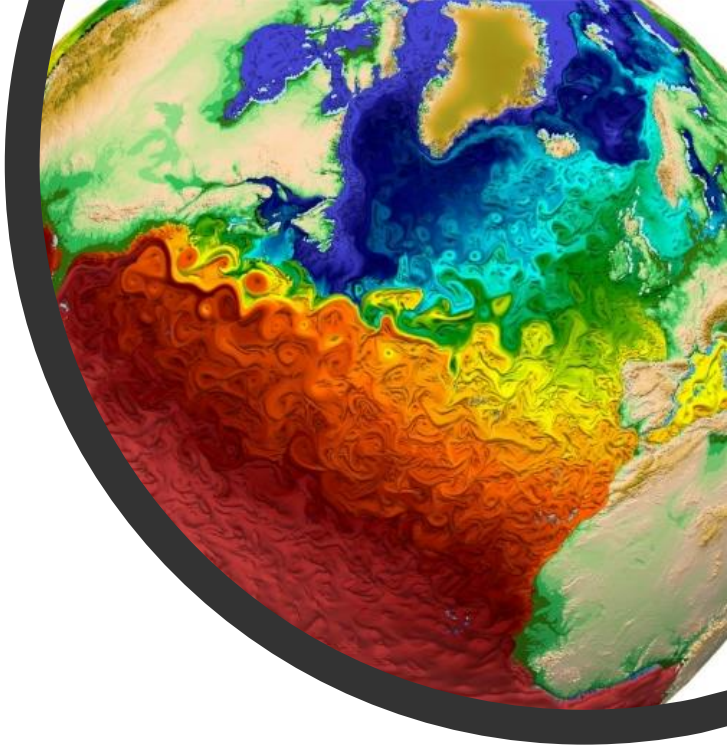
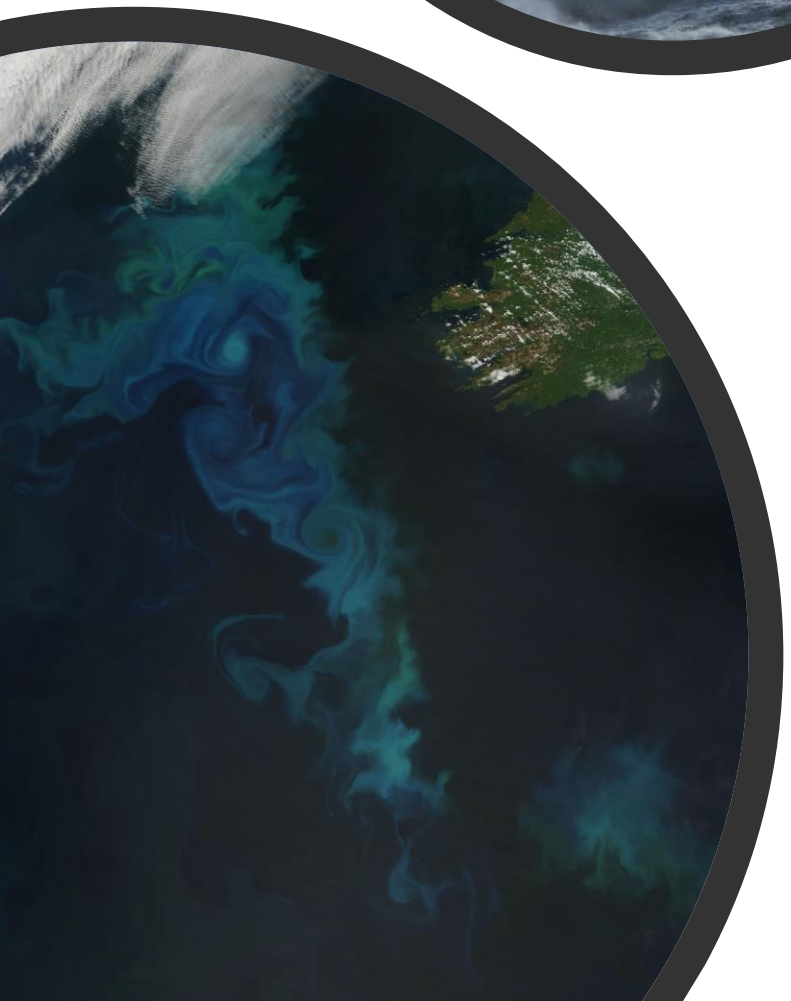




Addressing the impacts of climate change on NAFO fisheries

Dan Boyce
www.danielboyce.ca

Global climate picture: The highlights

Trends:

- Warming: surface and bottom
- Reduced sea ice
- Reduced mixing, increased stratification, reduced nutrient flux
- Acidification
- Hypoxia: dead zones
- Increased salinity
- Greater extremes

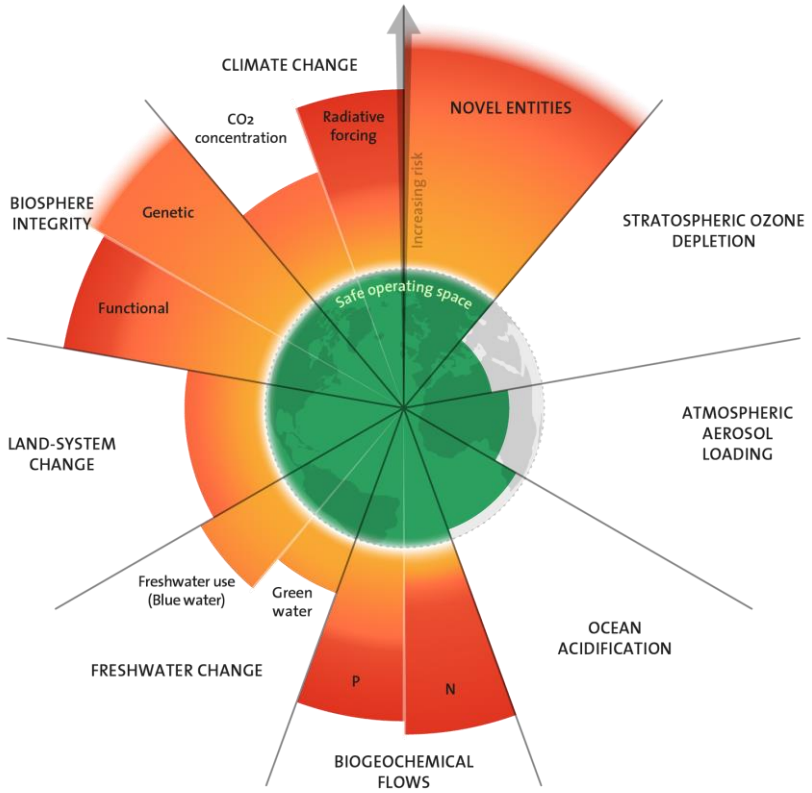
Biological impacts:

- Reduced NPP, altered size and community composition
- Ecological disruption: Geographic shifts, phenology, abundance, mortality, growth, trophic structure, disease
- Fisheries: 4.1% decline in MSY since 1930 (Free *et al.* 2019 *Science*)

→ Significant geographic variation

→ Heightened uncertainty

Departing Earth's safe operating spaces



Richardson *et al.* 2023 (*Science Advances*)

Outline (Terms of Reference)

- Review the most recent ocean **climate change predictions** in the Northwest Atlantic for the following 10 years and 50 years and summarize how this may affect the ecosystem and the likely impacts on managed stocks and non-target species.
- Identify any **new data requirements** needed to detect and monitor climate-related changes in the key ocean variables, including fished stocks, bycatch species, and changes in catch and effort patterns and distributional shifts across stock boundaries. Comment on the existing and potential methods by which such data sets could be collected.
- Summarize the literature and data available to address potential **climate change impacts** on NAFO-managed stocks, non-target species and associated ecosystems.
- Describe the data available to determine **climate change-related distributional shifts** of the managed stocks across stock boundaries, including transboundary stocks.
- Identify how the long-term unidirectional changes and shorter-term extreme variability in environmental conditions characteristic of climate change could **be incorporated into stock NAFO stock assessments**.

1. Climate *changes*

2. Climate *impacts*

3. Climate *resilience*

Outline (Terms of Reference)

1. Climate *changes*

- Historical
- Projected
- Direction, magnitude
- Scales of variance

2. Climate *impacts*

- Species, ecosystems, fisheries
- NAFO species

3. Climate *resilience*

- Data and monitoring
- Knowledge and approaches
- NAFO Roadmap

Methods

1) **Literature review:** >800 peer-reviewed studies, reports, assessments relevant to the ToRs; summarized and tabulated (Appendices).

2) **Climate models:** 2 High resolution CMIP6 climate models projecting surface and bottom temperature under contrasting emission scenarios.
   - Trends evaluated to 2050 across the NAFO area.

3) **Projected climate impacts:** Magnitude and timing of climate impacts on NAFO managed species using the Climate Risk Index for Biodiversity (CRIB) framework
   - Species distributions
   - Climate projections
   - Species thermal niche

The NW Atlantic is a climate change hotspot


Study says 2023's crazy Atlantic ocean heat, low Antarctic sea ice give glimpse of much hotter world

- Surface warming: Globally extreme; 2012, 2023 anomalously warm
- Bottom warming: Warming more modestly
- Oxygen: Decline virtually everywhere since 1960
- Acidification: Increasing more rapidly than global average
- Reduced mixing, nutrient flux, phytoplankton, NPP → yet increased bloom frequency, intensity
- Sea ice: Decline since 1969, 2010, 2011, 2021 lowest values
- Salinity: Increasing due to evaporation

**Spatial variability in nature, magnitude of changes


MONGABAY

Climate change threatens the North Atlantic's currents, ecosystems and stability (analysis)

Analysis by Pitamber Kaushik on 7 November 2023


Ocean off Newfoundland currently has greatest temperature increase in North America, says researcher

It's part of an upward trend in Atlantic Ocean temperatures, says ocean scientist

CBC News · Posted: Jul 23, 2023 6:30 AM ADT | Last Updated: July 24, 2023

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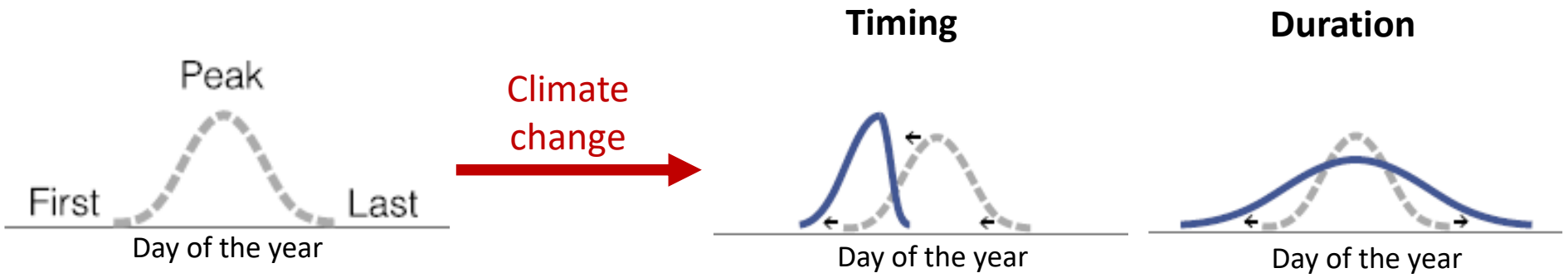
Article | Open access | Published: 01 March 2023

Coastal phytoplankton blooms expand and intensify in the 21st century

Yanhui Dai, Shangbo Yang, Dan Zhao, Chuanmin Hu, Wang Xu, Donald M. Anderson, Yun Li, Xiao-Peng Song, Daniel G. Boyce, Luke Gibson, Chunmiao Zheng & Lian Feng

Complex climate changes

- Shifting phenology
- Geographic movement: Warming spreading northward and deeper
- Increased variability and extremes: “Black swans”
- Novel climate: *e.g.,* heatwaves
- Climate tipping points: *e.g.,* AMOC slow down
- Climate variability: *e.g.,* Shifted towards more positive NAO since 2012

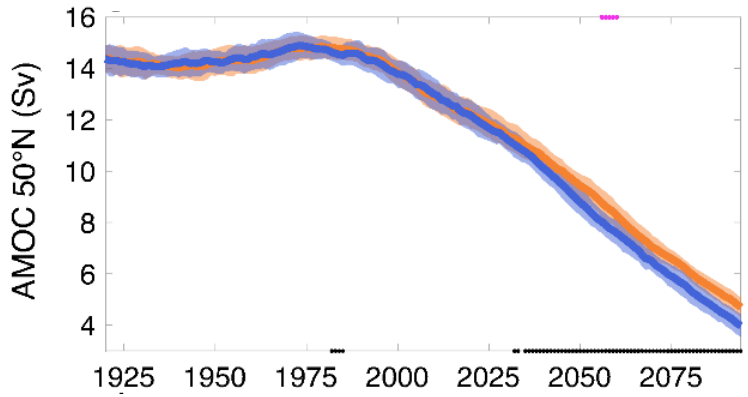


The NW Atlantic will remain a climate change hotspot

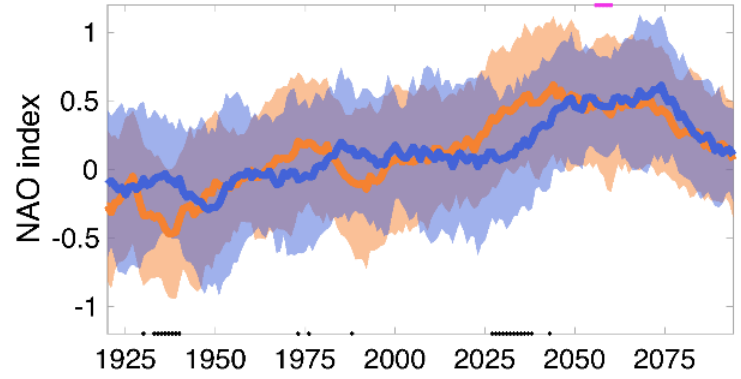
Projections to 2100:

- Surface warming: up to ~4°C (~2X the global average)
- Bottom warming: up to ~3°C
- Sea ice: ~15% decline per degree warming
- Near permanent heatwave conditions at many locations
- Increased stratification, reduced mixing, nutrient flux, primary production with spatial variability
- Reduction in AMOC
- Increased intensity of NAO (possibly)
- Marine animal biomass: -25.5% (Canadian EEZ), but increases at high latitudes (Bryndum-Buchholz et al. 2020)
- 41% of transboundary fish stocks projected to shift by 2100 (Palacios-Abrantes et al. 2022)

AMOC



NAO

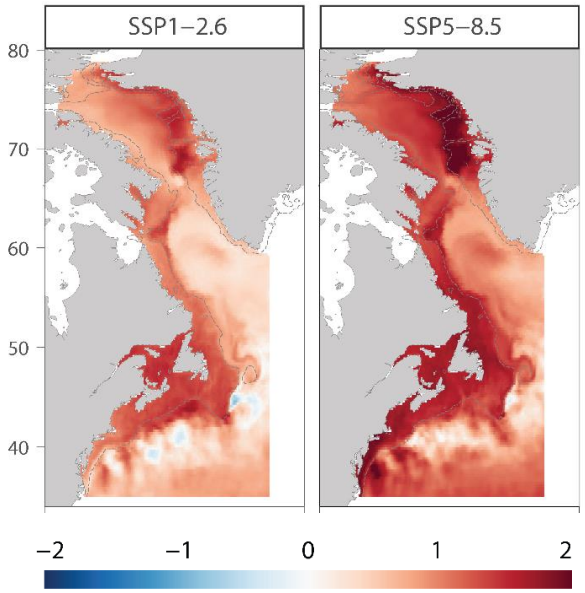


Gu *et al.* 2024 (*Nat. Comm.*)

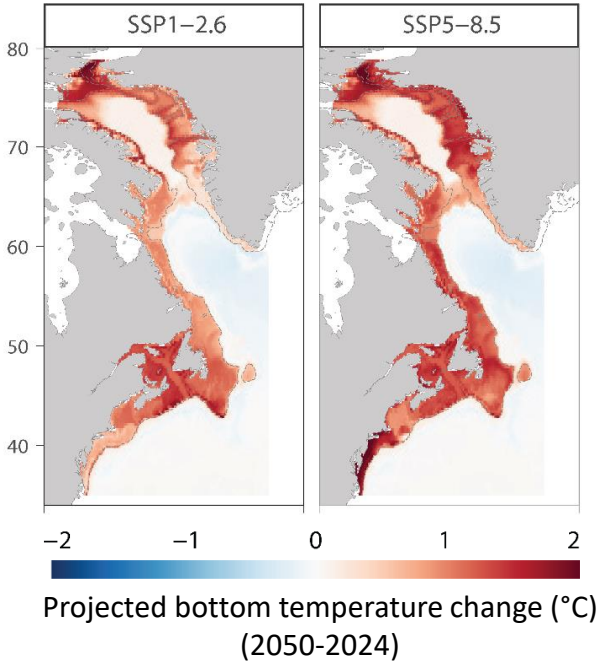
Climate projections

Temperature projections to 2050:

- Ensemble projections from two high resolution CMIP6 ESM models
- Trend: difference in decadal averaged temperature (2050-2024)



- **Average warming:** ~1°C
- **Spatial variability:** >2.5°C vs. slight cooling



- **Average warming:** ~0.5°C
- **Spatial variability:** >2°C vs. slight cooling
- **Grand Banks:** Greater warming of bottom than surface in some areas

Climate impacts on marine life

Marine climate

Temperature

Oxygen

pH

Salinity

Mixing

Sea ice

Currents

Nutrients

Temporal change

Increase

Decline

Extent

Seasonal shifts

Variability

Heatwaves

Extremes

Impact pathways

Productivity

Mortality

Range shifts

Food web structure

Life history

Body size

Adaptation

Metabolism

Population status

Habitat availability

Growth

Reproduction

Predation

Prey availability

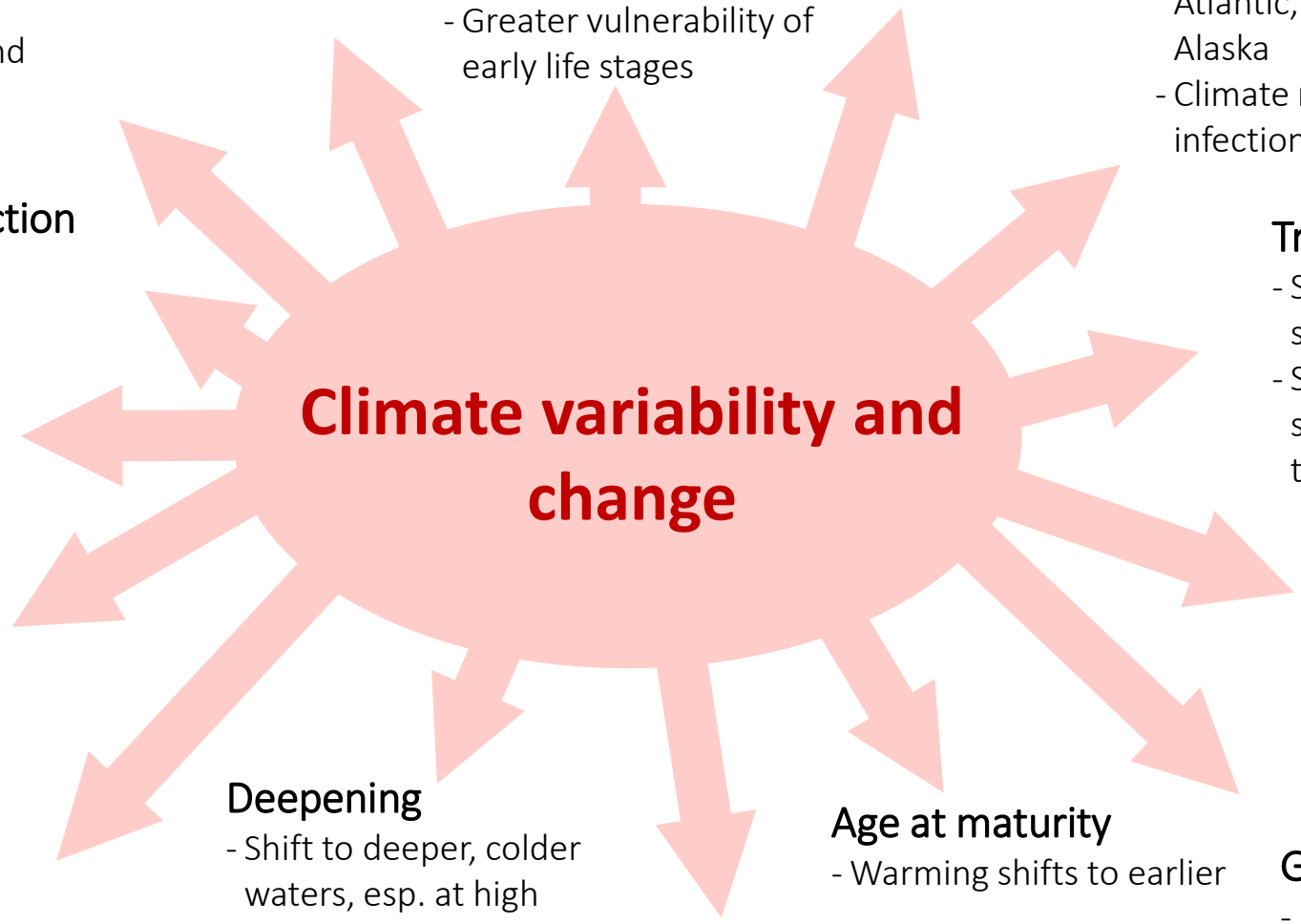
Stressors

Disease

Deepening

Calcification

Marine life



Climate variability and change

Body size
- Warming reducing body sizes for primary/secondary producers
- 60% decline in body mass of marine species between 1970 and 2008 (Shackell et al. 2010)

Mortality
- Hypoxia, warming, associated with mass mortality

Thermal bottlenecks
- Greater vulnerability of early life stages

Novel ecosystems
- Unknown function

Disease
- Increased geographic, seasonal range
- Poleward range shift of *Vibrio* in the North Atlantic, the North Sea, the Baltic Sea, and Alaska
- Climate rendering spp. more susceptible to infection

Range expansion/contraction
- Variable

Trophic mismatch
- Shifting phenology affects early life stages, recruitment
- Shrimp egg-hatching times related to spring timing of phytoplankton and temperature

Calcification rates
- Reduced

Growth & metabolism
- Variable

Primary production
- Reduced globally, increased at poles
- Composition changes

Deepening
- Shift to deeper, colder waters, esp. at high latitudes

Age at maturity
- Warming shifts to earlier

Geographic shifts
- Northward ('tropicalization')
- Poleward shifts in 17 of 36 commercial fish stocks between 1968 and 2007 in US waters (Nye et al. 2009)

Predator-prey interactions
- Temperature an overarching driver of trophic control (direct + indirect)
- Complex effects on plankton, endotherms

Trophic amplification
- Warming has disproportionate impacts on high trophic species

Climate impacts on NAFO species

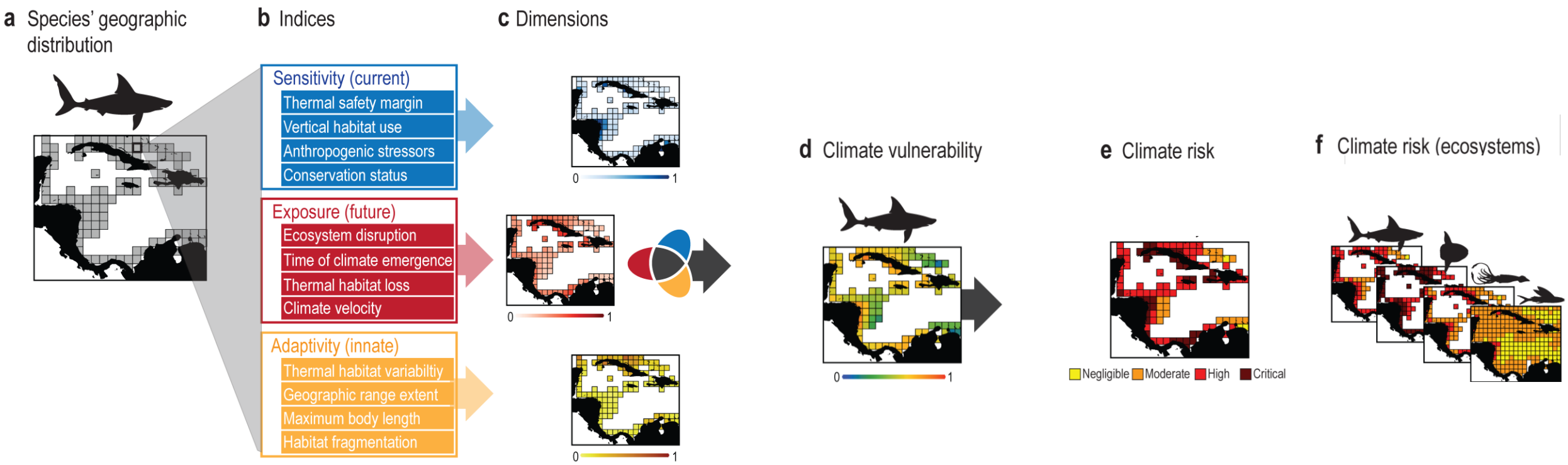
Climate Risk Index for Biodiversity (CRIB): Spatially explicit climate risk for species, stocks, ecosystems

nature climate change ARTICLES
https://doi.org/10.1038/s41558-022-01437-y

A climate risk index for marine life

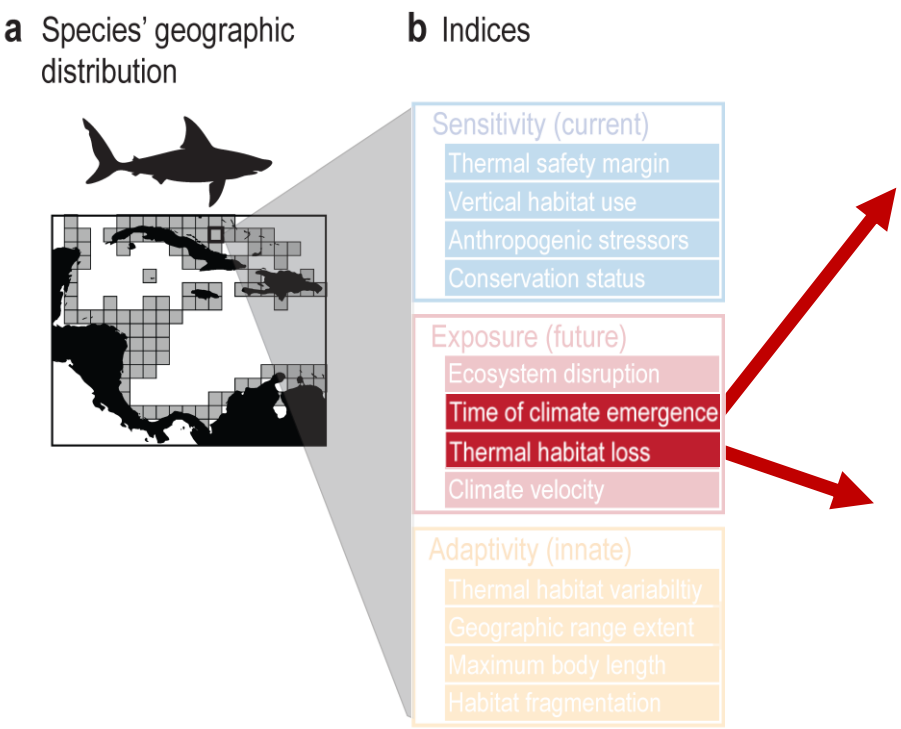
Daniel G. Boyce[1,2], Derek P. Tittensor[1,3], Cristina Garilao[4], Stephanie Henson[5], Kristin Kaschner[6], Kathleen Kesner-Reyes[7], Alex Pigot[8], Rodolfo B. Reyes Jr.[7], Gabriel Reygondeau[9], Kathryn E. Schleit[10], Nancy L. Shackell[2], Patricia Sorongon-Yap[7] and Boris Worm[1]

Climate change is impacting virtually all marine life. Adaptation strategies will require a robust understanding of the risks to species and ecosystems and how those propagate to human societies. We develop a unified and spatially explicit index to comprehensively evaluate the climate risks to marine life. Under high emissions (SSP5-8.5), almost 90% of ~25,000 species are at high or critical risk, with species at risk across 85% of their native distributions. One tenth of the ocean contains ecosystems where the aggregated climate risk, endemism and extinction threat of their constituent species are high. Climate change poses the greatest risk for exploited species in low-income countries with a high dependence on fisheries. Mitigating emissions (SSP1-2.6) reduces the risk for virtually all species (98.2%), enhances ecosystem stability and disproportionately benefits food-insecure populations in low-income countries. Our climate risk assessment can help prioritize vulnerable species and ecosystems for climate-adapted marine conservation and fisheries management efforts.

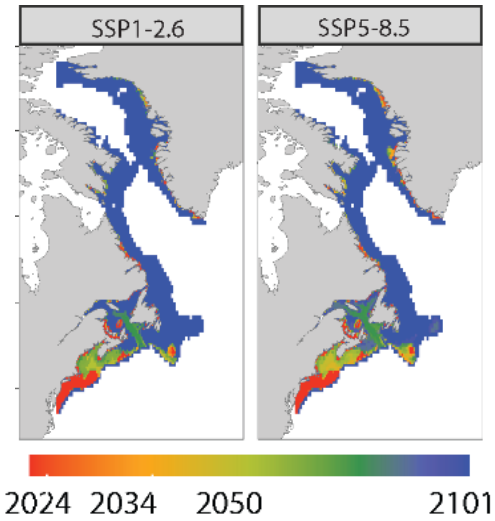


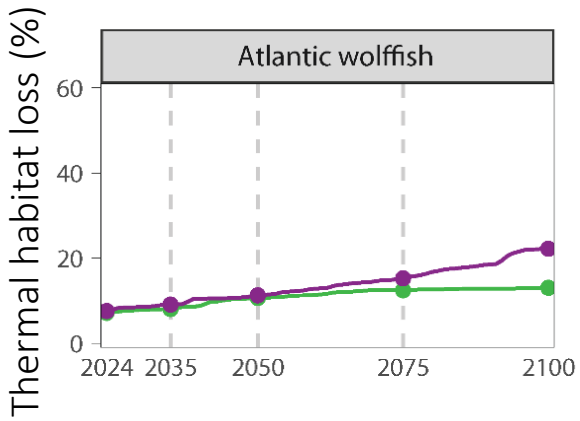
Boyce *et al.* 2022 (*Nature Climate Change*)

Example: Atlantic wolffish (*Anarhichas lupus*)



Projected climate exposure





Observed climate responses

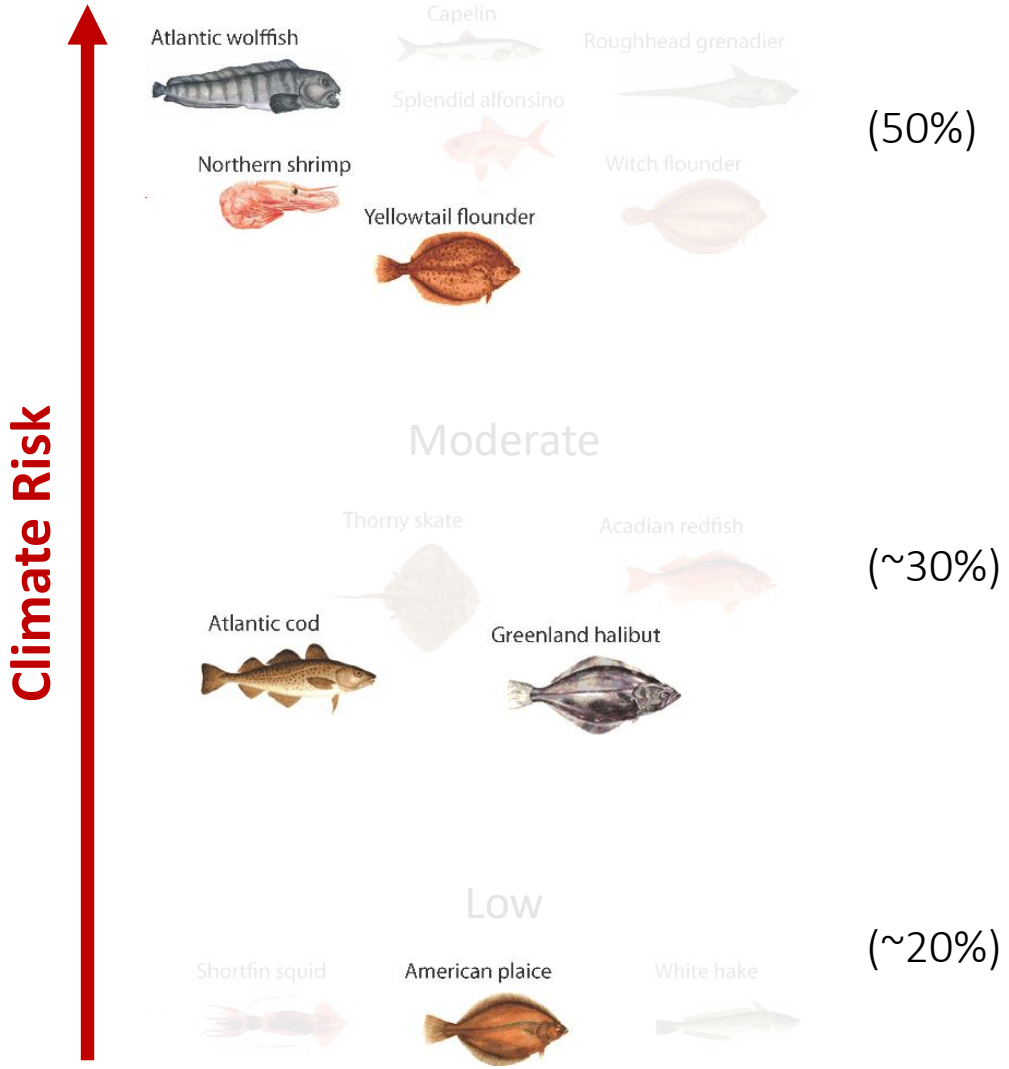
Species	Studies
Atlantic wolffish	(Árnason, Gunnarsson, Steinarsson, Daníelsdóttir, & Björnsson, 2019; Barhri et al., 2021; Bianucci, Fennel, Chabot, Shackell, & Lavoie, 2016; Bluemel, Fischer, Kulka, Lynam, & Ellis, 2022; Brennan, Blanchard, & Fennel, 2016; Dutil, Proulx, Chouinard, Borcard, & Larocque, 2014; Fock, 2007; Grant & Hiscock, 2014; Gunnarsson, 2017; Hansen & Falk-Petersen, 2002; A. K. Imsland, Foss, Sparboe, & Sigurdsson, 2006; Albert K. Imsland, Gunnarsson, Foss, Sigurdsson, & Sigurdsson, 2009; S. G. Lamarre, Blier, Driedzic, & Le François, 2010; Simon G. Lamarre, Le Frangois, Driedzic, & Blier, 2009; Lavin et al., 2022; Lemieux, Tardif, Dutil, & Blier, 2010; Magnussen, Imsland, & Foss, 2008; McCarthy, Moksness, Pavlov, & Houlihan, 1999; Orlov, Orlova, Rybakov, Emelianova, & Vedishcheva, 2023)

***High climate risk**

Boyce *et al.* 2022 (*Nature Climate Change*)

Climate impacts on NAFO species

Many studies



(50%)

(~30%)

(~20%)

Climate impacts on NAFO species

Few studies

Climate Risk

High

Atlantic wolffish

Capelin

Roughhead grenadier

Splendid alfonsino

Witch flounder

Northern shrimp

Yellowtail flounder

(50%)

Moderate

Thorny skate

Acadian redfish

Atlantic cod

Greenland halibut

(~30%)

Low

Shortfin squid

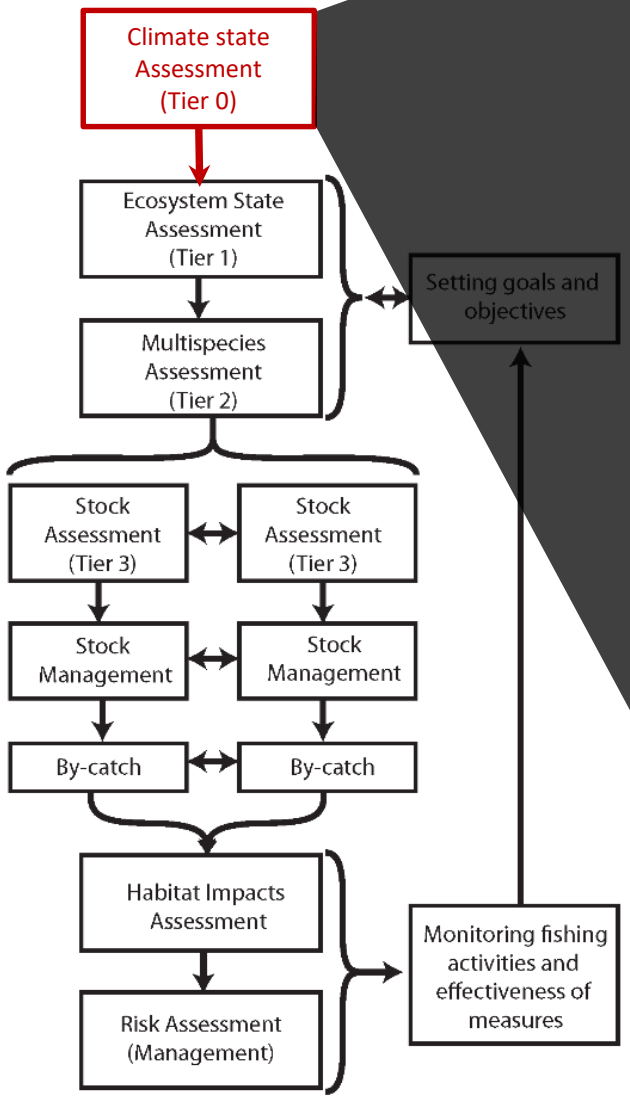
American plaice

White hake

(~20%)

Climate resilience in NAFO fisheries

NAFO Ecosystem Approach to Fisheries Roadmap



Annual report: Climate state, changes across the NAFO area

- Historical, future, phenology, variability

1. Remote sensing:

- 1970s onward: daily, high resolution, synoptic (temperature, wind, NPP, etc.)
- Used in fisheries elsewhere but rarely in NAFO, Canada

2. Projections and forecasts:

- Used in fisheries (*e.g.,* NOAA, CSIRO) to develop anticipatory capacity
- High resolution (~10km2) short-term (~5-20 years) projections (local, regional models)
- Forecasts desirable

3. Integrated climate data: Facilitate its interpretation and use

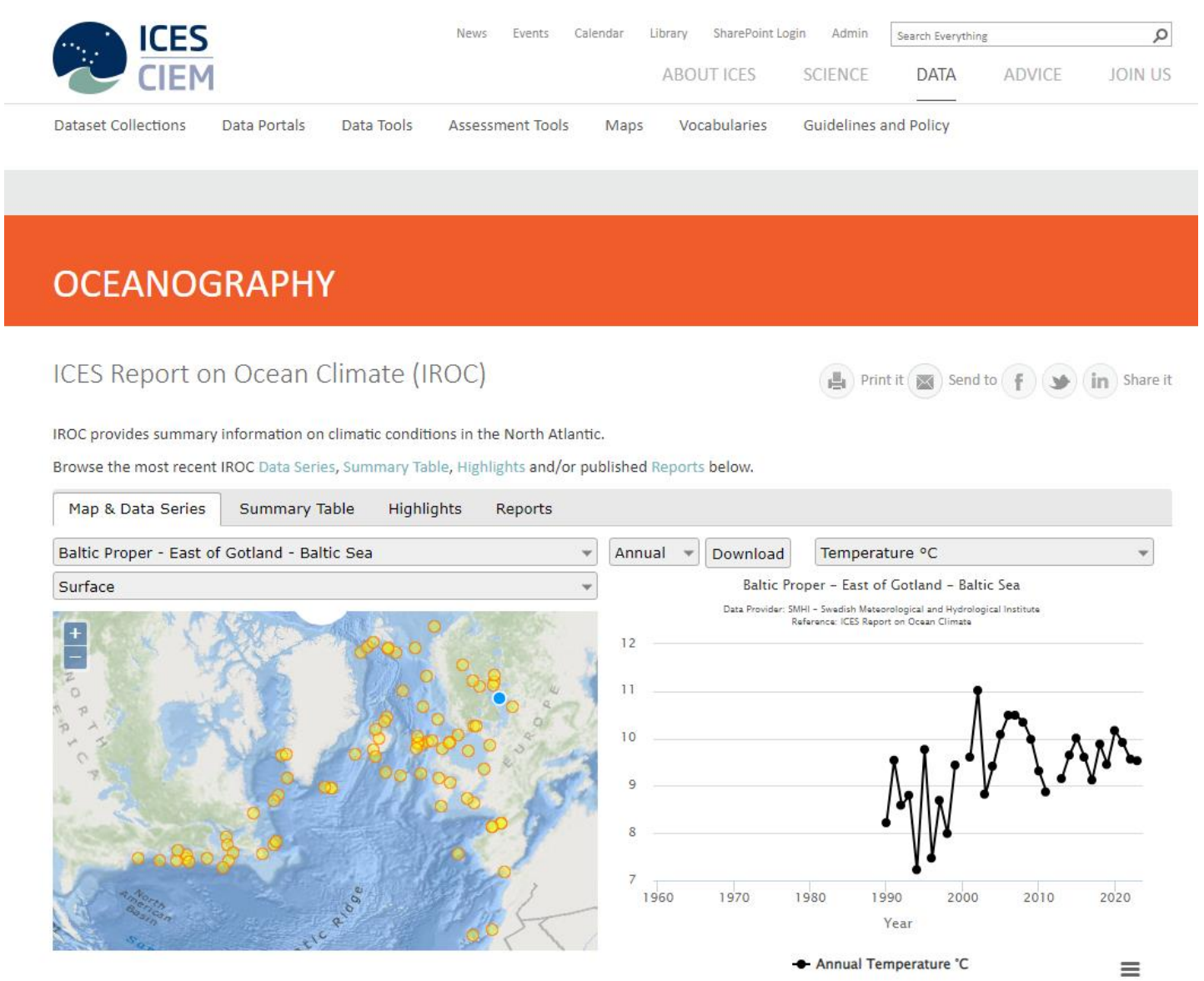
- Examples: NL climate index, Glorys, Copernicus, bottom temperature

4. Available climate data: Released with report

- Example: ICES Report on Ocean Climate (IROC)

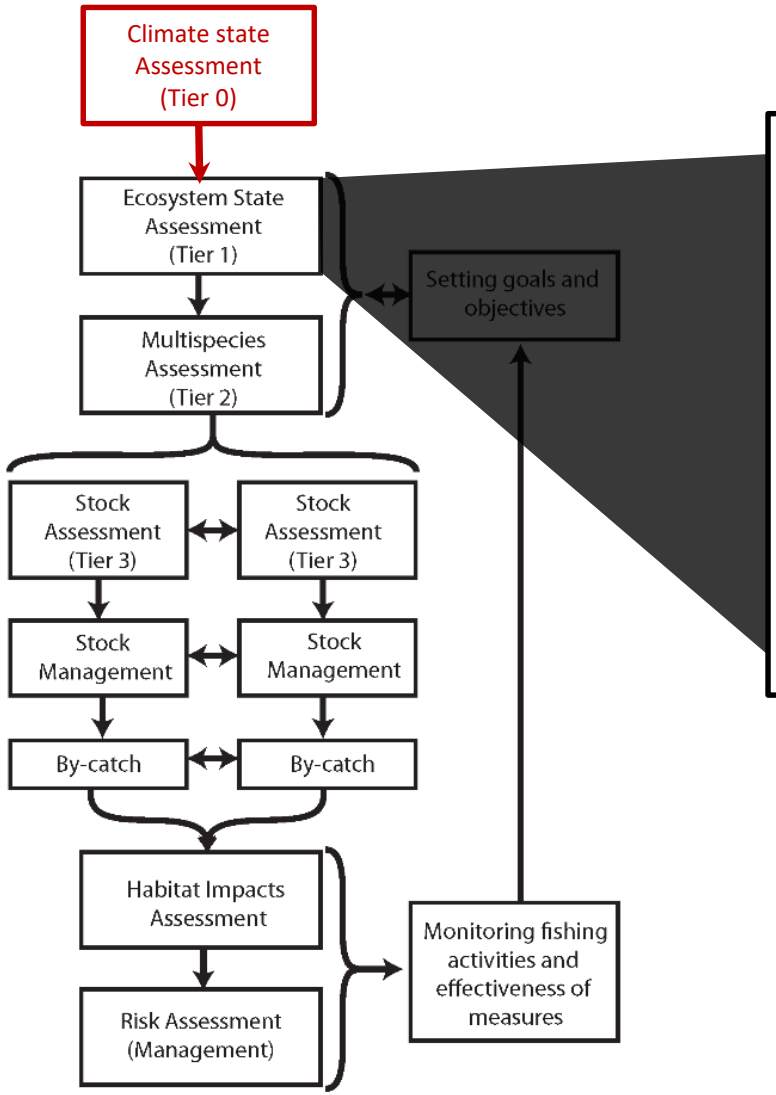
Climate resilience in NAFO fisheries

[ICES Oceanography - IROC]



Climate resilience in NAFO fisheries

NAFO Ecosystem Approach to Fisheries Roadmap



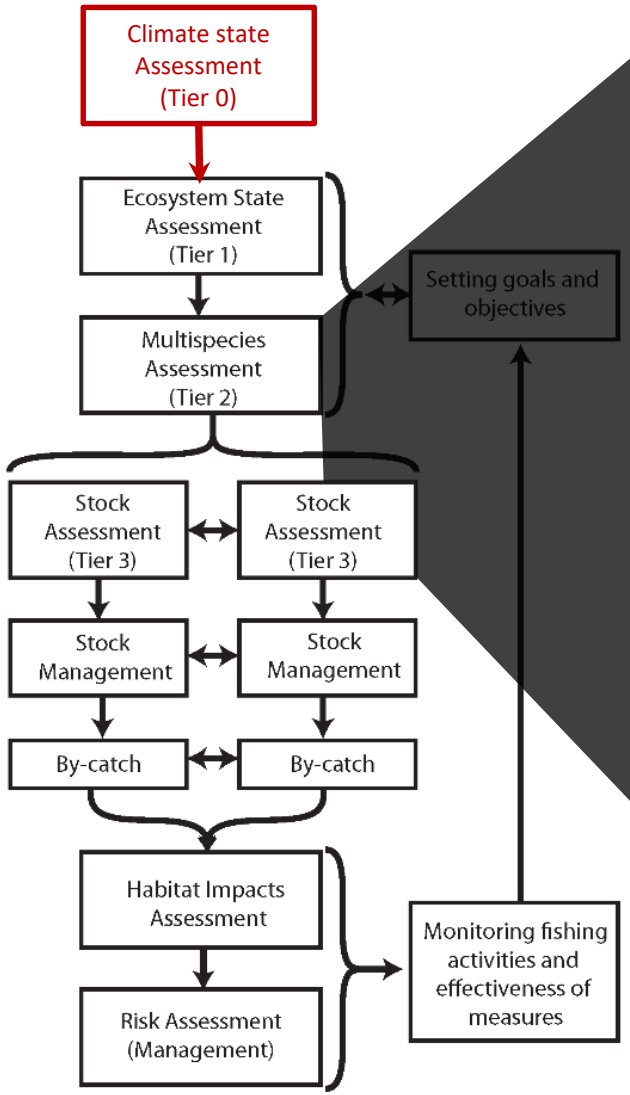
1. **Climate-driven productivity shifts:**
   - Climate variability and change impacts on ecosystem productivity and catch potential

2. **Disease monitoring:**
   - *e.g.,* using eDNA, species distribution models

3. **Climate risk monitoring:**
   - Geographic patterns of ecosystem level climate risk

Climate resilience in NAFO fisheries

NAFO Ecosystem Approach to Fisheries Roadmap



1. Species distribution shifts:

- Monitor: Survey coverage appropriateness
- Dynamic species distribution models (tier 3)
- Joint species distribution models (tier 2)
- Leverage real-time & forecasted climate data

2. Phenology match-mismatch:

- Monitor: Climate-driven recruitment failures
- Monitor: Survey coverage appropriateness
- Example: Phytoplankton-shrimp

3. Climate-driven trophic interactions:

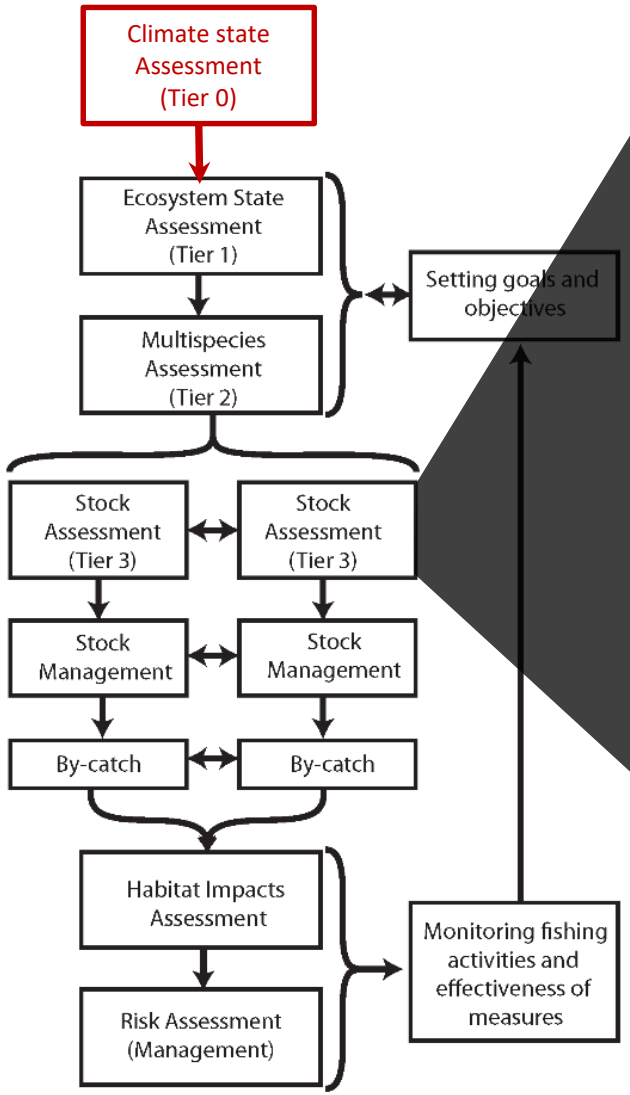
- Example: cod-shrimp

4. Climate risk:

- Assessed and monitored at the species and stock level as a standard practice

Climate resilience in NAFO fisheries

NAFO Ecosystem Approach to Fisheries Roadmap



1. **Climate informed stock assessments:** Where assessment models exist (33% of stocks)
   - Management strategy evaluations (MSE): Climate in operating models
   - Climate conditioned advice: Risk equivalency

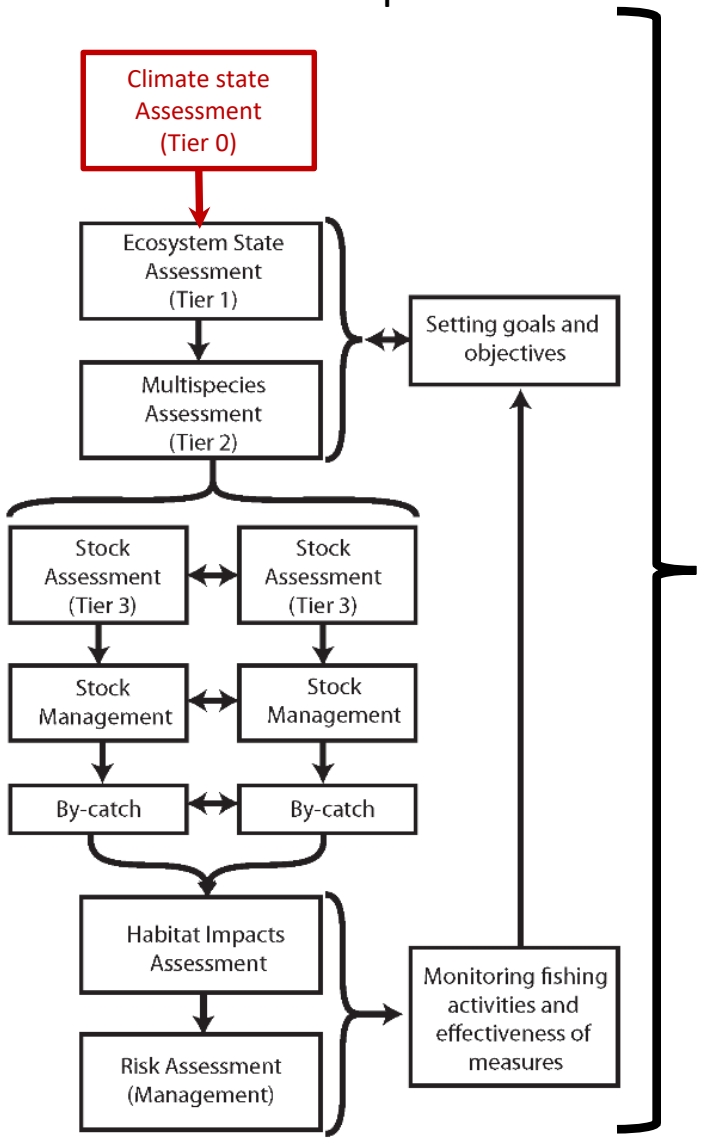
2. **Climate-considered harvest advice:** Where assessment models do not exist (66% of stocks)
   - Approach less well defined: Relies on knowledge of climate impacts
   - "Climate buffers" where uncertainty is high: *e.g.,* Peruvian anchoveta
   - Threshold-based harvest control rules: *e.g.,* California sardine

3. **Climate impacts on early life stages:**
   - "Thermal bottlenecks": Early life stages are often more sensitive to climate change, but less well evaluated → critical knowledge gap

4. **Climate risk:**
   - Standard component of stock assessments

Climate resilience in NAFO fisheries

NAFO Ecosystem Approach to Fisheries Roadmap



1. **Multidisciplinary collaboration:** Fisheries assessment is increasingly a multidisciplinary endeavor
   - Collaboration: climate scientists, oceanographers, ecologists, fisheries, social science involved in the assessment and advice provision

2. **Climate risk:**
   - Priority for governmental and intergovernmental organizations (FAO, NOAA, DFO)
   - Core climate impact knowledge helping to make informed decisions
   - Spatially-explicit, quantitative, reproducible: Monitor risk

3. **Climate response database:**
   - Scientific literature on climate changes and their impacts on NAFO species
   - “Evergreen”: Updated with new information

Summary

The NW Atlantic Ocean is a climate change hotspot now and in the future:

- The marine climate of the Northwest Atlantic is dynamic: strong seasonality, climate variability, change

Impacts on marine life are numerous and complex:

- Winners and losers: Depends on location, taxonomy
- Novel, less predictable marine world: Challenge for management

Pathways to foster climate resilience:

- Good data & knowledge as a foundation: Evidence-based decision making
- Sustainable management: Healthy populations more resilient
- Monitoring: Climate-driven shifts
- Assessments: Climate-considered harvest advice
- Multidisciplinary collaboration: Vital under climate change
- Avoid “analysis paralysis”: Planning and action