate effects on both species.	- Stock has been declining for a decade from unsustainable levels but is above MSY level as of 2023. - Biomass slightly below the 20-year median. - Decline in CPUE in recent years, possibly due to abnormal ice conditions. - Poor recruitment noted below approximately 150,000 tonnes of SSB. - Future projections under various scenarios suggest a need for cautious management to avoid exceeding MSY mortality levels.
K.A. Katherine A. K.A. Sosebee et al., *Assessment of Thorny Skate (Amblyraja*	Thorny Skate (Amblyraja radiata) in NAFO Divisions	- Commercial landings data (1985-2021). - Canadian and EU-Spain research survey data.	- Assessment primarily based on trends in commercial landings, research survey biomass and abundance indices, and size	- Climate change or variability was not directly included in the assessment methods.	- Overall decline in Thorny Skate in Divs. 3LNO until 1996, followed by stabilization at low levels and a general increase in recent years.

radiata Donovan, 1808) in NAFO Divisions 3LNO and Subdivision 3Ps, NAFO SCR D Northwest Atlantic Fisheries Organization 1–32 (2022)	3LNO and Subdivision 3Ps	- Canadian At-Sea Fisheries Observers' data on size distributions.	structure data from commercial and survey catches. - Utilized Canadian spring and fall research surveys to estimate abundance and biomass trends, along with EU-Spain survey data for additional insights. - No specific model described for estimating spawning stock biomass, recruitment, or mortality rates directly.	However, shifts in distribution patterns and size structure could be indirectly influenced by environmental changes.	- Fishing mortality decreased from late 1980s peak, stabilizing around 4% since 2012. - Abundance and biomass indices from research surveys indicate slow stock growth, with distribution concentrated on the southwestern Grand Banks and northward along the edge. - The current TAC for skates in the NRA of Divs. 3LNO exceeds the average commercial catch during a period of very slow stock growth.
K. Sosebee et al., *An Assessment of White Hake (Urophycis tenuis, Mitchill 1815) in NAFO Divisions 3N, 3O, and Subdivision 3Ps*, NAFO SCR D Northwest Atlantic Fisheries Organization 1–31 (2023)	White Hake (Urophycis tenuis) in NAFO Divisions 3N, 3O, and Subdivision 3Ps	- Canadian and EU-Spain research survey data. - Commercial landings and TAC data. - Size distributions from commercial fisheries and surveys.	- Utilized survey indices for biomass and abundance trends, including Canadian spring and autumn, and EU-Spain surveys. - Analysis of commercial landings and size distributions. - No specific stock assessment model detailed; relies on survey data for biomass and abundance estimation.	- Marine ecosystem changes and potential impacts of Silver Hake competition and predation on White Hake recovery noted. - White Hake distribution associated with warmer bottom temperatures.	- Biomass and abundance indices indicate fluctuations with a very large 1999 year-class followed by decline and recent slow recovery. - Low recruitment observed since 2002, with recent minor increases. - Landings and TAC data show management adjustments and fishing pressure trends.
D.M. Parsons et al., *An assessment of the Witch flounder resource in NAFO Divisions 3NO*, NAFO SCR D Northwest Atlantic Fisheries Organization 1–51 (2022)	Witch Flounder (Glyptocephalus cynoglossus) in NAFO Divisions 3NO	- Canadian and non-Canadian catch data for 2021. - Spring and fall survey indices in NAFO Divs. 3NO (2010-2020). - Historical catch data and Total Allowable Catches (TACs) dating back to the 1960s. - Commercial length frequencies and research vessel survey data.	- A surplus production model within a Bayesian framework was employed to provide TAC advice. - Model incorporates catch data, survey biomass indices, and accounts for process errors and observation errors. - Utilizes a Schaefer form surplus production model, with estimates for intrinsic rate of population growth (r), carrying capacity (K), catchability (q), and process and observation errors. - Projections made under various catch scenarios to estimate future stock status and risks.	- Climate change or variability effects were not directly included in the model. - Historical data on catch and survey trends indirectly reflect environmental influences on stock distribution and abundance.	- Stock size decreased from the late 1960s to late 1990s, increased from 1999 to 2013, then declined sharply from 2013 to 2015, with a small increase since. - MSY estimated at 3,824 t from a total stock biomass (Bmsy) of 60,510 t at a fishing mortality rate (Fmsy) of 0.062. - In 2021, stock is at 47% Bmsy with a 0.095 risk of being below Blim. - Projections to 2025 under various fishing levels show biomass likely to remain stable or grow, with low probability of biomass falling below Blim.

R. Nygaard, *Assessment of wolffish in NAFO subarea 1*, NAFO SCR D Northwest Atlantic Fisheries Organization 1–14 (2023)	Atlantic Wolffish (Anarhichas lupus), Spotted Wolffish (Anarhichas minor) in NAFO Subarea 1	- Commercial fishery data including catch and effort, length distribution in catches, and TAC data. - Research survey data from the EU-Germany (EU-G) survey and Greenland Shrimp Fish (SFW) survey, covering biomass and abundance indices.	- Wolffish assessment based on historical catch data, research survey indices of biomass and abundance, and observations of species composition through research work. - Analysis of changes in catch levels and survey indices to infer stock status, with emphasis on the impact of fishing gear changes (sorting grids) and catch reporting practices. - No specific stock assessment model described for quantitative estimation of spawning stock biomass, recruitment, or mortality rates.	- While not explicitly addressed in the assessment, observations of distribution shifts and length frequencies could imply indirect consideration of climate or environmental variability. - The implementation of sorting grids in the shrimp fishery and their effect on bycatch could reflect adaptations to ecosystem changes.	- Increasing survey indices for both Atlantic and Spotted Wolffish in recent decades, suggesting recovery or growth in stock. - Decline in commercial catches attributed to reduced directed fishery and changes in target species, rather than stock abundance. - The introduction of sorting grids in shrimp fisheries has likely benefited wolffish by reducing bycatch. - Increased survey indices and observed length frequencies indicate better recruitment and possibly improved stock conditions.
D.M. Parsons et al., *2023 Assessment of Yellowtail Flounder in NAFO Divisions 3LNO*, NAFO SCR D Northwest Atlantic Fisheries Organization 1–65 (2021)	Yellowtail Flounder (Limanda ferruginea) in NAFO Divisions 3LNO	- Canadian and Spanish survey data. - TACs and commercial landings data. - Biological sampling of catches for size composition.	- Surplus production model within a Bayesian framework used for assessment since 2018. - Relies on catch data and Spanish survey (Div. 3NO) information for recent updates due to the absence of Canadian survey data. - Estimates biomass, fishing mortality, and other population dynamics through relative estimates from the Bayesian production model. - Projections made under various catch scenarios in a precautionary approach framework.	- Increased bottom temperatures noted at the time of fishing in 2022, suggesting potential climate influence. - Historical data on catch and survey trends could indirectly reflect environmental influences on stock distribution and abundance.	- Biomass declined to near Bmsy (1.08 times Bmsy) with fishing mortality at 0.53 Fmsy in 2022. - Despite some recovery signs, the stock has shown general declining trends since 2012, with Spanish survey series continuing to decline from 2016 to 2022. - Projections under various fishing mortality scenarios suggest a need for cautious management to avoid exceeding MSY mortality levels.

Table S7: Climate impacts on NAFO managed species.

Table S8 | Climate impacts on NAFO managed species. Summary of studies evaluating the climate impacts on NAFO managed species, their methods and data, geographic focus, and findings.

Species	Reference	Methods and Data	Geographic Focus	Length of Study	Key Findings
American Plaice (Hippoglossoides platessoides)	W.R. R. Bowering & W.B. B. Brodie, *Distribution of commercial flatfishes in the Newfoundland-Labrador region of the Canadian Northwest Atlantic and changes in certain biological parameters since exploitation*, 27 NETHERLANDS JOURNAL OF SEA RESEARCH 407–422 (1991), https://linkinghub.elsevier.com/retrieve/pii/007775799190042Y	The study employed a controlled experimental approach, monitoring the development of eggs and larvae of American plaice under varying temperature conditions. Data collection involved observations and measurements of developmental milestones in laboratory settings.	Not specific; laboratory-based.	The study focused on early developmental stages of American plaice.	**Temperature:** Higher temperatures were found to accelerate developmental rates and shorten the duration of the egg and larval stages. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not specifically addressed. **Ocean Circulation:** Not specifically addressed. **Mixing:** Not specifically addressed. **Nutrient Supply:** Not specifically addressed. **Food Availability:** Not specifically addressed. **Predation:** Not specifically addressed. **Geographic Distribution:** Indirect implications on potential shifts in geographic distribution due to changes in development rates and survival. **Phenology:** Changes in the timing of developmental milestones were noted, with potential implications for synchrony with prey availability. **Climate Extremes:** Not directly addressed, but rapid developmental changes under higher temperatures may imply vulnerability to extreme events. **Other Effects:** Overall, the study suggests that temperature increases could lead to faster development but also might increase vulnerability to adverse environmental conditions if such changes occur outside the optimal temperature range.

American Plaice (Hippoglossoides platessoides)	W. R. Bowering & W. B. Brodie, *Distribution, age and growth, and sexual maturity of American plaice (Hippoglossoides platessoides (Fabricius)) on Flemish Cap (NAFO Division 3M)*, 16 JOURNAL OF NORTHWEST ATLANTIC FISHERY SCIENCE 49–61 (1994)	Data from surveys conducted on board the research vessel Gadus Atlantica from 1978 to 1985 using a stratified random design. Methods included otolith examination for age, and probit analysis for maturity.	Flemish Cap, NAFO Division 3M.	1978-1985	**Temperature:** No direct effects of temperature change were addressed, but the study involved capturing data on bottom temperatures during surveys. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed, though implications exist about prey availability through habitat descriptions. **Predation:** Not specifically addressed. **Geographic Distribution:** Found primarily in shallower areas; southern and southwestern areas of Flemish Cap. **Phenology:** Not directly addressed, but data collection occurred during specific seasonal frames which may imply seasonal behavioral patterns. **Climate Extremes:** Not addressed. **Other Effects:** The study primarily focuses on the biological aspects of growth and maturity, with some mention of environmental conditions during data collection.
American Plaice (Hippoglossoides platessoides), among other groundfish species.	Heino O. Fock, *Driving-forces for Greenland offshore groundfish assemblages: Interplay of climate, ocean productivity and fisheries*, 39 JOURNAL OF NORTHWEST ATLANTIC FISHERY SCIENCE 103–118 (2007)	Principal component analysis of German survey data from 1981 to 2006, focusing on groundfish assemblages on the Greenland shelf. The study correlated these assemblages with climate indicators, ocean productivity, and fishing pressures.	Greenland offshore, specifically the Greenland shelf.	1981–2006	**Temperature:** American plaice was affected by climate, as indicated by significant correlations between climate indicators and principal components associated with this species. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** The study linked general fish assemblage patterns to large-scale climate oscillations that influence ocean currents.

					Mixing: Not specifically addressed. **Nutrient Supply:** Indirectly related through correlations with ocean productivity measures. **Food Availability:** The study noted the influence of ocean productivity, which is tied to food availability, on fish assemblages. **Predation:** Not specifically addressed but implied through community interactions and assemblage changes. **Geographic Distribution:** Shifts in assemblages, including American plaice, were linked to environmental factors. **Phenology:** Not specifically addressed. **Climate Extremes:** The study discussed the impact of climate variability on the entire ecosystem, which includes American plaice. **Other Effects:** The complex interplay of fisheries pressure and climate effects on the ecosystem was highlighted.
American Plaice (Hippoglossoides platessoides)	Sherry Y. Gauthier et al., *Hyperactive antifreeze protein in flounder species: The sole freeze protectant in American plaice*, 272 FEBS JOURNAL 4439–4449 (2005)	The study investigated the presence and characteristics of antifreeze proteins (AFPs) in American plaice using methods like size-exclusion chromatography, circular dichroism (CD) spectroscopy, and mass spectrometry.	Not specified; laboratory-based research.	Not specified; focus on specific physiological responses rather than a longitudinal study.	**Temperature:** Identified hyperactive antifreeze proteins that significantly lower the freezing point of body fluids, enabling survival in colder waters. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed, but implications for survival in colder temperatures suggest adaptations to varying food availability under ice-covered waters. **Predation:** Not specifically addressed.

					Geographic Distribution: Implies potential for range expansion or shifts in distribution due to enhanced freeze tolerance. **Phenology:** Not specifically addressed. **Climate Extremes:** Suggests enhanced survival capabilities under extreme cold conditions. **Other Effects:** The presence of unique AFPs suggests evolutionary adaptations to cold environments.
American Plaice (Hippoglossoides platessoides)	Howell & Caldwell	Experimental study examining effects of temperature (2, 6, 10, and 14 °C) on embryonic and larval stages of American plaice in lab conditions. Techniques included regular measurements of growth rates, yolk utilization efficiency, and survival.	Laboratory-based, simulating environmental conditions.	Not specified; focused on early life stages.	**Temperature:** Elevated temperatures accelerated development but reduced survival rates at the highest temperature tested (14 °C). Optimal growth occurred at intermediate temperatures (6 to 10 °C). **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed but implies effects on survival rates due to growth differences at varying temperatures. **Predation:** Not specifically addressed but relates indirectly through changes in size and survival rates of larvae at different temperatures. **Geographic Distribution:** Not directly addressed, but implications for habitat suitability based on temperature tolerances. **Phenology:** Temperature affected the timing of development stages, with warmer temperatures leading to faster development. **Climate Extremes:** High mortality at 14 °C suggests vulnerability to extreme temperature conditions.

					Other Effects: High temperature extremes negatively affect embryonic and larval survival, highlighting the critical temperature thresholds for development stages.
Demersal and pelagic species including American plaice	Kristin M. Kleisner et al., *Marine species distribution shifts on the U.S. Northeast Continental Shelf under continued ocean warming*, 153 PROGRESS IN OCEANOGRAPHY 24–36 (2017), http://dx.doi.org/10.1016/j.pocean.2017.04.001	The study utilized high-resolution global climate models alongside historical species distribution data from trawl surveys to project changes in thermal habitat suitability for various marine species on the U.S. Northeast Continental Shelf.	U.S. Northeast Continental Shelf	1968–2013 for historical data; future projections for 80 years	**Temperature:** Significant projected warming (3.7 °C to 5.0 °C increase) is expected to reduce suitable thermal habitat for American plaice in the Gulf of Maine, potentially leading to habitat loss in this region. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Changes in ocean circulation such as a weakening Atlantic Meridional Overturning Circulation, which may impact temperature and habitat distribution. **Mixing:** Not specifically addressed. **Nutrient Supply:** Not directly addressed. **Food Availability:** Not directly addressed but changes in habitat could imply shifts in food web dynamics. **Predation:** Not specifically addressed. **Geographic Distribution:** Predicted northward shifts in the distribution of thermal habitats, leading to a potential decrease in habitat availability for American plaice in traditional areas. **Phenology:** Not directly addressed. **Climate Extremes:** The impact of increasing temperature extremes could further stress populations. **Other Effects:** The study emphasizes the complexity of predicting exact species movements due to multiple interacting factors including temperature, species interactions, and fishing pressure.
American Plaice (Hippoglossoides platessoides)	Rajeev Kumar et al., *Recruitment synchrony in spatially structured Newfoundland and Labrador populations of*	Mixed-effect cohort models were used to analyze recruitment synchrony and correlations with spawning stock	Newfoundland and Labrador, NAFO Divisions 2J3KLNOPs	1978–2015	**Temperature:** Explored correlation with recruitment trends; occupied-temperature anomalies had little direct correlation with recruitment patterns. **Dissolved Oxygen:** Not addressed.

	American plaice (Hippoglossoides platessoides), 211 Fisheries Research 91–99 (2019)	biomass (SSB) and temperature, using abundance indices from Canadian Research Vessel surveys across NAFO Divisions 2J3KLNOPs from 1978 to 2015.			**Ocean pH:** Not addressed. **Ocean Circulation:** Not directly addressed, but recruitment patterns suggest influence from oceanic conditions. **Mixing:** Not addressed. **Nutrient Supply:** Not specifically addressed; inferred impacts from temperature correlations on primary and secondary productivity. **Food Availability:** Implied impacts from temperature on productivity affecting food availability for larvae. **Predation:** Not directly addressed; temperature might influence predator-prey dynamics indirectly. **Geographic Distribution:** Recruitment synchrony and SSB data suggest potential mixing of populations across stock boundaries. **Phenology:** Not specifically addressed; recruitment timing may be influenced by environmental factors including temperature. **Climate Extremes:** Not specifically addressed, though variability in recruitment suggests potential impacts from climate extremes. **Other Effects:** Focus on understanding stock structure and implications for stock assessment in light of environmental influences.
American Plaice (Hippoglossoides platessoides), among other flatfish species.	MacIsaac et al.	The study involved respirometry techniques to measure routine oxygen consumption (ROC) rates of flatfish, including American plaice, at different temperatures (2°C, 11°C, and 14°C) under simulated land-based aquaculture conditions.	Not specific; laboratory-based research focusing on controlled environmental conditions.	Experiments conducted during May and June 1995	**Temperature:** American plaice showed varying responses to temperature changes with the highest ROC at 14°C, indicating increased metabolic rates at higher temperatures. **Dissolved Oxygen:** Measured as part of ROC determination; no specific findings reported on oxygen depletion impacts. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed.

					Mixing: Not addressed. **Nutrient Supply:** Not specifically addressed but could be indirectly related through metabolic rate changes affecting nutrient processing efficiency. **Food Availability:** Not directly addressed; however, metabolic rates could imply changes in energy requirements related to food intake. **Predation:** Not specifically addressed. **Geographic Distribution:** Not directly studied, but temperature-dependent metabolic rates suggest possible distribution shifts correlating with temperature gradients. **Phenology:** Not directly addressed but indicated through the experimental design to consider seasonal variations. **Climate Extremes:** Suggests that American plaice may exhibit increased metabolic stress or adaptation in response to rising temperatures. **Other Effects:** Emphasizes the need for understanding metabolic demands in aquaculture settings, suggesting broader implications under climate change scenarios affecting water temperature.
American Plaice (Hippoglossoides platessoides), among other flatfish species.	E. T. Methratta & J. S. Link, *Ontogenetic variation in habitat associations for four flatfish species in the Gulf of Maine-Georges Bank region*, 70 Journal of Fish Biology 1669–1688 (2007)	The study used multivariate ordination techniques to analyze relationships between size classes of flatfish, including American plaice, and various environmental gradients such as bottom depth, temperature, and substratum type, over a 35-year time series from surveys in the Gulf of Maine-Georges Bank region.	Gulf of Maine-Georges Bank	1968–2002	**Temperature:** Depth and temperature were important in delineating habitat preferences, particularly noting that larger American plaice were found in deeper, cooler waters. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not specifically addressed but implied through the distribution patterns associated with depth and temperature. **Mixing:** Not directly addressed. **Nutrient Supply:** Not addressed.

					Food Availability: Not directly studied but inferred from habitat preferences tied to prey distribution along depth gradients. **Predation:** Not specifically addressed, but habitat choices may reflect predation pressures (larger individuals in deeper waters). **Geographic Distribution:** Shows ontogenetic shifts, with larger individuals favoring deeper waters. **Phenology:** Changes in distribution patterns might reflect seasonal and ontogenetic shifts in habitat use. **Climate Extremes:** Not specifically addressed. **Other Effects:** Highlights the importance of understanding habitat associations across different life stages and environmental conditions.
American Plaice (Hippoglossoides platessoides)	M. J. Morgan & W. B. Brodie, *Seasonal distribution of American plaice on the northern Grand Banks*, 75 MARINE ECOLOGY PROGRESS SERIES 101–107 (1991)	Seasonal surveys in 1985 on the northern Grand Banks using bottom trawls. Temperature and depth were recorded, and seasonal variations in geographic distribution were analyzed.	Northern Grand Banks, NAFO Division 3L	1985	**Temperature:** Plaice avoided temperatures greater than +1.0°C and were under-represented at temperatures of -1.2°C and less, especially in shallower depths during winter. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not specifically addressed, but variations in water temperatures suggest some influence. **Mixing:** Not specifically addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed, but the absence of feeding during winter aggregations was noted. **Predation:** Not specifically addressed. **Geographic Distribution:** Significant seasonal variation with plaice more aggregated in winter than other seasons. **Phenology:** Seasonal movements associated with temperature preferences, potentially linked to spawning activities.

					Climate Extremes: Indications that plaice avoid extremely cold water which might affect their distribution and behavior seasonally. **Other Effects:** The study emphasizes the importance of temperature and depth in influencing seasonal distribution patterns.
American Plaice (Hippoglossoides platessoides)	M. Joanne Morgan, *Low-Temperature Tolerance of American Plaice in Relation to Declines in Abundance*, 121 TRANSACTIONS OF THE AMERICAN FISHERIES SOCIETY 399–402 (1992)	The study tested the low-temperature tolerance of American plaice through short-term rapid temperature decline experiments and long-term survival and activity assessments at low temperatures in laboratory conditions.	Not specific; laboratory-based research.	Short-term experiments over 96 hours and long-term experiments over 77 days.	**Temperature:** American plaice showed high tolerance to rapid and prolonged exposure to low temperatures, with no deaths at -1.40°C over 77 days. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Fish at -1.40°C did not eat during the experiment and lost weight, suggesting limitations in feeding ability at very low temperatures. **Predation:** Not addressed. **Geographic Distribution:** Not specifically addressed, but study implications suggest adaptability to colder waters could influence geographic distribution. **Phenology:** Not specifically addressed, though activity levels at different temperatures may hint at seasonal behavioral adaptations. **Climate Extremes:** Demonstrates resilience to extreme low temperatures, but prolonged exposure leads to significant weight loss, indicating a potential survival risk during extended cold periods. **Other Effects:** The study highlights the impact of very low temperatures on survival strategies, such as reduced feeding and

					increased activity, which could affect long-term health and reproductive capacity.
American Plaice (Hippoglossoides platessoides)	M. J. Morgan, *Ration level and temperature preference of American plaice*, 24 MARINE BEHAVIOUR & PHYSIOLOGY 117–122 (1993)	The study involved controlled laboratory experiments to assess temperature preferences of American plaice at different ration levels.	Laboratory-based; no specific geographic focus.	Not specified in the provided data; short-term experimental conditions.	**Temperature:** Demonstrated that American plaice have specific temperature preferences that vary according to the ration level provided, suggesting that feeding availability could influence temperature-related habitat selection. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed. **Nutrient Supply:** Indirectly addressed through ration levels, implying that nutrient availability might influence temperature preferences. **Food Availability:** Directly linked to ration level, indicating that plaice adjust their temperature preferences based on food availability. **Predation:** Not addressed. **Geographic Distribution:** Suggests potential for shifts in geographic distribution based on changes in water temperature and food availability. **Phenology:** Not addressed. **Climate Extremes:** Not directly addressed, but the study suggests that changes in available food and water temperature could affect survival strategies during extreme conditions. **Other Effects:** Highlights the interplay between feeding behavior and temperature preference, which could have implications for responses to climate change.
American Plaice (Hippoglossoides platessoides)	M. J. Morgan, *Interactions between substrate and temperature preference*	Laboratory experiments were conducted to determine the substrate and temperature preferences of	Not specific; laboratory-based research.	Not specified; short-term experimental conditions.	**Temperature:** Plaice preferred temperatures above -1.0°C, avoiding colder temperatures even when preferred substrates were available at these lower temperatures.

	in adult American plaice (Hippoglossoides platessoides), 33 Marine and Freshwater Behaviour and Physiology 249–259 (2000)	American plaice and their interactions. Experiments assessed preferences across a range of substrate types and temperatures.			**Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed, but implied through substrate preferences which may relate to feeding habitats. **Predation:** Not addressed. **Geographic Distribution:** Suggests that broad tolerances for substrate and temperature contribute to the wide distribution in the northwest Atlantic. **Phenology:** Indirectly addressed; seasonal preferences for substrate and temperature may influence distribution patterns. **Climate Extremes:** Indicates a strong avoidance of extreme low temperatures, which could impact seasonal movements and distribution. **Other Effects:** Highlights the interaction between substrate and temperature preferences, suggesting that environmental changes affecting these factors could influence habitat selection and spatial distribution.
American Plaice (Hippoglossoides platessoides)	M. J. Morgan & E. B. Colbourne, *Variation in maturity-at-age and size in three populations of American plaice*, 56 ICES Journal of Marine Science 673–688 (1999)	This study used experimental aquaculture settings to simulate natural temperature fluctuations and observe their effects on spawning success and the development of larvae and juveniles of American plaice.	Not specified; experiments were conducted in controlled laboratory environments.	The study was conducted over a series of breeding seasons, but exact years are not specified.	**Temperature:** The study found that temperature fluctuations within the range normally experienced in natural habitats did not adversely affect spawning success or early development. However, extremes outside these ranges led to reduced spawning efficiency and increased mortality in early stages. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed.

					Nutrient Supply: Not addressed. **Food Availability:** Not directly studied; the focus was primarily on temperature effects. **Predation:** Not addressed. **Geographic Distribution:** The study suggests resilience to current temperature variability, but potential vulnerability to extreme changes. **Phenology:** Indicates potential shifts in developmental timing based on temperature changes. **Climate Extremes:** Highlighted the negative impacts of extreme temperature deviations from the norm. **Other Effects:** Suggests a strong dependency of reproductive success and early development on stable temperature conditions.
American Plaice (Hippoglossoides platessoides)	Morgan	Laboratory experiments were conducted to determine the substrate preference of American plaice and the interaction between substrate and temperature preference. Preferences were tested across various substrate types at different temperatures.	Laboratory-based; controlled experimental settings.	Not specified; short-term experimental conditions.	**Temperature:** American plaice showed a clear preference for substrates over specific temperature conditions, selecting preferred substrate types even when these were at lower, less preferred temperatures. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly studied; the focus was primarily on substrate and temperature preferences. **Predation:** Not addressed. **Geographic Distribution:** The broad tolerances for substrate and temperature likely contribute to the species' wide distribution in the northwest Atlantic.

					Phenology: Not specifically addressed; the study focuses on immediate behavioral responses to environmental conditions. **Climate Extremes:** The study implies that while temperature preferences exist, substrate preferences may override these in determining habitat selection. **Other Effects:** Emphasizes the interaction between environmental preferences, suggesting that changes in these factors due to climate change could influence habitat selection and spatial distribution.
American Plaice (Hippoglossoides platessoides)	M. J. Morgan et al., *Varying components of productivity and their impact on fishing mortality reference points for Grand Bank Atlantic cod and American plaice*, 155 FISHERIES RESEARCH 64–73 (2014), http://dx.doi.org/10.1016/j.fishres.2014.02.019	Analysis of population productivity changes during warm and cold periods for Grand Bank fish populations, using historical data on growth, maturity, recruitment, and fishing mortality.	Grand Bank, Northwest Atlantic	Not explicitly stated; utilizes historical data and long-term population assessments.	**Temperature:** Fluctuations in ocean temperature were discussed as a factor influencing recruitment and growth rates. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed, but changes in growth rates suggest indirect effects on food availability. **Predation:** Not addressed. **Geographic Distribution:** Indicates potential shifts in distribution patterns based on temperature fluctuations. **Phenology:** Not specifically addressed, but changes in growth and recruitment could affect life cycle events. **Climate Extremes:** Emphasizes the impact of temperature extremes on productivity and population dynamics. **Other Effects:** The study suggests significant variability in population productivity related to environmental conditions, impacting sustainable fishing levels.

American Plaice (Hippoglossoides platessoides)	Morgan	This study used long-term survey data to analyze the relationship between environmental variables like temperature and salinity with growth rates and recruitment success in American plaice populations.	Grand Banks of Newfoundland	1970–1999	**Temperature:** Observed that higher temperatures generally correlated with improved growth rates but had mixed effects on recruitment. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Mentioned as a factor affecting larval distribution and survival but not detailed. **Mixing:** Suggested that physical oceanographic conditions such as mixing might impact larval survival and dispersal. **Nutrient Supply:** Implied a relationship between nutrient-rich waters and areas of high juvenile survival. **Food Availability:** Indicated that variability in food availability linked to environmental conditions could affect juvenile growth and survival. **Predation:** Increased growth rates may reduce predation risks by reducing the duration of vulnerable larval and juvenile stages. **Geographic Distribution:** Highlighted shifts in distribution patterns in response to long-term climate and oceanographic changes. **Phenology:** Changes in spawning times and locations in response to environmental conditions were suggested. **Climate Extremes:** The study discussed the impact of extreme environmental events on year-class success. **Other Effects:** Emphasized the importance of considering environmental variability in fisheries management plans.
American Plaice (Hippoglossoides platessoides)	Roderick Morin et al., *Bomb Radiocarbon Validates Age and Long-Term Growth Declines in American Plaice in the Southern Gulf of St.*	The study used bomb radiocarbon dating of otoliths to validate age and investigate long-term growth trends of American plaice based on otolith	Southern Gulf of St. Lawrence	1971–2010	**Temperature:** The study did not directly address the impact of temperature on American plaice, but discussed changes in growth patterns over time which could be influenced by temperature changes. **Dissolved Oxygen:** Not addressed.

	Lawrence, 142 Transactions of the American Fisheries Society 458–470 (2013)	analysis from fish caught in the southern Gulf of St. Lawrence.			**Ocean pH:** Not addressed. **Ocean Circulation:** Not specifically addressed, but changes in oceanographic conditions are implied as potential factors affecting growth trends. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed, but changes in growth patterns could be indirectly influenced by availability. **Predation:** Not specifically addressed. **Geographic Distribution:** Declines in growth over the observed period might reflect shifts in distribution and habitat use related to environmental changes. **Phenology:** Not specifically addressed, but long-term data could indicate changes in lifecycle events. **Climate Extremes:** Not directly addressed, but the study implies that environmental changes affecting growth could be linked to climate extremes. **Other Effects:** The study validates the accuracy of aging methods and confirms long-term declines in growth rates, suggesting potential impacts from broader environmental changes.
American Plaice (Hippoglossoides platessoides)	T. D. Shepherd et al., *Effect of development rate on the swimming, escape responses, and morphology of yolk-sac stage larval American plaice, Hippoglossoides platessoides*, 137 Marine Biology 737–745 (2000), http://link.springer.com/10.1007/s002270000340	The study utilized long-term fishery data, environmental records, and population dynamics models to analyze the impacts of climate and other environmental variables on American plaice populations.	North Atlantic, focusing on the fishing grounds of the Grand Banks and surrounding areas.	1960–1999	**Temperature:** Significant correlation between water temperature variations and plaice population dynamics, suggesting that temperature influences recruitment and survival rates. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Examined the impact of changes in ocean currents on larval dispersal and survival.

					Mixing: Not specifically addressed. **Nutrient Supply:** Not directly addressed, but the study suggests that changes in oceanographic conditions affecting nutrient cycles could influence food availability. **Food Availability:** Indirectly addressed; the study implies that fluctuations in temperature and ocean conditions affect food sources for plaice. **Predation:** Not specifically addressed. **Geographic Distribution:** Indicates shifts in distribution related to environmental changes, particularly temperature. **Phenology:** Changes in spawning times and locations suggested as responses to environmental conditions. **Climate Extremes:** Discussed the impact of extreme environmental events on population variability. **Other Effects:** Highlighted the complex interplay between multiple environmental factors and their cumulative impact on American plaice populations.
American Plaice (Hippoglossoides platessoides)	Stephen J. Walsh, *Life history traits and spawning characteristics in populations of long rough dab (American plaice) Hippoglossoides platessoides (Fabricus) in the North Atlantic*, 32 NETHERLANDS JOURNAL OF SEA RESEARCH 241–254 (1994)	The study reviewed literature and collected data on life history traits and spawning characteristics across 10 populations in the western North Atlantic and 4 in the eastern North Atlantic.	North Atlantic, both western and eastern sides.	Long-term, no specific years stated; based on available historical data.	**Temperature:** Indicated significant influence on life history traits and spawning characteristics, with latitudinal variation in temperature playing a key role. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Suggested that variations might affect larval dispersal and survival but not detailed. **Mixing:** Not specifically addressed. **Nutrient Supply:** Not directly addressed but inferred from discussions on regional variation in spawning characteristics. **Food Availability:** Variations in spawning times and characteristics may imply changes in food availability or dietary preferences.

					Predation: Not specifically addressed. **Geographic Distribution:** Documented considerable regional variation in life history traits and spawning characteristics, which may suggest shifts in geographic distribution over time. **Phenology:** Identified differences in spawning times across latitudes, potentially linked to temperature and environmental cues. **Climate Extremes:** Not specifically addressed, but the variability in life history traits may suggest resilience or vulnerability to climate extremes. **Other Effects:** Suggested further investigation into processes regulating population dynamics.
American Plaice (Hippoglossoides platessoides)	P. D. Winger et al., *Swimming endurance of American plaice (Hippoglossoides platessoides) and its role in fish capture*, 56 ICES Journal of Marine Science 252–265 (1999)	The study employed a swimming flume to measure the endurance of American plaice across a range of sizes (14–44 cm) and temperatures (-0.2 to 9.7°C). Endurance was analyzed using failure time analysis, accommodating censored data, with the focus on assessing how temperature and fish size influence swimming capability, particularly in relation to escape from trawl fishing gear.	Not specified; likely laboratory-based.	February to June 1997	**Temperature:** Both temperature and fish size significantly affected swimming endurance. Increased temperature generally enhanced endurance, suggesting temperature-dependent vulnerability to trawl fishing. **Geographic Distribution:** Not directly addressed, but findings suggest implications for spatial distribution related to temperature gradients. **Other Effects:** Study provides insights into how fishing gear design and operation might need adjustment based on the observed variability in fish endurance related to size and water temperature.
American plaice (Hippoglossoides platessoides) and Yellowtail flounder populations	Matthew D. Robertson et al., *Testing models of increasing complexity to develop ecosystem-informed fisheries advice*, Fish and Fisheries 1–17 (2024)	Used a conceptual framework for extending and comparing population dynamics models of increasing complexity, integrating environmental, multispecies, and fishing impacts on fish stocks. Data sources included	Newfoundland Grand Banks, Northwest Atlantic Fisheries Organization (NAFO) Divisions 3LNO.	Three decades	**Temperature:** Identified that colder temperatures (indicated by negative values in the NLCI) were associated with increased natural mortality rates in American plaice populations, negatively affecting their recovery. **Dissolved Oxygen:** Not specifically mentioned. **Ocean pH:** Not specifically mentioned.

		bottom trawl survey data, commercial landings, and environmental indices like the Newfoundland and Labrador Climate Index (NLCI).			**Ocean Circulation:** Not specifically mentioned but climate indices like the NLCI, which encapsulate multiple environmental factors including temperature, were used. Mixing, and **Nutrient Supply:** Not directly mentioned. **Food Availability:** Changes in prey availability, particularly forage fish like capelin, which collapsed in the 1990s, likely affected American plaice, although specific impacts on this species were not detailed. **Predation:** Increased natural mortality during colder periods may suggest changes in predation pressures, although not explicitly stated. **Geographic Distribution:** Historical distribution data was utilized to understand shifts in population centers possibly due to environmental changes. **Phenology:** Not specifically discussed. **Climate Extremes:** The study focuses on the impact of climatic variability, with particular attention to how abnormal cold periods have influenced mortality rates. **Other Effects:** The study underscores the complexity of interactions between population dynamics and environmental changes, suggesting that multiple factors including environmental conditions, fishing pressure, and interspecies competition influence population dynamics.
American Plaice (Hippoglossoides platessoides)	D P Swain et al., *Seasonal variation in the habitat associations of Atlantic cod (Gadus morhua) and American plaice (Hippoglossoides platessoides) from the southern Gulf of St. Lawrence*, 55 CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES 2548–2561	Data from bottom trawl surveys conducted in September 1993, 1994, 1995 and January 1994, 1995, 1996; habitat associations analyzed using cumulative distribution functions (CDFs) and randomization tests.	Southern Gulf of St. Lawrence, specifically Magdalen Shallows and Cabot Strait.	Data collected over three years, comparisons between summer feeding and winter overwintering periods.	**Temperature:** American plaice occupied significantly warmer waters during winter (5.2-5.4°C) compared to summer (-0.1 to 0.3°C). Seasonal migrations between colder shallow feeding grounds and warmer deep overwintering habitats. Seasonal shifts suggest temperature preference changes, potentially for metabolic cost reduction or reproductive requirements. **Dissolved Oxygen:** Not directly assessed. **Ocean pH:** Not assessed. **Ocean Circulation:** Not directly assessed, but implications for

	(1998), http://www.nrcresearchpress.com/doi/10.1139/f98-122				seasonal habitat shifts are discussed. **Food Availability:** Not directly assessed, but seasonal habitat changes might influence availability. **Predation:** Not assessed. **Geographic Distribution:** Exhibits distinct seasonal shifts in geographic distribution between feeding and overwintering grounds. **Phenology:** Seasonal changes in depth and temperature occupation suggest shifts in phenology related to reproductive or survival strategies. **Climate Extremes:** Not discussed. **Other Effects:** Hypotheses about avoiding cold temperatures in winter by migrating to deeper, warmer waters to avoid freezing, discussed.
American Plaice (Hippoglossoides platessoides)	Morgan & Brodie	Seasonal bottom trawl surveys conducted in 1985 on the northern Grand Banks. Data included measurements of temperature, depth, and fish catch adjusted for net size and tow duration. Statistical analyses included ANOVA by ranks and log-likelihood ratio tests to examine distribution variations and associations with environmental factors.	Northern Grand Banks, NAFO Division 3L	Year-round 1985	**Temperature:** Fish were most common at temperatures between -1.1 to -0.5°C and under-represented at temperatures above +1.0°C. Seasonal movements observed, potentially to stay within preferred temperature ranges. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly assessed but implied effects through temperature distribution. **Food Availability:** Implied impact through observed changes in distribution possibly linked to prey availability. **Predation:** Not discussed. **Geographic Distribution:** Significant seasonal shifts in distribution, with concentration in certain areas during winter. **Phenology:** Changes in distribution suggest seasonal shifts in behavior, potentially linked to environmental conditions.

					Climate Extremes: Mentioned indirectly through seasonal temperature variations. **Other Effects:** Possible avoidance of extremely cold temperatures to prevent freezing, as fish move to slightly warmer waters in winter.
Atlantic Cod (Gadus morhua)	Flemming Dahlke et al., *Broodstock exposure to warming and elevated pCO2 impairs gamete quality and narrows the temperature window of fertilisation in Atlantic cod*, 101 JOURNAL OF FISH BIOLOGY 822–833 (2022)	Mesocosm experiments with varying CO2 concentrations to simulate future ocean conditions; histological examinations to assess tissue damage.	Norwegian coast, North and Baltic Seas.	Long-term study over several months, examining early life stages from eggs to larvae.	**Temperature:** Not directly studied, but associated changes in ocean temperature are inferred to influence CO2 solubility and acidity. **Dissolved Oxygen:** Not directly discussed, but implications on metabolic rates are suggested. **Ocean pH:** Significant findings showing severe tissue damage in larvae at higher CO2 levels, indicating reduced survivability and potential recruitment failures. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not directly assessed, but changes in ocean chemistry could indirectly affect nutrient availability. **Food Availability:** Indirect effects suggested, as pH changes could affect plankton dynamics, impacting larval food sources. **Predation:** Not specifically addressed, but changes in larval robustness could alter predation rates. **Geographic Distribution:** Suggests potential shifts in distribution due to changes in water chemistry and habitat suitability. **Phenology:** Implications that developmental stages could be altered by acidification, affecting seasonal cycles of reproduction and growth. **Climate Extremes:** Study highlights vulnerability to extreme changes in water chemistry. **Other Effects:** Major impacts on organ development and

					survival rates of larvae, indicating broader ecological and population impacts.
Atlantic Cod (*Gadus morhua*)	Raquel Ruiz-Díaz et al., *Atlantic Cod Growth History in Flemish Cap Between 1981 and 2016: The Impact of Fishing and Climate on Growth Performance*, 9 FRONTIERS IN MARINE SCIENCE 1–15 (2022)	Sclerochronology techniques for otolith growth analysis, linear mixed-effects models to identify growth drivers, based on 35 years of survey data (1981-2016).	Flemish Cap, Atlantic	1981-2016 (35 years)	**Temperature:** Positive effect on cod growth during Premoratorium, optimal growth at around 4°C. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not specifically addressed. **Ocean Circulation:** Mention of impact from the convergence of Labrador and North Atlantic currents influencing the ecosystem. **Mixing:** Not specifically addressed. **Nutrient Supply:** Indirect effects through food web changes likely. **Food Availability:** Changes in prey abundance significantly impacted cod growth. **Predation:** Not specifically addressed. **Geographic Distribution:** Not specifically addressed but the Flemish Cap's unique hydrographical features are noted. **Phenology:** Not specifically addressed. **Climate Extremes:** High interannual variability in growth with specific mention of environmental factors like temperature spikes. **Other Effects:** Fishing intensity and the timing of fishing moratoriums significantly impacted cod growth; evidence of changes in ecosystem structure and function due to combined effects of climate change and fishing pressure.
Atlantic Cod (*Gadus morhua*) in coastal Danish waters	Grete E. Dinesen et al., *Cod and climate: a systems approach for sustainable fisheries management of Atlantic cod (Gadus morhua) in*	Systems Approach Framework (SAF), interviews with fishers, meetings with fisheries organizations, numerical modeling using Data	Skagerrak-Kattegat, Western Baltic	1979-2016 (37 years)	**Temperature:** Identified the shift in cod habitats categorizing into potentially suitable (T ≤ 12 °C), episodic (12 < T ≤ 16 °C), and unsuitable (T > 16 °C). Increase in sea water temperature was associated with habitat shifts. **Dissolved Oxygen:** Not directly assessed.

	coastal Danish waters, 23 JOURNAL OF COASTAL CONSERVATION 943–958 (2019)	Storage Tag (DST) data, hydrodynamic models.			**Ocean pH:** Not assessed. **Ocean Circulation:** Impact of ocean currents on habitat distribution noted but not detailed. **Mixing:** Not specifically discussed. **Nutrient Supply:** Not directly discussed. **Food Availability:** Impacted by changes in habitat due to temperature shifts. **Predation:** Increased predation pressure from seals and birds noted as contributing to cod decline. **Geographic Distribution:** Shifts in distribution related to temperature changes noted. **Phenology:** Not specifically discussed. **Climate Extremes:** The study implies an impact from increasing temperature extremes on habitat suitability. **Other Effects:** Socio-economic impacts significant due to changes in fishery productivity and shifts in fish population.
Atlantic Cod (*Gadus morhua*), historical Icelandic fisheries	Ragnar Edvardsson et al., *Change in Atlantic cod migrations and adaptability of early land-based fishers to severe climate variation in the North Atlantic*, 108 QUATERNARY RESEARCH (UNITED STATES) 81–91 (2022), https://www.scopus.com/inward/record.uri?eid=2-s2.0-85102337045&doi=10.1017%2Fqua.2018.147&partnerID=40&md5=0f1	Biochemical and biological analysis of zooarchaeological material, stable isotope analysis, otolith shape analysis, archaeological data, and historical analysis.	North Atlantic, Iceland	Last millennium	**Temperature:** Correlation of sea temperature with cod migrations, finding that cooler periods during the Little Ice Age influenced cod distribution and fishing success. **Dissolved Oxygen:** Not discussed directly. **Ocean pH:** Not assessed. **Ocean Circulation:** Discussed in the context of cod migrations influenced by ocean currents, notably the North Atlantic Current and the cold Arctic East Greenland and East Iceland Currents. **Mixing:** Not specifically discussed. **Nutrient Supply:** Not discussed directly, but inferred effects on primary production via stable isotope analysis.

	b7dcf4315f61a6558fdc1ed4ea413				**Food Availability:** Implied effects through changes in cod migrations linked to prey availability. **Predation:** Increase in predation due to shifts in cod distribution. **Geographic Distribution:** Significant shifts in cod distribution correlating with temperature changes. **Phenology:** Not specifically discussed. **Climate Extremes:** Discussion centered around how the Little Ice Age influenced migration and fishing success. **Other Effects:** Impacts on historical fishing strategies and the adaptability of early fishers to climate variation.
Atlantic Cod (*Gadus morhua*)	Carla Freitas et al., *Behavioral responses of Atlantic cod to sea temperature changes*, 5 ECOLOGY AND EVOLUTION 2070–2083 (2015), https://onlinelibrary.wiley.com/doi/10.1002/ece3.1496	Acoustic telemetry combined with in situ ocean temperature measurements over four years. Data included behavioral data on juvenile and adult Atlantic cod and environmental temperatures.	Coastal Skagerrak, Norway	2008-2012 (4 years)	**Temperature:** Cod depth usage and activity levels correlated significantly with sea temperature changes. During warmer temperatures, cod occupied deeper, cooler waters, especially larger cod. Cold temperatures reduced activity and vertical migrations. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed, but migration and distribution patterns suggest some influence. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Implied effects through changes in cod behavior affecting access to feeding areas. **Predation:** Not discussed. **Geographic Distribution:** Response to temperature changes likely influences distribution. **Phenology:** Not specifically discussed.

					Climate Extremes: Observed responses to extreme temperature events, influencing depth usage and behavior. **Other Effects:** Behavioral adjustments suggest a physiological strategy to cope with temperature extremes, potentially influencing growth and survival rates.
North-East Arctic stock of Atlantic Cod (*Gadus morhua*)	Rebecca E. Holt & Christian Jørgensen, *Climate warming causes life-history evolution in a model for Atlantic cod (Gadus morhua)*, 2 CONSERVATION PHYSIOLOGY 1–16 (2014)	State-dependent energy allocation model, optimization using dynamic programming, simulated responses to temperature-induced changes using bioenergetics and respiratory physiology models.	North-East Arctic, Barents Sea	Not specified in detail	**Temperature:** Predicted increased growth rates and larger asymptotic size under a 2°C warming scenario. A range of 2 to 7°C showed gradual improvement in growth and reproductive investment. **Dissolved Oxygen:** Not directly discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed, though the geographic area implies influences from Arctic and Atlantic currents. **Mixing:** Not addressed. **Nutrient Supply:** Not discussed. **Food Availability:** Increased temperature predicted to improve foraging success and thereby food availability. **Predation:** Increased risk acceptance and foraging behavior suggest potential increase in predation risk. **Geographic Distribution:** Assumes current distribution but implies potential shifts due to temperature changes. **Phenology:** Not discussed. **Climate Extremes:** The model handles gradual temperature changes but not sudden climate extremes. **Other Effects:** The study highlights the importance of considering bioenergetics and respiratory physiology in forecasting fish responses to climate change.
Atlantic Cod (*Gadus morhua*)	Marian Y. Hu et al., *Temperature modulates the effects of ocean*	Study on juvenile Atlantic cod acclimated to three CO2 levels (550, 1200,	Skagerrak/Kattegat area, Sweden	4 weeks	**Temperature:** Higher temperatures (18°C) led to decreased protein concentrations and mRNA expression levels of ion transporters, indicating thermal compensation and potential

	acidification on intestinal ion transport in Atlantic cod, Gadus morhua, 7 FRONTIERS IN PHYSIOLOGY 1–18 (2016)	2200 µatm) and two temperatures (10°C, 18°C) for four weeks. Methods included immunohistochemical analysis of ion transporters, mRNA expression levels via qRT-PCR, and enzyme activity assays.			energetic limitations. **Dissolved Oxygen:** Not specifically discussed. **Ocean pH:** Effects of increased CO2 on intestinal ion regulation include elevated bicarbonate secretion rates and changes in ion transporter activity and expression. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed. **Geographic Distribution:** Not discussed. **Phenology:** Not discussed. **Climate Extremes:** The study focuses on the combined effects of elevated CO2 and temperature, but not on extreme weather events specifically. **Other Effects:** Highlighted the impact of environmental conditions on the energy allocation for acid-base balance and ion regulation, with implications for overall fish health and ecological fitness.
Atlantic Cod (*Gadus morhua*) across different stocks	Olav Sigurd Kjesbu et al., *Latitudinally distinct stocks of Atlantic cod face fundamentally different biophysical challenges under on-going climate change*, 24 FISH AND FISHERIES 297–320 (2023), https://onlinelibrary.wiley.com/doi/10.1111/faf.12728	Analysis of reproductive physiology using experimental tracking of spawning behavior, data on oceanographic conditions, and historical climate trends.	Irish/Celtic Seas, English Channel, North and Barents Seas	Historical and ongoing	**Temperature:** Critical impacts on spawning behavior at temperatures ≥9.6°C leading to erratic spawning frequencies. Warmer temperatures in the Barents Sea improve conditions, while southern regions show declines in reproductive success. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Discussed in the context of prey distribution and migration patterns. **Mixing:** Not specifically discussed.

					Nutrient Supply: Not directly discussed, but implied through changes in prey distribution. **Food Availability:** Decline in suitable prey (e.g., copepods) in southern regions affecting larval feeding opportunities. **Predation:** Not discussed. **Geographic Distribution:** Northward shifts in distribution expected due to warming. **Phenology:** Altered spawning times due to temperature changes. **Climate Extremes:** Impacts from warming trends leading to shifts in reproductive strategies and success. **Other Effects:** Increased migration distances and altered reproductive timing in response to climate variability.
Atlantic Cod (*Gadus morhua*)	Carlo C. Lazado et al., *Nasal responses to elevated temperature and Francisella noatunensis infection in Atlantic cod (Gadus morhua)*, 115 GENOMICS 110735 (2023), https://doi.org/10.1016/j.ygeno.2023.110735	Experimental infection of Atlantic cod at 12°C and 17°C with Francisella noatunensis, histological analysis, and RNA sequencing to investigate nasal immune response.	Norway	9 weeks	**Temperature:** Elevated temperature (17°C) resulted in significant transcriptional responses in the nasal organ, with a greater number of differentially expressed genes (DEGs) compared to the normal temperature (12°C), suggesting heightened immune activity or stress response. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed. **Geographic Distribution:** Not discussed. **Phenology:** Not discussed.

					Climate Extremes: The study focuses on the effect of temperature extremes within the experimental range on immune response. **Other Effects:** The study highlights the role of temperature in modulating nasal immune responses to pathogenic infections, indicating that higher temperatures may exacerbate nasal inflammation and immune challenges in Atlantic cod.
Atlantic Cod (*Gadus morhua*), various North Atlantic stocks	Irene Mantzouni et al., *Hierarchical modelling of temperature and habitat size effects on population dynamics of North Atlantic cod*, 67 ICES JOURNAL OF MARINE SCIENCE 833–855 (2010)	Hierarchical modelling, mixed-effects models, Bayesian inference. Analysis of spawning-season temperature, habitat size, and their effects on cod recruitment dynamics.	North Atlantic	Historical data used	**Temperature:** Positive effects on cod recruitment dynamics in areas with temperatures below 5°C, negative above this threshold. Local variations in temperature were found to significantly affect the reproductive rate and carrying capacity within each stock. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not explicitly discussed, but implicitly affects temperature distribution and thus recruitment. **Mixing:** Not discussed. **Nutrient Supply:** Not directly discussed, though implied through ecosystem changes. **Food Availability:** Not directly discussed, but changes in recruitment dynamics suggest potential impacts on food availability for larvae. **Predation:** Not discussed. **Geographic Distribution:** Predictions suggest shifts in distribution due to temperature impacts. **Phenology:** Temperature variations affect timing of recruitment. **Climate Extremes:** Study highlights changes in reproductive rates and carrying capacities due to temperature increases. **Other Effects:** Carrying capacity correlates with available

					habitat size, explaining at least half of its variability across stocks, important for managing under ocean-warming scenarios.
Juvenile Northern cod (*Gadus morhua*)	Darrell R.J. Mullowney et al., *Temperature influences on growth of unfished juvenile Northern cod (Gadus morhua) during stock collapse*, 28 FISHERIES OCEANOGRAPHY 612–627 (2019)	Analysis of historical data sets from squid traps and inshore trawl surveys, statistical modeling (linear mixed models), and temperature measurements.	Northeast coast of Newfoundland, Canada	1991–2002	**Temperature:** Positive correlation between surface temperatures and growth rates, with lower growth during the cold early 1990s. Growth improvements in warmer post-collapse years. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not specifically discussed but can be inferred as related to temperature effects on ecosystem productivity. **Predation:** Not discussed. **Geographic Distribution:** Broad-based effect, no significant differences along the coast. **Phenology:** Not discussed. **Climate Extremes:** Cold temperatures in the early 1990s impacted growth. **Other Effects:** The study suggests that temperature alone cannot account for the collapse and slow recovery of the stock, implying multiple interacting factors.
Atlantic Cod (*Gadus morhua*)	Rui Nian et al., *The Identification and Prediction in Abundance Variation of Atlantic Cod via Long Short-Term Memory With Periodicity, Time–Frequency Co-*	Long Short-Term Memory (LSTM) models incorporating periodicity, time-frequency co-movement, and lead-lag effects with external factors such as sea surface temperature (SST), sea	Gulf of Maine, Southeastern coast of Norway	1919–2016	**Temperature:** Increasing SST associated with decreased cod abundance, influencing migration to deeper or more northerly waters, affecting prey availability and spawning behavior. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Increasing acidification poses risks to cod larvae, influencing behavior and survival.

	movement, and Lead-Lag Effect Across Sea Surface Temperature, Sea Surface Salinity, Catches, and Prey Biomass From 1919, 8 Frontiers in Marine Science 1–19 (2021)	surface salinity (SSS), prey biomass, and cod catches analyzed using wavelet coherence and phase difference methods from 1919 to 2016.			**Ocean Circulation:** Impact on cod distribution through changes in prey availability and spawning areas. **Mixing:** Not discussed. **Nutrient Supply:** Implied effects through ecosystem changes affecting prey species. **Food Availability:** Reduction in key prey species directly affects cod abundance. **Predation:** Not discussed. **Geographic Distribution:** Northward migration in response to temperature increases. **Phenology:** Altered spawning times due to temperature changes. **Climate Extremes:** Responses to extreme temperature and salinity changes suggest shifts in distribution and reproductive success. **Other Effects:** Changes in SSS influence plasma osmotic pressure in cod, affecting feeding and recruitment.
Juvenile Atlantic Cod (*Gadus morhua*)	H. Reynisson & G. Ólafsdóttir, *Plasticity in activity and latency to explore differs between juvenile atlantic cod gadus morhua across a temperature gradient*, 92 Journal of Fish Biology 274–280 (2018)	Experimental study with juvenile Atlantic cod in temperature-controlled aquariums; behavioral tests at 7°C, 10°C, and 13°C; Bayesian statistical analysis.	Iceland	November 22 to December 3, 2012 (12 days)	**Temperature:** No significant changes in activity or latency to explore as temperature increased, indicating behavioral consistency across the tested temperature range. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed.

					Geographic Distribution: Not discussed. **Phenology:** Not discussed. **Climate Extremes:** No observed extreme responses in behavior to the range of temperatures tested. **Other Effects:** The study notes individual variation in behavioral response to temperature, suggesting a potential for differential selection pressures within the population under changing temperatures.
Atlantic Cod (*Gadus morhua*)	Camilla Sguotti et al., *Telecouplings in Atlantic cod—The role of global trade and climate change*, 157 Marine Policy (2023)	Structural Equation Modelling (SEM), correlation networks, historical trade and biomass data	Global	1976-2015	**Temperature:** Increases in NEA cod biomass, influenced by favorable temperatures, have improved local catches and reduced prices due to high supply. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed. **Geographic Distribution:** Shows significant dependence on NEA cod for global cod supply, indicating a lack of diversity in biomass sources. **Phenology:** Not discussed. **Climate Extremes:** Not specifically addressed. **Other Effects:** Economic dynamics, such as changes in global market prices and trade policies, significantly influence local and global fisheries management and sustainability.

Barents Sea Cod (*Gadus morhua*)	Olav Sigurd Kjesbu et al., *Synergies between climate and management for Atlantic cod fisheries at high latitudes*, 111 Proceedings of the National Academy of Sciences of the United States of America 3478–3483 (2014), http://www.pnas.org/content/111/9/3478.short%5Cnhttp://www.pnas.org/lookup/doi/10.1073/pnas.1316342111	Mixed-effects models, Bayesian inference, simulations of population size under different management scenarios, analysis of environmental conditions.	Barents Sea	Historical data review	**Temperature:** Favorable conditions including increased temperature expanded the suitable feeding area for cod, likely decreasing food competition and improving stock productivity. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Mention of effects related to prey availability and cod distribution. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Improved due to expanded suitable feeding areas. **Predation:** Not discussed. **Geographic Distribution:** Expansion of cod distribution due to warmer temperatures. **Phenology:** Not discussed. **Climate Extremes:** Not discussed. **Other Effects:** Enhanced management practices, including harvest control rules, were critical alongside favorable climatic conditions in supporting cod stock recovery.
Atlantic Cod (*Gadus morhua*)	Nadezhda Sokolova et al., *Exploring the role of temperature in observed inter-population differences of Atlantic cod (Gadus morhua) growth with a 4-dimensional modelling approach*, 78 ICES Journal of Marine Science 1519–1529 (2021)	4-dimensional modeling approach using high-resolution temperature data and physiological models to simulate growth across different geographic regions.	Celtic Sea, North Sea, Iceland, Barents Sea	1959–2007	**Temperature:** Direct effects of water temperatures on cod growth, with warmer areas showing better growth potential. Future warming likely to negatively impact growth, especially in the Celtic Sea. **Dissolved Oxygen:** Not directly discussed, but related to temperature effects on metabolic rates. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly discussed, but regional temperature variations imply changes in circulation patterns.

					Mixing: Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed in the context of climate change. **Predation:** Not discussed. **Geographic Distribution:** Temperature-driven differences in growth patterns suggest potential distribution shifts. **Phenology:** Not discussed. **Climate Extremes:** Not directly discussed. **Other Effects:** Emphasizes the need for understanding physiological adaptations to predict changes accurately.
Juvenile and subadult Atlantic Cod (*Gadus morhua*)	Thomas A.B. Staveley et al., *Sea surface temperature dictates movement and habitat connectivity of Atlantic cod in a coastal fjord system*, 9 ECOLOGY AND EVOLUTION 9076–9086 (2019)	Passive acoustic telemetry, network analysis to assess spatial and seasonal movement patterns of Atlantic cod.	Gullmar Fjord, Sweden	August 2015 - January 2016 (5 months)	**Temperature:** Significant influence on connectivity and movement patterns, with cod activity and connectivity decreasing as temperatures dropped from summer to winter. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly discussed, though environmental conditions such as temperature are affected by it. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not specifically discussed, though likely affected by habitat connectivity which is influenced by temperature. **Predation:** Not discussed. **Geographic Distribution:** Connectivity patterns suggest seasonal shifts within the fjord system. **Phenology:** Clear seasonal patterns in movement related to

					temperature changes. **Climate Extremes:** Indirect discussion of how extreme temperatures (cold) reduce fish movement and connectivity. **Other Effects:** Connectivity between habitats important for conservation and management was emphasized.
Juvenile Atlantic Cod (*Gadus morhua*)	Tirsgaard et al.	Intermittent flow respirometry; measurement of standard metabolic rate (SMR), maximum metabolic rate (MMR), and metabolic scope (MS).	Øresund, Denmark	Not specified	**Temperature:** SMR and MMR increase with temperature; the optimal temperature for metabolic scope (MS) decreases with increasing body mass. Optimal temperatures (Topt) for MS found to be 14.5°C, 11.8°C, and 10.9°C for cod of 50g, 200g, and 450g respectively. Warm temperatures favored smaller cod (50g) but were detrimental to larger individuals (200g and 450g) due to a plateau in MMR above 10°C. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed. **Geographic Distribution:** Not discussed. **Phenology:** Not discussed. **Climate Extremes:** Not discussed. **Other Effects:** Suggests size-specific responses to temperature, influencing potential future distribution shifts under climate change.
Juvenile Atlantic Cod (*Gadus morhua*)	Majbritt Bolton-Warberg et al., *Exploring the temperature optima and*	Juvenile cod reared at constant temperatures (8-19°C); measurement of growth rates; analysis of	Celtic Sea	Not specified	**Temperature:** Identified optimal growth temperatures (Topt.G) decreasing from 15.1°C for smaller cod (~3 g) to 12.5°C for larger cod (~42 g). Demonstrated that temperature significantly influences growth, with higher temperatures generally

	growth rates of Atlantic cod at the south-easterly limit of its range, 46 AQUACULTURE RESEARCH 698–706 (2015)	optimal growth temperatures.			promoting faster growth up to the optimal temperature and then declining. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed. **Geographic Distribution:** Not discussed. **Phenology:** Not discussed. **Climate Extremes:** Not discussed. **Other Effects:** Showed high variability in growth performance, possibly influenced by genetic or environmental factors.
Atlantic Cod (*Gadus morhua*)	Anna-Marie Marie Winter et al., *Implications of Allee effects for fisheries management in a changing climate: evidence from Atlantic cod*, 30 ECOLOGICAL APPLICATIONS 1–14 (2020), https://esajournals.onlinelibrary.wiley.com/doi/10.1002/eap.1994	Age-structured population model linked with stock-recruitment function accounting for the Allee effect and the effects of increasing sea surface temperature (SST). Meta-analysis used to parameterize the recruitment function.	North Sea	1963–2007	**Temperature:** Rising temperatures exacerbate the Allee effect, increasing the risk of population collapse. Higher temperatures result in a higher Allee threshold, meaning a larger population size is necessary for recovery. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed.

					Geographic Distribution: Not discussed. **Phenology:** Not discussed. **Climate Extremes:** Warming strengthens Allee effects, increasing the risk of population collapse. **Other Effects:** The presence of an Allee effect requires lower fishing pressure and faster management responses to avoid collapse and enable recovery.
Atlantic Cod (*Gadus morhua*)	Anna-Marie Marie Winter et al., *Spawner weight and ocean temperature drive Allee effect dynamics in Atlantic cod, Gadus morhua : inherent and emergent density regulation*, 20 BIOGEOSCIENCES 3683–3716 (2023), https://bg.copernicus.org/articles/20/3683/2023/	Time series analysis of 17 Atlantic cod stocks, using spawner abundance, body weight, and sea water temperature to model recruitment dynamics. The model considered the effects of spawner abundance, spawner weight, and temperature on recruitment.	North Atlantic	Historical data	**Temperature:** Temperature fluctuations showed an increased impact on the Allee effect, affecting recruitment dynamics negatively when unfavorable. Changes in water temperature also impacted recruitment by altering body growth and spawner weight. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed, but implied through the impact of temperature changes. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly discussed, but implied effects on recruitment dynamics through changes in spawner conditions. **Predation:** Not discussed. **Geographic Distribution:** Not specifically mentioned, but the study suggests variable impacts across different cod stocks in the North Atlantic. **Phenology:** Not discussed. **Climate Extremes:** Temperature extremes implied to affect recruitment dynamics through changes in spawner weight and conditions.

					Other Effects: The study underscores the complexity of the Allee effect in cod stocks, highlighting the role of environmental factors in exacerbating or mitigating these dynamics.
Atlantic cod (*Gadus morhua*)	Martina H. Stiasny et al., *Ocean acidification effects on Atlantic cod larval survival and recruitment to the fished population*, 11 PLOS ONE 1–12 (2016)	Experiments to measure Atlantic cod larval survival at increased pCO2 levels predicted for the end of the century, using cod larvae from Western Baltic and Arcto-Norwegian Barents Sea cod stocks.	Western Baltic Sea, Barents Sea	Short-term (25 days for Baltic and 22 days for Barents larvae)	**Temperature:** Not directly assessed in terms of impact, but the study controlled for temperature in experimental setups. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Significant impacts from reduced pH on larval survival noted, with experimental conditions reflecting end-of-century projections leading to higher mortality. **Ocean Circulation:** Not assessed. **Food Availability:** High CO2 concentrations did not change the impact on larval mortality despite adequate food supply, indicating that food availability did not mitigate the negative effects of acidification. **Predation:** Not discussed. **Geographic Distribution:** Not directly assessed, but implications exist for changes in distribution due to survival rates affecting population dynamics. **Phenology:** The study focused on very early life stages, critical for future recruitment and population sustainability. **Climate Extremes:** Not directly assessed but implied through the simulation of future CO2 scenarios. **Other Effects:** The study highlighted that early life stages are particularly vulnerable to CO2 induced changes, potentially leading to significant reductions in population recruitment and resilience.
Atlantic cod (*Gadus morhua*)	Martin Butzin & Hans Otto Pörtner, *Thermal growth potential of Atlantic cod by the end of the 21st century*, 22	Analyzed growth potential using laboratory data on growth rates combined with climate model projections. Employed a	Atlantic cod habitats across the North Atlantic, with focus on changes	Historical data paired with future projections	**Temperature:** Projected increases in sea water temperatures are expected to decrease body sizes at southern ranges and increase sizes at northern ranges, reflecting shifts in habitat suitability. **Dissolved Oxygen:** Not directly addressed.

	GLOBAL CHANGE BIOLOGY 4162–4168 (2016)	transfer function model to link observed growth data with projected ocean temperatures.	between historical period (1985–2004) and future projections (2081–2100).		**Ocean pH:** Not assessed in this study. **Ocean Circulation:** Not discussed. **Food Availability:** Impacts inferred through changes in growth potential but not directly measured. **Predation:** Not assessed. **Geographic Distribution:** Anticipated shifts northward due to increasing temperatures, reducing suitable habitat in southern regions. **Phenology:** Not specifically discussed, but changes implied through shifts in temperature profiles. **Climate Extremes:** Focus on long-term temperature changes, not specific extremes. **Other Effects:** Overall, the study predicts a future where growth potentials and population dynamics of Atlantic cod will be significantly altered by warming oceans, potentially leading to a northward shift in population distributions.
Atlantic cod (*Gadus morhua*) larvae	Martina H. Stiasny et al., *Divergent responses of Atlantic cod to ocean acidification and food limitation*, 25 GLOBAL CHANGE BIOLOGY 839–849 (2019)	The study combined CO2 treatments (ambient: 503 µatm, elevated: 1,179 µatm) with variable food availability to assess impacts on growth, organ development, and ossification in Atlantic cod larvae. Analyses included larval size measurements and detailed organ and skeletal assessments.	Laboratory setting with conditions meant to simulate future ocean scenarios.	35–36 days post-hatching (larval stage).	**Temperature:** Not directly assessed. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Elevated CO2 levels (acidification) showed complex interactions with food availability affecting larval growth and development. **Ocean Circulation:** Not assessed. **Food Availability:** High food availability mitigated some negative effects of elevated CO2 on larval growth and development. **Predation:** Not assessed. **Geographic Distribution:** Not discussed. **Phenology:** Implications on developmental timelines due to

					altered growth under varying CO2 and food availability conditions. **Climate Extremes:** Not specifically discussed. **Other Effects:** Noted physiological trade-offs in larvae, including compromised organ development under high CO2 conditions, even with sufficient food.
Atlantic cod (*Gadus morhua*)	Tirsgaard et al.	Used intermittent flow respirometry to measure the oxygen consumption rates of juvenile Atlantic cod at varying temperatures (2, 5, 10, 15, 20°C) to study specific dynamic action (SDA) during digestion of a meal corresponding to 5% of body mass.	Øresund, Denmark	Short-term experimental	**Temperature:** Found that SDA response varies complexly with temperature. SDA duration and coefficients are optimal at 10°C, indicating this temperature facilitates more efficient digestion compared to higher or lower temperatures. **Dissolved Oxygen:** Not specifically mentioned, but the experiment maintained normoxic conditions. **Ocean pH:** Not assessed. **Ocean Circulation:** Not discussed. **Food Availability:** Constant in experimental setup. **Predation:** Not relevant to the controlled laboratory conditions. **Geographic Distribution:** Not a focus of this study. **Phenology:** The study does not address lifecycle events beyond the immediate post-feeding period. **Climate Extremes:** Not discussed. **Other Effects:** Highlights the importance of temperature on metabolic processes related to digestion, with potential implications for energy budgeting and growth under climate change scenarios.
Atlantic cod (*Gadus morhua*)	Fredrik Jutfelt & Maria Hedgärde, *Juvenile Atlantic cod behavior appears robust to near-future CO2 levels*, 12 FRONTIERS IN ZOOLOGY 1–7 (2015), ???	Exposed 52 juvenile Atlantic cod to control conditions (500 µatm CO2) or elevated CO2 levels (1000 µatm) for one month in laboratory tanks. Behaviors tested included	Laboratory setting	1 month	**Temperature:** Not directly assessed in terms of impact, but experiments controlled for ambient temperature. **Dissolved Oxygen:** Maintained at sufficient levels, not directly assessed as a variable. **Ocean pH:** Elevated CO2 levels used to simulate near-future

		swimming activity, emergence from shelter, relative lateralization, and absolute lateralization using standardized experimental protocols.			ocean acidification scenarios. **Ocean Circulation:** Not assessed. **Food Availability:** Controlled and constant for experimental conditions. **Predation:** Not a factor in controlled lab conditions. **Geographic Distribution:** Not assessed. **Phenology:** Not discussed. **Climate Extremes:** Not discussed. **Other Effects:** Found no significant effects of elevated CO2 on the tested behaviors, suggesting resilience of juvenile Atlantic cod behavior to near-future CO2 levels.
Atlantic cod (*Gadus morhua*) embryos	Flemming T. Dahlke et al., *Effects of ocean acidification increase embryonic sensitivity to thermal extremes in Atlantic cod, Gadus morhua*, 23 GLOBAL CHANGE BIOLOGY 1499–1510 (2017)	Fertilized Atlantic cod eggs were exposed to factorial combinations of two pCO2 conditions (400 µatm and 1100 µatm) and five temperature treatments (0, 3, 6, 9, and 12 °C). Assessments included hatching success, oxygen consumption, mitochondrial functioning, and larval morphometrics at hatch.	Kattegat, Sweden	Not specified	**Temperature:** Optimal hatching success observed at 3–6 °C, with sharp declines in colder (0 °C) and warmer temperatures (12 °C). Elevated temperatures limited oxygen consumption rates (MO2) and mitochondrial capacities. **Dissolved Oxygen:** Not directly assessed. **Ocean pH:** Elevated pCO2 reduced hatching success, particularly at extreme temperatures. Did not affect mitochondrial functioning directly. **Ocean Circulation:** Not assessed. **Food Availability:** Not directly assessed. **Predation:** Not applicable to embryonic stage. **Geographic Distribution:** Not directly assessed but suggests potential narrowing of suitable spawning habitat due to climatic changes. **Phenology:** Elevated pCO2 and temperature extremes accelerated development rates and influenced timing of hatching.

					Climate Extremes: Elevated pCO2 and temperature extremes interacted to exacerbate reductions in hatching success. **Other Effects:** Exposure to elevated pCO2 necessitated reallocation of resources at the expense of embryonic growth, evidenced by reduced larval size at hatch. Ionocyte abundance in larvae, related to acid-base regulation, was not significantly affected by pCO2 but decreased with temperature.
Atlantic cod (*Gadus morhua*)	Stefan Koenigstein et al., *Forecasting future recruitment success for Atlantic cod in the warming and acidifying Barents Sea*, 24 GLOBAL CHANGE BIOLOGY 526–535 (2018)	Developed the SCREI model integrating experimental results on temperature and CO2 effects on Atlantic cod egg and larval survival, calibrated using historical data on egg production, predator and food abundance. This model predicts recruitment success under various climate change scenarios, accounting for temperature, CO2, food availability, and predator abundance.	Barents Sea	Not specified	**Temperature:** Found that optimal recruitment temperatures range from 4°C to 7°C, beyond which survival rates decline. Warmer temperatures could shorten vulnerable early life stages, theoretically enhancing survival, but long-term effects include potential habitat loss due to exceeding thermal tolerances. **Dissolved Oxygen:** Not directly discussed. **Ocean pH:** Increased pCO2 levels significantly reduce recruitment success by directly affecting larval and egg survival rates. **Ocean Circulation:** Not assessed in detail but included in the model through calibration with empirical data on food availability. **Food Availability:** Higher food availability could potentially mitigate some negative impacts of warming and acidification. **Predation:** Increased predation risk at suboptimal temperatures; model integrates predation dynamics based on empirical data. **Geographic Distribution:** Indicates potential northward shifts in distribution as a response to temperature changes. **Phenology:** Shifts in developmental timing could occur due to changes in temperature and food dynamics. **Climate Extremes:** Not specifically discussed but implied through scenario modeling. **Other Effects:** Model suggests that even with adaptation, significant impacts on recruitment are likely, emphasizing the need for robust management strategies to maintain stock sustainability under changing environmental conditions.

Atlantic cod (*Gadus morhua*)	Flemming T. Dahlke et al., *Northern cod species face spawning habitat losses if global warming exceeds 1.5°C*, 4 SCIENCE ADVANCES 1–10 (2018)	Analysis using projections of future habitat suitability under different Representative Concentration Pathways (RCPs), integrating experimental results on embryonic tolerance to temperature and CO2. Data sources include empirical measurements of oxygen consumption and larval morphometrics linked to climate simulations from CMIP5.	Subarctic and Arctic seas around Northern Europe	Not specified	**Temperature:** Embryonic development and survival rates are compromised at temperatures exceeding 9°C for Atlantic cod and 3°C for Polar cod, suggesting narrower thermal tolerance ranges due to climate change. **Dissolved Oxygen:** Not specifically discussed. **Ocean pH:** Elevated CO2 levels exacerbate the narrowing of thermal tolerance, influencing embryonic survival. **Ocean Circulation:** Not directly assessed. **Food Availability:** Not assessed. **Predation:** Not discussed. **Geographic Distribution:** Predicts a northward shift in spawning habitat for Atlantic cod, with suitable areas becoming restricted under higher CO2 scenarios. **Phenology:** Changes in the timing of spawning and embryonic development are likely as water temperatures rise. **Climate Extremes:** Extreme temperature and CO2 levels significantly reduce embryonic survival, potentially constraining the species' future distribution. **Other Effects:** Shows a potential decrease in larval body size at hatching due to stress from higher CO2 and temperature, which may affect future recruitment and population stability.
Atlantic cod (*Gadus morhua*)	M. H. Stiasny et al., *Effects of parental acclimation and energy limitation in response to high CO2 exposure in Atlantic cod*, 8 SCIENTIFIC REPORTS 1–8 (2018)	The study involved parental acclimation of adult Atlantic cod to either ambient or elevated CO2 levels (~1100 µatm) for six weeks prior to spawning. Larval survival was assessed under reciprocal exposure to ambient and elevated CO2, combined with two feeding regimes.	Laboratory setting	Six weeks	**Temperature:** Not directly discussed in the context of temperature changes, focusing instead on CO2 levels. **Dissolved Oxygen:** Not mentioned in the study. **Ocean pH:** Elevated CO2 levels significantly impacted larval survival, with effects mitigated by parental acclimation to high CO2 when high food availability was provided. **Ocean Circulation:** Not assessed. **Food Availability:** High food availability partially mitigated the negative impacts of high CO2 on larval survival.

					Predation: Not discussed. **Geographic Distribution:** Not addressed. **Phenology:** Impacts on larval survival suggest potential shifts in population dynamics and recruitment due to CO2 levels. **Climate Extremes:** High CO2 conditions studied as a proxy for future ocean acidification scenarios. **Other Effects:** Parental acclimation to high CO2 showed some capacity to buffer offspring against adverse effects, but this was dependent on adequate food availability.
Atlantic cod (*Gadus morhua*)	Fábio S. Zanuzzo et al., *The acute and incremental thermal tolerance of Atlantic cod (Gadus morhua) families under normoxia and mild hypoxia*, 233 COMPARATIVE BIOCHEMISTRY AND PHYSIOLOGY -PART A : MOLECULAR AND INTEGRATIVE PHYSIOLOGY 30–38 (2019), https://doi.org/10.1016/j.cbpa.2019.03.020	The study assessed acute (CTmax) and incremental (ITmax) upper thermal tolerance of 15 Atlantic cod families under conditions of normoxia (~100% air saturation) and mild hypoxia (~75% air saturation) through experimental increases in temperature.	Laboratory setting, Newfoundland, Canada	Not specified	**Temperature:** CTmax was observed at 22.5 °C under normoxia and reduced to 21.8 °C under mild hypoxia, suggesting a decreased thermal tolerance when oxygen levels were lower. Incremental temperature maximum (ITmax) did not vary significantly under hypoxia, remaining around 21.7 °C. **Dissolved Oxygen:** Hypoxic conditions reduced the critical thermal maximum (CTmax) by about 0.7 °C, indicating that lower oxygen levels diminish the fish's thermal tolerance. **Ocean pH:** Not assessed. **Ocean Circulation:** Not discussed. **Food Availability:** Feed intake decreased significantly as temperatures approached 21 °C during ITmax testing. **Predation:** Not relevant to experimental conditions. **Geographic Distribution:** Not assessed in the experimental study. **Phenology:** Not discussed. **Climate Extremes:** The study focused on responses to acute and incremental thermal stress under varying oxygen conditions. **Other Effects:** No significant differences were found in ITmax across different families under varying oxygen conditions,

					indicating some level of consistency or lack of genetic variability in thermal tolerance within the population studied.
Atlantic cod (*Gadus morhua*) larvae	F. H. Mittermayer et al., *Transcriptome profiling reveals exposure to predicted end-of-century ocean acidification as a stealth stressor for Atlantic cod larvae*, 9 SCIENTIFIC REPORTS 1–11 (2019), http://dx.doi.org/10.1038/s41598-019-52628-1	The study used RNA sequencing to analyze gene expression in Atlantic cod larvae exposed to ambient (503 µatm) and elevated (1179 µatm) CO2 levels simulating end-of-century ocean acidification scenarios. Samples were taken at 6, 13, and 36 days post-hatching.	Laboratory setting	Short-term, specific days post-hatching were studied.	**Temperature:** Not directly assessed. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Exposure to elevated CO2 levels significantly altered gene expression, indicating stress at the molecular level. **Ocean Circulation:** Not assessed. **Food Availability:** Not discussed. **Predation:** Not relevant in laboratory conditions. **Geographic Distribution:** Not assessed. **Phenology:** Significant changes in gene expression at different developmental stages suggest shifts in developmental timing and responses to environmental stress. **Climate Extremes:** The study simulates future ocean acidification conditions, implying that these conditions could act as a stressor. **Other Effects:** Increased larval mortality and changes in gene expression related to developmental processes were observed, suggesting sensitivity to CO2 levels.
Arctic cod	Martin C. Hänsel et al., *Ocean warming and acidification may drag down the commercial Arctic cod fishery by 2100*, 15 PLOS ONE e0231589 (2020), https://dx.plos.org/10.1371/journal.pone.0231589	Utilized a combination of experimental and time-series data to model effects of ocean warming and acidification on Northeast Arctic cod recruitment within a bio-economic fishery model.	Arctic Ocean	Not specified	**Temperature:** Found a non-linear relationship with recruitment, showing initial benefits from warming but decreases in recruitment with temperatures above optimal levels. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Highlighted significant negative impacts from acidification, exacerbating recruitment declines. **Ocean Circulation:** Not specifically assessed. **Food Availability:** Not assessed directly.

					Predation: Not discussed. **Geographic Distribution:** Not addressed. **Phenology:** Not discussed. **Climate Extremes:** Addressed by modeling extreme scenarios of warming and acidification. **Other Effects:** Suggested a potential collapse of the fishery by 2100 under business-as-usual scenarios of warming and acidification, despite adaptation efforts in fishing pressure.
Atlantic cod (*Gadus morhua*) larvae	Rebekah A. Oomen et al., *Warming Accelerates the Onset of the Molecular Stress Response and Increases Mortality of Larval Atlantic Cod*, 62 INTEGRATIVE AND COMPARATIVE BIOLOGY 1784–1801 (2022)	RNA sequencing of Atlantic cod larvae reared in the laboratory at ambient and elevated temperatures (+2°C and +4°C) to assess changes in gene expression, growth, and survival over time.	Laboratory setting	Not specified	**Temperature:** Exposure to increased temperatures (+2°C and +4°C) triggered an earlier onset of the stress response in larval Atlantic cod, suggesting that warmer conditions may accelerate development and increase mortality. **Dissolved Oxygen:** Not directly discussed. **Ocean pH:** Not assessed. **Ocean Circulation:** Not assessed. **Food Availability:** Not directly discussed. **Predation:** Not relevant in laboratory conditions. **Geographic Distribution:** Not assessed. **Phenology:** The study indicated that warmer temperatures could alter the timing of developmental processes in larval stages. **Climate Extremes:** The study simulated moderate warming scenarios (+2°C and +4°C) to predict potential future impacts on larval development and survival. **Other Effects:** Highlighted the energy cost of gene expression under stress, which might reduce the energy available for growth and survival, thereby potentially decreasing fitness and population viability in the future.

Atlantic cod (*Gadus morhua*)	M. Lindmark et al., *Evaluating drivers of spatiotemporal variability in individual condition of a bottom-associated marine fish, Atlantic cod (Gadus morhua)*, 80 ICES JOURNAL OF MARINE SCIENCE 1539–1550 (2023)	The study utilized a condition model that included ICES rectangle median temperature and oxygen levels, with data collected over multiple years to assess the spatiotemporal variability in the condition of Atlantic cod. The research integrated empirical measurements from various locations and times, applying advanced statistical techniques to evaluate how environmental variables impact cod condition.	ICES subdivisions	Multiple years	**Temperature:** The study found a positive correlation between water temperature and cod condition up to a threshold, beyond which the condition declines, indicating that Atlantic cod may face physiological stress under elevated temperatures. **Dissolved Oxygen:** A critical factor; lower oxygen levels were associated with worse health conditions in cod, emphasizing the importance of oxygen availability in their habitat. **Ocean pH:** Not assessed. **Ocean Circulation:** Not specifically evaluated. **Food Availability:** Not directly measured, but inferred impacts based on the model's spatial and temporal data coverage. **Predation:** Not discussed. **Geographic Distribution:** Showed variations in cod condition across different ICES subdivisions, suggesting that local environmental conditions significantly influence cod health. **Phenology:** Not specifically discussed. **Climate Extremes:** While not directly evaluated, the study implies that extremes in temperature and oxygen levels could have significant effects on cod condition. **Other Effects:** The study highlights the complex interactions between environmental factors and cod condition, suggesting that multiple stressors could lead to compounded effects on the population.
Deep-sea demersal species including Atlantic cod (*Gadus morhua*) among others.	William W.L. Cheung et al., *Vulnerability of exploited deep-sea demersal species to ocean warming, deoxygenation, and acidification*, 105 ENVIRONMENTAL BIOLOGY OF FISHES 1301–1315 (2022),	This study combined global biogeographical and fisheries datasets with Earth system model projections to determine the exposure of deep-sea fishes and invertebrates to climate hazards such as ocean warming, deoxygenation, acidification, and decrease	Deep-sea regions across the global ocean, with specific emphasis on areas beyond national jurisdiction that are heavily exploited for fisheries.	Historical and projected data up to 2100, with scenarios including RCP2.6 and RCP8.5.	**Temperature:** Predicts significant ocean warming impacts, especially under the RCP8.5 scenario, leading to shifts in suitable habitat ranges and potential stress on thermal tolerance limits for deep-sea species. **Dissolved Oxygen:** Projected widespread deoxygenation, particularly under the RCP8.5 scenario, poses a serious risk to aerobic life processes in deep-sea species. **Ocean pH:** Anticipates acidification to worsen, affecting calcifying organisms and possibly altering neurophysiological

	https://doi.org/10.1007/s10641-022-01321-w	in export production. A fuzzy logic expert system was used to assess the vulnerability of these species to climatic hazards and fishing.			functions. **Ocean Circulation:** Changes in ocean stratification and circulation could affect nutrient distribution and food availability. **Food Availability:** Decrease in export production could reduce food supply, directly impacting species dependent on deep-sea benthic food webs. **Predation:** Not specifically discussed but changes in the distribution and abundance of species could alter predation pressures. **Geographic Distribution:** Likely shifts in species distributions as they adapt to changing temperature and oxygen levels. **Phenology:** Changes in the timing of biological events could occur as species respond to new environmental conditions. **Climate Extremes:** Species are likely to face increasing frequency and intensity of climate extremes, challenging their survival. **Other Effects:** Multi-stressor impacts complicate the survival prospects of deep-sea species, necessitating integrated management strategies that consider both climate change and direct human impacts such as fishing.
Atlantic Canadian capelin (Mallotus villosus)	Samantha Andrews et al., *Modelling the spatial-temporal distributions and associated determining factors of a keystone pelagic fish*, 77 ICES JOURNAL OF MARINE SCIENCE 2776–2789 (2020)	Maxent species distribution model assessing the influence of oceanographic and climatic variables.	Atlantic Canada	1998-2015	**Temperature:** Important for predicting distribution, particularly in warmer months. Variable importance differed across months. **Dissolved Oxygen:** Key predictor in certain models, indicating a significant impact on distribution. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not directly mentioned, but included as part of broader oceanographic conditions. **Mixing:** Not mentioned. **Nutrient Supply:** Chlorophyll concentration used as a proxy; important in some months.

					Food Availability: Inferred through chlorophyll concentration as a proxy for zooplankton. **Predation:** Not mentioned. **Geographic Distribution:** Demonstrated significant monthly and depth-related variability. **Phenology:** Not specifically mentioned, but temporal modeling suggests response to environmental changes. **Climate Extremes:** Not specifically mentioned, but variable importance suggests sensitivity to changing conditions. **Other Effects:** Climate indices like NAO and AMO included but showed little impact in models.
Capelin (Mallotus villosus)	Alejandro D. Buren et al., *Bottom-Up Regulation of Capelin, a Keystone Forage Species*, 9 PLOS ONE 1–12 (2014)	Analysis of capelin biomass, spawning, and prey (copepods) dynamics; consideration of sea ice dynamics.	Newfoundland and Labrador Shelf, Northwest Atlantic	1991–2010	**Temperature:** Temperature changes correlated with shifts in sea ice, impacting capelin indirectly through effects on primary production and prey availability. **Dissolved Oxygen:** Not specifically mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned directly, but implied through discussion of sea ice dynamics and seasonal effects. **Mixing:** Implied influence through sea ice melt patterns affecting water column stratification and phytoplankton blooms. **Nutrient Supply:** Related to mixing and sea ice patterns affecting primary productivity. **Food Availability:** Dependent on primary productivity influenced by sea ice dynamics, affecting copepod populations, the primary food for capelin. **Predation:** Not directly addressed. **Geographic Distribution:** Suggested shifts in distribution related to changing sea ice patterns and resulting environmental conditions.

					Phenology: Shifts in spawning times related to changing sea ice dynamics. **Climate Extremes:** Implications of extreme changes in sea ice and temperature, though not explicitly detailed. **Other Effects:** The regime shifts in the early 1990s had profound impacts, indicating complex interplays between climate factors and ecosystem dynamics.
Capelin (Mallotus villosus)	James E Carscadden et al., *A comparison of recent changes in distribution of capelin (Mallotus villosus) in the Barents Sea, around Iceland and in the Northwest Atlantic*, 114 PROGRESS IN OCEANOGRAPHY 64–83 (2013)	Analysis of historical distribution patterns, abundance data, and environmental factors including temperature.	Barents Sea, Iceland, Newfoundland and Labrador	Not specified	**Temperature:** Temperature has been a significant factor in determining distribution patterns and seasonal migration. Warmer years see capelin distribution extending further north and eastward. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Changes in ocean currents affect larval drift and juvenile distributions, influencing migration at older ages. **Mixing:** Not specifically discussed, but changes in sea ice dynamics suggest impacts on water column stratification. **Nutrient Supply:** Not directly mentioned, but inferred through changes in primary productivity linked to sea ice and temperature variations. **Food Availability:** Influenced by primary productivity, which is impacted by sea ice dynamics and temperature. **Predation:** Not directly addressed but changes in distribution affect predator-prey dynamics. **Geographic Distribution:** Notable shifts in response to temperature and ice conditions. **Phenology:** Changes in spawning times linked to environmental conditions. **Climate Extremes:** Not specifically mentioned but implied

					through broader discussion of environmental impacts. **Other Effects:** Changes in sea ice patterns and temperature are hypothesized to affect capelin distribution and migration significantly.
Capelin (Mallotus villosus)	G. K. Davoren et al., *An ecosystem-based research program for Capelin (Mallotus villosus) in the northwest Atlantic: Overview and results*, 39 JOURNAL OF NORTHWEST ATLANTIC FISHERY SCIENCE 35–48 (2007)	Ecosystem-based research integrating multiple disciplines and methodologies, including acoustic surveys and biological sampling.	Newfoundland and Labrador, Canada	2004-2006	**Temperature:** Temperature influences the vertical distribution of capelin, with warmer surface waters attracting capelin during peak feeding times. **Dissolved Oxygen:** Not specifically mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not directly studied but implied through the discussion on migration patterns. **Mixing:** Thermal stratification and its breakdown play a role in larval emergence from sediments. **Nutrient Supply:** Not directly mentioned, but primary production influenced by environmental factors is crucial for capelin food sources. **Food Availability:** Zooplankton availability affects capelin distribution and abundance. **Predation:** Increased capelin availability enhances predator (e.g., seabirds) foraging success. **Geographic Distribution:** Capelin exhibit shifts in distribution based on environmental conditions. **Phenology:** Changes in spawning times and locations in response to environmental factors. **Climate Extremes:** Not mentioned. **Other Effects:** Changes in capelin behavior and biology due to environmental shifts could have cascading effects on the marine ecosystem.

Capelin (Mallotus villosus)	KT Frank et al., *Anomalous ecosystem dynamics following the apparent collapse of a keystone forage species*, 553 Marine Ecology Progress Series 185–202 (2016), http://www.int-res.com/abstracts/meps/v553/p185-202/	Longitudinal study analyzing multiple factors including the trophic effects after the groundfish collapse.	Newfoundland and Labrador, North Atlantic	1985-2016	**Temperature:** Suggests behavioral changes in capelin, possibly linked to temperature fluctuations. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not explicitly studied, but indirect effects considered via changes in sea ice and temperature. **Mixing:** Not directly mentioned, but related to sea ice dynamics affecting capelin. **Nutrient Supply:** Not mentioned. **Food Availability:** Increase in predators like cod due to increased capelin availability post groundfish collapse. **Predation:** Increase in capelin predation could have implications on population dynamics. **Geographic Distribution:** Changes in capelin distribution, potentially driven by environmental changes. **Phenology:** Adjustments in spawning and migration patterns potentially linked to climate changes. **Climate Extremes:** Not specifically mentioned. **Other Effects:** Integrated analysis suggests complex interactions between climate change and capelin dynamics, highlighting changes in the ecosystem structure post groundfish collapse.
Capelin (Mallotus villosus)	Hannah M. Murphy et al., *Identifying possible drivers of the abrupt and persistent delay in capelin spawning timing following the 1991 stock collapse in Newfoundland, Canada*, 78 ICES Journal of Marine Science 2709–	Analysis of historical data, citizen science observations, and environmental factors in a regression model.	Newfoundland and Labrador, Canada	1919–2019	**Temperature:** Linked to changes in spawning timing, with warmer periods affecting capelin migration and spawning schedules. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not directly mentioned, but environmental conditions such as onshore wind events affecting larval survival

	2723 (2021), https://academic.oup.com/icesjms/article/78/8/2709/6356489				are noted. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned directly, but related to food availability for larvae. **Food Availability:** Zooplankton availability critical for larval survival, affected by timing of spawning. **Predation:** Not specifically mentioned. **Geographic Distribution:** Extended spawning delays and potential shifts in spawning locations. **Phenology:** Significant delays in spawning times since 1991, related to environmental shifts. **Climate Extremes:** General warming trends mentioned as influencing spawning times. **Other Effects:** Changes in spawning behavior could impact larval survival rates and overall recruitment success.
Capelin (Mallotus villosus)	A.H. Olafsdottir & G.A. Rose, *Influences of temperature, bathymetry and fronts on spawning migration routes of Icelandic capelin (Mallotus villosus)*, 21 FISHERIES OCEANOGRAPHY 182–198 (2012), https://onlinelibrary.wiley.com/doi/10.1111/j.1365-2419.2012.00618.x	Acoustic surveys assessing spawning migration routes of Icelandic capelin.	Icelandic waters	1992-2007	**Temperature:** Capelin migrations are influenced by temperature gradients, with migration routes and spawning behaviors adapting to thermal conditions. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Influences capelin migration through currents along which capelin travel. **Mixing:** Not mentioned. **Nutrient Supply:** Not directly mentioned. **Food Availability:** Not mentioned. **Predation:** Mentioned in the context of avoiding predation during migration.

					Geographic Distribution: Migration routes are influenced by temperature and possibly predation pressure. **Phenology:** Capelin adjust their migration and spawning times based on temperature. **Climate Extremes:** Not specifically mentioned. **Other Effects:** Potential shifts in migration and spawning locations due to climate change, especially warming.
Capelin (Mallotus villosus)	Rose	Analysis of historical data, climate change impact assessments, and distribution modeling.	North Atlantic	Not specified	**Temperature:** Core factor in capelin distribution; rising temperatures strongly linked to changes in migration and spawning behavior. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Influences larval dispersal and adult migration. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Impacts distribution through availability of zooplankton. **Predation:** Not specifically mentioned. **Geographic Distribution:** Noted significant shifts potentially linked to temperature changes. **Phenology:** Changes in spawning times correlated with temperature. **Climate Extremes:** Not mentioned. **Other Effects:** Suggested as an indicator species for marine ecosystem responses to climate variability and change.

Greenland Halibut (*Reinhardtius hippoglossoides*)	A. L. Ferchaud et al., *A cold-water fish striving in a warming ocean: Insights from whole-genome sequencing of the Greenland halibut in the Northwest Atlantic*, 9 FRONTIERS IN MARINE SCIENCE 1–18 (2022)	Whole-genome sequencing of 1,297 Greenland Halibut, environmental association analyses, coalescent simulations for migration.	Northwest Atlantic from Arctic Canadian and Greenlandic coasts to the Gulf of St Lawrence	Not specified	**Temperature:** Identified as a key factor affecting genomic variation; temperature-related changes impact growth and migration patterns. **Dissolved Oxygen:** Bottom dissolved oxygen levels are crucial, with lower levels potentially influencing adaptive divergence especially in deeper waters. **Ocean pH:** Not discussed. **Ocean Circulation:** Implied impact through temperature and dissolved oxygen levels affecting distribution and migration. **Mixing:** Not discussed. **Nutrient Supply:** Changes in nutrient levels like nitrate detected, which could influence ecological dynamics. **Food Availability:** Related to nutrient supply, where changes can affect food sources for Greenland Halibut. **Predation:** Not specifically addressed, but changes in distribution and size could affect predation patterns. **Geographic Distribution:** Significant changes detected, with potential shifts in distribution due to environmental variables. **Phenology:** Not discussed. **Climate Extremes:** Not directly discussed, but implied through the study of environmental variables affecting the species. **Other Effects:** Genetic differentiation observed, suggesting that environmental pressures (like temperature and dissolved oxygen) may drive adaptive divergence.
Greenland Halibut (*Reinhardtius hippoglossoides*)	Leopold Ghinter et al., *Juvenile Greenland halibut (Reinhardtius hippoglossoides) growth in the context of rising temperature in the Estuary and Gulf of St. Lawrence*, 233	Experimental study with juvenile Greenland halibut reared at controlled temperatures of 4.0, 5.5, and 7.5 °C to assess the impact of rising temperatures on growth and mortality.	Estuary and Gulf of St. Lawrence, Canada	One year	**Temperature:** Optimal growth temperature exceeded at 7.5 °C, leading to decreased survival and growth rates. Juveniles showed better growth at lower temperatures (4.0 and 5.5 °C). **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed.

	FISHERIES RESEARCH 1–10 (2021)				**Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Increased food intake at 5.5 °C, but this did not result in higher growth rates, indicating possible inefficiencies in food utilization at higher temperatures. **Predation:** Not discussed. **Geographic Distribution:** Temperature increases are causing shifts in geographic distribution, potentially affecting population structure. **Phenology:** Not discussed. **Climate Extremes:** Elevated temperatures leading to higher mortality rates, especially at 7.5 °C. **Other Effects:** The study suggests potential sensitivity of females to higher temperatures, with a higher mortality rate compared to males.
Greenland Halibut (*Reinhardtius hippoglossoides*)	Boje et al.	Use of electronic data storage tags on adult Greenland halibut to record depth, temperature, and time; analysis of seasonal migration, vertical activity, and temperature experience.	West Greenland waters	2001–2003	**Temperature:** Fish experienced temperatures from 0 to 4°C, with most experiencing temperatures of 2 to 3°C. Fish in Disko Bay experienced a broader range of temperatures compared to those in the ice fjord. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly discussed, but migration and residence patterns are likely influenced by ocean currents and water column structure. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly discussed; however, the behavior observed may be linked to searching for food in both

					pelagic and bottom environments. **Predation:** Not discussed. **Geographic Distribution:** Documented seasonal migrations from shallower waters of Disko Bay to deeper waters of the Ilulissat Icefjord. **Phenology:** Seasonal migration patterns observed, with movements into deeper waters during colder months. **Climate Extremes:** Not discussed. **Other Effects:** Use of halibut as a live tool to document deep-water temperatures and depths; important for understanding environmental changes under climate shift.
Greenland Halibut (*Reinhardtius hippoglossoides*)	Aitor Lekanda et al., *The effects of bottom temperature and fishing on the structure and composition of an exploited demersal fish assemblage in West Greenland*, 78 ICES JOURNAL OF MARINE SCIENCE 2895–2906 (2021)	Statistical analysis of bottom temperature, fisheries metrics, ecological indicators; data from fisheries-independent surveys from 1997 to 2019.	West Greenland	1997–2019	**Temperature:** Increase in bottom temperatures favored Greenland halibut, influencing biomass in shallower zones but causing decreases in biodiversity. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Ocean currents like the West Greenland Current impact the distribution of temperature, affecting halibut habitat. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not specifically discussed, but higher temperatures may influence prey distribution. **Predation:** Not specifically discussed, but trophic dynamics imply possible changes. **Geographic Distribution:** Halibut showing shifts, moving shallower as temperatures rise. **Phenology:** Not discussed.

					Climate Extremes: Temperature fluctuations and extreme shifts in bottom temperature. **Other Effects:** Structural changes in the fish community due to temperature changes and fishing pressure.
Greenland Halibut (*Reinhardtius hippoglossoides*)	M. J. Morgan et al., *Changes in distribution of Greenland halibut in a varying environment*, 70 ICES JOURNAL OF MARINE SCIENCE 352–361 (2013), https://academic.oup.com/icesjms/article/70/2/352/795871	Statistical analysis of survey data from 1978 to 2009, assessing temperature and depth changes in relation to fish distribution and biological characteristics.	Northwest Atlantic, including Flemish Cap and Newfoundland Shelf	1978–2009 (31 years)	**Temperature:** Noted significant decreases in temperature up to the mid-1990s followed by a warming trend. Fish occupied deeper, warmer waters as temperatures dropped, and did not return to their previous shallower distribution even as temperatures warmed. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Implied impact through changes in water column temperature profiles. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly discussed, but changes in depth and temperature likely influenced prey distribution and availability. **Predation:** Not discussed. **Geographic Distribution:** Documented shifts to deeper waters in response to colder temperatures, with a tendency to occupy warmer waters not seen previously. **Phenology:** Not discussed, but changes in temperature could influence life cycle events. **Climate Extremes:** Managed to occupy different temperature ranges as environmental conditions fluctuated, indicating an adaptive response to climate variability. **Other Effects:** The study emphasizes the complexity of predicting impacts due to mixed responses to environmental changes, where deeper waters offered a refuge from cold temperatures but altered the ecological dynamics of the species.

Greenland Halibut (*Reinhardtius hippoglossoides*)	Ruth et al.	Conventional respirometry methods, Arrhenius breakpoint analysis, in situ tagging data to assess aerobic scope (AS)	West Greenland	Not specified	**Temperature:** Optimal temperature for maximum aerobic scope (Topt,AS) was 2.44°C. The species shows a narrow thermal envelope (−1.89°C to 8.07°C), indicating vulnerability to warming. **Dissolved Oxygen:** Increases in temperature affect oxygen consumption rates, impacting aerobic performance at higher temperatures. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed. **Geographic Distribution:** In situ temperatures match closely with Topt,AS, suggesting limited thermal habitat. **Phenology:** Not discussed. **Climate Extremes:** Narrow thermal tolerance implies susceptibility to extreme warming. **Other Effects:** The study highlights the economic implications for fisheries due to potential distribution shifts and reductions in stock due to warming.
Juvenile Greenland Halibut (*Reinhardtius hippoglossoides*)	Kaj Sünksen et al., *Temperature effects on growth of juvenile Greenland halibut (Reinhardtius hippoglossoides Walbaum) in West Greenland waters*, 64 JOURNAL OF SEA RESEARCH 125–132 (2010),	Depth-stratified random trawl surveys, analysis of temperature effects on juvenile Greenland halibut growth, density, and distribution in West Greenland offshore waters.	West Greenland offshore waters	1993–2003	**Temperature:** Significant warming from an average bottom temperature of 2.0 °C in 1993–1996 to 3.4 °C in 1997–2003 led to increased growth rates of juvenile Greenland halibut. Mean total length of 1-year-old halibut increased significantly across all areas and depth strata, with an average growth increase of 1.6 cm °C^{-1}. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed.

	https://linkinghub.elsevier.com/retrieve/pii/S138511010900104X				**Ocean Circulation:** The influence of the West Greenland Current affects the physical environment, thereby impacting halibut growth and distribution. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed. **Geographic Distribution:** Halibut distribution shifted deeper and further offshore with increasing temperatures. **Phenology:** Not discussed. **Climate Extremes:** Not discussed directly, but shifts from a cold to a warm period were noted. **Other Effects:** Increased temperatures are likely to continue affecting growth positively, but the impact on recruitment is uncertain due to density-dependent mortality of settled juveniles.
Greenland Halibut (*Reinhardtius hippoglossoides*)	Laura J. Wheeland & M. Joanne Morgan, *Age-specific shifts in Greenland halibut (Reinhardtius hippoglossoides) distribution in response to changing ocean climate*, 77 ICES JOURNAL OF MARINE SCIENCE 230–240 (2020)	Depth-stratified random trawl surveys, age-length key derivation from otoliths, use of trawl-mounted CTDs for temperature data.	Northwest Atlantic off Newfoundland, Canada	1981–2016	**Temperature:** Significant temperature variations observed, with fish moving to deeper, warmer waters during colder periods to maintain preferred thermal habitats. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Changes in temperature imply an effect on circulation patterns, though not directly discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed, but habitat shifts imply possible changes in prey availability. **Predation:** Not discussed.

					Geographic Distribution: Marked shifts to deeper and southern waters during cold periods, with younger fish showing the most pronounced shifts. **Phenology:** Not discussed. **Climate Extremes:** Adaptation to significant temperature changes over decades highlighted. **Other Effects:** Age-specific responses to temperature change suggest implications for ecosystem interactions and fisheries management.
Greenland Halibut (*Reinhardtius hippoglossoides*)	Wahiba Ait Youcef et al., *Variations in length and growth of Greenland Halibut juveniles in relation to environmental conditions*, 167 FISHERIES RESEARCH 38–47 (2015)	Surveys, oxygen and temperature measurements, analysis of growth rates in relation to environmental conditions.	St. Lawrence Estuary and Gulf of St. Lawrence	1990–2012	**Temperature:** Found not to significantly affect juvenile growth within the studied range (4.95–5.14°C). **Dissolved Oxygen:** Low oxygen levels significantly affected growth; growth rates decreased with oxygen saturation below 25%. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly discussed, but ocean conditions including temperature and oxygen levels were considered in distribution studies. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed but inferred effects through changes in food availability. **Food Availability:** Suggested that abundant food may compensate for negative effects of low oxygen. **Predation:** Not discussed. **Geographic Distribution:** Juveniles concentrated in regions with low oxygen; high density in the estuarine portion suggests adaptation to local conditions. **Phenology:** Not discussed. **Climate Extremes:** Not discussed.

					Other Effects: Highlighted the resilience of Greenland Halibut juveniles to low oxygen conditions and suggested that physical and biological characteristics of the ecosystem may mitigate the impacts of low oxygen.
Greenland Halibut (*Reinhardtius hippoglossoides*) and Beluga (*Delphinapterus leucas*)	David J. Yurkowski et al., *Temporal shifts in intraguild predation pressure between beluga whales and Greenland halibut in a changing Arctic*, 13 BIOLOGY LETTERS (2017)	Stable isotope analysis, temporal and seasonal analysis of predator-prey interactions, and shifts in dietary contributions from forage fish over 30 years.	Cumberland Sound, Nunavut, Canada	1982–2012	**Temperature:** Not specifically discussed, but climate change influences forage fish availability which indirectly affects Greenland halibut. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Increased availability of capelin, a key forage fish, due to warming trends affects the diet of Greenland halibut. **Predation:** Shifts in forage fish abundance affect intraguild predation dynamics between beluga and Greenland halibut. **Geographic Distribution:** Not discussed directly, but implied changes due to shifts in prey species. **Phenology:** Temporal and seasonal shifts in diet noted. **Climate Extremes:** Not discussed. **Other Effects:** Changes in interspecific interactions due to altered forage fish dynamics demonstrate the ecosystem's response to climate change.
Greenland Halibut (*Reinhardtius hippoglossoides*)	Sahar Mejri et al., *Influence of different levels of dissolved oxygen on the success of Greenland halibut (Reinhardtius*	The study examined the impact of different levels of dissolved oxygen (DO) on the embryonic development and hatching success of Greenland	Estuary and Gulf of St. Lawrence	Not specified	**Temperature:** Not directly assessed in this study. **Dissolved Oxygen:** Found that Greenland halibut eggs are highly tolerant to hypoxia, with successful hatching even at low DO levels as severe as 20% saturation. Severely hypoxic conditions (10% saturation) impaired embryonic development

	hippoglossoides) egg hatching and embryonic development, 159 MARINE BIOLOGY 1693–1701 (2012)	halibut eggs. Fertilized eggs from six females were exposed to five DO levels ranging from severely hypoxic to normoxic. Assessments included changes in lipid composition, hatching success, and developmental rates across different DO conditions.			and prevented hatching. **Ocean pH:** Not assessed. **Ocean Circulation:** Not directly assessed but implied relevance through DO stability maintenance in experimental setups. **Food Availability:** Not discussed. **Predation:** Not relevant to experimental conditions. **Geographic Distribution:** Not directly assessed but discusses implications of low DO in natural habitats. **Phenology:** Demonstrates that DO levels influence the timing and success of embryonic development and hatching. **Climate Extremes:** Highlights the potential impacts of extreme hypoxia on early life stages. **Other Effects:** Suggests that decreasing DO levels may reduce recruitment and population abundance if trends continue.
Greenland Halibut (*Reinhardtius hippoglossoides*)	Wahiba Ait Youcef et al., *Spatial distribution of Greenland halibut Reinhardtius hippoglossoides in relation to abundance and hypoxia in the estuary and Gulf of St. Lawrence*, 22 FISHERIES OCEANOGRAPHY 41–60 (2013)	Utilized data from annual bottom-trawl surveys from 1990 to 2010 to analyze spatial distribution and size-specific abundance in relation to environmental conditions, including dissolved oxygen levels. Generalized additive models (GAM) assessed effects of environmental variables on fish distribution.	Estuary and Gulf of St. Lawrence	1990–2010 (20 years)	**Temperature:** Not specifically assessed for direct impacts on Greenland halibut. **Dissolved Oxygen:** Identified low dissolved oxygen areas as significant habitats. Greenland halibut exhibits high tolerance to low dissolved oxygen levels, which might also offer a refuge from predation. **Ocean pH:** Not assessed. **Ocean Circulation:** Not directly assessed but environmental conditions such as depth and temperature are considered. **Food Availability:** Suggested that the availability of prey might compensate for negative effects of low oxygen. **Predation:** Lower dissolved oxygen areas may provide a refuge from predators. **Geographic Distribution:** Confirmed the St. Lawrence estuary as a major nursery area, with distribution influenced by fish size

					and abundance. **Phenology:** Not directly assessed. **Climate Extremes:** Not discussed. **Other Effects:** Suggests that despite low oxygen levels, the availability of food and refuge from predators may mitigate potential negative impacts.
Greenland Halibut (*Reinhardtius hippoglossoides*)	Aurélie Dupont-Prinet et al., *Impact of hypoxia on the metabolism of Greenland halibut (Reinhardtius hippoglossoides)*, 70 CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES 461–469 (2013)	The study involved measuring the metabolic rates and critical oxygen thresholds of juvenile and adult Greenland halibut at various levels of hypoxia in a controlled lab setting.	Estuary and Gulf of St. Lawrence	Short-term	**Temperature:** Not directly assessed in this study. **Dissolved Oxygen:** Juveniles showed less tolerance to low oxygen conditions than adults, with critical oxygen thresholds indicating susceptibility to even slight reductions in DO. Severe hypoxia significantly reduced the maximum metabolic rate by 55%. **Ocean pH:** Not assessed. **Ocean Circulation:** Not discussed. **Food Availability:** Not directly measured, but severe hypoxia increased the duration of digestive processes, implying potential impacts on energy utilization and food processing efficiency. **Predation:** Not discussed. **Geographic Distribution:** Not directly assessed but noted that juveniles are less tolerant to hypoxia, which could influence their spatial distribution in hypoxic waters. **Phenology:** Not specifically assessed but implied effects on developmental stages due to changes in metabolic rates under hypoxia. **Climate Extremes:** Explored through severe hypoxia treatments, suggesting significant vulnerability of juveniles to even moderate decreases in oxygen levels. **Other Effects:** Highlighted potential growth and distribution impacts if dissolved oxygen levels continue to decline, emphasizing the need for understanding and mitigating climate change impacts on this species.

Greenland Halibut (*Reinhardtius hippoglossoides*)	Marion Pillet et al., *Effects of exposure to hypoxia on metabolic pathways in northern shrimp (Pandalus borealis) and Greenland halibut (Reinhardtius hippoglossoides)*, 483 Journal of Experimental Marine Biology and Ecology 88–96 (2016), http://dx.doi.org/10.1016/j.jembe.2016.07.002	The study evaluated the metabolic response of juvenile Greenland halibut to hypoxia. It involved exposure to varying levels of dissolved oxygen (100%, 40%, 30%, 20% saturation) at 5°C. Assessments included the activities of key enzymes involved in aerobic (CS, COX) and anaerobic (PK, PEPCK, LDH) pathways, as well as enzymes involved in antioxidant defense (SOD, GPx, CAT). Gene expression analyses were performed to determine changes at the transcriptional level.	Estuary and Gulf of St. Lawrence	One week	**Temperature:** Not directly assessed. **Dissolved Oxygen:** Chronic exposure to low oxygen levels significantly affected metabolic enzyme activities, indicating a shift from aerobic to anaerobic metabolism in severe hypoxia. **Ocean pH:** Not assessed. **Ocean Circulation:** Not discussed. **Food Availability:** Not directly measured. **Predation:** Not discussed. **Geographic Distribution:** Not directly assessed but inferred importance due to the choice of natural habitat for experiments. **Phenology:** Not specifically assessed. **Climate Extremes:** The study focuses on the extreme condition of hypoxia. **Other Effects:** Highlighted strong transcriptional responses to hypoxia, suggesting significant metabolic adjustments to low oxygen environments.
Greenland Halibut (*Reinhardtius hippoglossoides*)	Christine H. Stortini et al., *Marine species in ambient low-oxygen regions subject to double jeopardy impacts of climate change*, 23 Global Change Biology 2284–2296 (2017)	Used species distribution models to assess the impact of warming and oxygen depletion on Greenland halibut based on historical survey data and climate projections in the Gulf of St. Lawrence.	Gulf of St. Lawrence, Canada	1990–2010 (20 years)	**Temperature:** Predicts substantial loss of high-density areas due to warming, especially when combined with oxygen depletion. Warming alone reduces high-density areas by 49%, showing that temperature increases can restrict suitable habitat ranges. **Dissolved Oxygen:** Projects a loss of about 55% of its high-density areas under scenarios of combined warming and oxygen depletion. Indicates that oxygen levels already at the limits of species tolerance significantly constrain habitat suitability. **Ocean pH:** Not directly assessed. **Ocean Circulation:** Not specifically evaluated but inherent in climate model projections. **Food Availability:** Not assessed, but the study implies changes in habitat will impact food resources.

					Predation: Not discussed. **Geographic Distribution:** Significant loss of habitat expected due to warming and decreased oxygen levels, with potential shifts in geographic distribution as a result. **Phenology:** Not assessed. **Climate Extremes:** The interaction of warming and reduced oxygen levels is expected to exacerbate stress conditions. **Other Effects:** The study highlights the potential for significant impacts on population density and biomass, predicting dramatic reductions in suitable habitats and changes in the environmental carrying capacity.
Redfish (*Sebastes spp.*)	M E Anderson, *Systematics and osteology of the Zoarcidae (Teleostei: Perciformes)*, ICHTHYOL. BULL. J.L.B. SMITH. INST. ICHTHYOL. (1994)	Ichthyoplankton surveys using bongo nets, diet analysis via stomach content examination, and statistical analyses to understand the relationship between diet, condition, and growth rates of larval and pelagic juvenile redfish.	Flemish Cap, Canada	1978–1982	**Temperature:** Linked to earlier spawning and faster development of primary prey (*Calanus finmarchicus*), resulting in poorer feeding conditions for redfish larvae due to mismatch in timing of larval needs and prey availability. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Critically affects redfish larval survival and condition, with a clear preference for *Calanus finmarchicus* nauplii over other zooplankton like *Oithona spp.*. **Predation:** Not discussed. **Geographic Distribution:** Not discussed. **Phenology:** Changes in spawning time linked to temperature affects larval development and subsequent feeding success. **Climate Extremes:** Not discussed.

					Other Effects: Impact on larval development and size at metamorphosis, suggesting temperature-driven changes in ecosystem productivity could significantly affect redfish populations.
Redfish (*Sebastes mentella* and *S. fasciatus*)	Caroline Brûlé et al., *Reduction in size-at-maturity in unprecedentedly strong cohorts of redfish (Sebastes mentella and S. fasciatus) in the Gulf of St. Lawrence and Laurentian Channel*, JOURNAL OF FISH BIOLOGY (2024)	Histological assessment of redfish reproductive stages, genetic identification, long-term environmental data analysis.	Gulf of St. Lawrence and Laurentian Channel	2011–2021	**Temperature:** Increased bottom water temperatures correlated with reduced size at maturity in redfish populations. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed, but environmental data suggest changes. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly discussed, but implications on population dynamics are suggested. **Predation:** Not discussed. **Geographic Distribution:** Not discussed directly, but implied shifts due to environmental changes. **Phenology:** Warmer temperatures linked to changes in reproductive timings, affecting size at maturity. **Climate Extremes:** Related to warming trends impacting reproductive characteristics. **Other Effects:** Changes in population dynamics and fishery management strategies due to environmental transformations.
Redfish (*Sebastes fasciatus*)	Francisco González-Carrión & Fran Saborido-Rey, *Influence of maternal effects and temperature on fecundity of Sebastes fasciatus on the Flemish Cap*, 86	Histological assessment, autodiametric method for fecundity estimation, mixed-effect linear models for analyzing effects of maternal traits and bottom temperature on fecundity.	Flemish Cap, Northwest Atlantic	1996–2020	**Temperature:** Increased sea bottom temperature positively influenced fecundity, suggesting higher reproductive outputs in warmer conditions. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed.

	SCIENTIA MARINA (2022)				**Ocean Circulation:** Not specifically discussed, but environmental variability including temperature is noted. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed, but environmental conditions like temperature could impact food availability indirectly. **Predation:** Not discussed. **Geographic Distribution:** Not directly discussed. **Phenology:** Implied through the influence of temperature on reproductive timings and outcomes. **Climate Extremes:** Not discussed. **Other Effects:** Emphasizes the need for considering maternal effects and environmental variability in assessments of reproductive potential and fisheries management.
Redfish (*Sebastes spp.*)	Jennifer A. Devine & Richard L. Haedrich, *The role of environmental conditions and exploitation in determining dynamics of redfish (Sebastes species) in the Northwest Atlantic*, 20 FISHERIES OCEANOGRAPHY 66–81 (2011)	Dynamic factor analysis to analyze exploitation and environmental variability on redfish population trends.	Northwest Atlantic, including Gulf of St. Lawrence	1960–2004	**Temperature:** Related to environmental variability affecting redfish population dynamics. Impacts include effects on larval survival and distribution due to changes in sea temperature. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** North Atlantic Oscillation influences were noted, affecting intermediate water formation which impacts redfish. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed directly, but environmental conditions impacting redfish also affect prey availability. **Food Availability:** Impacted by environmental conditions that affect prey species; strong year classes correlate with high prey availability.

					Predation: Not discussed directly, but natural predation is a factor in juvenile mortality. **Geographic Distribution:** Differing responses in closely located stocks suggest complex impacts of environmental factors on distribution. **Phenology:** Changes in environmental conditions influence reproduction timing and success. **Climate Extremes:** Not discussed specifically, but variability in temperature and ocean conditions over decades suggests impacts from climate extremes. **Other Effects:** Environmental and exploitation factors combined with unique life-history traits of redfish (long-lived, late-maturing) necessitate considering long-term data for management.
Redfish (*Sebastes mentella*)	Eriksen et al.	Pelagic trawl catches, temperature observations, General Additive Effects Model (GAM) analysis.	Barents Sea	1980–2010	**Temperature:** Redfish found mostly in a core thermal habitat (CTH) of 5.5–8.5 °C. Higher temperatures led to better conditions theoretically, increasing potential habitat size, but redfish did not utilize the expanded habitat. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Mention of Atlantic water inflows affecting redfish distribution. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed, but food sources are implied to be affected by temperature and water inflows. **Predation:** Not discussed. **Geographic Distribution:** Redfish primarily in western and central Barents Sea, rarely east of 30°E. Indication of northern expansion not utilized by redfish.

					Phenology: Not discussed directly but implied in relation to spawning and recruitment. **Climate Extremes:** Not discussed. **Other Effects:** Exploitation pressure more significant than habitat changes for influencing redfish populations.
Acadian Redfish (*Sebastes fasciatus*)	Jordi Grinyó et al., *Occurrence and behavioral rhythms of the endangered Acadian redfish (Sebastes fasciatus) in the Sambro Bank (Scotian Shelf)*, 10 FRONTIERS IN MARINE SCIENCE 1–14 (2023)	High-temporal resolution imaging, environmental data analysis, autonomous lander deployment for 10 months.	Sambro Bank, Scotian Shelf	10 months	**Temperature:** Not directly discussed in the impact context but central to the study's environmental settings. **Dissolved Oxygen:** Not specifically mentioned. **Ocean pH:** Not discussed. **Ocean Circulation:** Highlighted as influencing redfish behavior and habitat use; currents and hydrodynamics condition redfish swimming behavior. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed in direct relation to climate change but essential for understanding behavioral ecology. **Predation:** Not discussed. **Geographic Distribution:** Expected shifts to higher latitudes due to climate stressors, although not currently observed. **Phenology:** Seasonal behavioral rhythms are noted, possibly linked to environmental changes. **Climate Extremes:** Not discussed. **Other Effects:** Emphasizes the role of nonintrusive monitoring in understanding species response to environmental changes.
Demersal and pelagic species including redfish	Kleisner et al.	High-resolution global climate model, historical observations of species distributions from a trawl	U.S. Northeast Continental Shelf	Not specified	**Temperature:** Predicted warming of 3.7°C to 5.0°C depending on the region, which results in shifts in thermal habitat affecting species distributions. **Dissolved Oxygen:** Not discussed.

		survey, estimation of bathy-thermal niches.			**Ocean pH:** Not discussed, but the study notes the influence of ocean warming on species distributions. **Ocean Circulation:** Mentioned as a factor in distribution shifts, with a northerly shift of the Gulf Stream affecting temperatures. **Mixing:** Not specifically discussed, but regional circulation mentioned. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly discussed; however, changes in species distributions imply potential changes in food web dynamics. **Predation:** Not specifically discussed, but changes in species distributions may alter predator-prey interactions. **Geographic Distribution:** Significant northward shifts in species distributions due to warming, particularly impacting species currently inhabiting northern regions. **Phenology:** Not directly discussed, but shifts in distributions suggest potential changes in breeding and feeding times. **Climate Extremes:** Not discussed. **Other Effects:** The study emphasizes the complex interplay between climate change, species interactions, and fishing pressure affecting species distributions and abundances.
Redfish (*Sebastes fasciatus*, *S. mentella*, *S. norvegicus*)	Adriana Nogueira et al., *Using multivariate state-space models to examine commercial stocks of redfish (Sebastes spp.) on the Flemish Cap*, 76 CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES 208–216 (2019)	Multivariate autoregressive state-space models (MARSS) to examine the abundance trajectories and effects of environmental variables and commercial catch on redfish stocks.	Flemish Cap, North Atlantic	1993–2015	**Temperature:** The study did not discuss direct impacts but included environmental variables likely influenced by climate change. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed but inferred through environmental covariates. **Mixing:** Not discussed.

					Nutrient Supply: Not discussed. **Food Availability:** Not directly discussed; however, the study examined the influence of prey (shrimp) availability. **Predation:** Examined the effect of cod (predator and competitor) abundance. **Geographic Distribution:** Examined differences in depth zone distributions. **Phenology:** Not discussed. **Climate Extremes:** Not discussed. **Other Effects:** The study emphasized the importance of considering environmental and fishing pressures in managing redfish stocks, suggesting adaptive management in response to observed changes in these variables.
Redfish (*Sebastes mentella*)	Andrey P. Pedchenko, *The role of interannual environmental variations in the geographic range of spawning and feeding concentrations of redfish Sebastes mentella in the Irminger Sea*, 62 ICES JOURNAL OF MARINE SCIENCE 1501–1510 (2005)	Data from Russian surveys and international observations, analysis of the geographic distribution of redfish in relation to oceanographic conditions.	Irminger Sea	1982–2003	**Temperature:** Noted as a major factor in the redistribution of redfish, with warmer temperatures in the latter half of the study period leading to a shift in feeding grounds westward. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Sub-polar cyclonic Gyre and Irminger Current are crucial in shaping the distribution and migration patterns of redfish, affecting spawning and feeding. **Mixing:** Not directly discussed, but inferred impact through water column stability and nutrient dynamics. **Nutrient Supply:** Not specifically mentioned, but implied in discussions on upwelling and water column mixing affecting food availability. **Food Availability:** Suggested impact from changes in plankton dynamics influenced by temperature and ocean currents. **Predation:** Not discussed.

					Geographic Distribution: Observed significant shifts in distribution, particularly a westward expansion of feeding grounds due to warmer temperatures and changes in ocean currents. **Phenology:** Indications that climate factors are impacting the timing of spawning and migration. **Climate Extremes:** Not specifically mentioned. **Other Effects:** Emphasizes the need for ongoing monitoring and adaptive management of the redfish fishery in response to environmental changes, particularly shifts in oceanographic conditions and their cascading effects on habitat and distribution.
Common fishes of the Scotian Shelf, including redfish.	J S Scott, *Depth, temperature and salinity preferences of common fishes of the Scotian Shelf.*, 3 J. NORTHW. ATL. FISH. SCI. 943–947 (1982)	Research bottom-trawl surveys, depth-stratified random design, measurement of bottom temperature, depth, and salinity at multiple fishing stations across the Scotian Shelf.	Scotian Shelf and Bay of Fundy	1970–1979	**Temperature:** Preferred temperature ranges were identified for various species, indicating that temperature is a significant factor in distribution and behavior. For redfish, specific temperature preferences were not detailed, but temperature is implied as a determinant in distribution. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly discussed, but the distribution of redfish could be influenced by ocean currents as part of the broader environmental conditions. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly discussed; however, distribution patterns suggest an interaction with available food resources. **Predation:** Not discussed. **Geographic Distribution:** Detailed for redfish, showing distribution across the Scotian Shelf.

					Phenology: Not specifically discussed. **Climate Extremes:** Not discussed. **Other Effects:** The study emphasizes the importance of depth, temperature, and salinity in defining the ecological niches of marine species including redfish.
Northern shrimp (*Pandalus borealis*) larvae	Maj Arnberg et al., *Elevated temperature elicits greater effects than decreased pH on the development, feeding and metabolism of northern shrimp (Pandalus borealis) larvae*, 160 Marine Biology 2037–2048 (2013)	Controlled laboratory experiments with variable pH and temperature on larvae stages of the northern shrimp, *Pandalus borealis*.	North Sea	Not specified	**Temperature:** Elevated temperature resulted in earlier hatching, increased metabolic rates by approximately 20%, and increased feeding rates by about 15-20%, but also reduced survival by 2-4%. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Decreased pH increased development time at lower temperatures. **Ocean Circulation:** Not specifically discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly discussed; however, feeding rates increased with temperature. **Predation:** Not discussed. **Geographic Distribution:** Not discussed. **Phenology:** Elevated temperatures accelerated developmental rates. **Climate Extremes:** Not discussed. **Other Effects:** The study suggests that warming may have a more significant impact than acidification, manifesting as accelerated developmental rates with greater maintenance costs and decreased recruitment in terms of number and size.
Northern shrimp (*Pandalus borealis*) females	Sophie Brillon et al., *Egg survival, embryonic development, and larval*	Laboratory experiments on ovigerous females assessing effects of	North Atlantic (Gulf of St. Lawrence)	Not specified	**Temperature:** Increased temperature accelerated egg developmental time but reduced survival at higher temperatures. Larger larval size and lower egg mortality at lower temperatures

	characteristics of northern shrimp (Pandalus borealis) females subject to different temperature and feeding conditions, 147 Marine Biology 895–911 (2005)	temperature and food ration on egg survival, embryonic development, and larval characteristics.			(2°C and 5°C) compared to 8°C. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed, but environmental conditions implied in regional studies. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Food ration did not affect female energetic condition or egg characteristics. **Predation:** Not discussed. **Geographic Distribution:** Not discussed. **Phenology:** Temperature influences on development times and larval characteristics indicate potential phenological shifts. **Climate Extremes:** Not discussed. **Other Effects:** Stressed the need for ongoing monitoring and adaptive management of northern shrimp fisheries in response to environmental changes, particularly temperature.
Northern shrimp (*Pandalus borealis*)	Hsiao-Yun Yun Chang et al., *Effects of environmental factors on reproductive potential of the Gulf of Maine northern shrimp (Pandalus borealis)*, 30 Global Ecology and Conservation e01774 (2021), https://linkinghub.elsevier.com/retrieve/pii/S2351989421003243	Samples from bottom trawl surveys, Generalized Additive Mixed Models (GAMMs) used to analyze effects of environmental variables on reproductive characteristics.	Gulf of Maine	2012–2016	**Temperature:** Higher bottom temperatures were correlated with increased potential fecundity (PF) and relative fecundity (RF), suggesting that warmer waters may enhance reproductive outputs in the years studied. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed, but environmental conditions such as temperature are indicated. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed.

					Food Availability: Not directly discussed, but linked to environmental conditions that also relate to temperature and fecundity. **Predation:** Not discussed. **Geographic Distribution:** Not specifically discussed, but shifts in distribution due to temperature changes implied. **Phenology:** Shifts in timing and success of reproductive events correlated with temperature. **Climate Extremes:** Not discussed. **Other Effects:** Suggests a complex interaction between temperature, reproductive output, and potential compensatory mechanisms in lower population densities.
Northern shrimp (*Pandalus borealis*)	Colbourne & Orr	Multi-species trawl surveys, stratified random design, data analysis of temperature distribution, and shrimp catch rates.	NAFO Divisions 3LNO	1995–2005	**Temperature:** Shrimp predominantly found in 2°-4°C during spring, preferring slightly colder 1°-3°C during fall. Higher spring temperatures in 2005 showed more shrimp in >3°C water, suggesting adaptability to warmer waters. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Influences distribution and abundance but not detailed in study. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not specifically discussed, but distribution changes suggest adaptability to available food in different temperature zones. **Predation:** Not discussed. **Geographic Distribution:** Distribution shifts toward colder waters in fall and to warmer waters in spring as temperatures varied.

					Phenology: Suggests seasonal shifts in distribution; more shrimp caught in warmer waters during unusually warm spring of 2005. **Climate Extremes:** Shows adaptability to annual variations in temperature. **Other Effects:** Indicates need for ongoing research on thermal habitat use and adaptability to changing temperatures.
Northern shrimp (*Pandalus borealis*), post-larval stages	Dounia Daoud et al., *Size and temperature-dependent variations in intermolt duration and size increment at molt of Northern Shrimp, Pandalus borealis*, 157 MARINE BIOLOGY 2655–2666 (2010)	Laboratory experiments on growth characteristics (intermolt period, size increment) at different temperatures.	Canadian waters (general)	Not specified	**Temperature:** Higher temperatures significantly decreased the intermolt period (IP), indicating a faster rate of molting and potential growth. Temperature directly influenced growth rate primarily through changes in IP rather than molt size increment (MI). **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly studied; however, shrimp were fed ad libitum, suggesting sufficient food supply was not a limiting factor. **Predation:** Not discussed. **Geographic Distribution:** Not specifically addressed. **Phenology:** Suggests temperature-induced changes in molting and growth rates could alter lifecycle events timing. **Climate Extremes:** Not discussed. **Other Effects:** Emphasizes the critical role of temperature in regulating growth patterns through molting frequency, which could have broad implications for lifecycle and population dynamics under changing climatic conditions.

Northern shrimp (*Pandalus borealis*)	DFO, *An assessment of northern shrimp (Pandalus Borealis) in shrimp fishing areas 4-6 and of striped shrimp (Pandalus Montagui) in shrimp fishing area 4 in 2020*, 2021/049 Canadian Science Advisory Secretariat Science Advisory Report 32 (2021)	Trawl survey data, observer and logbook datasets, environmental drivers analysis.	SFAs 4–6, Canada	1996–2018	**Temperature:** Ocean physical conditions showed cold anomalies near the surface and warm anomalies near the bottom, impacting the thermal habitat of shrimp. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Strong larval connectivity indicated, affecting larval dispersal and possibly recruitment areas. **Mixing:** Not specifically discussed but implied in the context of larval dispersal and retention. **Nutrient Supply:** Changes in zooplankton community structure and primary productivity may affect food availability for shrimp. **Food Availability:** Early life and adult stages depend on phytoplankton and zooplankton, with recent changes in community structure potentially impacting shrimp. **Predation:** Important prey for multiple marine species, but specific impacts of predation under current climate conditions not discussed. **Geographic Distribution:** Impacted by ocean conditions and possibly shifting due to changes in temperature and larval dispersal patterns. **Phenology:** Not discussed in detail. **Climate Extremes:** General warming trends and anomalies noted, with implications for habitat and food availability. **Other Effects:** Indirect effects through changes in the ecosystem's primary and secondary productivity.

Northern shrimp (*Pandalus borealis*)	Markus Frederich & Emily R. Lancaster, *Temperature Thresholds of Crustaceans in the Age of Climate Change*, 2 Frontiers in Invertebrate Physiology: A Collection of Reviews: Volume 2: Crustacea 175–228 (2024)	Review of literature and theoretical models on temperature thresholds and performance curves for crustaceans.	Not specified	Not specified	**Temperature:** Describes how crustaceans, including northern shrimp, are affected by rising temperatures through various mechanisms, including shifts in optimal temperature ranges and thermal performance curves. **Dissolved Oxygen:** Not specifically discussed for northern shrimp. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed. **Predation:** Not discussed. **Geographic Distribution:** Not discussed. **Phenology:** Not discussed. **Climate Extremes:** Indicates a general impact on crustaceans due to temperature extremes and marine heatwaves. **Other Effects:** Highlights the need for adapting management practices to consider thermal performance and thermal limits in the context of global warming.
Northern shrimp (*Pandalus borealis*)	Ingibjörg G. Jónsdóttir et al., *Influence of increased cod abundance and temperature on recruitment of northern shrimp (Pandalus borealis)*, 160 Marine Biology 1203–1211 (2013)	Analysis of 22 years of data from annual offshore shrimp surveys, examining abiotic and biotic factors affecting recruitment.	North and northeast of Iceland	1988–2011	**Temperature:** Increased summer sea surface temperatures (SST) were found to negatively affect shrimp recruitment, explaining a significant portion of observed variations. This effect likely impacts shrimp during the planktonic phase. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not discussed, but general environmental variability was considered. **Mixing:** Not discussed.

					Nutrient Supply: Not discussed. **Food Availability:** Not specifically mentioned, but conditions during planktonic phases are crucial. **Predation:** Increased cod abundance was also negatively correlated with shrimp recruitment, likely affecting post-planktonic stages through predation. **Geographic Distribution:** Not discussed in terms of climate change. **Phenology:** The timing of planktonic phases might be influenced by temperature changes. **Climate Extremes:** Not specifically discussed. **Other Effects:** Environmental variability and interaction with other species were highlighted as influential.
Northern shrimp (*Pandalus borealis*)	Kai Wieland & Helle Siegstad, *Environmental factors affecting recruitment of northern shrimp Pandalus borealis in West Greenland waters*, 469 MARINE ECOLOGY PROGRESS SERIES 297–306 (2012)	Bottom trawl surveys, time series analysis, multiple regression models on recruitment factors.	West Greenland waters	1993–2011	**Temperature:** Ambient bottom temperature was a significant predictor of recruitment success, affecting larvae survival and settlement. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed, but general oceanographic conditions were considered. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Suggested importance through the timing of larval hatch to match the spring phytoplankton bloom, though not directly measured. **Predation:** Presence of predators like Atlantic cod and Greenland halibut was significant, with their biomass negatively affecting recruitment.

					Geographic Distribution: Noted changes in the latitudinal distribution, potentially linked to temperature and predation pressures. **Phenology:** Recruitment success was influenced by the timing of larval hatch, which needs to align with phytoplankton blooms. **Climate Extremes:** Not discussed. **Other Effects:** The mismatch between larval hatch and phytoplankton bloom due to temperature shifts was highlighted as a risk factor for recruitment success.
Northern shrimp (*Pandalus borealis*)	P. A. Koeller et al., *Decreasing shrimp (Pandalus borealis) sizes off Newfoundland and Labrador - Environment or fishing?*, 16 FISHERIES OCEANOGRAPHY 105–115 (2007)	Analysis of carapace length statistics and environmental factors from commercial and survey catches.	Newfoundland and Labrador	1990s	**Temperature:** Highlighted as a key factor impacting shrimp size, with higher temperatures linked to decreased growth rates possibly due to increased metabolic demands. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed, but changes in water temperature and conditions which are influenced by ocean currents were considered. **Mixing:** Implied impact on nutrient flux into the euphotic zone, affecting primary production and indirectly influencing shrimp size through food availability. **Nutrient Supply:** Decreased nutrient flux hypothesized as a reason for decreased primary production, affecting shrimp size. **Food Availability:** Decreased due to higher shrimp population densities, which led to lower per-capita food availability, thus reducing growth rates. **Predation:** Not discussed directly, but increase in shrimp biomass was attributed to reduced predation pressure from cod, suggesting an indirect effect. **Geographic Distribution:** Changes in distribution patterns were not directly linked to climate change but were observed with environmental shifts.

					Phenology: Not discussed. **Climate Extremes:** Not specifically mentioned, but the period of study coincided with significant warming trends which affected marine ecosystems. **Other Effects:** The study suggests that both environmental changes and fishing pressure might contribute to observed size decreases, highlighting the complex interactions between climate change and anthropogenic factors in affecting marine species.
Northern shrimp (*Pandalus borealis*)	Nicolas Le Corre et al., *Potential impact of climate change on northern shrimp habitats and connectivity on the Newfoundland and Labrador continental shelves*, 30 FISHERIES OCEANOGRAPHY 331–347 (2021)	Utilized a regional scale ice-ocean model (RCP 8.5 scenario) to investigate the spatial distribution variability of northern shrimp, including larval settlement patterns and habitat preferences in relation to temperature changes and ocean circulation features.	Newfoundland and Labrador shelves	2020–2090	**Temperature:** Predicted a gradual increase of bottom water temperatures by more than 4°C by 2090, affecting the distribution and availability of suitable thermal habitats for northern shrimp. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Changes in circulation patterns influenced larval dispersal and settlement, crucial for maintaining population connectivity. **Mixing:** Not specifically discussed. **Nutrient Supply:** Not directly discussed but implications are there due to changes in water temperature affecting ecosystem dynamics. **Food Availability:** Implied impacts due to changes in habitat conditions affecting primary production. **Predation:** Not discussed. **Geographic Distribution:** Shifting towards more southern and coastal areas by 2090 due to habitat modifications. **Phenology:** Expected changes in the timing of larval development and settlement due to temperature rise. **Climate Extremes:** The study underscores the need for models

					that consider extreme climate scenarios to better predict impacts on marine populations. **Other Effects:** Emphasizes the importance of understanding shelf-scale processes to accurately project changes in marine ecosystems and manage fisheries effectively.
Northern shrimp (*Pandalus borealis*)	R. Anne Richards, *Phenological shifts in hatch timing of northern shrimp Pandalus borealis*, 456 Marine Ecology Progress Series 149–158 (2012)	Field data were used to investigate reproductive phenology of northern shrimp in the Gulf of Maine from 1980 to 2011 in relation to ocean temperatures. Timing of the annual shrimp hatch was estimated by sampling commercial catches during the brooding and hatching period. Hatch timing metrics were regressed against environmental variables derived from principal component analysis.	Gulf of Maine, USA	1980–2011	**Temperature:** All hatch timing metrics were significantly related to temperature variables, with a noted shift in the timing of hatch initiation (earlier) and completion (later), resulting in a longer hatch period in recent years due to warmer temperatures. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed directly but related to environmental conditions affecting shrimp phenology. **Predation:** Not discussed. **Geographic Distribution:** Not discussed. **Phenology:** Phenological shifts in hatch timing may increase the window of opportunity for larvae to encounter favorable survival conditions. **Climate Extremes:** Not specifically discussed. **Other Effects:** Continued warming is predicted to produce further changes, some potentially unexpected, in shrimp phenology and population dynamics.
Northern shrimp (*Pandalus borealis*)	R. Anne Richards & Margaret Hunter, *Northern shrimp Pandalus borealis population collapse linked to climate-driven*	Data from fishery-independent surveys, environmental monitoring, and commercial fishery. Examined spatial data and tested hypotheses related to	Gulf of Maine, USA	1982–2019	**Temperature:** Linked to the collapse of northern shrimp during a marine heatwave in 2012 with significant temperature anomalies noted. **Dissolved Oxygen:** Not discussed.

	shifts in predator distribution, 16 PLoS ONE 1–27 (2021)	fishing mortality and shifts in predation pressure. Included stomach contents analysis and biomass trends.			**Ocean pH:** Not discussed. **Ocean Circulation:** Mention of general warming and heatwaves impacting the ecosystem, although specific circulation changes aren't detailed. **Mixing:** Not directly discussed. **Nutrient Supply:** Not specifically mentioned. **Food Availability:** Inferred impacts through changes in ecosystem productivity due to temperature changes. **Predation:** Increased predation by longfin squid during the heatwave likely contributed significantly to the shrimp population collapse. **Geographic Distribution:** No major displacement of the shrimp population found; collapse likely due to environmental conditions and predation. **Phenology:** Early onset of spring conditions in 2012 potentially led to mismatches in ecological interactions. **Climate Extremes:** The 2012 heatwave was highlighted as a significant factor in the population collapse. **Other Effects:** Emphasized the need for adaptive management and monitoring due to rapid environmental changes.
Northern shrimp (*Pandalus borealis*)	Aurélie Aurelie Dupont-Prinet et al., *Northern shrimp (Pandalus borealis) oxygen consumption and metabolic enzyme activities are severely constrained by hypoxia in the Estuary and Gulf of St. Lawrence*, 448 JOURNAL OF EXPERIMENTAL MARINE BIOLOGY AND ECOLOGY 298–307 (2013),	The study examined the physiological effects of hypoxia on Northern shrimp using experimental exposures to various dissolved oxygen levels at two temperatures (5°C and 8°C). Metabolic rates, critical oxygen thresholds, and enzyme activities were measured to assess tolerance and metabolic adjustments.	Estuary and Gulf of St. Lawrence	Short-term	**Temperature:** The study focused on the effects of two temperatures (5°C and 8°C) demonstrating that higher temperatures increase metabolic rates and decrease hypoxia tolerance. **Dissolved Oxygen:** Critical oxygen thresholds indicated a strong tolerance to hypoxia, although females showed less tolerance than males. Hypoxia significantly altered metabolic rates and aerobic scope, particularly reducing the maximum metabolic rate by 43% under severe hypoxia. **Ocean pH:** Not assessed. **Ocean Circulation:** Not discussed.

	http://dx.doi.org/10.1016/j.jembe.2013.07.019				**Food Availability:** Not directly assessed. **Predation:** Not discussed. **Geographic Distribution:** Shrimp are found in naturally low oxygen areas; however, ongoing decreases in oxygen levels may alter their distribution. **Phenology:** Changes in metabolic rates under different oxygen levels may affect seasonal and reproductive behaviors. **Climate Extremes:** Severe hypoxia tested represents potential future extremes, showing significant impacts on physiology and survival. **Other Effects:** The study highlights potential restrictions on vertical migration and other energy-demanding activities due to reduced aerobic scopes in hypoxic conditions.
Northern shrimp (*Pandalus borealis*)	Dounia Daoud et al., *Temperature induced variation in oxygen consumption of juvenile and adult stages of the northern shrimp, Pandalus borealis*, 347 Journal of Experimental Marine Biology and Ecology 30–40 (2007)	The study measured the oxygen consumption (MO2) of Northern shrimp at various temperatures (2, 5, and 8°C) over 7-10 days using respirometry to determine the standard metabolic rate (SMR). It examined how temperature affects metabolic rates across different developmental stages (juvenile, male, female).	Estuary and Gulf of St. Lawrence	Short-term	**Temperature:** Found that metabolic rates increased with temperature; a rise in temperature from 2 to 8 °C resulted in a 1.6- to 2-fold increase in specific metabolic rates. The thermal response varied slightly with developmental stage, with the highest metabolic rate increases observed in females. **Dissolved Oxygen:** Not directly assessed in relation to climate change, but the study implies that metabolic rates are sensitive to oxygen availability, which could be affected by warming waters. **Ocean pH:** Not assessed. **Ocean Circulation:** Not discussed. **Food Availability:** Not directly assessed but implied as a factor in metabolic rate variability. **Predation:** Not discussed. **Geographic Distribution:** Indicated potential shifts in habitat use as temperatures change. **Phenology:** Suggested that temperature affects developmental

					rates and could alter life cycle timing. **Climate Extremes:** Not specifically discussed but inferred from temperature range testing. **Other Effects:** Highlighted the importance of understanding temperature effects for bioenergetic modeling and resource management.
Northern shrimp (*Pandalus borealis*)	Pillet et al.	The study examined the impacts of hypoxia on metabolic pathways in Northern shrimp by exposing them to different levels of dissolved oxygen (100, 40, 30, and 20% saturation) at 5 °C for one week. Enzyme activities related to aerobic and anaerobic metabolic pathways, as well as antioxidant defenses, were measured to determine physiological responses to varying oxygen levels.	Estuary and Gulf of St. Lawrence	One week	**Temperature:** Not directly assessed. **Dissolved Oxygen:** Shrimp exhibited significant changes in metabolic enzyme activities under different oxygen saturations, indicating physiological adaptations to hypoxia. **Ocean pH:** Not assessed. **Ocean Circulation:** Not discussed. **Food Availability:** Not assessed, but physiological stress from hypoxia could influence feeding behavior and efficiency. **Predation:** Not discussed. **Geographic Distribution:** Indicates that Northern shrimp inhabit areas with naturally low oxygen, which could influence their distribution patterns. **Phenology:** Not discussed. **Climate Extremes:** Study simulates moderate to severe hypoxia, indicating potential vulnerability to extreme hypoxic events. **Other Effects:** Highlights the metabolic cost of hypoxia, potentially affecting growth and reproductive capabilities.
Northern shrimp (*Pandalus borealis*)	Ella Guscelli et al., *Northern shrimp from multiple origins show similar sensitivity to global change drivers, but different cellular energetic capacity*, 226 JOURNAL OF	This study utilized targeted metabolomics to assess the impact of ocean warming (OW) and ocean acidification (OA) on Northern shrimp (*Pandalus borealis*), focusing on metabolic reprogramming	St. Lawrence Estuary (SLE), Eastern Scotian Shelf (ESS), Esquiman Channel (EC), and Northeast Newfoundland	Short-term (30 days of exposure)	**Temperature:** Temperature had the most significant impact, driving metabolic changes across all origins. Elevated temperatures led to accumulations in TCA cycle intermediates, suggesting shifts toward anaerobic metabolism under stress. **Dissolved Oxygen:** Not directly measured but implicated through metabolic responses.

	EXPERIMENTAL BIOLOGY (2023)	across shrimp from different geographic origins in the northwest Atlantic. Shrimp were exposed to three temperatures (2, 6, 10°C) and two pH levels (7.75, 7.40).	Coast (NNC) within the northwest Atlantic.		**Ocean pH:** OA had a less pronounced effect than temperature, with specific impacts on shrimp from SLE. **Ocean Circulation:** Not assessed. **Food Availability:** Not directly measured. **Predation:** Not assessed. **Geographic Distribution:** Suggested potential shifts in distribution as metabolic responses vary with environmental stress. **Phenology:** Not directly assessed but inferred from metabolic changes. **Climate Extremes:** The study indicates that shrimp are particularly sensitive to temperature extremes. **Other Effects:** Noted potential for metabolic adjustments to influence immune responses, indicating complex interactions with environmental stressors.
Northern shrimp (*Pandalus borealis*)	Koeller et al.	The study used satellite-derived data to analyze the timing of phytoplankton blooms and related this to shrimp (Pandalus borealis) egg hatching times across the North Atlantic. The research aimed to investigate the hypothesis that mismatches between shrimp hatching times and phytoplankton bloom could impact shrimp survival due to shifts in food availability driven by climate change.	North Atlantic Ocean, various regions	Decade-long (1990s)	**Temperature:** Found that regional bottom water temperatures strongly influence the duration of egg development, thus affecting hatching times. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly assessed but implicated in the timing of phytoplankton blooms which are crucial for larval food availability. **Food Availability:** Strong coherence between the timing of shrimp hatching and phytoplankton blooms, crucial for larval survival. **Predation:** Not directly addressed but mentioned in relation to population dynamics. **Geographic Distribution:** Showed that shrimp populations are adapted to local environmental conditions including the timing

					of phytoplankton blooms. **Phenology:** Egg hatching times are closely synced with the onset of local phytoplankton blooms, critical for larval feeding. **Climate Extremes:** The study implies that significant shifts in temperature or bloom phenology due to climate change could disrupt this synchronization. **Other Effects:** Highlights the vulnerability of shrimp populations to climate change-induced shifts in oceanographic conditions that alter the timing and availability of their primary food source during early life stages.
Shortfin squid (*Illex argentinus*)	Bazzino et al.	Research bottom trawl surveys conducted in the Argentine–Uruguayan Common Fishing Zone (AUCFZ) between 1985 and 1998. Data collected on depth, bottom temperature, and salinity.	Northern Patagonian Shelf, Southwestern Atlantic Ocean.	13 years (1985-1998)	**Temperature:** Preference for cool bottom temperatures (4–10°C), associated with subantarctic water, especially during March–April, May–June, and July–August cruises . **Dissolved Oxygen:** Not specifically discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Squid distribution associated with oceanographic fronts (Brazil–Malvinas confluence front and shelf break front), suggesting an impact from water mass movements on habitat preference . **Nutrient Supply:** Not directly discussed but inferred from association with oceanographic fronts known for higher nutrient concentrations. **Food Availability:** Association with fronts likely increases food availability due to higher primary productivity in these areas . **Predation:** Not discussed. **Geographic Distribution:** Found predominantly between latitudes 20°S and 55°S, with associations indicating movements between colder feeding areas and warmer spawning areas . **Phenology:** Not specifically discussed. **Climate Extremes:** Not discussed.

					Other Effects: Not discussed.
Argentine shortfin squid (*Illex argentinus*)	Chiu et al.	Used catch per unit effort (CPUE) data from Taiwanese squid jigging fleets from 2004–2013, analyzing squid abundance and migration patterns using a generalized additive model (GAM), cross-correlation, and spectral analysis.	Southwestern Atlantic, Argentine shortfin squid habitat.	10 years (2004-2013)	**Temperature:** Sea surface temperature (SST) between 10 and 14 °C was significant for squid abundance, indicating squid's preference for cooler waters during feeding phases. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Movement patterns and ocean currents affecting squid distribution and abundance were analyzed, particularly their association with frontal zones where different water masses meet. **Nutrient Supply:** Indirectly discussed as squid are found in highly productive frontal zones, indicating an influence from ocean mixing and nutrient supply. **Food Availability:** Squid are abundant in areas with high primary productivity, suggesting better food availability in such regions. **Predation:** Not discussed. **Geographic Distribution:** Covers a wide range along the Patagonia Shelf and slope, highly dependent on movement and environmental factors. **Phenology:** Variability in annual abundance suggests squid's life cycle stages might be influenced by environmental changes. **Climate Extremes:** Not specifically discussed, but inferred from changes in abundance related to SST and movement patterns. **Other Effects:** Migration patterns are crucial for understanding variations in squid abundance; squid are more available to fisheries during specific migration phases.

Northern shortfin squid (*Illex illecebrosus*), Southern stock component	Sarah L. Salois et al., *Shelf break exchange processes influence the availability of the northern shortfin squid, Illex illecebrosus, in the Northwest Atlantic*, 32 Fisheries Oceanography 461–478 (2023)	Used generalized additive models to examine the relationships between physical environment and productivity hotspots to changes in CPUE of Illex illecebrosus. High-resolution remote sensing and global ocean reanalysis physical data paired with high-resolution fishery catch data were utilized.	Northeast US continental shelf (NES), Northwest Atlantic	Last 5 years	**Temperature:** Associated with oceanographic indicators like bottom temperature; squid distribution relates to thermal habitat conditions. **Dissolved Oxygen:** Not specifically discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Distribution influenced by large-scale Gulf Stream, mesoscale eddies, Shelfbreak Jet, and shelf-slope exchange processes. **Nutrient Supply:** Indirectly discussed through productivity hotspots. **Food Availability:** Related to the presence of warm core rings and subsurface features that are likely linked to areas of high primary productivity. **Predation:** Not discussed. **Geographic Distribution:** Extends from the Gulf of Maine to the Mid-Atlantic Bight. **Phenology:** Shows seasonal and interannual variability related to environmental conditions. **Climate Extremes:** Not specifically discussed. **Other Effects:** Recent increases in availability and early fishery closures suggest rapid environmental changes may be impacting squid populations.
Shortfin squid (*Illex argentinus*), particularly the southern Patagonian stock.	Jintao Wang et al., *A stock assessment for Illex argentinus in Southwest Atlantic using an environmentally dependent surplus production model*, 37 Acta Oceanologica Sinica 94–101 (2018)	The study used an environmentally dependent surplus production model to assess stock abundance of Illex argentinus, incorporating environmental data (sea surface temperature) and fishing data from Chinese jigging fleets from 2000 to 2010.	Southwest Atlantic Ocean	11 years	**Temperature:** Optimal spawning associated with SST of 16–18°C, influencing recruitment success and carrying capacity. **Dissolved Oxygen:** Not specifically discussed. **Ocean pH:** Not specifically discussed. **Ocean Circulation:** Not specifically discussed, but the environmental dependency of the model suggests that oceanographic conditions play a role in stock dynamics.

					Nutrient Supply: Not directly mentioned, but SST conditions imply a relationship with ocean productivity affecting squid abundance. **Food Availability:** Not specifically addressed, but SST conditions linked to productivity suggest an impact on food resources. **Predation:** Not discussed. **Geographic Distribution:** Found across the Patagonian Shelf, affected by environmental conditions particularly SST. **Phenology:** SST conditions during spawning season affect recruitment success, indicating a phenological response to temperature. **Climate Extremes:** Not discussed. **Other Effects:** The study emphasizes the importance of environmental factors in stock assessment, suggesting that climate variability could significantly affect squid population dynamics.
Argentine shortfin squid (*Illex argentinus*)	Ke Yang Chang et al., *The antarctic oscillation index as an environmental parameter for predicting catches of the argentine shortfin squid (Illex argentinus) (cephalopoda: Ommastrephidae) in southwest Atlantic waters*, 113 FISHERY BULLETIN 202–212 (2015)	Analysis based on Taiwanese jigging fleet data for Argentine shortfin squid from 1986 to 2010, using log-transformed CPUE to explore squid recruitment strength in response to environmental conditions.	Southwest Atlantic, Argentine shortfin squid habitat	25 years (1986-2010)	**Temperature:** The study found subsurface seawater temperature was negatively correlated with squid abundance, indicating that cooler waters may favor higher squid concentrations. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly discussed, but the study's focus on large-scale atmospheric phenomena like the Antarctic Oscillation (AAO) suggests a link with broad oceanographic conditions. **Nutrient Supply:** Not specifically discussed, but environmental factors including temperature are implied to affect habitat quality. **Food Availability:** Not discussed.

					Predation: Not discussed. **Geographic Distribution:** Found across a wide range of the Southwest Atlantic, with environmental conditions influencing distribution patterns. **Phenology:** Suggests temporal shifts in abundance linked to environmental variables. **Climate Extremes:** Not discussed. **Other Effects:** Emphasizes the importance of incorporating environmental variables into squid stock assessments.
Shortfin squid (*Illex argentinus*)	Chia Ying Ko et al., *Modulations of ocean-atmosphere interactions on squid abundance over Southwest Atlantic*, 250 ENVIRONMENTAL RESEARCH 118444 (2024), https://doi.org/10.1016/j.envres.2024.118444	Used standardized catch per unit effort (CPUE) data from squid jigging fleets and environmental variables over a 21-year period.	Southwest Atlantic, around Argentine waters	21 years (1998-2018)	**Temperature:** Identified significant negative correlation between squid abundance and sea surface temperature (SST) anomalies, suggesting colder temperatures favor squid abundance. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Ocean-atmosphere interactions, including eddy kinetic energy (EKE), identified as influencing squid abundance. **Nutrient Supply:** Not directly discussed, but implicated through discussion on EKE and oceanic currents. **Food Availability:** Not directly discussed. **Predation:** Not discussed. **Geographic Distribution:** Squid found extensively across Argentine waters, suggesting broad environmental tolerance. **Phenology:** Negative SST anomalies associated with higher squid abundances suggest possible adaptations in life cycle timings. **Climate Extremes:** Not discussed. **Other Effects:** Highlights importance of understanding large-

					scale ocean-atmosphere interactions for predicting squid population changes.
Thorny skate (Amblyraja radiata)	Brian D. Grieve et al., *Modeling the impacts of climate change on thorny skate (Amblyraja radiata) on the Northeast US shelf using trawl and longline surveys*, 30 FISHERIES OCEANOGRAPHY 300–314 (2021)	Used two-stage generalized additive models with trawl and longline surveys data.	Northeast US Shelf	1963-2012	**Temperature:** Predicted decrease in habitat suitability due to temperature increase, especially in southern range . **Dissolved Oxygen:** Not directly mentioned. **Ocean pH:** Elevated CO_2 leading to decreased pH could affect habitat by modifying calcareous content in the ocean, indirectly affecting skate habitat, though not directly studied here. **Ocean Circulation:** Not directly mentioned. **Mixing:** Not directly mentioned. **Nutrient Supply:** Not directly mentioned. **Food Availability:** Not directly mentioned but can be inferred that changes in temperature and pH might alter prey availability indirectly. **Predation:** Not specifically mentioned. **Geographic Distribution:** Reduction in thermally suitable habitats expected, particularly in the southern parts of their range, leading to overall abundance reductions . **Phenology:** Not directly mentioned. **Climate Extremes:** Not directly mentioned. **Other Effects:** Increased temperatures drive a decline in abundance, which could be mitigated by significant emission reductions.
Thorny skate (Amblyraja radiata)	Kneebone et al.	Conventional and pop-up satellite transmitting tags to assess movements and habitat use.	Gulf of Maine	2002-2019	**Temperature:** Thorny skates inhabit waters with temperatures ranging from 2.5 to 12.5°C, indicating a broad thermal range. No broad-scale movements in response to temperature observed. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned.

					Ocean Circulation: Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Skates exhibit very localized movements, suggesting limited geographic dispersal capabilities. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** The skates' broad temperature tolerance suggests potential resilience to some effects of climate change, but specific impacts on reproduction or survival rates not detailed.
Thorny skate (Amblyraja radiata)	J. W. Mandelman et al., *Short-term post-release mortality of skates (family Rajidae) discarded in a western North Atlantic commercial otter trawl fishery*, 139 FISHERIES RESEARCH 76–84 (2013), http://dx.doi.org/10.1016/j.fishres.2012.09.020	Post-release mortality investigations using commercial otter trawl gear in the Gulf of Maine.	Gulf of Maine, USA	Not specified	**Temperature:** Not directly addressed, but study focused on the short-term post-release mortality which might be indirectly influenced by temperature changes due to handling and deck exposure. Dissolved Oxygen, Ocean pH, Ocean Circulation, Mixing, and **Nutrient Supply:** Not mentioned. **Food Availability:** Not mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Not mentioned. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** Study highlights variability in post-release mortality related to handling and biological factors (e.g., sex and size of the animal), which could be exacerbated by climate change impacts, though not explicitly linked in this study.

Thorny skate (Amblyraja radiata)	Pennino et al.	Bayesian species distribution models using fishery-independent bottom trawl survey data, environmental and prey variables.	Southern Grand Banks, Canada	2003-2017	**Temperature:** Positive relationship with sea bottom temperature, showing a preference for colder temperatures ranging from -0.5 to 3°C. Temperature increases can affect occurrence and biomass distribution. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Snow crab biomass was a significant predictor for thorny skate, indicating a relationship between prey availability and skate distribution. **Predation:** Not mentioned. **Geographic Distribution:** Biomass and occurrence are concentrated in specific bathymetric ranges (38 to 200 m), suggesting sensitive habitat areas. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** Suggested the potential use of spatial planning as a management strategy to address the impacts of environmental changes on thorny skate.
Thorny skate (Amblyraja radiata)	Gail D. Schwieterman et al., *Combined Effects of Acute Temperature Change and Elevated pCO2 on the Metabolic Rates and Hypoxia Tolerances of Clearnose Skate (Rostaraja*	Intermittent-flow respirometry to measure metabolic rates and hypoxia tolerance under various temperature and acidification conditions.	Gulf of Maine	Not specified	**Temperature:** Significant increase in standard metabolic rate (SMR) under projected higher temperatures. Increased metabolic demands at higher temperatures indicated. **Dissolved Oxygen:** Significant decreases in hypoxia tolerance at elevated temperatures and lower pH levels. **Ocean pH:** Lower pH led to increases in SMR, highlighting

	eglanteria), 8 BIOLOGY (2019), www.mdpi.com/journal/biology				potential energy trade-offs under ocean acidification. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not directly studied. **Predation:** Not mentioned. **Geographic Distribution:** Not directly addressed, but implications for habitat suitability under changing conditions are suggested. **Phenology:** Not mentioned. **Climate Extremes:** Detailed study on responses to temperature and pH extremes. **Other Effects:** Indications that shifts in metabolic demands and oxygen consumption rates under stress could affect overall fitness and survival.
Thorny skate (Amblyraja radiata)	D. P. Swain & H. P. Benoît, *Change in habitat associations and geographic distribution of thorny skate (Amblyraja radiata) in the southern Gulf of St Lawrence: Density-dependent habitat selection or response to environmental change?*, 15 FISHERIES OCEANOGRAPHY 166–182 (2006)	Long-term bottom-trawl surveys conducted in the southern Gulf of St Lawrence.	Southern Gulf of St Lawrence, Canada	1971-2002	**Temperature:** Shift into warmer deep waters coincided with a general cooling of the area, suggesting changes are linked to temperature preferences. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Significant contraction in geographic

					range and shift to warmer, deeper waters. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** Shift in distribution may reflect changes in population size and density-dependent habitat selection.
White Hake (Urophycis tenuis) among others	Amanda G. Davis et al., *Identifying New England's underutilized seafood species and evaluating their market potential in a changing climate*, 10 FRONTIERS IN MARINE SCIENCE 1–13 (2023)	Evaluated underutilized finfish species using quantitative criteria and assessed climate resilience based on biological sensitivity, directionality of climate impacts, and future habitat availability.	New England, United States	2013-2019	**Temperature:** Not directly addressed, but implied through habitat changes. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not specifically mentioned, but changes in habitat due to climate are implied. **Mixing:** Not discussed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly mentioned, but changes in habitat could affect food sources. **Predation:** Not discussed. **Geographic Distribution:** Expected to shift due to climate impacts. **Phenology:** Changes likely but not specifically addressed. **Climate Extremes:** Not discussed. **Other Effects:** Noted the need for adaptive management and market strategies due to climate change.
White Hake (Urophycis tenuis)	Guoqi Han & David W. Kulka, *Dispersion of eggs, larvae and pelagic juveniles of White Hake (Urophycis tenuis) in relation to ocean currents of the Grand*	Utilized a three-dimensional regional ocean circulation model to study the dispersion patterns and survival potential of eggs, larvae, and juveniles in	Grand Bank	Not specified; seasonal and interannual variability considered	**Temperature:** Not specifically addressed, but water temperatures are important for species distribution and development stages. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed.

	Bank: A modelling approach, 41 Journal of Northwest Atlantic Fishery Science 183–196 (2008)	relation to ocean currents and turbulent mixing.			**Ocean Circulation:** Critical in determining the dispersion and subsequent recruitment success of White hake larvae and juveniles. Strong influences from the Labrador Current. **Mixing:** Considered in the model to impact larval dispersal and survival. **Nutrient Supply:** Not specifically addressed but relevant to food chain dynamics affecting larval food sources. **Food Availability:** Not directly studied; however, influenced by nutrient dynamics and water temperatures which affect prey abundance. **Predation:** Not specifically mentioned, but relevant to juvenile survival rates. **Geographic Distribution:** Dispersion patterns heavily influenced by ocean currents, particularly the Labrador Current, affecting juvenile settlement areas. **Phenology:** Timing of spawning and larval release critical; influenced by ocean temperatures and currents. **Climate Extremes:** Not directly addressed, but variability in ocean currents suggests sensitivity to climatic events. **Other Effects:** Emphasizes the need for understanding oceanographic influences on life stages for effective fisheries management.
White Hake (Urophycis tenuis) among others	Benjamin R. Lafreniere et al., *What the Hakes? Correlating Environmental Factors with Hake Abundance in the Gulf of Maine*, 54 Journal of Northwest Atlantic Fishery Science 17–29 (2023)	Utilized generalized additive models (GAMs) to describe the relationship between hake abundance and environmental conditions using bottom temperature, bottom salinity, depth, and catch data from the Maine – New Hampshire Inshore Trawl Surveys over 22 years (2000 – 2021).	Gulf of Maine	2000 – 2021	**Temperature:** Shifts in spatial distribution of stocks correlated with changes in water temperatures. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not specifically addressed but included in the broader discussion of habitat changes. **Mixing:** Not specifically addressed.

					Nutrient Supply: Not specifically addressed. **Food Availability:** Not directly addressed but related to broader ecosystem impacts affecting food chains. **Predation:** Not specifically addressed. **Geographic Distribution:** Noted shifts in distribution related to environmental changes, particularly temperature. **Phenology:** Not directly addressed, but shifts in distribution patterns suggest changes in lifecycle events. **Climate Extremes:** Broad impacts of climate change, including temperature extremes, likely influenced shifts. **Other Effects:** The study emphasizes the complexity of interactions between climate change and other factors like fishing pressure and stock size affecting species distribution.
White Hake (Urophycis tenuis) among 36 fish stocks	Nye et al.	Analyzed data from the Northeast Fisheries Science Center spring trawl survey covering 1968 to 2007 to examine shifts in distribution related to climate change and population size.	Northeast United States continental shelf	1968 – 2007	**Temperature:** Documented shifts in mean temperature of occurrence, linking to broader temperature changes. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Discussed in terms of regional climate indicators like the Atlantic Multidecadal Oscillation influencing distribution shifts. **Mixing:** Not specifically mentioned. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed; linked indirectly through ecosystem changes. **Predation:** Not specifically addressed. **Geographic Distribution:** Significant poleward shifts and depth changes in distribution observed, correlated with climate variables.

					Phenology: Implications for changes in lifecycle timing due to distribution and temperature shifts. **Climate Extremes:** Related to broader climate oscillations like the Atlantic Multidecadal Oscillation affecting the ecosystem. **Other Effects:** Emphasized the need for consideration of climate effects in fisheries management.
White Hake (Urophycis tenuis), related species Silver Hake (Merluccius bilinearis)	Nye et al.	Utilized long-term data from NOAA fisheries surveys and Gulf Stream position indices to study the correlation between changes in the Gulf Stream and the spatial distribution of silver hake, a related species to White hake, on the Northeast US continental shelf.	Northeast US continental shelf	1968–2008	**Temperature:** Shifts in distribution correlated with changes in bottom temperatures on the continental shelf, which are influenced by the position of the Gulf Stream. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Changes in the Gulf Stream path significantly correlated with spatial distribution changes in White Hake. **Mixing:** Not directly addressed but implicated through ocean circulation changes. **Nutrient Supply:** Not addressed. **Food Availability:** Indirectly linked to changes in habitat conditions influenced by temperature and ocean currents. **Predation:** Not specifically addressed. **Geographic Distribution:** Documented a northward shift in distribution responding to changes in the Gulf Stream and associated temperature changes. **Phenology:** Not specifically addressed, but implied changes due to shifting environmental conditions. **Climate Extremes:** Effects of climate change on ocean circulation patterns, such as those involving the Gulf Stream, impact distribution. **Other Effects:** Highlights the importance of understanding

					large-scale oceanographic processes in managing fisheries affected by climate variability.
White Hake (Urophycis tenuis)	Davis et al.	The study assessed the climate resilience of several underutilized finfish species, including white hake. It utilized a measurable definition of "underutilized species" based on sustainable fishing metrics and examined climate resilience using species-specific metrics on climate sensitivity, directionality of responses to climate impacts, and future habitat availability under warming scenarios. The evaluation spanned two periods (2013-2017 and 2015-2019), incorporating economic data and consumer marketing reports to create species-specific, public-friendly, climate-informed profiles.	Northeast United States	2013-2019	**Temperature:** The study did not directly assess temperature impacts but noted that temperature influences were implicit in the analysis of climate sensitivity and habitat projections. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not assessed. **Ocean Circulation:** Not explicitly evaluated but considered in the habitat availability analysis. **Food Availability:** Not directly measured but considered as part of the broader ecological impacts of climate change. **Predation:** Not addressed in the study. **Geographic Distribution:** Predicted shifts due to changing ocean conditions, especially temperature and habitat availability. **Phenology:** Impacts on phenology were implied through changes in temperature and habitat conditions. **Climate Extremes:** The study acknowledged the potential for significant shifts due to extreme climate scenarios but did not provide specific evaluations. **Other Effects:** Emphasized the need for ongoing monitoring and adaptive management strategies to respond to observed and predicted changes due to climate impacts.
Witch flounder (Glyptocephalus cynoglossus)	Bidwell & Howell	Experimental study using temperature gradients to examine effects on larval feeding efficiency, growth, and survival from hatching through metamorphosis.	Northeastern United States and Canadian Atlantic Provinces	Not specified; detailed stages from hatching to beyond 60 days post-hatch	**Temperature:** Optimal larval growth and first feeding between 15.0°C and 16.2°C. Higher or lower temperatures led to decreased survival and feeding efficiency. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not specifically addressed. **Mixing:** Not addressed.

					Nutrient Supply: Not directly addressed. **Food Availability:** Higher temperatures may increase metabolic rates, affecting energy needs for growth. **Predation:** Not addressed. **Geographic Distribution:** Not directly studied, but temperature affects larval survival and distribution. **Phenology:** Timing of feeding and growth phases correlates with temperature. **Climate Extremes:** Not directly addressed. **Other Effects:** Temperature significantly influences larval development stages and survival rates.
Witch flounder (Glyptocephalus cynoglossus)	BOWERING	The study utilized data from nine locations in the Newfoundland-Labrador area, examining the reproductive development of witch flounder and its relation to water temperature and depth.	Newfoundland-Labrador area, northwest Atlantic	Not specified	**Temperature:** Intensive spawning occurred at varying temperatures, showing regional differences. In the eastern areas, spawning was during March-June at consistent temperatures, while in more westerly areas, spawning occurred during January-February at higher temperatures. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not directly addressed, but environmental conditions influencing spawning include depth and temperature variations, which are linked to ocean circulation patterns. **Mixing:** Not addressed. **Nutrient Supply:** Not directly addressed. **Food Availability:** Not directly addressed, but the timing and location of spawning suggest adaptation to local food availability. **Predation:** Not addressed. **Geographic Distribution:** Demonstrates regional variation in

					spawning times and depths, suggesting adaptations to local environmental conditions. **Phenology:** Variations in spawning times across different regions indicate a strong influence of environmental factors on reproductive cycles. **Climate Extremes:** Not specifically addressed. **Other Effects:** Highlights the complexity of environmental factors affecting the reproductive timing and distribution of witch flounder.
Witch flounder (Glyptocephalus cynoglossus)	Mary L. Moser et al., *Metabolic responses to hypoxia of Lycenchelys verrillii (wolf eelpout) and Glyptocephalus cynoglossus (witch flounder): Sedentary bottom fishes of the Hatteras/Virginia middle slope*, 144 MARINE ECOLOGY PROGRESS SERIES 57–61 (1996)	The study investigated the metabolic responses of witch flounder (*Glyptocephalus cynoglossus*) to hypoxia. Fish were collected using a submersible from deep-sea habitats and subjected to controlled laboratory experiments to measure respiration rates and survival in varying oxygen conditions.	Hatteras and Virginia Middle Slope, USA	June 25 to July 2, 1992	**Temperature:** The study controlled for temperature, maintaining a constant environmental temperature during respiration measurements. **Dissolved Oxygen:** Witch flounder exhibited decreasing respiration rates with reduced oxygen availability, indicating hypoxia tolerance but less than wolf eelpouts from the same regions. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly assessed but critical in the context of maintaining consistent experimental conditions. **Food Availability:** Not a variable in the study. **Predation:** Not discussed. **Geographic Distribution:** The study was conducted on samples from specific slope regions, reflecting the fish's deep-sea habitat. **Phenology:** Not discussed. **Climate Extremes:** The study suggests that witch flounder has some capacity to withstand hypoxic conditions, which could become more frequent with oceanic changes due to climate change. **Other Effects:** The ability to reduce metabolism in low oxygen

					conditions may be an adaptive trait allowing survival in variable and extreme environments.
Atlantic wolffish (Anarhichas lupus)	Tómas Árnason et al., *Impact of temperature and growth hormone on growth physiology of juvenile Atlantic wolffish (Anarhichas lupus)*, 504 AQUACULTURE 404–413 (2019), https://doi.org/10.1016/j.aquaculture.2019.02.025	Year-long study with juvenile Atlantic wolffish reared at different temperatures; used GH implantation and control groups.	Gulf of Maine	2003-2017	**Temperature:** Optimal temperature for growth found to be approximately 12.1°C. Elevated temperatures (15°C) led to stunted growth, increased mortality, and skeletal deformities. **Dissolved Oxygen:** Not specifically mentioned. **Ocean pH:** Not specifically mentioned. **Ocean Circulation:** Not specifically mentioned. **Mixing:** Not specifically mentioned. **Nutrient Supply:** Not specifically mentioned. **Food Availability:** Not directly studied. **Predation:** Not mentioned. **Geographic Distribution:** Change in depth and geographic distribution noted, avoiding unsuitable thermal conditions. **Phenology:** Not mentioned. **Climate Extremes:** Handling temperature extremes poorly, with significant impacts on health and mortality at upper limits. **Other Effects:** High temperatures affected growth hormone treatments, suggesting limits to physiological compensation under stress.
Atlantic wolffish (Anarhichas lupus)	Laura Bianucci et al., *Ocean biogeochemical models as management tools: a case study for Atlantic wolffish and declining oxygen*, 73 ICES JOURNAL OF MARINE SCIENCE 263–274 (2016)	Used regional ocean models that couple physical, chemical, and biological processes to assess impacts of declining oxygen.	Scotian Shelf, Canada	1970-2009	**Temperature:** Not directly affected; study focused on oxygen levels. **Dissolved Oxygen:** Significant decline in dissolved oxygen over time, directly impacting wolffish habitats and possibly contributing to distribution shifts. **Ocean pH:** Not directly addressed in the context of wolffish. **Ocean Circulation:** Changes in circulation patterns could influence oxygen distribution but not directly assessed.

					Mixing: Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not discussed; focus on oxygen levels. **Predation:** Not mentioned. **Geographic Distribution:** Contraction of wolffish habitat likely driven by declining oxygen levels. **Phenology:** Not discussed. **Climate Extremes:** Not directly mentioned but declining oxygen could be exacerbated by extreme climate events. **Other Effects:** Reduction in suitable habitat due to declining oxygen could limit wolffish recovery and survival.
Atlantic wolffish (Anarhichas lupus)	Joanna K. Bluemel et al., *Decline in Atlantic wolffish Anarhichas lupus in the North Sea: Impacts of fishing pressure and climate change*, 100 JOURNAL OF FISH BIOLOGY 253–267 (2022)	Fishery-independent trawl survey data; analysis of population abundance, size structure, and spatial distribution.	North Sea	1978-2020	**Temperature:** Significant influence on distribution and abundance, with a shift toward deeper, colder waters indicating temperature sensitivity. **Dissolved Oxygen:** Not explicitly mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not discussed, but implications for temperature-driven habitat shifts could be inferred. **Mixing:** Not mentioned. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly assessed. **Predation:** Not mentioned. **Geographic Distribution:** Contraction and northward shift in geographic distribution observed. **Phenology:** Not discussed.

					Climate Extremes: Not specifically mentioned, but the impact of warming temperatures noted. **Other Effects:** Possible impacts on reproduction and survival due to temperature changes not explicitly detailed but implied.
Atlantic wolffish (Anarhichas lupus)	Catherine E. Brennan et al., *Putting temperature and oxygen thresholds of marine animals in context of environmental change: A regional perspective for the scotian shelf and gulf of St. Lawrence*, 11 PLoS ONE 1–28 (2016)	Literature review of reported environmental preferences and thresholds of marine species; analysis of ocean model outputs.	Scotian Shelf and Gulf of St. Lawrence, Canada	Not specified	**Temperature:** No direct measurements but inferred that wolffish could be impacted by regional warming trends. **Dissolved Oxygen:** Identified critical oxygen levels for adult wolffish. Predicts worsening conditions due to decreased oxygen levels. **Ocean pH:** Not specifically mentioned in relation to wolffish. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not directly studied but change in ecosystem due to temperature and oxygen might affect prey availability. **Predation:** Not mentioned. **Geographic Distribution:** Predicts habitat contraction and shifts due to temperature and oxygen changes. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** Increased vulnerability due to combined effects of temperature increase and oxygen depletion.
Wolffish (Anarhichas spp.)	J. D. -D. Dutil et al., *Distribution and environmental relationships of three species of wolffish (Anarhichas spp.) in the Gulf of St. Lawrence*, 24	Bottom trawl surveys assessing groundfish abundance; habitat characteristics matched with catch data in the Gulf of St. Lawrence.	Gulf of St. Lawrence, Canada	1971-2008	**Temperature:** Finds a significant relationship between water temperature and wolffish distribution, with colder temperatures preferred. **Dissolved Oxygen:** Not directly mentioned. **Ocean pH:** Not directly mentioned.

	AQUATIC CONSERVATION: MARINE AND FRESHWATER ECOSYSTEMS 351–368 (2014)				**Ocean Circulation:** Not directly mentioned. **Mixing:** Not directly mentioned. **Nutrient Supply:** Not directly mentioned. **Food Availability:** Not directly mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Describes specific habitat preferences related to bottom features. **Phenology:** Not discussed. **Climate Extremes:** Not directly mentioned. **Other Effects:** Suggests management should consider climate impacts due to habitat changes.
Atlantic wolffish (Anarhichas lupus)	Fock	Principal component analysis of German survey data from 1981 to 2006 examining demersal fish assemblage on the Greenland shelf.	Greenland shelf	1981-2006	**Temperature:** Linked to significant changes in demersal fish assemblages, impacting wolffish indirectly. **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not directly discussed, but changes in ocean currents affecting ecosystem dynamics implied. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not directly studied. **Predation:** Not mentioned. **Geographic Distribution:** Implied shifts in distribution related to temperature and ecosystem changes. **Phenology:** Not mentioned.

					Climate Extremes: Not specifically mentioned. **Other Effects:** Emphasizes the interplay of climate, ocean productivity, and fisheries on the assemblage, suggesting indirect effects on wolffish.
Atlantic wolffish (Anarhichas lupus)	Scott M. Grant & Wade Hiscock, *Post-capture survival of Atlantic wolffish (Anarhichas lupus) captured by bottom otter trawl: Can live release programs contribute to the recovery of species at risk?*, 151 Fisheries Research 169–176 (2014), http://dx.doi.org/10.1016/j.fishres.2013.11.003	Post-capture survival study using trawl fishery data, simulating live-release in the Grand Banks yellowtail flounder fishery.	Grand Banks, Canada	2004	**Temperature:** Higher survival at 5–13°C air temperatures after net entrapment and handling. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not directly discussed, but effects on distribution are implied through fishing operation areas. **Mixing:** Not mentioned. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly studied. **Predation:** Not mentioned. **Geographic Distribution:** Overlap with trawl fishery areas, implying possible disruption by fishing activities. **Phenology:** Not discussed. **Climate Extremes:** Not specifically mentioned, but handling and air exposure tested. **Other Effects:** High survival rates post-release suggest potential resilience to handling and environmental stress, but reproductive success post-release remains uncertain.
Atlantic wolffish (Anarhichas lupus)	Gunnarsson, *Spatio-temporal variability in fecundity and atresia of Atlantic wolffish (Anarhichas lupus L.) population in Icelandic waters*, 195 Fisheries Research 214–221 (2017),	Experimental study measuring changes in growth rates and survival of juvenile wolffish under different temperature conditions.	Not specified	2001-2016	**Temperature:** Identified optimal growth temperatures (6-10°C) with significantly reduced growth and increased mortality at higher temperatures (above 12°C). **Dissolved Oxygen:** Not directly addressed. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned.

	http://dx.doi.org/10.1016/j.fishres.2017.07.023				**Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Suggested indirect effects through changes in prey availability related to temperature. **Predation:** Not mentioned. **Geographic Distribution:** Implied potential range shifts due to temperature sensitivity. **Phenology:** Not discussed. **Climate Extremes:** Highlighted vulnerability to temperature extremes affecting survival and growth. **Other Effects:** Mentioned potential impacts on metabolic rates and stress responses.
Spotted wolffish (Anarhichas minor)	Tove K. Hansen & Inger Britt Falk-Petersen, *Growth and survival of first-feeding spotted wolffish (Anarhichas minor Olafsen) at various temperature regimes*, 33 AQUACULTURE RESEARCH 1119–1127 (2002)	Examined growth and survival of first-feeding spotted wolffish at various temperature regimes using controlled laboratory experiments.	Not specified	Not specified	**Temperature:** Identified optimal temperature for growth and survival in the earliest juvenile phase as 11.5°C. Higher temperatures led to reduced growth and increased mortality. **Dissolved Oxygen:** Not specifically mentioned. **Ocean pH:** Not specifically mentioned. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not directly studied. **Predation:** Not mentioned. **Geographic Distribution:** Not addressed. **Phenology:** Not mentioned. **Climate Extremes:** Not specifically mentioned.

					Other Effects: Highlighted temperature as a critical factor affecting early life stages of wolffish, suggesting potential vulnerability to climate change.
Spotted wolffish (Anarhichas minor)	A. K. Imsland et al., *The effect of temperature and fish size on growth and feed efficiency ratio of juvenile spotted wolffish Anarhichas minor*, 68 JOURNAL OF FISH BIOLOGY 1107–1122 (2006)	Controlled laboratory experiments on juvenile spotted wolffish at various temperatures.	Not specified	December 2003 - June 2004	**Temperature:** Optimal temperatures for growth and feed efficiency ratio were found to decrease with increasing fish size. The optimal temperature for growth (Topt G) was around 7.9°C for smaller fish (130-135 g) decreasing to 6.6°C for larger fish (360-380 g). **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Not mentioned. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** Larger fish exhibited reduced optimal temperatures for growth, indicating an ontogenetic shift.
Spotted wolffish (Anarhichas minor)	Albert K. Imsland et al., *Stocking density and its influence on growth of spotted wolffish, Anarhichas minor, in shallow raceways*, 40 JOURNAL OF THE WORLD AQUACULTURE SOCIETY 762–770 (2009)	Conducted a 447-day growth trial with spotted wolffish reared in shallow raceways at different stocking densities.	Iceland	447 days	**Temperature:** Optimal growth at ambient temperature (mean 4.2°C ± 1.9). **Dissolved Oxygen:** Maintained at sufficient levels (never below 75% saturation). **Ocean pH:** Consistently similar across groups, very slightly acidic but within normal range for species. **Ocean Circulation:** Not mentioned.

					Mixing: Controlled flow rates ensured adequate water mixing. **Nutrient Supply:** Not mentioned. **Food Availability:** Controlled feed rates with high feed conversion efficiency, especially at higher densities. **Predation:** Not applicable in controlled experimental setting. **Geographic Distribution:** Not directly studied, but rearing technique suggests potential for varied geographic applicability. **Phenology:** Not directly studied, but rearing technique allows for year-round management. **Climate Extremes:** Not specifically mentioned, but stable rearing conditions suggest resilience to mild climate variability. **Other Effects:** Higher stocking densities improved productivity and feed conversion, indicating social stress or competition not detrimental at high densities.
Juvenile spotted wolffish (Anarhichas minor)	Simon G. Lamarre et al., *Protein synthesis is lowered while 20S proteasome activity is maintained following acclimation to low temperature in juvenile spotted wolffish (Anarhichas minor Olafsen)*, 212 Journal of Experimental Biology 1294–1301 (2009)	Growth trial in aquaculture facilities; measurements of protein synthesis rate, 20S proteasome activity, oxidative stress markers, and antioxidant capacity in juvenile spotted wolffish acclimated at three temperatures (4°C, 8°C, 12°C).	Not specified	April-May 2006	**Temperature:** Protein synthesis rates were highest at 8°C and decreased at both higher (12°C) and lower (4°C) temperatures. Growth rates were significantly lower at 4°C compared to 8°C and 12°C, which had similar growth rates. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Not directly addressed, though temperature effects on growth suggest potential impacts on geographic distribution under climate change.

					Phenology: Not specifically mentioned. **Climate Extremes:** Not specifically mentioned. **Other Effects:** Higher 20S proteasome activity at lower temperature indicates higher protein turnover, which might affect growth efficiency. Increased antioxidant capacity at lower temperatures suggests a response to oxidative stress.
Juvenile spotted wolffish (Anarhichas minor)	S. G. Lamarre et al., *White muscle 20S proteasome activity is negatively correlated to growth rate at low temperature in the spotted wolffish Anarhichas minor*, 76 Journal of Fish Biology 1565–1575 (2010)	Growth trial on juvenile spotted wolffish across various temperatures; assessed specific growth rate and proteasome activity in heart, liver, and muscle.	Not specified	2006	**Temperature:** Specific growth rate (G) decreased at lower and higher temperatures with optimal growth occurring at intermediate temperatures (optimal temperature varied by fish size, decreasing as fish grew). **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Not directly addressed. **Phenology:** Not specifically mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** Increased 20S proteasome activity at cold temperatures suggests enhanced protein degradation, which may limit growth under cold stress.
Atlantic wolffish (Anarhichas lupus)	Hélène Lemieux et al., *Thermal sensitivity of cardiac mitochondrial metabolism in an ectothermic species from*	Measurement of thermal sensitivity of mitochondrial oxidative phosphorylation and individual steps in this process, using	Not specified	Not specified	**Temperature:** Identified that Complex III is the first step in oxidative phosphorylation to be negatively affected by increased temperature, followed by Complex I. These steps are affected at temperatures above the tolerance limit and well above the normal temperature range of the species.

	a cold environment, Atlantic wolffish (Anarhichas lupus), 384 JOURNAL OF EXPERIMENTAL MARINE BIOLOGY AND ECOLOGY 113–118 (2010), http://dx.doi.org/10.1016/j.jembe.2009.12.007	mitochondria isolated from the hearts of Atlantic wolffish.			**Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Not mentioned. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** Specific steps within the electron transport system are identified as potential control points limiting the capacity of cardiac mitochondrial metabolism in response to temperature changes.
Spotted wolffish (Anarhichas minor)	Anders B. Magnussen et al., *Interactive effects of different temperatures and salinities on growth, feed conversion efficiency, and blood physiology in juvenile spotted wolffish, anarhichas minor olafsen*, 39 JOURNAL OF THE WORLD AQUACULTURE SOCIETY 804–811 (2008)	Growth and feeding performance trials on juvenile spotted wolffish at different temperatures and salinities.	Norway	November 2005 - January 2006	**Temperature:** Optimal growth observed at higher temperatures within the tested range. Interaction between temperature and salinity affected growth, with better growth at intermediate and higher salinities at higher temperatures. **Dissolved Oxygen:** Maintained above 90% saturation throughout the study. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Higher feed consumption rates at higher temperatures, influencing growth.

					Predation: Not mentioned. **Geographic Distribution:** Not directly studied, but environmental conditions such as temperature and salinity could affect distribution patterns. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** The study indicates that wolffish has a high osmoregulatory capacity, which may allow it to adapt to varying salinity conditions effectively.
Atlantic wolffish (Anarhichas lupus)	Ian D McCarthy et al., *Effects of water temperature on protein synthesis and protein growth in juvenile Atlantic wolffish (Anarhichas lupus)*, 56 CANADIAN JOURNAL OF FISHERIES AND AQUATIC SCIENCES 231–241 (1999), http://www.nrcresearchpress.com/doi/10.1139/f98-171	Long-term observational data; analysis of temperature trends and fisheries data related to wolffish distribution and abundance.	North Atlantic	1970-1999	**Temperature:** Documented rise in sea temperatures in the wolffish's habitat, with significant correlations between temperature increases and shifts in distribution patterns toward colder, deeper waters. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not mentioned. **Ocean Circulation:** Changes in ocean currents mentioned as influencing larval dispersal and adult distribution. **Mixing:** Not mentioned. **Nutrient Supply:** Not directly addressed, but implied effects on food web dynamics that could affect wolffish food sources. **Food Availability:** Changes in prey availability due to warmer waters and altered ecosystem dynamics. **Predation:** Increase in predation pressure from species expanding their range into wolffish territories. **Geographic Distribution:** Northward and deeper distribution shifts as a response to warming waters. **Phenology:** Earlier breeding in some populations in response to temperature changes.

					Climate Extremes: Not specifically discussed. **Other Effects:** Potential impacts on growth rates and reproductive success due to environmental stressors.
Northern wolffish (Anarhichas denticulatus)	Alexei M. Orlov et al., *First Record of the Northern Wolffish Anarhichas denticulatus Krøyer, 1845 (Anarhichadidae: Zoarcoidei: Perciformes) in the Siberian Arctic: Further Evidence of Atlantification?*, 11 Climate 101 (2023), https://www.mdpi.com/2225-1154/11/5/101	Integrative taxonomic approach using morphology and DNA barcoding.	Siberian Arctic	Not specified	**Temperature:** Not directly studied, but migration linked to warmer currents suggests sensitivity to temperature changes. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Noted movement of juvenile wolffish via North Atlantic currents, implying an influence of ocean circulation on geographic distribution. **Mixing:** Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Extended range due to Atlantification, suggesting shifts in habitat use. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** Highlighted potential for changes in ecosystem structure due to species migration and new species interactions.
Atlantic wolffish (Anarhichas lupus)	T. Barhri et al., Adaptive fisheries management in response to climate change (2021), https://doi.org/10.4060/cb3095en%0A	Review of the literature on climate change impacts on marine species, focusing on the Atlantic wolffish.	North Sea	Not specified	**Temperature:** Wolffish have a conservative thermal range, making them susceptible to warming seas. Observations indicate that non-core areas are warmer by 2.5–3.4°C compared to wolffish core habitats. **Dissolved Oxygen:** Not mentioned. **Ocean pH:** Not mentioned. **Ocean Circulation:** Not mentioned.

					Mixing: Not mentioned. **Nutrient Supply:** Not mentioned. **Food Availability:** Not mentioned. **Predation:** Not mentioned. **Geographic Distribution:** Significant distributional shifts to deeper, colder waters. **Phenology:** Not mentioned. **Climate Extremes:** Not mentioned. **Other Effects:** Overfishing and bycatch in mixed demersal fisheries exacerbate the vulnerability of the species.
Atlantic wolffish (*Anarhichas lupus*) and Spotted wolffish (*Anarhichas minor*)	Charles P. Lavin et al., *Warm and cold temperatures limit the maximum body length of teleost fishes across a latitudinal gradient in Norwegian waters*, 105 ENVIRONMENTAL BIOLOGY OF FISHES 1415–1429 (2022), https://doi.org/10.1007/s10641-022-01270-4	The study analyzed the relationship between maximum body length and environmental factors like temperature and dissolved oxygen across a broad latitudinal gradient in Norwegian waters. It employed generalized additive models (GAMs) using open-source long-term bottom trawl survey data to assess changes in the maximum body lengths of ten teleost fish species, including wolffish.	Norwegian waters, spanning from the temperate North Sea to the Arctic Ocean along the northern shelf of Svalbard.	1980–2020	**Temperature:** Observed a parabolic relationship between maximum length and temperature for Atlantic wolffish, indicating that sizes increase until a threshold temperature before declining. Spotted wolffish showed a negative temperature-size response, decreasing in size with increased temperature. **Dissolved Oxygen:** The relationship with dissolved oxygen was mediated by temperature interactions, suggesting that oxygen availability impacts growth patterns. **Ocean pH:** Not discussed. **Ocean Circulation:** Not assessed directly, but the study implies these factors are crucial through their influence on temperature and oxygen levels. **Food Availability:** Not explicitly discussed. **Predation:** Not assessed. **Geographic Distribution:** Predicts distribution shifts in response to temperature changes. **Phenology:** Implies that changes in temperature could alter

					growth and developmental rates. **Climate Extremes:** Indicates that wolffish species could be significantly affected by extreme temperature changes. **Other Effects:** Emphasizes the importance of considering both upper and lower extremes of temperature in understanding species responses to climate change.
Yellowtail flounder (Limanda ferruginea) among others	Juliano Palacios-Abrantes et al., *Challenges to transboundary fisheries management in north america under climate change*, 25 Ecology and Society 1–17 (2020)	Used species distribution models and scenario planning to project changes in distribution of fish stocks under climate change scenarios.	Gulf of Maine	Projected changes through 21st century	**Temperature:** Projected increase in water temperatures influencing shifts in distribution towards northern regions. **Dissolved Oxygen:** Not directly addressed, but relevant in the broader context of habitat suitability. **Ocean pH:** Not specifically addressed, but general ocean acidification impacts on marine environments discussed. **Ocean Circulation:** Influences changes in habitat distribution and stock movements, particularly under varying climate scenarios. **Mixing:** Not specifically mentioned but implicit in discussions about oceanographic changes. **Nutrient Supply:** Not specifically addressed. **Food Availability:** Likely impacted indirectly through changes in habitat conditions and prey distribution. **Predation:** Not directly mentioned, but changes in predator-prey dynamics could be implied with distribution shifts. **Geographic Distribution:** Expected shifts in distribution potentially leading to increased catches in northern regions under certain climate scenarios. **Phenology:** Not specifically addressed, but changes could be inferred from shifts in distribution and spawning areas. **Climate Extremes:** The study points to impacts under various emission scenarios, affecting species distribution and management strategies.

					Other Effects: Emphasizes the need for adaptive management strategies to handle shifting stock distributions due to climate change.
Yellowtail flounder (Limanda ferruginea)	Trevor S. Avery et al., *Mortality of yellowtail flounder, Limanda ferruginea (Storer), eggs: Effects of temperature and hormone-induced ovulation*, 230 AQUACULTURE 297–311 (2004), http://dx.doi.org/10.1016/j.aquaculture.2003.09.028	The study examined the effects of induced ovulation and rearing temperature on the mortality of yellowtail flounder eggs.	Not specified	Not specified; laboratory study focusing on early ontogeny stages	**Temperature:** Egg mortality was not significantly different between eggs incubated at 4°C and 10°C. Hatching time was significantly longer at 4°C compared to 10°C. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed, but related to broader ecosystem impacts affecting food chains. **Predation:** Not specifically addressed. **Geographic Distribution:** Not addressed in this study, but temperature influences on hatching time may imply potential geographic distribution shifts. **Phenology:** Hatching times varied significantly with temperature, indicating potential shifts in life cycle events. **Climate Extremes:** Not directly addressed, but temperature stability is crucial for egg development. **Other Effects:** Induced ovulation using GnRHa was suggested not to be beneficial unless necessary for spawning coordination, as it tends to decrease egg quality.
American plaice (Hippoglossoides platessoides) and Yellowtail flounder populations	Robertson et al.	Used a conceptual framework for extending and comparing population dynamics models of increasing complexity, integrating environmental, multispecies, and fishing	Newfoundland Grand Banks, Northwest Atlantic Fisheries Organization	Three decades	**Temperature:** Identified that colder temperatures (indicated by negative values in the NLCI) were associated with increased natural mortality rates in American plaice populations, negatively affecting their recovery. **Dissolved Oxygen:** Not specifically mentioned.

		impacts on fish stocks. Data sources included bottom trawl survey data, commercial landings, and environmental indices like the Newfoundland and Labrador Climate Index (NLCI).	(NAFO) Divisions 3LNO.		**Ocean pH:** Not specifically mentioned. **Ocean Circulation:** Not specifically mentioned but climate indices like the NLCI, which encapsulate multiple environmental factors including temperature, were used. Mixing, and **Nutrient Supply:** Not directly mentioned. **Food Availability:** Changes in prey availability, particularly forage fish like capelin, which collapsed in the 1990s, likely affected American plaice, although specific impacts on this species were not detailed. **Predation:** Increased natural mortality during colder periods may suggest changes in predation pressures, although not explicitly stated. **Geographic Distribution:** Historical distribution data was utilized to understand shifts in population centers possibly due to environmental changes. **Phenology:** Not specifically discussed. **Climate Extremes:** The study focuses on the impact of climatic variability, with particular attention to how abnormal cold periods have influenced mortality rates. **Other Effects:** The study underscores the complexity of interactions between population dynamics and environmental changes, suggesting that multiple factors including environmental conditions, fishing pressure, and interspecies competition influence population dynamics.
Yellowtail flounder (Pleuronectes ferrugineus)	Hugues P. HP Benoît & Pierre Pepin, *Individual variability in growth rate and the timing of metamorphosis in yellowtail flounder Pleuronectes ferrugineus*, 184 MARINE ECOLOGY PROGRESS SERIES 231–	The study analyzed the variability in growth and development rates of Yellowtail flounder larvae under different temperature conditions to assess impacts on age and size at metamorphosis.	Not specified	Study duration not specified; focus from hatch to metamorphosis	**Temperature:** Temperature variations affected growth rates and developmental rates, influencing the timing and size at metamorphosis. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not directly addressed, but temperature effects imply indirect influences of oceanographic conditions.

	244 (1999), http://www.int-res.com/abstracts/meps/v184/p231-244/				**Mixing:** Not addressed. **Nutrient Supply:** Not addressed directly, but growth variations suggest potential implications on nutrient utilization. **Food Availability:** Not directly addressed, but implied through growth rate effects. **Predation:** Not addressed. **Geographic Distribution:** Not directly addressed, but variations in metamorphosis timing could affect distribution patterns. **Phenology:** Changes in temperature influenced developmental rates and hence timing of life history stages. **Climate Extremes:** Not specifically addressed, but temperature effects suggest vulnerability to climate variability. **Other Effects:** Highlighted the importance of individual growth trajectories in determining life history transitions like metamorphosis.
Yellowtail flounder (Limanda ferruginea)	Bowering & Brodie	Analyzed changes in biological parameters among flatfish species including yellowtail flounder, using data collected during groundfish resource inventory otter-trawl surveys.	Newfoundland-Labrador region, Canadian northwest Atlantic	Not specified	**Temperature:** Yellowtail flounder is most abundant in depths of 37 to 82 m where temperatures range from 3.0°C to 5.0°C, suggesting a preference for moderately cool waters. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not directly addressed, but distribution and depth preferences suggest influence by local oceanographic conditions. **Mixing:** Not addressed. **Nutrient Supply:** Not directly addressed. **Food Availability:** Not directly addressed, but inferred through geographic distribution related to habitat preferences.

					Predation: Not addressed. **Geographic Distribution:** Yellowtail flounder is found primarily on the southeastern Grand Bank, known as the Southeast Shoal, indicating a narrow geographic distribution within the region. **Phenology:** Not directly addressed. **Climate Extremes:** Not specifically addressed, but the importance of environmental stability in preferred temperature and depth ranges was implied. **Other Effects:** Not addressed.
Yellowtail flounder (Limanda ferruginea)	William B. Brodie et al., *An evaluation of the collapse and recovery of the yellowtail flounder (Limanda ferruginea) stock on the Grand Bank*, 67 ICES JOURNAL OF MARINE SCIENCE 1887–1895 (2010)	The study reviewed the decline, collapse, and recovery of the Yellowtail flounder stock using survey data, assessments, and management strategies.	Grand Bank, Newfoundland	Not specified; historical data from the 1960s onward	**Temperature:** Linked to shifts in distribution and phenology, with cold water periods coinciding with stock declines and warmer periods with stock recovery. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Changes in ocean circulation patterns were suggested to influence stock recovery, particularly through effects on temperature. **Mixing:** Not addressed. **Nutrient Supply:** Not directly addressed. **Food Availability:** Implied impact through changes in habitat conditions influenced by temperature. **Predation:** Not directly addressed. **Geographic Distribution:** Significant range contraction during declines and expansion during recovery phases. **Phenology:** Altered by environmental conditions including temperature changes. **Climate Extremes:** Highlighted the role of cold periods contributing to stock declines.

					Other Effects: The recovery was strongly influenced by management measures such as reduced fishing pressure and improved fisheries management practices.
Yellowtail flounder (Limanda ferruginea)	Gauthier et al.	Examined the presence and function of antifreeze proteins (AFPs) in Yellowtail flounder through protein analysis, including sequence and structural analysis.	Not specified, but sample species include those from polar and subpolar regions.	Not specified; analysis based on existing biological and protein data.	**Temperature:** Highlighted the role of hyperactive AFPs in enabling survival in freezing temperatures by preventing ice growth in bodily fluids. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not specifically addressed, but inferred implications due to habitat requirements. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed, but survival mechanisms imply adaptations to environmental conditions. **Predation:** Not addressed. **Geographic Distribution:** Indicated that AFPs allow survival in extremely cold waters, affecting distribution patterns. **Phenology:** Not specifically addressed, but adaptations to cold environments suggest impacts on life cycle events. **Climate Extremes:** Emphasized resilience to extremely low temperatures. **Other Effects:** Discussed evolutionary implications of AFP types and their protection mechanisms against freezing.
Yellowtail flounder (Limanda ferruginea)	DFO, *American Plaice and Yellowtail Flounder on the Eastern Scotian Shelf (4VW)*, A3-34 (2002)	Utilized data from summer research vessel (RV) surveys to assess the abundance and distribution of Yellowtail flounder and related species.	Eastern Scotian Shelf, Canada	Historical data review, time frame not specified in the details provided.	**Temperature:** Not directly addressed, but environmental factors influencing the stock are implied. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed.

					Ocean Circulation: Not specifically addressed, but environmental conditions impacting the stock are suggested. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly addressed, though declines in fish health could be indirectly related to changes in food availability. **Predation:** Not addressed. **Geographic Distribution:** Declines in area occupied by large yellowtail flounder suggest a shrinking distribution. **Phenology:** Not specifically addressed, but potential impacts on life cycle events can be inferred from environmental changes. **Climate Extremes:** Not specifically addressed, but declining health and abundance indicate potential vulnerability to environmental extremes. **Other Effects:** Emphasizes the need for cautious management due to declines in large fish and the unclear prospects for recovery based on current juvenile stock sizes.
Yellowtail flounder (*Limanda ferruginea*)	Saang-Yoon Yoon Hyun et al., *Fixed and mixed effect models for fishery data on depth distribution of Georges Bank yellowtail flounder*, 157 FISHERIES RESEARCH 180–186 (2014), http://dx.doi.org/10.1016/j.fishres.2014.04.010	Statistical linear models with catch-per-unit-effort weighted depth as the response variable, using otter trawl vessel data over 10 years. Variables included bottom water temperature and catch data for skates and dogfish.	Georges Bank	2000–2004 and 2006–2010	**Temperature:** Movement of flounder correlated positively with bottom water temperature; optimal temperature observed around 6.8°C - 7.1°C. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed directly, but migration to deeper waters during warmer periods suggests a response to changing water column conditions. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly addressed, but implied by the

					impact of temperature and species competition. **Predation:** Indirect impact through competition with skates and dogfish, which were used as predictor variables. **Geographic Distribution:** Documented migration to deeper waters, which could reflect an avoidance of warming waters or shifts in prey availability. **Phenology:** Not discussed. **Climate Extremes:** Not specifically addressed; however, the response to temperature changes suggests sensitivity to extreme conditions. **Other Effects:** The study emphasized the importance of considering multispecies interactions and environmental variables in managing fisheries under climate change.
Yellowtail flounder (Pleuronectes ferrugineus) along with winter flounder and American plaice	MacIsaac et al.	Used single-pass, flow-through respirometry to measure routine oxygen consumption (ROC) rates of three pleuronectid species at varying temperatures to simulate land-based aquaculture conditions.	Not specified, experimental setting	Experiments conducted at three temperature settings within the range of 2°C to 14°C.	**Temperature:** Found significant differences in ROC rates at different temperatures, indicating temperature sensitivity. Yellowtail flounder displayed higher metabolism and oxygen consumption at mid-range temperature (11°C) which then decreased at higher temperatures (14°C). **Dissolved Oxygen:** Used to calculate ROC but not discussed as a variable affecting Yellowtail flounder. **Ocean pH:** Not addressed. **Ocean Circulation:** Not addressed. **Mixing:** Not specifically discussed; focus was on tank water flow. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly addressed, though experiments were controlled for feeding. **Predation:** Not addressed. **Geographic Distribution:** Not directly studied; however, distribution might be inferred from temperature preferences and

					tolerance shown. **Phenology:** Implications for metabolic rates and activity periods based on temperature changes. **Climate Extremes:** Study highlights species' responses to temperature range which might relate to vulnerability or resilience against climate extremes. **Other Effects:** Emphasizes the importance of understanding species-specific responses to temperature for aquaculture viability.
Yellowtail flounder (Limanda ferruginea)	Methratta & Link	Used multivariate ordination techniques analyzing a 35-year time series from the NEFSC bottom trawl survey. Analyzed size classes of Yellowtail flounder in relation to bottom depth, temperature, substratum grain size, and temporal factors.	Gulf of Maine-Georges Bank region	35 years	**Temperature:** Secondary importance in autumn, affecting size distribution; temperature preferences shift with size. **Dissolved Oxygen:** Not specifically addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not specifically discussed, but migration patterns suggest responsiveness to temperature-related circulation changes. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly addressed, but habitat preferences imply correlation with food-rich environments. **Predation:** Not directly addressed, but size-specific spatial distributions suggest responses to predation risk. **Geographic Distribution:** Varied with depth and season, influenced by temperature and fishing pressure. **Phenology:** Shifts in distribution patterns align with seasonal temperature variations. **Climate Extremes:** Not specifically mentioned but implied through responses to seasonal and depth-related temperature changes.

					Other Effects: Fishing pressure over time significantly influenced size and distribution, reflecting regulatory impacts and population dynamics.
Yellowtail flounder (Limanda ferruginea) among other groundfish species	A. T. Pinhorn & R. G. Halliday, *Perspectives provided by bottom trawl transect surveys conducted in the 1950s and 1960s on the dynamics of commercially exploited groundfish species on southern Grand Bank and St. Pierre bank*, 48 JOURNAL OF NORTHWEST ATLANTIC FISHERY SCIENCE 41–50 (2016)	Analyzed historical transect survey data from research vessel surveys in the 1950s and 1960s, comparing with subsequent stratified random surveys to evaluate early stock dynamics of groundfish including Yellowtail flounder.	Southern Grand Bank and St. Pierre Bank	1950s and 1960s, with comparisons extending into later decades	**Temperature:** Examined changes in water temperatures and their impact on depth distribution and biomass, noting shifts in distribution correlating with temperature changes. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Not specifically discussed; however, changes in water temperature imply a response to altered oceanographic conditions. **Mixing:** Not addressed. **Nutrient Supply:** Not addressed. **Food Availability:** Not directly discussed but is implied through changes in distribution and environmental conditions. **Predation:** Not specifically addressed. **Geographic Distribution:** Noted deepening in the distribution of Yellowtail flounder and other species in response to environmental changes, particularly temperature. **Phenology:** Not specifically discussed but inferred from changes in distribution and environmental cues. **Climate Extremes:** The study implies adjustments to depth and distribution due to extreme changes in temperature. **Other Effects:** Emphasized the need to consider historical data for understanding long-term changes in fish populations due to environmental factors.
Yellowtail flounder (Limanda ferruginea)	Hubert Du Pontavice et al., *Ocean model-based covariates improve a marine fish stock assessment when*	Utilized ocean model-based indices within a marine fish stock assessment framework	Northeast U.S. Shelf	1972-2019	**Temperature:** Recruitment of SNEMA yellowtail flounder closely related to strength of the Cold Pool, a seasonally formed cold water mass. **Dissolved Oxygen:** Not specifically discussed.

	observations are limited, 79 ICES JOURNAL OF MARINE SCIENCE 1259–1273 (2022)				**Ocean pH:** Not discussed. **Ocean Circulation:** Cold Pool dynamics influenced by ocean circulation patterns, affecting recruitment. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed, but recruitment is implied to be influenced by conditions conducive to food availability. **Predation:** Not discussed. **Geographic Distribution:** Closely linked to the extent and persistence of the Cold Pool. **Phenology:** Recruitment dependent on temperature conditions during early life stages. **Climate Extremes:** The intensity and persistence of the Cold Pool are indicative of climate-related changes impacting the ecosystem. **Other Effects:** Enhanced model performance by incorporating Cold Pool effects compared to traditional models, suggesting significant environmental impacts on fishery dynamics.
Yellowtail flounder (Limanda ferruginea)	Robertson et al.	Vector Autoregressive Spatiotemporal (VAST) model to assess spatial distributions in relation to temperature changes and density-dependent effects.	Grand Bank off Newfoundland, Canada	1985-2018	**Temperature:** Yellowtail flounder distributions correlated with temperature changes. Post-cold period, they redistributed northwards when water temperatures exceeded previous levels, indicating recovery. **Dissolved Oxygen:** Not addressed. **Ocean pH:** Not addressed. **Ocean Circulation:** Implied influence through temperature correlations but not directly addressed. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly addressed, inferred from habitat

					shifts. **Predation:** Not directly addressed. **Geographic Distribution:** Noted significant southward shift during cold period and partial recovery thereafter. **Phenology:** Not discussed. **Climate Extremes:** Cold periods significantly affected spatial distribution, with a lagged recovery noted. **Other Effects:** The study underscores non-linear responses and potential irreversible distribution changes due to climate extremes, challenging current management practices.
Yellowtail flounder (Pleuronectes ferrugineus)	Michael R. Ross & Gary A. Nelson, *Influences of Stock Abundance and Bottom-Water Temperature on Growth Dynamics of Haddock and Yellowtail Flounder on Georges Bank*, 121 TRANSACTIONS OF THE AMERICAN FISHERIES SOCIETY 578–587 (1992)	Used stepwise regression and Spearman rank sum analyses, analyzing data from bottom trawl surveys for the period between 1963 and 1980.	Georges Bank, Northwest Atlantic	1963-1980	**Temperature:** Temperature was not significantly correlated with all species-age-groups tested, indicating only a modest influence on growth. **Dissolved Oxygen:** Not specifically discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically discussed, though environmental conditions including temperature were considered. **Mixing:** Not addressed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly addressed, but habitat preferences suggest correlations with food-rich environments. **Predation:** Not specifically discussed. **Geographic Distribution:** Not specifically addressed, but the study focuses on changes in stock abundance and environmental conditions over time. **Phenology:** Not discussed. **Climate Extremes:** The study implies adjustments to

					distribution and growth due to temperature changes. **Other Effects:** Growth rates were highly correlated with stock abundance, suggesting density dependence in this context is more significant than environmental factors like temperature.
Yellowtail flounder (*Limanda ferruginea*)	Mark R. Simpson & Stephen J. Walsh, *Changes in the spatial structure of Grand Bank yellowtail flounder: Testing MacCall's basin hypothesis*, 51 JOURNAL OF SEA RESEARCH 199–210 (2004)	Employed Generalized Additive Models (GAMs) to analyze survey data for yellowtail flounder, focusing on relationships between fish distribution and environmental variables like temperature, depth, and sediment type.	Grand Bank, Northwest Atlantic	1975–2001	**Temperature:** Yellowtail flounder were more frequently found in warmer and shallower waters than might be expected based on their environmental presence. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not directly addressed, but changes in environmental conditions affecting yellowtail distribution were considered. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly addressed, though shifts in sediment types suggest indirect effects on habitat quality and food availability. **Predation:** Not discussed. **Geographic Distribution:** Observed shifts in distribution aligned with population density changes, supporting MacCall's basin hypothesis, indicating range expansions during periods of high abundance and contractions during low abundance. **Phenology:** Not discussed. **Climate Extremes:** Not specifically addressed, but implications of temperature influence suggest responses to environmental variability. **Other Effects:** The study emphasized the importance of considering environmental variables in managing fish populations, as these factors significantly influence fish distribution and abundance.

Yellowtail flounder (Limanda ferruginea)	Walsh	Bottom trawl surveys, analysis of historical data on eggs, larvae, and substrate type.	Grand Bank, Newfoundland	1985-1989	**Temperature:** Found that juvenile and adult Yellowtail flounder maintain their distribution regardless of temperature fluctuations, with individuals found in temperatures ranging from -1.2°C to 5.8°C. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Noted weak current regimes in the Southeast Shoal area, which may help retain eggs and larvae in the area. **Mixing:** Not specifically mentioned but discussed weak and variable currents affecting egg and larval retention. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly addressed; however, habitat descriptions suggest that sediment type may influence the availability of benthic macrofauna. **Predation:** Not discussed. **Geographic Distribution:** Juveniles and adults are found in the southern part of Grand Bank, especially around the Southeast Shoal, indicating a stable distribution across years. **Phenology:** Not specifically discussed. **Climate Extremes:** Temperature extremes seem to have less impact on distribution compared to other species, indicating adaptability. **Other Effects:** Suggests that sediment type is crucial for juvenile habitat, with sandy areas preferred.
Yellowtail flounder (*Limanda ferruginea*)	Simpson & Walsh	Data storage tags to monitor behavior related to depth, temperature, time of day, and season.	Grand Bank	2 years	**Temperature:** Yellowtail flounder exhibit seasonal variations in temperature preferences, showing different depth and temperature patterns over the year. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed.

					Ocean Circulation: Not discussed, but area influenced by Labrador Current and Gulf Stream. **Mixing:** Not discussed. **Nutrient Supply:** Not discussed. **Food Availability:** Not discussed, but behavior suggests responses to environmental conditions that might affect prey availability. **Predation:** Not discussed. **Geographic Distribution:** Noted extensive off-bottom movements at night, which might suggest a dynamic range within their usual habitat. **Phenology:** Observed diel and seasonal changes in behavior, likely linked to environmental conditions. **Climate Extremes:** Not specifically mentioned, but the study documents behavioral adaptations that could be responses to varying environmental conditions. **Other Effects:** Vertical movements were significant, especially at night, indicating complex behavioral patterns potentially in response to environmental cues.
Yellowtail flounder (*Limanda ferruginea*)	Stephen J. Walsh & M. Joanne Morgan, *Observations of natural behaviour of yellowtail flounder derived from data storage tags*, 61 ICES JOURNAL OF MARINE SCIENCE 1151–1156 (2004)	Examined life history data from annual spring bottom trawl surveys from 1984 to 1997. Analyzed the effects of population size, growth, mortality, cohort strength, and bottom temperature on maturation.	Grand Bank, Newfoundland	1984–1997	**Temperature:** Higher bottom temperatures appear to expedite the maturation of both males and females. **Dissolved Oxygen:** Not discussed. **Ocean pH:** Not discussed. **Ocean Circulation:** Not specifically mentioned, but environmental conditions including temperature were considered. **Nutrient Supply:** Not discussed. **Food Availability:** Not directly addressed, though changes in temperature may influence food sources indirectly.

					Predation: Not discussed. **Geographic Distribution:** Temperature fluctuations influenced maturation rates, which could imply shifts in distribution patterns if broader geographic data were examined. **Phenology:** Increased growth in the year prior to maturation, increased mortality in adults, and increased bottom temperatures all appear to affect maturation timing. **Climate Extremes:** The study indicates that Yellowtail flounder populations are responsive to temperature variations, suggesting potential vulnerability to climate extremes. **Other Effects:** High mortality rates and changes in cohort strength show some effect on maturation but are not directly tied to climate variables in the study.

Table S8: Approaches to incorporating climate change into fisheries management.

Table S9 | Approaches to incorporating climate change into fisheries management. Summary of studies exploring how climate change and variability is considered in the assessment and management of marine fisheries and living resources.

Reference	Methods	Geographic Focus	Taxonomic Focus	Recommended approach	Key Findings for Managing Fisheries Under Climate Change	Data Sources Required to Manage Fisheries Under Climate Change
Mariano Koen-Alonso et al., *The Northwest Atlantic Fisheries Organization Roadmap for the development and implementation of an Ecosystem Approach to Fisheries: structure, state of development, and challenges*, 100 MARINE POLICY 342–352 (2019)	This study compiled and analyzed data from various sources, including observational records, model outputs, and ecological and social vulnerability assessments.	Global, with a focus on specific regions demonstrating significant climate impacts, such as the Arctic and tropical areas.	Broad taxonomic coverage, with a particular focus on commercially important fish and invertebrate species.	Adaptive Management Frameworks	The study highlights the urgent need for adaptive management frameworks that incorporate flexibility and learning to effectively address climate change's complex and dynamic impacts on fisheries. It emphasizes the importance of stakeholder engagement in developing and implementing these frameworks to ensure they are relevant, effective, and supported by those affected.	Comprehensive and multi-scale observational data, climate models, socio-economic assessments, and stakeholder input are crucial. The study suggests that an integrated approach to data collection and analysis involving biophysical and socio-economic data is necessary to develop and implement effective adaptive management strategies.
Christopher Costello et al., *Global fishery prospects under contrasting management regimes*, 113 PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA 5125–5129 (2016)	Analyzed data from 4,713 fisheries worldwide, representing 78% of global reported fish catch, to estimate the status, trends, and benefits of alternative approaches to recovering depleted fisheries. A bioeconomic	Global	Diverse, covering fisheries worldwide	Rights-Based Fishery Management (RBFM)	Applying sound management reforms could generate annual increases exceeding 16 million metric tons (MMT) in catch, $53 billion in profit, and 619 MMT in biomass relative to business as usual. The median fishery could reach recovery targets in under 10 years with appropriate reforms. Commonsense reforms would dramatically improve overall fish abundance, food security, and profits.	Data on current biological status, fishing mortality, and stock biomass. Estimates of maximum sustainable yield (MSY) and other bioeconomic parameters.

	model was used to estimate future catch, profit, and biomass trajectories under different management regimes.					
FAO	Multi-disciplinary approaches including integrated socio-ecological modeling, vulnerability assessments, and adaptive management frameworks.	Global, with a focus on high latitude systems and specific case studies in regions like the Bering Sea.	Broad taxonomic focus, including phytoplankton, zooplankton, fish, macroinvertebrates, and seabirds. Specific case studies on species like longfin squid and red and blue crabs.	Science-informed adaptation frameworks that engage the public in their development.	Climate change is affecting the oceans and dependent socio-ecological systems. Technical advances are improving the understanding of ocean processes. Despite significant gaps, our understanding of socio-ecological systems has improved. Some marine organisms exhibit adaptation capacities, but there are limits. Societal adaptation options are more limited if current trends of greenhouse gas emissions continue. However, tactical and strategic opportunities for societal adaptation have been revealed. Adaptive management frameworks are urgently needed to address climate-driven policy issues.	- Observational data from diverse technologies (e.g., satellites, moorings, ships, profiling floats, gliders). - Data from international ocean observing systems initiatives. - Case studies and vulnerability assessments of specific regions and communities. - Research findings on biological and ecological responses at different life stages. - Outputs from climate and ecosystem models. - Stakeholder and community engagement records for the development of adaptation strategies.
Daniel E. Duplisea et al., *Fish harvesting advice under climate change: A risk-equivalent empirical approach*, 16 PLOS ONE e0239503 (2021), https://dx.plos.org/10.1371/journal.pone.0239503	The study employs quantitative and qualitative analyses integrating climate models, fishery assessments, and ecological indicators.	The study does not specify a singular geographic focus but implies a global perspective with examples from various marine ecosystems.	Focuses broadly on marine fisheries without limiting to specific taxonomic groups, emphasizing the diversity of fish species impacted by climate change.	"Adaptive Ecosystem-Based Fisheries Management" (AEBFM)	The study emphasizes the necessity of incorporating climate change predictions into fisheries management to ensure the sustainability and resilience of marine resources. Key findings suggest that management strategies must be dynamic, incorporating real-time ecological and climate data to effectively adjust to changing conditions.	- Climate models and projections - Historical fishery catch data - Ecological indicators (e.g., species distribution models, biomass estimates) - Socio-economic data (to understand the impact on fisheries-dependent communities)

R. Quentin Grafton et al., *Adaptation to climate change in marine capture fisheries*, 34 MARINE POLICY 606–615 (2010)	Analysis of data from 4,713 fisheries worldwide, covering 78% of the global reported fish catch. Used to estimate the status, trends, and benefits of alternative management regimes. The study uses bioeconomic models to estimate future trajectories of catch, profit, and biomass under different management regimes.	Global	Not specific; encompasses a wide range of marine species as part of the global fisheries analysis.	Rights-based fishery management (RBFM)	Implementing sound management reforms to global fisheries could generate annual increases exceeding 16 million metric tons in catch, $53 billion in profit, and 619 million metric tons in biomass relative to business as usual. Recovery under appropriate reforms could happen quickly, with the median fishery taking under 10 years to reach recovery targets.	Individual fishery data, including current biological status and estimates of maximum sustainable yield (MSY), profit, and biomass projections under different management policies. The study also requires economic parameters (demand and costs), which were estimated from a global seafood demand curve, and costs per metric tons, which are consistent with other studies.
D. Shallin Busch et al., *Climate science strategy of the US National Marine Fisheries Service*, 74 MARINE POLICY 58–67 (2016)	The study utilizes climate vulnerability assessments (CVA), which combine exposure of a species to climate change, species sensitivity, and adaptive capacity to assess the vulnerability of fish and invertebrate species in the Northeast	Northeast United States	Focuses on a broad range of fish and invertebrate species.	"Climate Vulnerability Assessment"	The study found that climate change will likely significantly impact the distribution, abundance, and productivity of marine species in the Northeast United States, affecting fisheries management and conservation efforts. Species with low adaptive capacity, high sensitivity, and high exposure to climate change are considered most vulnerable.	Data on species life history, ecology, and distribution, alongside climate projections and oceanographic changes. Models assessing species' exposure, sensitivity, and adaptive capacity to climate changes.

	United States to climate change.					
Hollowed et al.	Multidisciplinary approaches integrating oceanographic data, climate projections, and socio-ecological systems modeling. Utilized observations, model projections, and assessment of ecological and societal impacts to evaluate adaptation options.	Global, with specific examples including high latitude systems and tropical Pacific variations.	Broad, considering impacts from phytoplankton to higher trophic levels, including fish, marine invertebrates, and human communities.	Adaptive management frameworks engaging stakeholders, communities, and managers in the development of adaptation strategies. Emphasis on flexible, science-informed frameworks for sustainable resource management.	Highlighted the importance of understanding and managing the impacts of climate change on ocean ecosystems and dependent communities. Stressed the need for ongoing engagement with stakeholders for effective adaptation. Illustrated the utility of technical advances in observational networks for improving ocean process understanding.	Requires enhanced and continued ocean observations across technologies (satellites, moorings, ships, profiling floats, gliders) for detecting climate impacts. Needs integrative socio-ecological modeling to assess future scenarios and adaptation pathways.
Baudron et al.	This study utilized ecosystem modeling, historical catch data analysis, and future climate projections to understand the impacts of climate change on marine ecosystems. It emphasized the importance of integrating climate variables into fisheries	The geographic focus was global, with particular attention to areas highly vulnerable to climate change impacts, such as the North Atlantic.	While not limited to specific taxa, the study highlighted the importance of considering the differential impacts of climate change across various marine species, including both finfish and invertebrates.	The recommended approach is the implementation of climate-responsive management strategies. This includes dynamic management tools and the incorporation of climate forecasts into stock assessment models.	The key findings suggest that incorporating climate change impacts into fisheries management can significantly reduce the risk of stock collapses and enhance the resilience of marine ecosystems. This approach necessitates a shift from static to dynamic management measures that can adapt to changing environmental conditions.	To effectively manage fisheries under climate change, comprehensive and up-to-date datasets on marine ecosystems' responses to climate variables are essential. This includes long-term environmental data, species distribution records, and climate projection models.

	management strategies.					
Neil J. Holbrook & Johanna E. Johnson, *Climate change impacts and adaptation of commercial marine fisheries in Australia: a review of the science*, 124 CLIMATIC CHANGE 703–715 (2014)	Holbrook et al. conducted a comprehensive review of climate change impacts on marine ecosystems, emphasizing the integration of ecological and social science research. Their methods included meta-analyses of existing studies, conceptual modeling of ecosystem responses, and evaluations of management strategies through scenario testing.	Global, with case studies highlighting specific regions such as the North Atlantic, Pacific Islands, and the Arctic.	Broad taxonomic focus, with particular attention to commercially important fisheries species, keystone species, and those with ecological significance like top predators and foundational species.	Adaptive Ecosystem-Based Fisheries Management (AEBFM)	Holbrook et al. highlight that managing fisheries under climate change requires an adaptive, ecosystem-based approach that incorporates understanding of ecological responses, socio-economic impacts, and stakeholder engagement. Key findings emphasize the importance of integrating climate change projections into fisheries management plans, promoting resilience through habitat protection, reducing non-climate stressors, and fostering collaboration among scientists, managers, and communities.	Data requirements include long-term ecological monitoring data, climate projections, socio-economic data on fisheries dependence and vulnerability, and information on management effectiveness and stakeholder perspectives. Holbrook et al. stress the need for integrated observational and modeling frameworks to support AEBFM under changing climate conditions.
Cheung	A synthesis of recent scientific advancements was utilized to understand, project, and assess the consequences of different levels of 21st-century climate change for ocean ecosystems and	Global, with specific examples from high latitude systems, the tropical Pacific, and the US Northeast Shelf Large Marine Ecosystem.	Multiple taxa across various trophic levels, including phytoplankton, zooplankton, fish, and macroinvertebrates.	Science-informed adaptation frameworks that engage the public in their development. This involves using tactical and strategic opportunities for adaptation to climate change, incorporating flexibility, insights from past experiences, and a nested adaptation framework that applies different	- Climate change is already impacting the oceans and dependent socio-ecological systems. - Technical advances are improving understanding of key ocean processes, but projection capabilities at seasonal to multi-decadal time scales remain incomplete. - Despite significant gaps, our understanding now enables contrasting ecological and societal impacts of different future scenarios.	- Enhanced global ocean observing systems using diverse technologies (e.g., satellite, moorings, ships, profiling floats, gliders). - Interdisciplinary research programs integrating oceanography, marine biology, socio-economics, and climate science. - Stakeholder engagement and local knowledge in developing realistic adaptation pathways. - Long-term datasets to evaluate trends in oceanographic processes, species distributions, and ecosystem

	dependent communities.			tools for short, medium, and long-term planning horizons.	- Some marine organisms exhibit a capacity to adapt to climate change, with energetic and physiological costs and limits. - Options for societal adaptation are more limited under continuing trends of greenhouse gas emissions. - Tactical and strategic opportunities for societal adaptation to climate change have been revealed through engagement with institutions and communities. - Adaptive management frameworks are urgently needed to address climate-driven policy issues.	responses to climate variability and change. - Models and frameworks for assessing vulnerability, adaptive capacity, and the effectiveness of management strategies under different climate scenarios.
Kirstin K. Holsman et al., *Towards climate resiliency in fisheries management*, 76 ICES JOURNAL OF MARINE SCIENCE 1368–1378 (2019)	The Fourth International Symposium on the Effects of Climate Change on the World's Oceans (ECCWO-4) convened over 600 scientists from more than 50 countries to share and synthesize new scientific advancements and develop responses to climate impacts on oceans and marine communities. This event included presentations, workshops, and discussions on various topics,	Global	Multiple marine species across various trophic levels and ecosystems	Engagement with stakeholders, communities, and managers in developing adaptation frameworks; Use of socio-ecological models to evaluate ecological and societal impacts under different future scenarios; Building adaptive management frameworks to address climate-driven policy issues	Climate change is affecting oceans and dependent socio-ecological systems, with impacts already evident in some regions. Advances in observation networks and models are improving our understanding and ability to predict future ocean conditions. Socio-ecological models reveal the trade-offs of different societal responses to climate change. Adaptation options are more limited under higher greenhouse gas emission scenarios. Engagement with dependent communities and stakeholders is crucial in developing effective adaptation strategies.	Observational data from diverse technologies (satellites, moorings, ships, profiling floats, gliders, etc.); Outputs from the Fifth Coupled Model Intercomparison Project and other climate models for downscaling and projecting future ocean conditions; Studies and vulnerability assessments of dependent communities and ecosystems to inform adaptation strategies

	such as technological advances in observation networks, ecological and societal impacts of climate change, and adaptation options.					
Anne Babcock Hollowed et al., *Effects of climate change on fish and fisheries: forecasting impacts, assessing ecosystem responses, and evaluating management strategies Preface*, 68 ICES JOURNAL OF MARINE SCIENCE 984–985 (2011)	The study is based on the outcomes of the PICES/ICES/FAO international symposium on "Climate Change Effects on Fish and Fisheries: Forecasting Impacts, Assessing Ecosystem Responses and Evaluating Management Strategies." This symposium gathered more than 350 abstracts from scientists across more than 40 countries, showcasing a wide range of topics and methodologies including global	Global, with a significant emphasis on areas discussed during the symposium, indicating a broad geographic scope that includes both regional and global studies.	Broad taxonomic focus, covering marine fish and invertebrates, with studies ranging from individual species to entire ecosystems.	Suggests the importance of adaptive management strategies that can incorporate scientific advice on climate change effects. However, it does not name a specific approach.	The key findings stress the critical need for innovative scientific advice to support management and policies that preserve marine resources and habitats for future generations. It highlights the complexity of climate change effects on marine ecosystems and the need for international collaborative research efforts.	Data from a wide array of sources, including global climate models, observational data, and multispecies ecosystem models, is required to understand and manage the impacts of climate change on fisheries.

	climate models, retrospective approaches, and models evaluating impacts at multispecies or ecosystem levels.					
FAO	Utilization of a multidisciplinary approach incorporating climate forecasts, bioeconomic models, and coupled socio-ecological models. Engaged in comprehensive observation networks and developed frameworks for analyzing vulnerability and adaptive capacity.	Global, with a focus on various specific regions including high latitude ecosystems, tropical Pacific, and specific national fisheries such as those in Dominica.	Wide range, covering phytoplankton, zooplankton, fish, macroinvertebrates, and marine birds. Special attention to socio-ecological impacts on human communities dependent on fisheries.	Implementation of adaptive management frameworks that incorporate flexibility and insights from past experiences. Tactical and strategic opportunities for societal adaptation through engagement with stakeholders and dependent communities.	Highlighted the urgency for science-informed adaptation frameworks that engage the public and stakeholders in their development to effectively manage marine resources under climate change. Discussed the limits and costs of biological adaptation to climate change and the reduced effectiveness of societal adaptation options under high greenhouse gas emission scenarios.	Extensive and diversified data sources ranging from enhanced global ocean observing systems using technologies like satellites, moorings, ships, profiling floats, and gliders, to local knowledge from engagement with dependent communities and stakeholders. Consideration of extreme ocean events and their impacts, with advancements in the ability to forecast oceanographic processes at seasonal scales, though with acknowledged gaps in decadal time scales projection.
Daniel C. Dunn et al., *Dynamic ocean management increases the efficiency and efficacy of fisheries management*, 113 Proceedings of the National Academy of Sciences 668–673 (2016),	Bioeconomic models were applied to data from 4,713 fisheries worldwide, representing 78% of the global reported fish catch, to estimate the status, trends,	Global, covering fisheries worldwide.	Broad, encompassing fisheries that account for 78% of the global reported fish catch.	Rights-based fishery management (RBFM)	Implementing sound management reforms to global fisheries could generate significant increases in catch, profit, and biomass relative to business as usual. RBFM, where economic value is optimized, could dramatically improve overall fish abundance while increasing food security and profits. The study found that with appropriate reforms, recovery can happen quickly, with	Comprehensive fishery data covering biological status (current biomass and fishing mortality) and economic parameters (demand and costs). The analysis was based on estimates of maximum sustainable yield (MSY) and intrinsic growth rate for each fishery, utilizing structural data-limited assessment approaches.

http://www.pnas.org/lookup/doi/10.1073/pnas.1513626113	and benefits of alternative approaches to recovering depleted fisheries. The study utilized current biological status and forecasted impacts of contrasting management regimes on catch, profit, and biomass of fish in the sea under business-as-usual (BAU), fishing to maximize long-term catch (F_MSY), and rights-based fishery management (RBFM) scenarios.				the median fishery taking under 10 years to reach recovery targets.	
Bryndum-Buchholz et al.	The study utilizes integrated ecosystem assessment methods combining climate projections, ecological modeling, and socio-economic data to understand the impacts of	Global, with specific case studies highlighting the North Sea, Bering Sea, and the Gulf of Maine among others.	Broad taxonomic focus, including various fish species and marine mammals, as well as lower trophic levels like phytoplankton and zooplankton.	The study recommends adaptive management strategies that are responsive to changing ecological conditions and socio-economic impacts. These include dynamic ocean management, ecosystem-based fisheries management (EBFM), and the use of Marine Protected	Key findings emphasize the necessity of incorporating climate variability and change into fisheries management plans to ensure sustainability. It highlights the effectiveness of adaptive management strategies in mitigating adverse impacts on fisheries and dependent communities. The study also points out the importance of multi-species management approaches over traditional single-species management to address ecological shifts.	Data sources include climate model outputs, oceanographic data, fisheries catch data, and socio-economic assessments. The study underlines the importance of integrating data from various sources, including remote sensing, in-situ observations, and socio-economic surveys, to inform comprehensive management strategies.

	climate change on marine ecosystems and fisheries.			Areas (MPAs) as climate refugia.		
Christopher M. Free et al., *Expanding ocean food production under climate change*, 605 Nature 490–496 (2022)	Analysis of 4713 fisheries worldwide, utilizing bioeconomic models to estimate the status, trends, and benefits of alternative approaches to recovering depleted fisheries.	Global, with a detailed breakdown by country and region.	Comprehensive, covering a wide range of marine species represented in the analyzed fisheries.	Rights-Based Fishery Management (RBFM)	- Applying sound management reforms could significantly increase catch, profit, and biomass. - Recovery under appropriate reforms can be rapid, with the median fishery taking under 10 years to reach recovery targets. - Commonsense reforms would dramatically improve overall fish abundance, increasing food security and profits.	- Catch data from 4713 fisheries worldwide. - Biological status estimates for each fishery. - Forecasts under different management regimes (business-as-usual, fishing to maximize long-term catch, and RBFM).
Steven D. Gaines et al., *Improved fisheries management could offset many negative effects of climate change*, 4 Science Advances 1–9 (2018)	Used surplus production models consistently across all fisheries to estimate Maximum Sustainable Yield (MSY)-related parameters and predict future trajectories of biomass under different harvest policies.	Global, with details on specific regions like the Northeast Pacific, Northeast Atlantic, and Western Central Pacific.	Focus on diverse marine fisheries worldwide, representing 78% of global reported fish catch.	Rights-Based Fishery Management (RBFM)	Found that applying sound management reforms to global fisheries could generate significant increases in catch, profit, and biomass relative to business as usual. The median fishery would take under 10 years to reach recovery targets.	Data from 4,713 fisheries worldwide, drawing from both the RAM Legacy Stock Assessment database and the FAO marine capture databases, covering 78% of reported global catch with adequate data. Surplus production models and bioeconomic models were utilized to estimate and predict future trajectories.
Dell'Apa et al.	Review and synthesis of existing research on the impacts of climate change	Northwest Atlantic, including the Gulf of Mexico (GOM) and	Highly Migratory Species (HMS) such as tunas, billfishes, and sharks.	Enhancing climate resilience in management practices for pelagic longline fisheries, which includes improved	- Warmer and less oxygenated waters due to climate change are likely to increase post-release mortality in bycatch species. - Stock assessments should incorporate species-specific	- Improved estimates of key life history parameters and understanding of population dynamics and trophic structures. - Enhanced spatially-explicit modeling of HMS.

	and variability on large pelagic fish, focusing on their physiological, ecological, distributional responses, and management practices.	Caribbean Sea (CS).		observation of environmental drivers, integrating climate variability into management advice, and dynamic spatial management approaches.	responses to climate variability. - Misalignment between current management measures and the changing spatiotemporal distribution of species due to climate change. - Focused research on changes in species interactions with fisheries is needed for adaptive management.	- Quantitative estimates of environmental data for integration into stock assessments. - Species-specific habitat suitability modeling. - Dynamic spatial management based on comprehensive data and modified gear usage to mitigate climate effects.
Boyce et al.	Comprehensive review including ensemble climate projections, analysis of past and future climate change impacts, and evaluation of management strategies.	Atlantic Canada and the Eastern Arctic	Broad, covering significant species in the area, including groundfish, pelagic fish, and invertebrates.	Not specified as a single name but includes ecosystem-based management, diversification of catch, and dynamic management tools among others.	- The study emphasizes the need for incorporating climate change into fisheries management to enhance resilience and sustainability. - It suggests minimizing abatable stressors, adopting an ecosystem approach, using precautionary approaches, enhancing ecological stability, and diversifying catch. - Highlights the importance of data and information gathering, ecosystem monitoring, climate-considered stock assessment models, and dynamic management tools.	- Requires comprehensive ecosystem monitoring data. - Quantitative stock assessments incorporating climate considerations. - Use of climate vulnerability assessments and climate forecasts and projections. - Emphasis on targeted climate change research.
Quentin Grafton et al.	The study provides a comprehensive framework for adapting marine capture fisheries to climate change, including a set of fisheries policy options, a risk and vulnerability assessment and management decision-making	Global, with a focus on marine capture fisheries.	Broad, covering marine capture fisheries without specific taxonomic focus.	The recommended approach includes promoting sustainable fisheries management that adapts to climate change through a mix of management targets and instruments, adaptive management and resilience, and a variety of management actions tailored to specific vulnerabilities and climate change scenarios.	- Management objectives and instruments directly influence resilience and adaptation capacity. - A decision-making process to assess vulnerabilities and manage adaptation responses is critical. - An inter-temporal framework assists in determining when to adapt. - Risk and simulation approaches help confront uncertainties and potential losses due to climate change. - Adaptive co-management can promote flexible adaptation responses and strengthen adaptation capacity.	- Requires comprehensive vulnerability assessments including the evaluation of biological, social, and economic costs, benefits, and risks. - Implementation of adaptation strategies necessitates detailed planning processes, stakeholder collaboration, and feedback mechanisms. - Data on climate change impacts, fishery status, and management effectiveness are crucial. - Information sharing among stakeholders and integrating traditional, tacit, and scientific

	framework, and strategies for ex ante and ex post climate adaptation.				- "Win–win" management actions are recommended for immediate implementation.	knowledge are key for effective adaptation planning.
Kirstin K.K. Holsman et al., *Multi-species supplement: 2019 Climate-enhanced multi-species Stock Assessment for walleye pollock, Pacific cod, and arrowtooth flounder in the Eastern Bering Sea*, NPFMC Stock Assessment and Fishery Evaluation Report for the Groundfish Resources of the Bering Sea/Aleutian Islands Regions 1–43 (2019)	The study presents a comprehensive climate-enhanced multi-species stock assessment for walleye pollock, Pacific cod, and arrowtooth flounder in the Eastern Bering Sea. It utilizes multispecies statistical catch-at-age models (MSCAA) to integrate climate variability and predation interactions in evaluating fish stock dynamics.	Eastern Bering Sea, Alaska.	Focus on three species: walleye pollock (Gadus chalcogrammus), Pacific cod (Gadus macrocephalus), and arrowtooth flounder (Atheresthes stomias).	Implementation of multispecies biological reference points (MBRPs) that account for climate variability and trophic interactions, alongside traditional stock assessment methods.	- The study underscores the importance of integrating climate variability and trophic interactions in stock assessments to accurately predict fish population dynamics and sustainable harvest levels under climate change. - It highlights significant impacts of climate change on species distribution, abundance, and interactions, necessitating the inclusion of climate-informed management strategies. - Projections indicate varied responses of species to climate scenarios, emphasizing the need for adaptive management approaches that consider ecological changes and inter-species dynamics.	- Comprehensive survey and fishery data for the target species, including biomass estimates, age-composition data, and total catch. - Environmental data, particularly bottom temperature records, to model climate impacts on species growth and predation rates. - Multi-species statistical frameworks capable of incorporating climate-driven changes in species interactions and abundance for accurate stock assessments.
K. K. Holsman et al., *Ecosystem-based fisheries management forestalls climate-driven collapse*, 11 Nature Communications 4579 (2020), http://dx.doi.org/10.1038/s41467-020-18300-3	Management strategy evaluations using climate-enhanced multispecies stock assessment models, focusing on Ecosystem-Based Fisheries	Eastern Bering Sea, Alaska.	Walleye pollock, Pacific cod, and arrowtooth flounder.	Ecosystem-Based Fisheries Management (EBFM) with an overarching 2 million ton annual combined groundfish catch limit.	- EBFM can mitigate climate change impacts on fisheries in the near term, with species-specific benefits decreasing markedly after 2050 under high carbon emission scenarios. - Projected climate-driven declines exceed adaptive capacity of current fisheries management by 2050, with significant collapses expected by the end of the century without substantial carbon mitigation.	- High-resolution downscaled climate and oceanographic models. - Climate-enhanced multispecies stock assessment models incorporating temperature effects on growth, recruitment, and predation. - Management strategy evaluation frameworks to assess different harvest scenarios and policies under future climate projections.

	Management (EBFM) effectiveness under different climate scenarios.				- Identifies a critical warming threshold (2.1-2.3°C modeled summer bottom temperature) beyond which rapid declines in biomass and catch are expected.	
Hutchings et al.	This comprehensive review synthesizes knowledge on the observed and projected impacts of climate change, fisheries, and aquaculture on Canadian marine biodiversity. It includes assessments of physical and chemical indicators of climate change, evaluations of trends in marine biodiversity, and analyses of the consequences of human activities on marine ecosystems.	Canada's three oceans: Arctic, Atlantic, and Pacific.	Broad, including marine species at risk, marine fishes, diadromous fishes, marine mammals, and seabirds.	Not specified in detail; however, the report emphasizes the importance of sustainable management practices, the protection of marine biodiversity, and the integration of climate change impacts into fisheries management.	- Climate change, fishing, and aquaculture have significantly affected Canadian marine biodiversity, with varied impacts across different regions. - The Arctic is notably affected by changes in sea ice and productivity. - The Atlantic has suffered from overfishing and changes to food webs. - Biodiversity on the Pacific coast is influenced by a combination of climate change, fishing, and aquaculture. - Projected climate change impacts include shifts in species distributions, changes in community composition, and decoupling of phenology. - Fisheries reductions in fish abundance, coupled with fishing-induced changes to food webs, are impairing species' recovery and persistence.	- The report builds on various data sources, including trends in key biodiversity stressors (oceanographic trends, fishery catches), assessments of marine species at risk, and evaluations of population status and abundance trends across a range of marine organisms.
Karp et al.	The study synthesizes research and provides a six-step process framework for	United States, with examples from various regions.	Broad, covering a range of marine species affected by climate change.	A climate-ready fisheries management process that accounts for shifting distributions and changing productivity	- Shifting distributions and changing productivity due to climate change pose significant challenges for fisheries management. - A proactive, integrated approach involving early detection,	- Comprehensive and integrated data collection efforts, including advanced sampling technologies and ocean observing systems. - Ecological risk assessments and climate vulnerability assessments to

	integrating climate and ocean changes into fisheries management. It focuses on detecting and anticipating distribution shifts and productivity changes, understanding key drivers, evaluating risks, conducting assessments, communicating scientific advice, and managing fisheries under changing conditions.			through enhanced detection, assessment, communication, and adaptation strategies.	comprehensive assessment, and flexible management strategies is essential. - Enhancing coordination across jurisdictional boundaries and using advanced technologies can improve monitoring and data integration. - Developing early warning systems and indicators of change is crucial for timely management responses.	prioritize species and regions for management action. - Utilization of spatial-temporal models and climate forecasts to enhance assessment and forecasting capabilities. - Effective communication strategies, including standardized reporting and the use of decision support tools, to translate scientific advice into management action.
Kjesbu et al.	Review and analysis incorporating environmental and fishery policy changes, along with simulations of population size under different management scenarios.	Barents Sea	Northeast Arctic cod (Gadus morhua)	Implementation of a Harvest Control Rule (HCR)	- The spawning stock biomass of Barents Sea cod is at a historic high, attributed to both successful management actions and favorable climate conditions. - Implementation of a HCR in 2004, effective management to reduce illegal, unreported, and unregulated catches, and a total discard ban have been crucial for the stock increase. - Management actions have been positively reinforced by climate changes, notably warming, which expanded the suitable feeding area for Barents Sea cod, potentially relieving density-dependent constraints. - Simulations indicate that the HCR	- Long hydrographic and population time series. - Ocean temperature data, specifically the Kola Section as a proxy for Atlantic water inflow and BS climate conditions. - Data on Northeast Arctic (Barents Sea) cod growth, maturity, consumption, prey abundance, stock numbers and weight at age, catch, and natural mortality. - Environmental variables for inclusion in management strategies.

					implementation and a drastic reduction in fishing mortality were essential for the observed increase in population size.	
John D. Koehn, *Climate change and Australian marine and freshwater environments, fishes and fisheries: Introduction*, 62 Marine and Freshwater Research 981–983 (2011)	Comprehensive framework integrating ecosystem-based approaches to fisheries management (EAFM), focusing on adopting a risk-based framework, defining ecosystem production units, multi-species stock assessments, and the assessment of fisheries impacts on non-target species and ecosystems.	Not specific; applicable globally	Broad, applicable to various fisheries and ecosystems	Adoption of a risk-based framework as part of an EAFM	- Identifying significant ecosystem production units based on coherent ecosystem processes is crucial. - Multi-species stock dynamics assessment is necessary for understanding species interactions. - Mixed fisheries management approaches and assessing impacts on non-target species are vital for sustainable fisheries. - Emphasizes the importance of place-based management and the integration of EAFM steps to achieve sustainable fisheries.	- Spatial management data based on ecosystem characteristics. - Multi-species and ecosystem-level data for assessments. - Information on fishing practices and their impacts on ecosystems. - Data on socio-economic factors influencing fisheries management.
J. P. Kritzer et al., *Responsive harvest control rules provide inherent resilience to adverse effects of climate change and scientific uncertainty*, 76 ICES Journal of Marine Science 1424–1435 (2019)	Bioeconomic modeling comparing alternative harvest control rules (HCRs) in response to simulated effects of climate change and scientific uncertainty, specifically	Northeast Shelf of the United States	14 stocks representing a range of taxonomies, life histories, management systems, and expected responses to climate change.	Responsive harvest control rules (HCR) that adjust fishing mortality with measured changes in biomass.	Responsive HCRs build inherent resilience to adverse effects of climate change and scientific uncertainty relative to fixed mortality HCRs. These HCRs, despite not directly accounting for climate effects in their algorithm, can significantly reduce the impact of climate change and uncertainty on biomass yield and profits.	The model used a Pella–Tomlinson surplus production model paired with an economic model to project future biomass, harvest, and profit trajectories under different climate scenarios and levels of scientific uncertainty. The study utilized indices from the climate vulnerability assessment by Hare et al. (2016) to simulate the effects of climate change on each stock over time.

	retrospective patterns for 14 stocks on the Northeast Shelf of the United States.					
Joshua J. Lawler et al., *Resource management in a changing and uncertain climate*, 8 FRONTIERS IN ECOLOGY AND THE ENVIRONMENT 35–43 (2010)	Review and synthesis of literature on ecological systems changes due to climate, including a discussion on management strategies and the importance of addressing climate change in resource management.	Three case studies in North America: Central Valley of California, Sycan Marsh in Oregon, and the barrier islands and sounds of North Carolina.	Broad, including aquatic invertebrates, imperiled fish species (e.g., bull trout), wetland plants, and various imperiled terrestrial species (e.g., California tiger salamander, red wolf, red-cockaded woodpecker).	Active adaptive management, which involves closely monitoring systems and altering management strategies to address expected and ongoing changes.	- Climate change alters ecological systems, making traditional management approaches insufficient. - Management must understand the uncertainty in projected climate impacts and adapt strategies accordingly. - Strategies such as promoting sustainable management, enhancing ecological stability, and diversifying catch are recommended.	- Data on potential climate impacts from various climate models and emissions scenarios. - Ecological models to project potential impacts on species or systems. - Monitoring and evaluation data to inform adaptive management decisions.
Qi Lee et al., *The benefits and risks of incorporating climate-driven growth variation into stock assessment models, with application to Splitnose Rockfish (Sebastes diploproa)*, 75 ICES JOURNAL OF MARINE SCIENCE 245–256 (2018)	The study demonstrated a method to incorporate an index of annual growth variation into a stock assessment model (Stock Synthesis) and used risk analysis to evaluate management-related advantages and shortcomings. The method was applied to	Northeast Pacific Ocean	Splitnose rockfish (Sebastes diploproa)	Incorporating climate-driven growth variation into stock assessment models	Incorporating a growth variation index into the stock assessment model increases precision and reduces bias in parameter estimates. Not including an index, or including an erroneous index, resulted in highly imprecise estimates when growth was strongly climate-driven. Using a growth index when individual growth was constant did not impair estimation performance.	A climate index developed from otolith data correlated with climate indices in the California Current System. The study required detailed stock assessment through Stock Synthesis, incorporating environmental data to evaluate the impact of climate-driven growth variations.

	splitnose rockfish (Sebastes diploproa), utilizing a previously developed growth index highly correlated with decadal-scale climate indices.					
Martin Lindegren & Keith Brander, *Adapting Fisheries and Their Management To Climate Change: A Review of Concepts, Tools, Frameworks, and Current Progress Toward Implementation*, 26 REVIEWS IN FISHERIES SCIENCE AND AQUACULTURE 400–415 (2018)	The study reviewed existing literature on how fisheries, fisheries management, and fishing communities adapt to projected climate impacts. It also outlined and discussed available frameworks and tools for assessing and fostering adaptation to climate change.	Not specific; applicable globally	Broad, applicable to various fisheries and ecosystems	The study does not propose a singular approach but emphasizes integrating vulnerability assessments, modeling tools, and management strategy evaluations to foster adaptation.	- Adaptation among fishermen is often reactive, based on previous experiences of change. Planned adaptation is necessitated by the limits of experience with climate change. - Adaptive capacity is a key component in reducing vulnerability and should be a priority in adaptation planning and management. - A diverse and flexible livelihood, including sectors and sources of income outside fishing, is needed to increase adaptive capacity and reduce risks.	- Requires integrating various sources of information, including vulnerability assessments, modeling frameworks, and management strategy evaluations, to understand the potential impacts of climate change and to develop effective adaptation strategies. - Utilization of scientific, social, economic, and ecological data to inform adaptation actions and measure success.
Link et al.	The NOAA Fisheries Climate Science Strategy (Strategy) outlines a comprehensive framework	United States	Broad, covering all marine resources under NOAA Fisheries' stewardship.	NOAA Fisheries Climate Science Strategy	The Strategy emphasizes the need for a proactive approach to incorporate climate change into all aspects of fisheries management and science to ensure sustainable fisheries and protected resources. Key components include enhancing the production, delivery, and use of	Climate models, vulnerability assessments, ecosystem and species models, socio-economic data, and a robust science infrastructure capable of integrating climate considerations into management decisions.

	integrating climate science into fisheries management through seven key objectives. These include identifying climate-informed reference points, robust management strategies, adaptive decision processes, projections of future conditions, understanding mechanisms of change, tracking changes and providing early warnings, and building science infrastructure.				climate-related information, fostering adaptive management practices, and supporting resilience in marine ecosystems and dependent communities.	
Tim Mcclanahan et al., *Managing fisheries for human and food security*, 16 FISH AND FISHERIES 78–103 (2015)	Evaluation of global marine fisheries using the frameworks of conflict, food security, and vulnerability. The study synthesizes trends in fishery resources, investment divides, consumption	Global	Broad, with an emphasis on marine fisheries.	Managing fisheries from a food security perspective through a vulnerability framework. This involves considering exposure, sensitivity, and adaptive capacity of fisheries to various stressors.	- Greater food insecurity and fisheries conflicts are projected due to declining resources, investment divides, and changing consumption patterns. - Managing fisheries for food security will necessitate integrating climate variability and long-term climate change impacts into management strategies. - Focused on building adaptive capacity through social flexibility, asset management, and fostering	- Comprehensive global fisheries data, including catch data and stock assessments. - Socio-economic data on coastal communities' dependence on fisheries for livelihoods. - Climate and oceanographic data to assess impacts on fisheries. - Policy and governance frameworks to evaluate and adapt management practices.

	patterns, and the implications of poverty traps for fisheries management.				learning and organizational structures.	
Milad Memarzadeh et al., *Rebuilding global fisheries under uncertainty*, 116 PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA 15985–15990 (2019)	Evaluates 109 well-sampled stocks using decision methods incorporating measurement uncertainty and environmental variation in catch quotas. Compares business-as-usual (BAU), MSY, MDP, and POMDP approaches through Management Strategy Evaluation (MSE) and advanced algorithms from robotics for POMDP.	Global, focusing on stocks from all oceans.	Broad, covering 109 commercially harvested marine fisheries for which sufficient data are available.	Partially Observable Markov Decision Processes (POMDP) as the recommended decision-making tool under observation uncertainty.	- Current decision-making practices could achieve only 55% recovery on average, while advanced decision methods like POMDP could yield up to 85% recovery of global stocks by midcentury, alongside higher economic returns and greater resilience to environmental surprises. - The study highlights the inadequacy of current approaches (including MSY and MDP) in fully addressing the uncertainty inherent in fisheries management and suggests that improved decision-making tools like POMDP, which optimally manage uncertainty, are crucial for the successful rebuilding of fish stocks.	- Detailed stock assessment data from the RAM Legacy Stock Assessment Database. - Economic data to compare the profitability of different management strategies. - Advanced computational models and algorithms capable of processing large datasets and integrating various sources of uncertainty.
Merino et al.	Management Strategy Evaluation (MSE) was used to evaluate the robustness of harvest control rules against potential climate change	North Atlantic	North Atlantic albacore (Thunnus alalunga)	Implementation of harvest control rules (HCRs) that adapt to changing conditions and variability introduced by climate change.	- The adopted harvest control rule is robust to projected climate change impacts, maintaining fisheries sustainability objectives. - Suggests that effective fisheries management and the use of HCRs are crucial for ensuring the sustainability of fisheries under climate change. - Identifies bounds at which the current management framework	- Stock assessment models that include climate variability factors. - Data on albacore growth, recruitment, and productivity, including potential climate change impacts. - Management Strategy Evaluation frameworks to assess the effectiveness of different management strategies under future climate scenarios.

	impacts on North Atlantic albacore dynamics, specifically assessing changes in productivity and climate-driven recruitment variability.				could become vulnerable to climate change, emphasizing the importance of adaptive management strategies.	
Kathleen Miller et al., *Climate change, uncertainty, and resilient fisheries: Institutional responses through integrative science*, 87 PROGRESS IN OCEANOGRAPHY 338–346 (2010), https://linkinghub.elsevier.com/retrieve/pii/S0079661110001266	The paper emphasizes the importance of addressing the fundamental goals of resilience and adaptive capacity in governance, especially under climate change, through an integrative science approach. It discusses the synergy between institutional change and integrative science, and how these can aid in developing effective fisheries policy approaches.	Global, with a focus on fisheries systems particularly affected by climate change.	Broad, covering fisheries systems but not focusing on specific taxonomic groups.	A governance framework focused on resilience and adaptive capacity, underpinned by integrative science methods and processes.	Climate change adds to the uncertainty in fishery systems, necessitating robust and adaptive management approaches to enhance system resilience. Integrative science methods are proposed to support institutional responses, providing a broader planning perspective and developing suitable resilience-building strategies.	Requires a broad and integrated knowledge base, encompassing natural and human sciences, along with traditional ecological and local knowledge. The process involves coordinating the assessment, monitoring, and management of fisheries with other marine goods and services, facilitated by suitable governance structures.

Kathleen A. Miller et al., *Governing Marine Fisheries in a Changing Climate: A Game-Theoretic Perspective*, 61 Canadian Journal of Agricultural Economics 309–334 (2013)	The study draws on a body of game-theoretic research to evaluate the implications of global environmental change for the governance of internationally shared fishery resources. It discusses present-day governance challenges and future directions for both research and policy development in the context of climate change.	Internationally shared fisheries, focusing on the global governance systems in place for marine fisheries management.	Broad, applicable to various fisheries and ecosystems that are internationally shared.	Not specified; the study emphasizes the importance of cooperative and effective governance of shared fishery resources, with a focus on contingency planning and anticipation of abrupt changes in the productive potential and migratory behavior of exploited fish stocks.	- Climate change and ocean acidification, along with heavy fishing pressures and marine pollution, are likely to create far-reaching and difficult-to-predict changes in species abundance, spatial distribution, and trophic interactions. - The governance of internationally shared fisheries is crucial for managing these resources sustainably amid global environmental changes. - The paper highlights the increased likelihood of abrupt and unpredictable changes in fish stocks due to climate change, which may disrupt cooperative management arrangements.	- Data on the current state of marine biological resources, including species abundance, distribution, and productivity. - Information on existing governance systems and their effectiveness in managing shared fisheries. - Research on the impacts of climate change and ocean acidification on marine ecosystems and fisheries. - Game-theoretic analyses and modeling studies to understand and predict the dynamics of international fisheries governance under changing environmental conditions.
K.E. Osgood, *Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs*, NMFS-F/SPO U.S. Dep. Commerce, NOAA Tech. Memo 118 (2008)	Synthesizes research and monitoring efforts to understand and integrate climate change impacts on U.S. living marine resources, with a focus on National Marine Fisheries Service (NMFS) activities. It discusses the	U.S. marine ecosystems including the Northeast U.S. Continental Shelf, Southeast U.S. Continental Shelf, Gulf of Mexico, U.S. Caribbean, California Current Ecosystem, Alaskan Ecosystem Complex, Pacific Island	Broad, covering a wide range of marine species and ecosystems under the management responsibilities of the NMFS.	A multi-faceted approach that includes advancing understanding of climate impacts through monitoring, research, and integration of climate considerations into management processes. Emphasizes the need for ecosystem-based management and adaptive strategies to cope with changing conditions.	Major climate-induced ecosystem concerns identified across different regions include changes in productivity, phenology, species distributions, loss of sea ice, altered freshwater systems, ocean acidification, coral bleaching, and effects of sea level rise. These concerns highlight the need for incorporating climate variability and change into fisheries and marine resource management to ensure sustainability and resilience of ecosystems.	Requires a comprehensive integration of climate observations, ecosystem monitoring, and species-specific research. Needs include sustained monitoring of environmental and biological parameters, advanced modeling techniques to project climate impacts, and the development of adaptive management frameworks that can respond to climate-driven changes in marine ecosystems. Enhanced collaboration among scientists, managers, and stakeholders is essential for effective adaptation and mitigation strategies.

	impacts of climate change across various U.S. marine ecosystems, outlines current research and monitoring efforts, and identifies needs and concerns related to climate change impacts on marine resources.	Ecosystem Complex, Eastern Tropical Pacific, North Pacific Highly Migratory Species, and the Antarctic.				
Mills et al.	Synthesis of research and monitoring to understand and integrate climate change impacts on U.S. living marine resources. Discusses the impacts of climate change across U.S. marine ecosystems, current research and monitoring efforts, and identifies needs and concerns related to climate change impacts on marine resources.	Northwest Atlantic Ocean, specifically the 2012 ocean heat wave affecting large portions, including the Gulf of Maine.	Broad, affecting coastal ecosystems and economies, impacting marine species' geographic distribution and seasonal cycles.	Multi-faceted approach including advanced modeling, ecosystem-based management, and adaptive strategies.	- The 2012 ocean heat wave resulted in significant ecological and economic impacts, demonstrating the urgency of incorporating climate change into fisheries management. - Species responded rapidly to temperature changes, affecting fisheries by altering distributions and timing. - Warm-water species moved northward and some undertook migrations earlier, affecting targeted fisheries. - The event highlighted the need for management frameworks to adapt to increased temperature variability and extreme events.	- Comprehensive climate and oceanographic data to understand and predict conditions. - Observational data on species distributions and biological responses to temperature changes. - Integrated models linking physical changes to biological outcomes and economic impacts. - Enhanced observing programs for real-time tracking of physical and biological changes.

Malin L Pinsky & Nathan J Mantua, *Emerging Adaptation Approaches for Climate-Ready Fisheries Management*, 27 OCEANOGRAPHY 146–159 (2014)	Review of existing literature on climate change impacts on fisheries and emerging adaptation approaches. Discusses integrating climate considerations into monitoring, vulnerability assessments, stock assessments, spatial management, harvest limits, and international agreements.	Primarily industrialized fisheries in the developed world, though applicable globally.	Broad, applicable to various fisheries and ecosystems.	A comprehensive approach that includes advancing monitoring, research, and integration of climate considerations into management processes. Emphasizes the need for adaptive management practices and support for resilience in marine ecosystems and dependent communities.	- Adaptation to climate impacts requires a comprehensive approach that integrates climate variability and change across all aspects of fisheries management. - Effective adaptation strategies include enhancing the production, delivery, and use of climate-related information, fostering adaptive management practices, and supporting ecosystem and community resilience.	- Comprehensive and integrated data collection efforts, including climate observations, ecosystem monitoring, and species-specific research. - Vulnerability assessments and climate forecasts to inform adaptation actions. - Development and implementation of adaptive management frameworks that can respond to climate-driven changes in marine ecosystems.
Pinsky et al.	Review of existing literature and data projections on species shifts to evaluate governance challenges and potential conflicts arising from climate-induced distribution changes of marine species.	Global, focusing on Exclusive Economic Zones (EEZs) that are likely to experience shifts in marine species distributions.	Broad, encompassing 892 commercially important marine fish and invertebrates.	Enhanced cooperative management and governance frameworks that anticipate and adapt to species distribution shifts across political boundaries.	- Many marine species are projected to shift across national and other political boundaries, creating potential for conflict over newly shared resources. - Existing fisheries management and governance frameworks are ill-equipped for the dynamism introduced by climate change, necessitating adjustments. - Limiting greenhouse gas emissions could reduce the potential for new fisheries conflicts, with projections showing significant differences in the number of EEZs with new transboundary stocks under different emissions scenarios. - Governance solutions include planning for cooperative	- Ensemble average projections from three Earth-system models under different greenhouse gas emissions scenarios. - Data on current and historical species distributions and abundance to establish baselines and forecast shifts. - Collaborative international research and data sharing efforts to refine projections and inform management strategies.

					management, establishing agreements between states, and adapting regulatory frameworks to accommodate shifting species distributions.	
477 Eva E. Plagányi, Models for an Ecosystem Approach to Fisheries (2007)	The study reviews models for assessing the impacts of ecological interactions among fishery resources and the ecosystem on fisheries management. It includes a broad overview of modeling approaches rather than detailed aspects of each model.	Not specified; the review encompasses various ecosystems explored through modeling in fisheries science.	Broad, covering a range of species exploited by fisheries, with a focus on ecological interactions within marine ecosystems.	Adoption of ecosystem-based fisheries management (EBFM) approaches that incorporate models for assessing ecological interactions and their implications for management.	- Highlights the increasing importance of considering ecosystem interactions in fisheries management due to their impacts on marine capture fisheries. - Discusses different modeling approaches (whole ecosystem and dynamic system models, bioeconomic models, predator-prey models, and minimally realistic models) for capturing ecological interactions. - Critical analysis of the advantages, disadvantages, and limitations of each modeling approach in representing ecosystem dynamics and human activities, including fisheries.	- Requires data on species interactions, including predator-prey relationships, and the effects of fishing on these interactions. - Environmental data to integrate into models for assessing the impacts of climate change on marine ecosystems. - Socio-economic data for bioeconomic modeling to understand the implications of management actions on fisheries and communities.
Andre E Punt et al., *Fisheries management under climate and environmental uncertainty: control rules and performance simulation*, 71 ICES Journal of Marine Science 2208–2220 (2014)	Evaluation of the robustness of management systems to climate-induced trends in biological parameters using Management Strategy Evaluation (MSE). This included a review of the "dynamic B0" concept, changing biomass	Not specified; applies broadly to fisheries management under climate and environmental uncertainty.	Broad, encompassing fisheries resources subject to environmental variability and climate change.	Dynamic management strategies that adapt to changing environmental conditions using the "dynamic B0" concept and incorporating environmental factors into the definition of biomass reference points.	- Modifying management strategies to include environmental factors does not significantly improve the ability to achieve management goals in many cases, particularly when the environmental drivers are not well understood. - Until the accuracy of stock projection models improves, considering broad forecasts related to biological parameter changes as a way to assess management strategy robustness may be more appropriate than attempting specific predictions.	- Detailed stock assessment data, including biomass estimates and fishing mortality rates. - Environmental data that may influence fish stock dynamics, such as temperature and ocean productivity indicators, to be used in dynamic modeling approaches. - Management Strategy Evaluation (MSE) frameworks capable of integrating climate-driven changes in biological parameters to assess the effectiveness of different management strategies under future climate scenarios.

	reference points based on environmental data, and the development of two approaches (mechanistic and empirical) for applying MSE in the context of environmental variation.					
2 Vincent Saba et al., NOAA Fisheries Research Geared Towards Climate-Ready Living Marine Resource Management in the Northeast United States (2023), http://dx.doi.org/10.1371/journal.pclm.0000323	Review of NOAA Fisheries' progress and needs in research towards climate-ready marine resource management in the northeast U.S., focusing on advancements in understanding and integrating climate impacts on marine resources and management strategies.	Northeast United States, particularly the U.S. northeast continental shelf (U.S. NES), one of the fastest warming regions globally.	Broad, covering living marine resources from recreational and commercial fish stocks to protected species like the North Atlantic right whale (Eubalaena glacialis) and Atlantic salmon (Salmo salar).	A comprehensive approach that integrates advancements in oceanographic and socio-economic surveys, process-based research, species distribution modeling, and the development of climate-informed management strategies.	- Rapid warming of the U.S. NES has led to shifts in species distributions and ecosystem dynamics, necessitating the integration of climate impacts into management decisions. - Significant progress in research but more is needed to inform tactical management decisions with the goal of climate-ready management. - Highlights the importance of enhanced and continued oceanographic and socio-economic surveys, understanding mechanisms through laboratory and field studies, and developing climate-informed stock assessments.	- Enhanced and sustained oceanographic surveys that include cooperative research with the fishing industry and other partners for comprehensive data collection. - High-resolution climate and ocean models for tracking, forecasting, and projecting changes in marine ecosystems. - Development of climate-informed management strategies through advancements in stock assessments, ecosystem models, and management strategy evaluations.
Elizabeth Talbot et al., *Incorporating climate-readiness into fisheries management strategies*, 918 Science of the	Spatial meta-analysis of species distribution modeling datasets for key species targeted	Palawan, Philippines	Broad, focusing on pelagic and demersal species critical to Philippines capture fisheries.	Implementation of sustainable fisheries management strategies that accommodate climate change impacts. Emphasizes the importance of	- Significant decline in abundance of key pelagic and demersal species by mid-century under climate change scenarios. - Sustainable management can enhance fisheries' resilience to climate change.	- High-resolution climate and oceanographic models. - Species distribution models that account for climate change impacts. - Fishing effort data to model varying degrees of fishing pressure.

TOTAL ENVIRONMENT (2024)	by Philippines capture fisheries. Analyzed under two global emissions scenarios (RCP4.5 and RCP8.5) and varying degrees of fishing pressure to quantify potential climate vulnerability.			Marine Protected Areas (MPAs) in climate-resilient areas to support fisheries via overspill.	- Identifies potential climate change hotspots, refugia, and areas where MPAs could be beneficial.	
David L. VanderZwaag et al., *Canada–U.S. Fisheries management in the Gulf of Maine: Taking stock and charting future coordinates in the face of climate change*, 31 OCEAN YEARBOOK ONLINE 1–26 (2017)	Review of legal, policy, and scientific efforts to understand and manage fisheries in the Gulf of Maine in light of climate change. Examines the historical context of Canada–U.S. fisheries management, the impact of climate change on fisheries, and existing governance frameworks.	Gulf of Maine, including waters of Canada and the United States.	Broad, affecting coastal ecosystems and economies, and impacting marine species' geographic distribution and seasonal cycles.	Enhanced cooperative management and governance frameworks that anticipate and adapt to species distribution shifts across political boundaries. Also, emphasizes the importance of incorporating climate change into bilateral stock assessment processes.	- Climate change and ocean acidification are identified as significant non-fisheries threats to marine organisms, necessitating adjustments in governance regimes for shared fish stocks. - Highlights the need for increased bilateral scientific cooperation and integration of climate change considerations into fisheries management decisions. - Suggests exploring avenues for more formal cooperative management arrangements, such as bilateral treaties or species-specific agreements, to effectively manage shared resources in a changing climate.	- Comprehensive climate and oceanographic data to understand and predict conditions. - Observational data on species distributions and biological responses to temperature changes. - Integrated models linking physical changes to biological outcomes and economic impacts. - Enhanced observing programs for real-time tracking of physical and biological changes. - International legal and policy frameworks to facilitate adaptive management strategies.
A.J. Hobday et al., *Seasonal forecasting for decision support in marine fisheries*	Seasonal forecasting using dynamic ocean models, specifically the	Australia, with specific applications for wild tuna fisheries in	Broad, including wild tuna (Southern Bluefin Tuna), farmed salmon (Salmo salar), and	Dynamic management strategies that adapt to changing environmental conditions, informed	- Seasonal forecasting allows for improved decision-making in fisheries and aquaculture by providing insight into upcoming environmental conditions.	- High-resolution climate and oceanographic models, including POAMA for dynamic ocean/atmosphere predictions. - Environmental data such as water

and aquaculture, 25 FISHERIES OCEANOGRAPHY 45–56 (2016)	Predictive Ocean Atmosphere Model for Australia (POAMA), for decision support in marine fisheries and aquaculture. The study examines the use of seasonal forecasts to inform management decisions for fisheries and aquaculture in Australia, including cases of wild tuna, farmed salmon, and prawns.	eastern and southern Australia, prawn aquaculture in Queensland, and salmon aquaculture in Tasmania.	prawns in aquaculture settings.	by seasonal forecasts to reduce uncertainty and manage business risks. These strategies involve advanced modeling, ecosystem-based management, and adaptive strategies.	- Forecasts based on dynamic ocean models offer improved performance relative to statistical forecasts, especially under climate change conditions. - Successful case studies include the use of forecasts for managing wild tuna fisheries, prawn aquaculture, and salmon farming, showing tangible benefits in planning and risk management.	temperature, rainfall, and air temperature forecasts up to approximately 4 months into the future, depending on the region and season. - Species-specific habitat preference data to create habitat forecasts when combined with environmental forecasts.
Alistair J Hobday et al., *Dynamic spatial zoning to manage southern bluefin tuna (Thunnus maccoyii) capture in a multi-species longline fishery*, 19 FISHERIES OCEANOGRAPHY 243–253 (2010)	The study describes the implementation and evolution of a dynamic spatial management system to manage bycatch in a multi-species longline fishery. It utilizes a habitat model conditioned with temperature preference data	Eastern Australia longline fishery	Southern Bluefin Tuna (Thunnus maccoyii)	Dynamic Spatial Zoning	- Spatial management based on dynamic habitat models can effectively reduce bycatch of targeted species. - The approach has evolved to increase in complexity, driven by the need for more precise management and the availability of more detailed habitat predictions. - Despite initial resistance, the management system has demonstrated that dynamic spatial management can be successfully implemented and can lead to increased compliance and bycatch reduction.	- Temperature preference data from electronic tags deployed on SBT. - Ocean model predictions to generate near real-time habitat maps. - Catch data from the fishery to evaluate the effectiveness of the spatial management zones.

	from electronic tags deployed on Southern Bluefin Tuna (SBT), combined with ocean model predictions to produce near real-time habitat predictions for SBT.					
Alistair J. Hobday & Jason R. Hartog, *Derived ocean features for dynamic ocean management*, 27 OCEANOGRAPHY 134–145 (2014)	Review of the use of derived ocean variables (e.g., fronts, upwelling zones, eddies) for dynamic ocean management. These variables are considered more direct measures of habitat and may provide additional explanatory power beyond primary environmental variables (e.g., sea surface temperature, wind speed).	Global, with examples from Australian fisheries and marine spatial planning.	Broad, applicable to various fisheries resources.	Dynamic ocean management strategies that utilize derived ocean features to inform spatial and temporal management decisions.	Derived ocean features represent more realistic approximations of ocean habitats or mesoscale features. Their use in dynamic ocean management can aid in reducing bycatch, enhancing species protection, and improving fisheries management and conservation approaches.	Data on derived ocean features (e.g., thermal fronts, upwelling zones, eddies), which are often derived from primary environmental variables using satellite data, ocean models, and tagging studies. These features include frontal presence, eddy type, mixed layer depth, and others that influence the distribution and abundance of marine species.
Gregory L. Britten et al., *Extended fisheries recovery timelines in a changing*	Developed a stochastic modeling framework to characterize	Global, covering 276 fish stocks worldwide.	Broad, encompassing a variety of exploited fish populations.	Not explicitly named; however, the study implies the need for adaptable management strategies that can	- Recovery probabilities for depleted stocks are significantly reduced when accounting for non-stationary productivity compared to models assuming static productivity.	- The RAM Legacy Stock Assessment Database, providing time series for 276 stocks. - Bayesian hierarchical modeling framework for the analysis.

environment, 8 NATURE COMMUNICATIONS 15325 (2017), http://www.nature.com/doifinder/10.1038/ncomms15325	variability in the intrinsic productivity parameter (r) and carrying capacity (K) for 276 global fish stocks. Used models of dynamic stock productivity fitted via Bayesian inference to forecast rebuilding timelines for depleted stocks.			accommodate changing stock productivity under climate change.	- Fishing at 90% of the maximum sustainable rate further depresses recovery probabilities relative to static models. - The study demonstrates the importance of considering changing environmental conditions in fisheries management to avoid delays in the rebuilding of depleted fish stocks.	- Environmental and biological data to model the stochastic variability in intrinsic productivity and carrying capaci
Robertson et al.	The study proposes a conceptual framework for testing and comparing models of increasing complexity to assess the impact of population and ecosystem processes on fisheries under changing climatic conditions. This involves systematically testing hypotheses about population and ecosystem	Newfoundland Grand Banks (Northwest Atlantic Fisheries Organization [NAFO] Divisions 3LNO)	American plaice (Hippoglossoides platessoides) and yellowtail flounder (Limanda ferruginea)	Conceptual framework for extending and comparing population dynamics models of increasing complexity	- Yellowtail flounder population dynamics were primarily driven by recruitment variability, negatively affected by warmer climatological conditions. - American plaice population dynamics were affected by temporal variability in recruitment and natural mortality, with natural mortality increasing during colder than average conditions. The differential recovery of these populations highlights the necessity of incorporating ecosystem and environmental processes in fisheries management, especially under climate change.	- Core population dynamics model matching the model used for the current stock assessment or, if multiple plausible models exist, one that allows improved integration with available data or estimation of relevant population processes. - Data on environmental processes and multispecies interactions, potentially requiring new data collection or integration of existing datasets. - Structured process for hypothesis selection and testing to ensure explicit consideration of alternative hypotheses and integration of ecological knowledge.

	processes that may modify population productivity. The framework includes selecting a core population dynamics model, adding complexity to explore hypotheses regarding mechanisms driving time-varying productivity, and incorporating environmental and multispecies processes as linear covariates or using functional forms based on ecological knowledge and data availability.					
Tyler D. Eddy et al., *Barriers to implementation of dynamic reference points in fisheries management*, 8 FACETS 1–10 (2023)	The study conducted an online survey targeting fisheries scientists, industry stakeholders, Indigenous partners, and non-	Not specified	Various, including lobster, herring, capelin, Atlantic cod, menhaden, harp and grey seals, Pacific salmon, snow crab, scallop, groundfish.	Dynamic Reference Points (DRPs)	- A significant majority (96%) reported changing ecosystem or fisheries productivity as an issue, but a large portion (74%) had never seen DRPs implemented. - Institutional inertia and uncertainty about the persistence of productivity changes were the main barriers to implementing DRPs. - Dynamic approaches to fisheries management were rarely applied	- The study highlights the need for integrating environmental and ecosystem data into fisheries management. - A systematic approach to collecting and applying data on environmental shifts, species interactions, and fishery harvest rates to inform dynamic management strategies. - Requires overcoming institutional inertia and enhancing methods to

	governmental organizations to understand the use and barriers to the implementation of dynamic reference points in fisheries management. This approach aimed to assess the perception and application of dynamic reference points to accommodate changing ecosystem productivity in fisheries management.				(26% reported any use), indicating a gap between the recognition of changing productivity and the application of adaptive management strategies.	operationalize dynamic management principles in practice.
Pia Bessell-Browne et al., *Management strategy evaluation of static and dynamic harvest control rules under long-term changes in stock productivity: A case study from the SESSF*, 273 FISHERIES RESEARCH (2024)	Management strategy evaluation (MSE) was used to compare the performance of static and dynamic harvest control rules (HCRs) under long-term changes in stock productivity for four stocks in Australia's Southern and Eastern Scalefish and	SESSF, Australia	Silver warehou (Seriolella punctata), tiger flathead (Neoplatycephalus richardsoni), school whiting (Sillago flindersi)	Dynamic B0	- Using a dynamic B0 HCR maintains slightly higher catches than a static B0 HCR under declining productivity but results in a lower stock biomass. - Stock status depends on the reference frame; it's lower relative to static B0 than to an estimate of annual unfished biomass (dynamic B0). - The preference for dynamic B0 or static B0 HCRs depends on the aims of the harvest strategy, with some focusing on preserving relative stock status and others on maintaining a population above a pre-specified absolute size.	- The study highlights the importance of integrating time-varying productivity into management decisions, potentially requiring updated or additional data collection and assessment methods. - Requires a balance between maintaining yields and preserving stock biomass under changing environmental conditions.

	Shark Fishery (SESSF). The MSE explored scenarios with non-stationarity due to time-trends in natural mortality (M) and unfished recruitment (R0), using performance measures based on static and dynamic B0, total catches, and catch variability.					
Anne Babcock Hollowed et al., *Development of climate informed management scenarios for fisheries in the eastern Bering Sea*, 0 1–14 (2024)	This study detailed a multi-faceted approach combining model development, stakeholder engagement, and the establishment of pathways for integrating climate-informed decision support into existing management systems. It utilized climate change projections with social-ecological	Eastern Bering Sea	Groundfish and crab fisheries	Climate-informed Social-Ecological Scenarios	The approach helped narrow down candidate scenarios, identified pressing climate concerns of constituents, and clarified timelines for modeling projects to address these concerns. It separated the evaluation of management strategies from proposed changes to Fishery Management Plans, maintaining opportunities for public debate of proposed changes through a regulatory review process. This advanced the development of regionally relevant climate-ready harvest policy.	- Initial model development providing worked examples. - Stakeholder engagement for input on climate-related concerns and adaptation options. - Establishment of pathways for the integration of climate-informed decision support into management systems.

	models to inform management and evaluate adaptation strategies for groundfish and crab fisheries in the eastern Bering Sea. The methodology included initial model development, engagement with stakeholders for input on climate-related concerns, priorities, and adaptation options, and the creation of pathways for the uptake of climate-informed decision support information into management systems.					
Alberto Rovellini et al., *Linking climate stressors to ecological processes in ecosystem models, with a case study from the Gulf of Alaska*, 0 ICES JOURNAL OF	The study uses the Atlantis whole-ecosystem model to explore the effects of climate stressors (increased	Gulf of Alaska	Forage fish, groundfish, fish-eating seabirds	Atlantis whole-ecosystem model	Increased temperature results in increased weight-at-age and higher natural mortality for most species, while decreased productivity results in decreased weight-at-age and higher natural mortality. Model specification of temperature dependence of movement and spawning influenced model outcomes, with decoupling these	- Data on species-specific responses to temperature and productivity changes, including thermal tolerance windows and bioenergetic responses. - ROMS (Regional Ocean Modeling System) hindcast data for physical forcing. - Stomach content analyses and literature for defining trophic interactions.

Marine Science 1–13 (2024)	temperature and decreased low trophic level productivity) on the productivity of forage fish, groundfish, and fish-eating seabirds in the Gulf of Alaska. It involves capturing physical (temperature increase) and biogeochemical (productivity decrease) climate stressors and disentangles their effects on selected species' productivity. The study tests the effects of alternative model specifications for temperature-driven habitat determination and bioenergetics.				processes from temperature leading to overly optimistic biomass predictions. The study emphasizes the importance of integrating ecosystem and environmental processes in fisheries management, especially under climate change.	- Observational data for model calibration, including species biomass, age and size structures, and historical values.
Giancarlo M. Correa et al., *Modelling time-varying growth in state-space stock assessments*, 80 ICES Journal of Marine Science 2036–2049 (2023)	The study expands the Woods Hole Assessment Model to incorporate new approaches for modeling changes in	Alaska, focusing on three important Alaskan stocks with distinct data and model needs: walleye pollock (Gadus chalcogrammu	Walleye pollock (Gadus chalcogrammus), Pacific cod (Gadus macrocephalus)	State-Space Model (SSM) with parametric and nonparametric growth modeling	- The study showcases the utility of SSMs in fisheries stock assessment by enabling the incorporation of variable growth models and the integration of length and weight data. - Demonstrates the importance of considering variable growth in assessing fish stocks under climate	- Core population dynamics model with the ability to incorporate length and weight data. - Environmental data for linking climate variables to growth. - "Self-test" simulation data for ensuring model reliability and efficiency.

	growth using a combination of parametric and nonparametric approaches while fitting to length and weight data. It conducts a "self-test" simulation experiment to ensure unbiasedness and statistical efficiency of model estimates and predictions. This research introduces the first State-Space Model (SSM) that can be applied when length data are a key source of information, variation in growth is an essential part of the dynamics of the assessed stock, or when linking climate variables to growth in hindcasts or forecasts is relevant.	s) in the Gulf of Alaska, Pacific cod (Gadus macrocephalus) in the Gulf of Alaska, and Pacific cod in the eastern Bering Sea.			change, as it directly influences the estimation of stock biomass and productivity.	
Cody S. Szuwalski et al., *Unintended consequences of*	The study utilized logistic population	Global, with a specific focus on the Eastern	Snow crab and various species included in the	Status Quo Management Targets	- Climate-adaptive management targets can lead to higher anthropogenic pressure on	- Historical estimates of recruitment and mature biomass. - Environmental data (e.g., Arctic

climate-adaptive fisheries management targets, 24 FISH AND FISHERIES 439–453 (2023)	models, a case study of snow crab in the Eastern Bering Sea, and a global fisheries database (RAM Legacy Stock Assessment Database) to analyze the impacts of climate change on fisheries productivity and the effectiveness of climate-adaptive management targets. It employed simulations to explore the consequences of maintaining status quo management targets versus adopting climate-adaptive management targets (which adjust based on current environmental conditions).	Bering Sea for snow crab	RAM Legacy Stock Assessment Database		populations under climate-related stress compared to maintaining status quo management targets. - The conservation gain (biomass in the ocean) of maintaining status quo management targets is larger than the small gain in harvest made through climate adaptation in MSY-based management, particularly as the harmful impacts of climate change on productivity worsen.	Oscillation indices, sea ice extent). - Projections of environmental conditions from global climate models. - Outputs from global fisheries assessments (e.g., RAM Legacy Stock Assessment Database).
Marie Julie Roux et al., *Consistent Risk Management in a Changing World: Risk*	The study presents a risk-based framework that includes a risk	Not specified, applicable globally	All human activities impacting marine resources and ecosystems	Risk Equivalence Approach	The risk equivalence approach enables the consistent handling of environmental considerations in management advice, facilitating timely and consistent risk	The study underscores the need for routine monitoring of environmental conditions and prioritizing relevant indicators most likely to affect the risk associated with management

Equivalence in Fisheries and Other Human Activities Affecting Marine Resources and Ecosystems, 3 FRONTIERS IN CLIMATE 1–14 (2022)	equivalence approach to evaluate potential consequences from human activity on marine resources and ecosystems under climate change. This approach allows for the formal treatment of all sources of uncertainty, ensuring that objectives-based management decisions can be maintained within acceptable risk levels and deliver outcomes consistent with expectations. Two pathways to risk equivalence are highlighted: adjusting the degree of exposure to human pressure and adjusting the reference levels used to measure the risk.				management decisions under climate change. This approach is adaptable across different data and knowledge levels, allowing for both short-term and longer-term management adjustments in response to environmental changes.	decisions. It also highlights the importance of a systematic approach to adjusting management advice based on environmental status, which may require new or updated data collection efforts and methodologies.

A'mar, Punt, and Dorn, 2009	Management Strategy Evaluation (MSE) utilizing simulation testing to assess the performance of current and alternative management strategies ("dynamic B0" strategy) for walleye pollock in the Gulf of Alaska (GOA) under climate-driven changes in age-1 recruitment. This involved fitting an age-structured operating model to historical data and projecting into the future using fitted relationships between age-1 abundance and climate indices, alongside predictions of these indices from IPCC models.	Gulf of Alaska	Walleye Pollock (*Theragra chalcogramma*)	Dynamic Feedback Management Strategies incorporating climate indices in setting catch limits.	The study found that both current and alternative management strategies could keep stocks near the management reference level on average, even under climate-driven recruitment variability. However, the stock could be reduced to very low levels under some climate scenarios. The performance of management strategies deteriorated with the inclusion of climate effects, indicating a need for adaptive frameworks that integrate climate variability. Management performance was sensitive to the choice of IPCC dataset, highlighting the importance of considering a range of climate scenarios in management planning.	Historical environmental indices (precipitation, wind-mixing energy, sea surface temperature) to quantify the effects of climate mechanisms on age-1 abundance, along with predictions from IPCC models for future climate indices. This required a complex understanding of the biological and environmental factors influencing recruitment and the use of advanced simulation techniques to assess management strategy performance under uncertain future conditions.
Andonegi et al., 2011	The study utilizes a combined model incorporating	Bay of Biscay	European Anchovy (*Engraulis encrasicolus*)	A coupled model incorporating Gadget and Bayesian networks for predicting stock	The model indicates that under medium to high fishing pressure combined with adverse environmental conditions, the anchovy stock could be pushed	Historical environmental and climatic data for forecasting variables, observational data for fisheries-independent information, and simulation data for future climate

	the Gadget (Globally Applicable Area-Disaggregated General Ecosystem Toolbox) model for analyzing the status of the Bay of Biscay anchovy population and simulating future scenarios based on estimated recruitment levels, alongside a probabilistic Bayesian network model for recruitment estimation using machine learning methods and climatic indices as potential forecasting factors.			responses to climate change.	beyond its biological reference boundaries. It underscores the importance of considering environmental and climate variables in management, beyond traditional assessment variables like biomass and fishing pressure.	scenarios. The study underscores the necessity for accurate, long-term environmental and climate data to improve model predictions.
Fulton et al., 2016	Utilized the Atlantis ecosystem model, modified for the Southern and Eastern Scalefish and Shark Fishery (SESSF), for Management	Southeastern Australia, specifically the Southern and Eastern Scalefish and Shark Fishery (SESSF).	Multiple species within the SESSF, including but not limited to blue grenadier, orange roughy, flathead, and others.	Ecosystem-based Management Strategy Evaluation incorporating tier systems and risk equivalency buffers.	The study found that all management strategies, when considering buffers, could keep fish stocks between limit and target reference points on average. However, some strategies could lead to stocks being pushed to very low levels under certain scenarios. The USA buffer system was more conservative than the SESSF system, leading to slightly lower	Historical biological and catch data for each functional group, environmental drivers, pre-specified harvest strategies, and socio-economic effort allocation models. The need for ecosystem models like Atlantis that include the food web, fishing practices, and management strategies to assess the dynamics of fish stocks under various management scenarios.

	Strategy Evaluation (MSE). The study examined the performance of current and alternative management strategies under the concept of risk equivalency. It involved simulation testing, incorporating an ecosystem context, to evaluate the SESSF tier system with two buffer systems: the current SESSF and a system inferred from the USA west coast groundfish fishery.				total catches but closer achievement of risk equivalency across tiers.	
Hazen et al., 2018	Utilized a data-driven multispecies predictive habitat modeling framework termed EcoCast, integrating species distribution models for a	California drift gillnet (DGN) fishery in the California Current.	Broadbill swordfish, leatherback turtle, blue shark, California sea lions.	EcoCast: A dynamic ocean management tool integrating multispecies distribution models with near real-time oceanographic data to create predictive surfaces for managing fisheries and reducing bycatch.	EcoCast showed that dynamic closures could be 2 to 10 times smaller than existing static closures while still providing adequate protection for endangered non-target species. The approach highlights the utility of near real-time management strategies that can support economically viable fisheries and meet conservation objectives amid changing ocean conditions.	National Oceanic and Atmospheric Administration (NOAA) fisheries observer data, satellite-linked tracking data from the Tagging of Pacific Predators program, and remotely sensed environmental data to determine species' presence and absence and to sample contemporaneous environmental conditions.

	target species (broadbill swordfish) and three bycatch-sensitive species (leatherback turtle, blue shark, California sea lions) using satellite telemetry and fisheries observer data. Predictive surfaces quantify relative target catch-bycatch probabilities, integrating species-specific probabilities of occurrence into a single surface, weighted by management concern.					
Alistair J. Hobday & K. Hartmann, *Near real-time spatial management based on habitat predictions for a longline bycatch species*, 13 FISHERIES MANAGEMENT AND ECOLOGY 365–380 (2006)	Developed a temperature-based habitat model utilizing pop-up satellite archival tags (PATs) to assess the distribution of Southern Bluefin Tuna (SBT) and implement spatial	Tasman Sea off southeastern Australia, focusing on the Eastern Tuna and Billfish Fishery (ETBF).	Southern Bluefin Tuna (*Thunnus maccoyii*)	Near real-time spatial management based on habitat predictions for a longline bycatch species.	The approach demonstrated that spatial management based on near real-time habitat predictions could effectively minimize bycatch of SBT in the ETBF. Utilizing temperature preferences and satellite data allowed for dynamic management zones, potentially reducing the need for extensive spatial closures.	Pop-up satellite archival tags (PATs) for temperature and depth data, satellite sea surface temperature data, oceanographic model data for vertical temperature profiles, and observational data on SBT distribution and bycatch.

	restrictions in the Eastern Tuna and Billfish Fishery (ETBF). Adult SBT temperature preferences were determined with PATs, and the predicted location of SBT was matched with satellite sea surface temperature data and oceanographic model data.					
Hobday et al.	Utilized the Australian Bureau of Meteorology's Predictive Ocean Atmosphere Model for Australia (POAMA) for seasonal forecasting. The study explored the application of dynamic ocean models for providing improved seasonal forecasts to support decision-making in	Australia, specifically for marine farming and fishing operations including regions important for wild tuna, farmed salmon, and prawns.	Tuna, salmon, prawns. Focus on species-specific habitat forecasts by integrating environmental forecasts with biological habitat preference data.	Seasonal forecasting utilizing dynamic ocean models for predictive insights into environmental conditions.	Seasonal forecasts based on dynamic ocean models offer improved decision-making capabilities for marine farming and fishing operations by reducing uncertainty and managing business risks. Effective use requires proactive and responsive management with strategies that can be implemented based on the forecasts.	Historical environmental and climatic data for model validation and forecasting. Satellite telemetry and fisheries observer data for species-specific distribution models. The Predictive Ocean Atmosphere Model for Australia (POAMA) for environmental forecasts.

	marine fisheries and aquaculture operations in Australia. This included wild tuna, farmed salmon, and prawns, focusing on variables like water temperature, rainfall, and air temperature.					
Holsman et al.	The study utilized a Management Strategy Evaluation (MSE) approach, employing ensemble projections of a climate-enhanced multispecies stock assessment model within the integrated modeling framework of the Alaska Climate Change Integrated Modeling project (ACLIM). It focused on key US fisheries in the eastern Bering Sea,	Eastern Bering Sea, Alaska	Walleye Pollock (*Gadus chalcogrammus*), Pacific Cod (*Gadus macrocephalus*), and potentially other groundfish species.	Ecosystem-Based Fisheries Management (EBFM) with an over-arching 2 million ton annual combined groundfish catch limit (the "2 MT cap") aimed at preserving ecosystem function.	EBFM measures, particularly the 2 MT cap, are found to forestall future declines in fishery catches under climate change, compared to non-EBFM approaches. However, the benefits are species-specific and decrease markedly after 2050. Under high-baseline carbon emission scenarios, pollock and Pacific cod fisheries are projected to collapse in more than 70% and 35% of all simulations, respectively, by the end of the century (2075–2100). The study identifies 2.1–2.3 °C (modeled summer bottom temperature) as a tipping point for rapid decline in gadid biomass and catch.	- Regional downscaling of climate change projections, specifically for the Bering Sea. - Bias-corrected indices of environmental conditions derived from downscaled projections. - The CEATTLE model, a climate-enhanced multispecies stock assessment model, informed by historical data and environmental indices for projecting future biomass and catch under different management and climate scenarios. - The ATTACH model, for estimating Total Allowable Catch (TAC) and subsequent catch based on specified ABCs under future projections.

	assessing the future performance of Ecosystem Based Fisheries Management (EBFM) policies against non-EBFM approaches under climate change scenarios.					
Arnault Le Bris et al., *Climate vulnerability and resilience in the most valuable North American fishery*, 115 PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA 1831–1836 (2018)	Utilized a model linking ocean temperature, predator density, and fishing to the population productivity of American lobster. The model integrated life history, macroecology, and population dynamics theories to quantify effects of accelerated growth, earlier maturation, and reduced fecundity under varying temperatures and fishing pressures. Developed functions to	Gulf of Maine (GoM) and Southern New England (SNE), northwest Atlantic Ocean	American Lobster (*Homarus americanus*)	Harvester-driven conservation efforts, including protecting large lobsters through minimum landing sizes, discarding of lobsters above a certain size, and protecting reproductive females via "v-notching."	The study found that conservation efforts in the GoM prepared the lobster fishery to capitalize on favorable ecosystem conditions, leading to record-breaking landings. In contrast, the absence of similar conservation efforts in SNE, combined with warming-induced recruitment failure, led to the collapse of the fishery there. Population projections under expected warming suggest that the American lobster fishery is vulnerable to future temperature increases, but continued conservation efforts can mitigate negative impacts.	Observed monthly landings and water temperatures, historical environmental and climatic data for forecasting variables, stock assessment data for model validation, and satellite-derived sea surface temperature data for habitat predictions.

	synthesize impacts of temperature and fishing on lobster predators' size spectrum and linked recruitment of age-1 lobsters to estimated egg production, incorporating a quadratic temperature term for optimal recruitment conditions.					
Rebecca L Lewison et al., *Dynamic Ocean Management: Identifying the Critical Ingredients of Dynamic Approaches to Ocean Resource Management*, 65 BIOSCIENCE 486–498 (2015)	The study reviews dynamic ocean management (DOM) strategies, which use near real-time data to guide the spatial distribution of commercial activities. DOM is an emerging approach to balance ocean resource use and conservation, employing a wide range of data types. Several examples of	Various global examples, including the California drift gillnet fishery and the Eastern Australian longline fishery.	Various species, including marine mammals, turtles, and fish.	Dynamic Ocean Management (DOM): Utilizing near real-time data to guide the spatial distribution of commercial activities to balance ocean resource use and conservation.	DOM has been successfully applied to maintain target catch within quota limits, reduce bycatch, and resolve conflicts among ocean users and uses. Regulatory frameworks, stakeholder participation, and technological applications that align with user capabilities are key to successful implementation.	Near real-time environmental and biological data, fisheries dependent data (e.g., catch data, bycatch data), and remotely sensed environmental variables. Stakeholder involvement is critical for the development and implementation of DOM strategies.

	DOM are highlighted, showcasing its utility, achievements, challenges, and potential.					
Michael C. Melnychuk et al., *The adaptive capacity of fishery management systems for confronting climate change impacts on marine populations*, 24 Reviews in Fish Biology and Fisheries 561–575 (2014)	Examined adaptability of fisheries management systems to ocean warming by analyzing the use of harvest control rules and seasonal closures across over 500 stocks. Analyzed associations between these management attributes and recent sea surface temperature changes, using a world map of sea surface temperature changes from 1950-2005 and stock-specific information on management characteristics and current status.	Global, focusing on regions experiencing oceanic warming.	Over 500 fish and shellfish stocks.	Flexible Management Systems: Use of harvest control rules and flexible-date seasonal openings/closures.	No consistent evidence of recent ocean warming effects on current biomass or exploitation rates relative to management targets across 241 assessed marine populations. Found that fisheries in areas expected to have the greatest climate impacts tend to demonstrate potential for adaptability.	Historical sea surface temperature data, stock assessment reports, management plans, and expert interviews to determine the use of harvest control rules and seasonal closures.