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Erin Fedewa[1]
Brendan Connors[2]
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David Kimmel[1]
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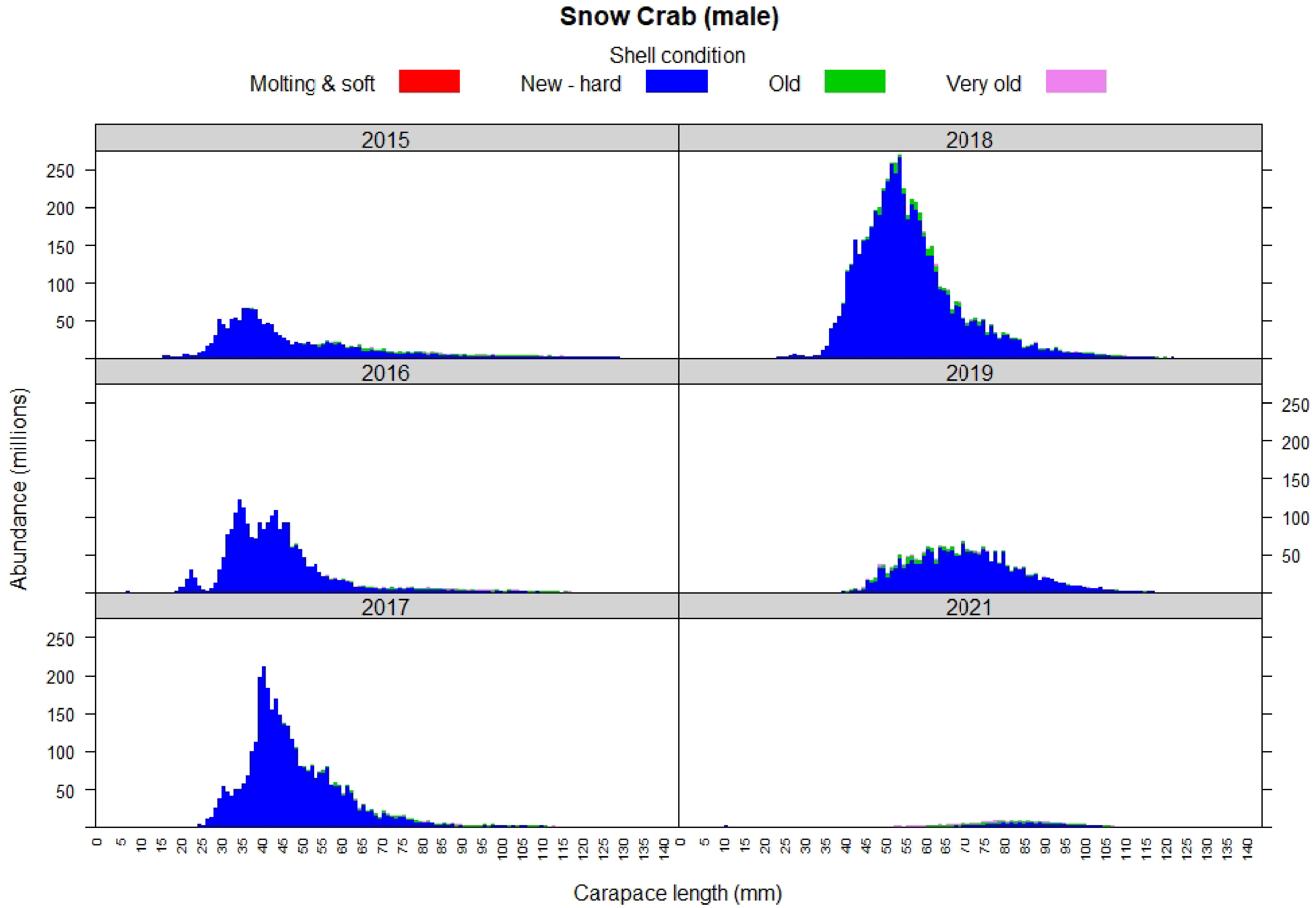
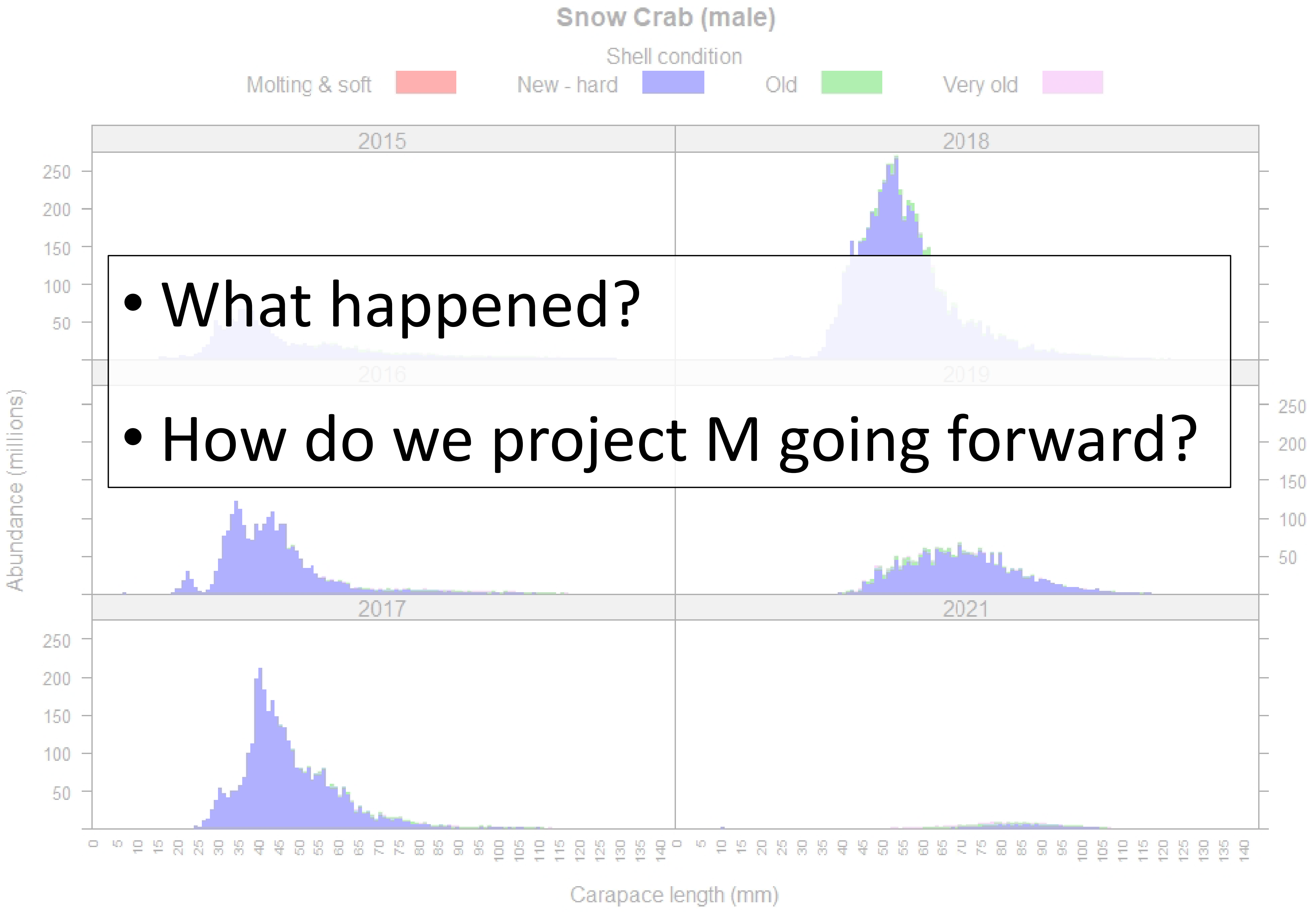
Climate change and snow crab


Snow Crab (male)
Shell condition
Molting & soft
New - hard
Old
Very old
2015
2018
2016
2019
2017
2021
Abundance (millions)
250
200
150
100
50
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
95
100
105
110
115
120
125
130
135
140
Carapace length (mm)



- What happened?
- How do we project M going forward?

Climate adaptation perspective

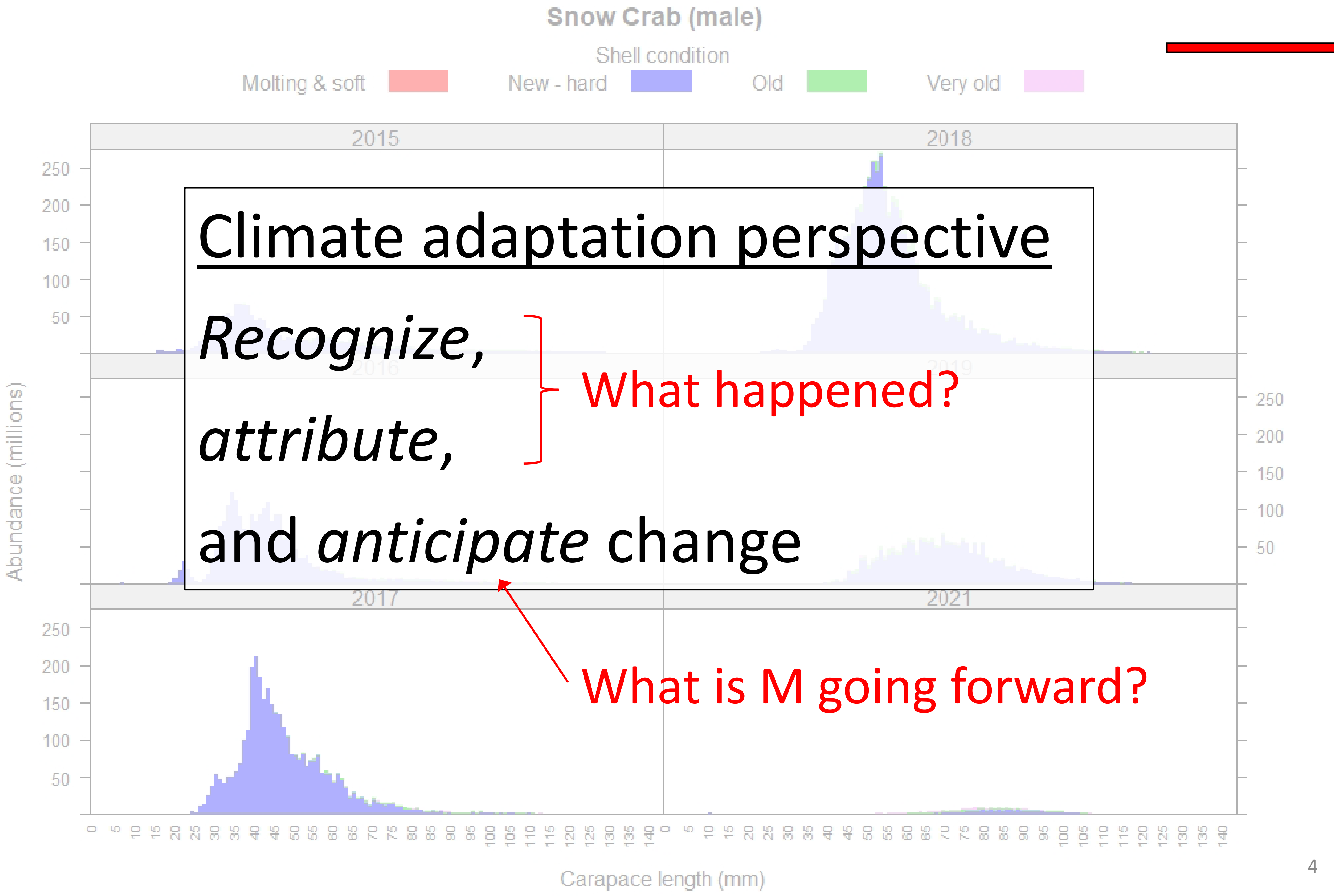
Recognize,

attribute,

What happened?

and *anticipate* change

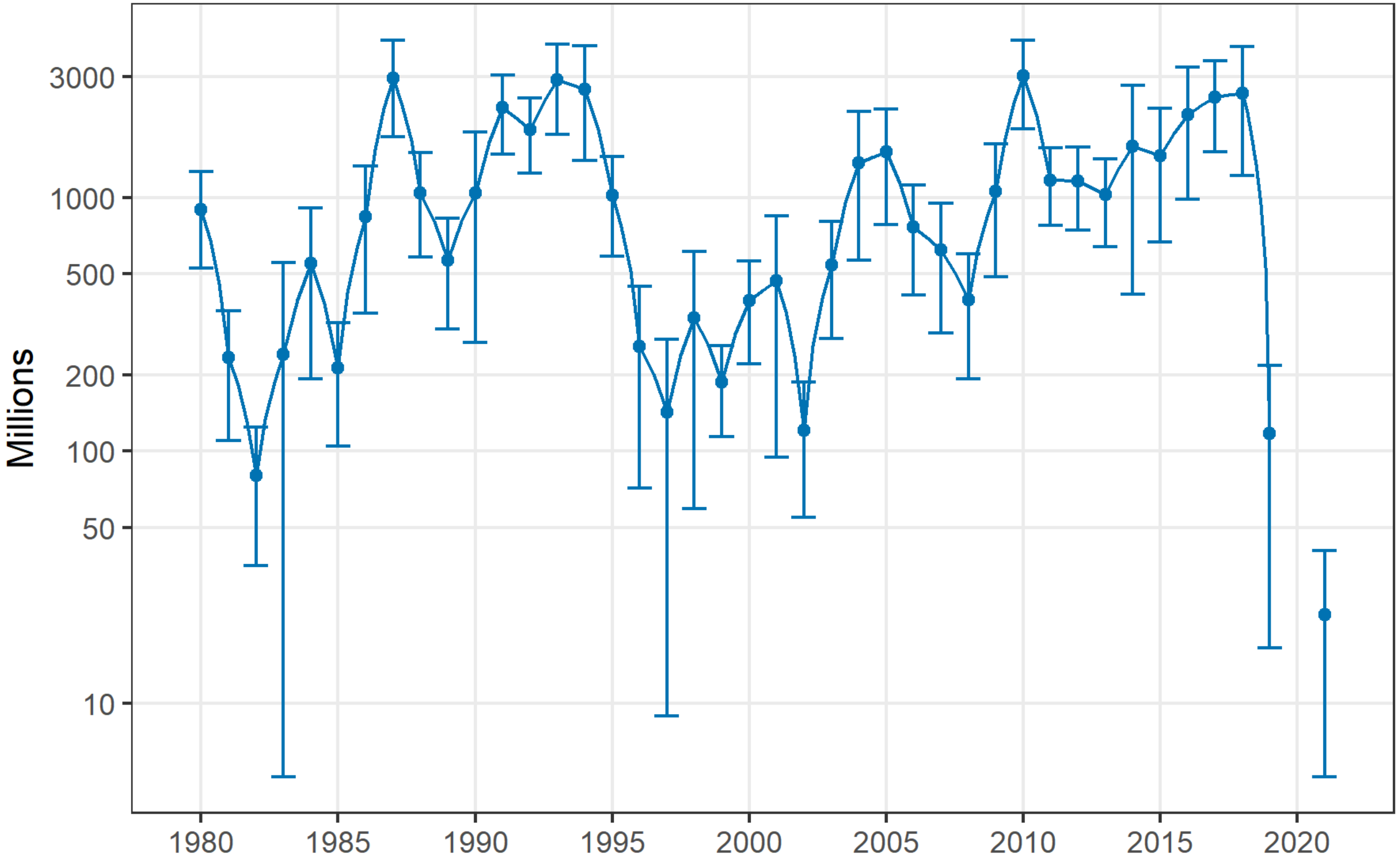
What is M going forward?



“What happened?” requires a simple answer

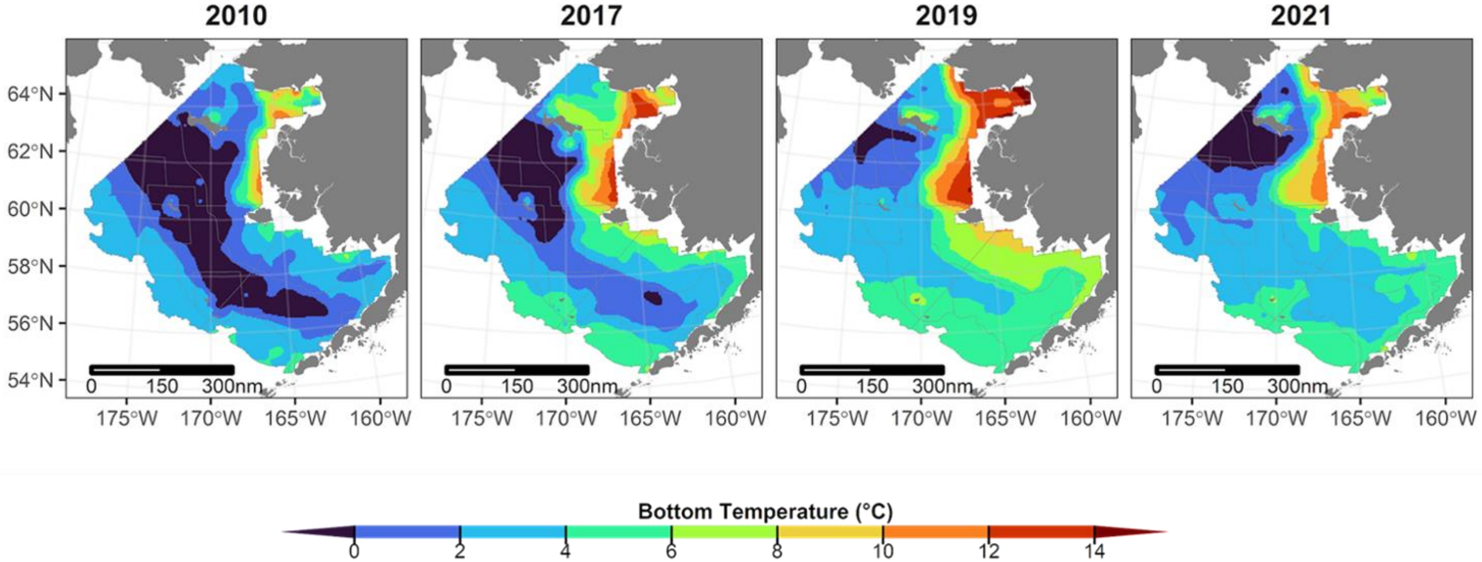
Immature female snow crab

Abundance and 95% CI



- Few observations
- Collinear covariates (predation, disease, etc.)
- Complex answers require an elephant’s worth of model on a mouse’s amount of data
- Impossible to rule out alternate explanations
- Focusing on *proximate* mechanisms may be fruitless

Collapse coincides with rapid borealization



nature climate change

LETTERS

PUBLISHED ONLINE: 18 MAY 2015 | DOI: 10.1038/NCLIMATE2647

Recent warming leads to a rapid borealization of fish communities in the Arctic

Maria Fossheim[1]*, Raul Primicerio[2], Edda Johannessen[1], Randi B. Ingvaldsen[1], Michaela M. Aschan[2] and Andrey V. Dolgov[3]

Arctic marine ecosystems are warming twice as fast as the global average[1]. As a consequence of warming, many incoming species experience increasing abundances and expanding distribution ranges in the Arctic[2]. The Arctic is expected to have the largest species turnover with regard to invading

ICES Journal of Marine Science

ICES Journal of Marine Science (2021), 78(9), 3017–3045. https://doi.org/10.1093/icesjms/fsab122

Review Article

Possible future scenarios in the gateways to the Arctic for Subarctic and Arctic marine systems: II. prey resources, food webs, fish, and fisheries

Franz J. Mueter[1,*], Benjamin Planque[2], George L. Hunt, Jr[3], Irene D. Alabia[4], Toru Hirawake[5], Lisa Eisner[6], Padmini Dalpadado[7], Melissa Chierici[2], Kenneth F. Drinkwater[7], Naomi Harada[8], Per Arneberg[2], and Sei-Ichi Saitoh[4]

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Ecological Applications, 18(2), 2008, pp. 309–320

SEA ICE RETREAT ALTERS THE BIOGEOGRAPHY OF THE BERING SEA CONTINENTAL SHELF

Franz J. Mueter[1,3] and Michael A. Litzow[2]

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[2]*Alaska Fisheries Science Center, National Marine Fisheries Service, 301 Research Court, Kodiak, Alaska 99615 USA*

Abstract. Seasonal ice cover creates a pool of cold bottom water on the eastern Bering Sea continental shelf each winter. The southern edge of this cold pool, which defines the ecotone between arctic and subarctic communities, has retreated ~230 km northward since the early 1980s. Bottom trawl surveys of fish and invertebrates in the southeastern Bering Sea (1982–2006) show a coincident reorganization in community composition by latitude.

frontiers in Marine Science

OPEN ACCESS

Borealization of the Arctic Ocean in Response to Anomalous Advection From Sub-Arctic Seas

Igor V. Polyakov[1,2], Matthew B. Alkire[3], Bodil A. Bluhm[4], Kristina A. Brown[5], Eddy C. Carmack[6], Melissa Chierici[8], Seth L. Danielson[7], Ingrid Ellingsen[8], Elizaveta A. Ershova[4,9], Katarina Gårdfeldt[10], Randi B. Ingvaldsen[4,11], Andrey V. Pnyushkov[12], Dag Slagstad[8] and Paul Wassmann[4]*

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Global Change Biology WILEY

RESEARCH ARTICLE

Deep demersal fish communities respond rapidly to warming in a frontal region between Arctic and Atlantic waters

Margrete Emblemsvåg[1,2] | Karl Michael Werner[3] | Ismael Núñez-Riboni[3] | Romain Frelat[4] | Helle Torp Christensen[5] | Heino O. Fock[3] | Raul Primicerio[2]

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[4]Wageningen University and Research

Abstract
The assessment of climate impact on marine communities dwelling deeper than the well-studied shelf seas has been hampered by the lack of long-term data. For a long time, the prevailing expectation has been that thermal stability in deep ocean layers

Approach

1. Create an index to measure the progress of borealization (*recognize*)
2. Evaluate the relationship between borealization and snow crab abundance (*recognize*)
3. Evaluate the evidence for human contributions to borealization (*attribute*)
4. Use climate models to project borealization & snow crab abundance, make inference about time-varying M (*anticipate*)

Ecosystem properties associated with borealization

Arctic

- More ice
- Late ice retreat
- ★ Cold summer bottom temp
- Ice-associated blooms
- Earlier blooms
- Aggregated phytoplankton
- Larger blooms
- Benthic production
- More *Calanus*
- ★ Less *Hematodinium*
- More Arctic groundfish
- ★ Fewer Pacific cod

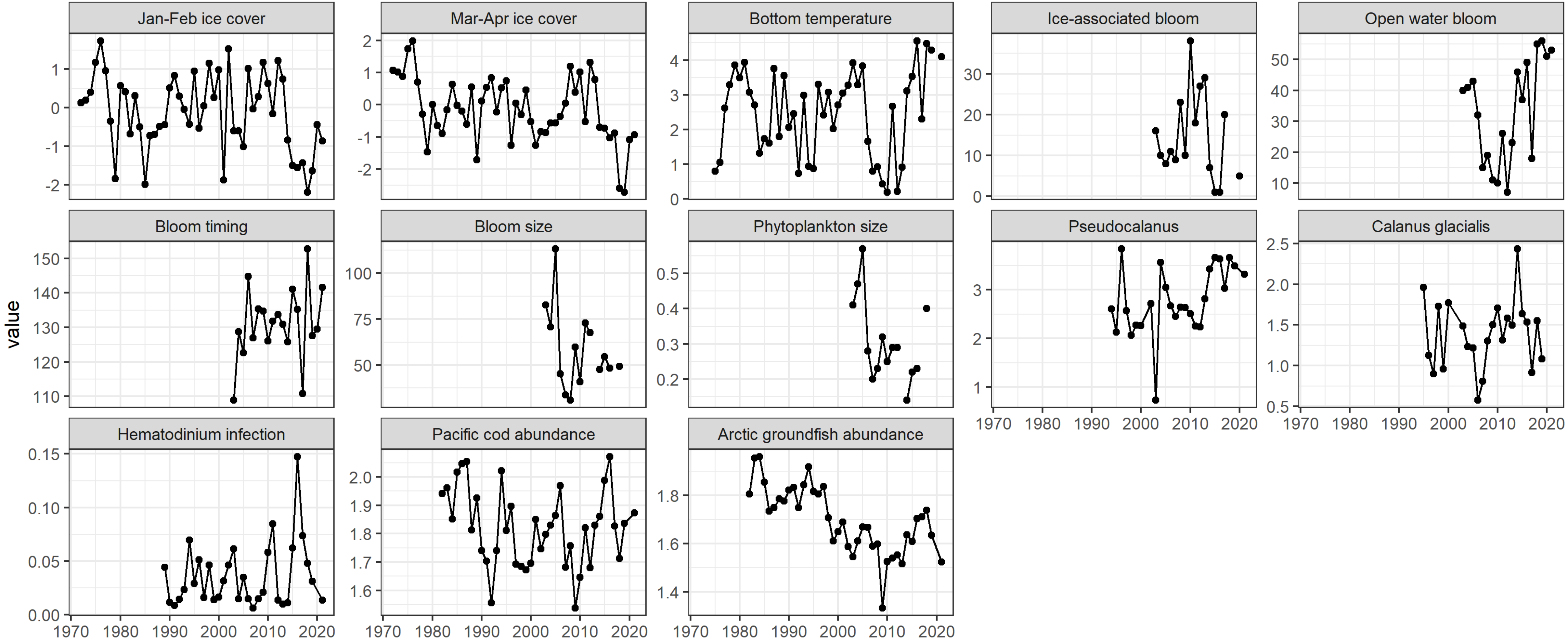
Subarctic

- Less ice
- Early ice retreat
- ★ Warm summer bottom temp
- Open-water blooms
- Later blooms
- Smaller phytoplankton
- Smaller blooms
- Pelagic production
- More *Pseudocalanus*
- ★ More *Hematodinium*
- Fewer Arctic groundfish
- ★ More Pacific cod

★ Hypothesized proximate mechanisms

1. Measure borealization

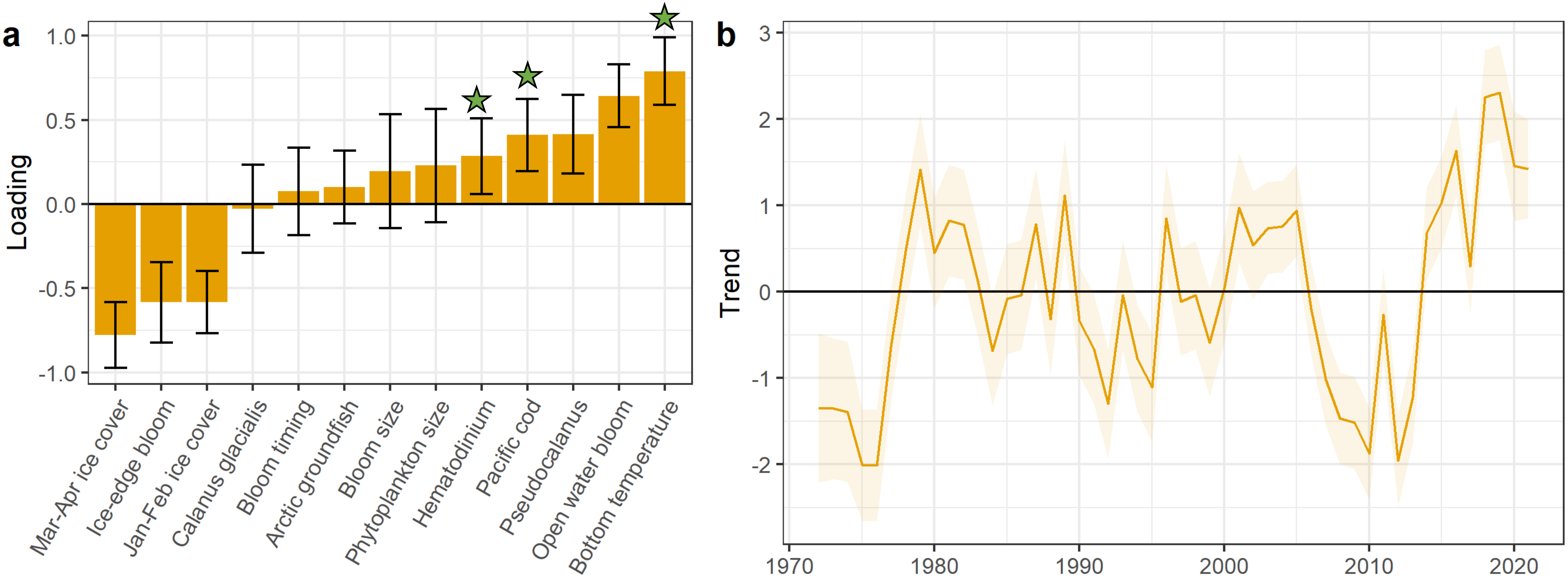
Time series for borealization index



1. Measure borealization

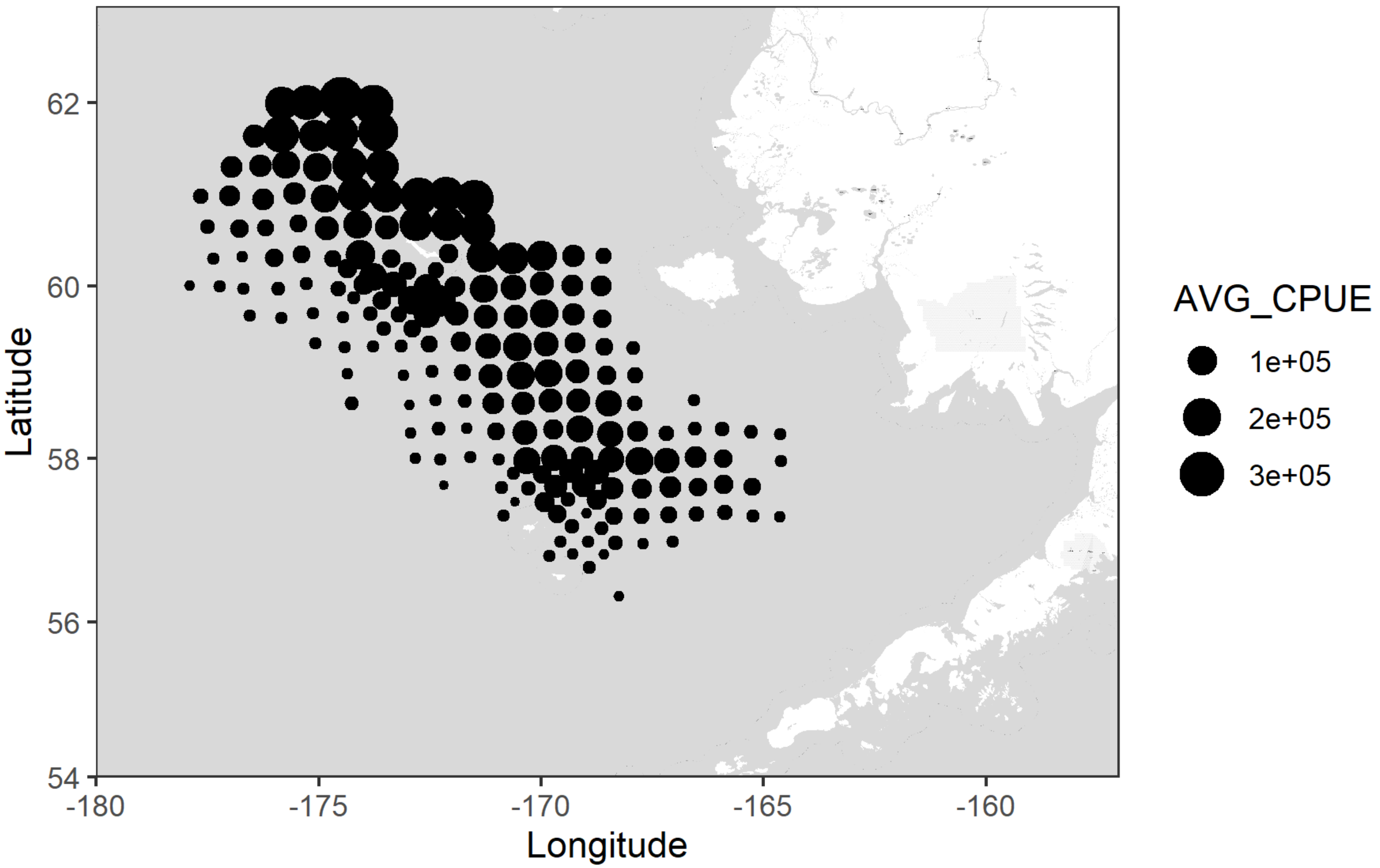
Borealization index: Dynamic Factor Analysis trend

Estimates with 95% confidence intervals

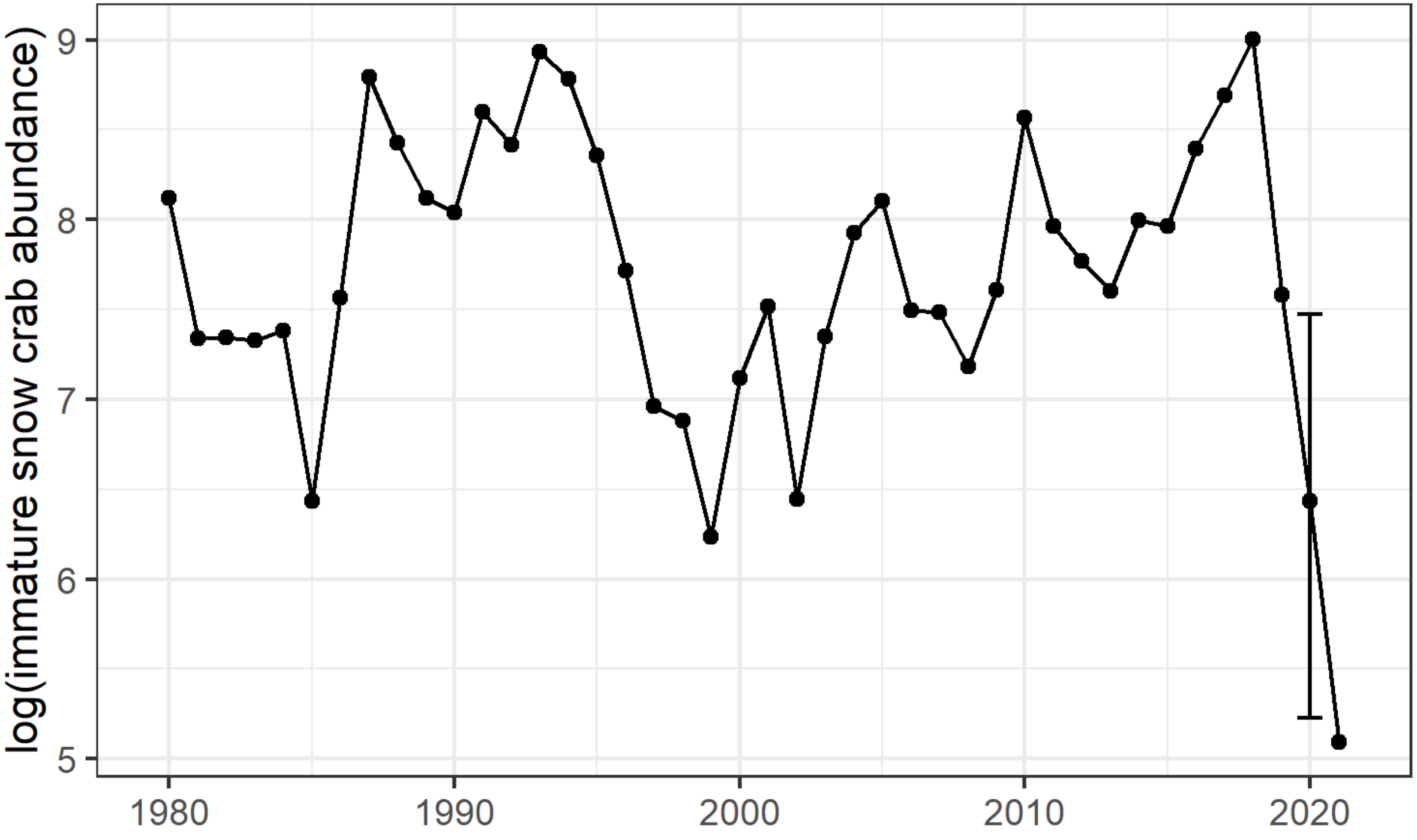


★ Hypothesized proximate mechanisms

Response variable: immature survey abundance in core range



Immature abundance with estimated 2020 value and uncertainty



Multiple imputation using:

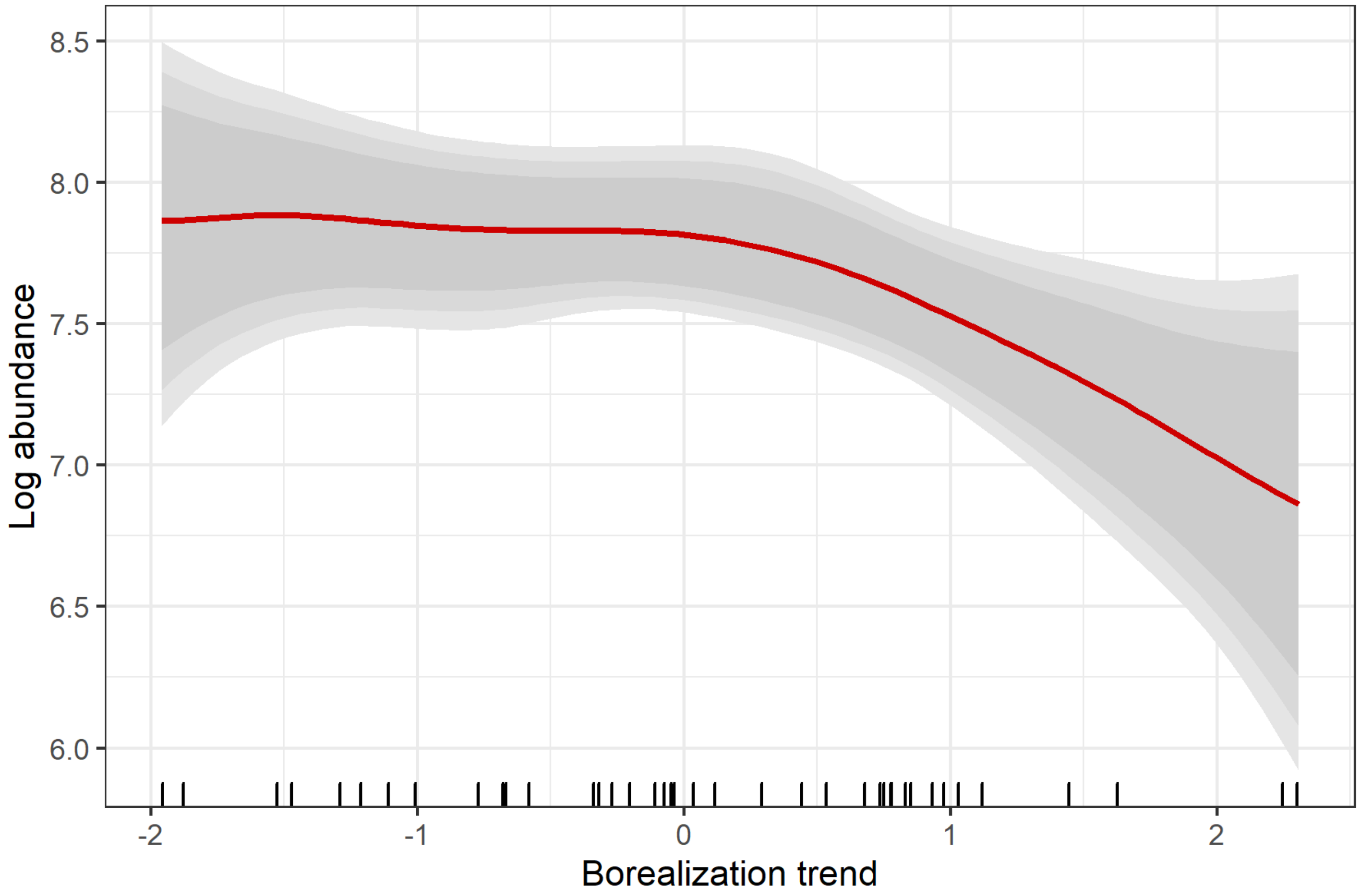
- Model mature male snow crab abundance
- Model mature female snow crab abundance
- Model age3+ pollock biomass
- Model age2+ yellowfin biomass
- Model female Alaska plaice biomass

Abundance declines with high borealization values

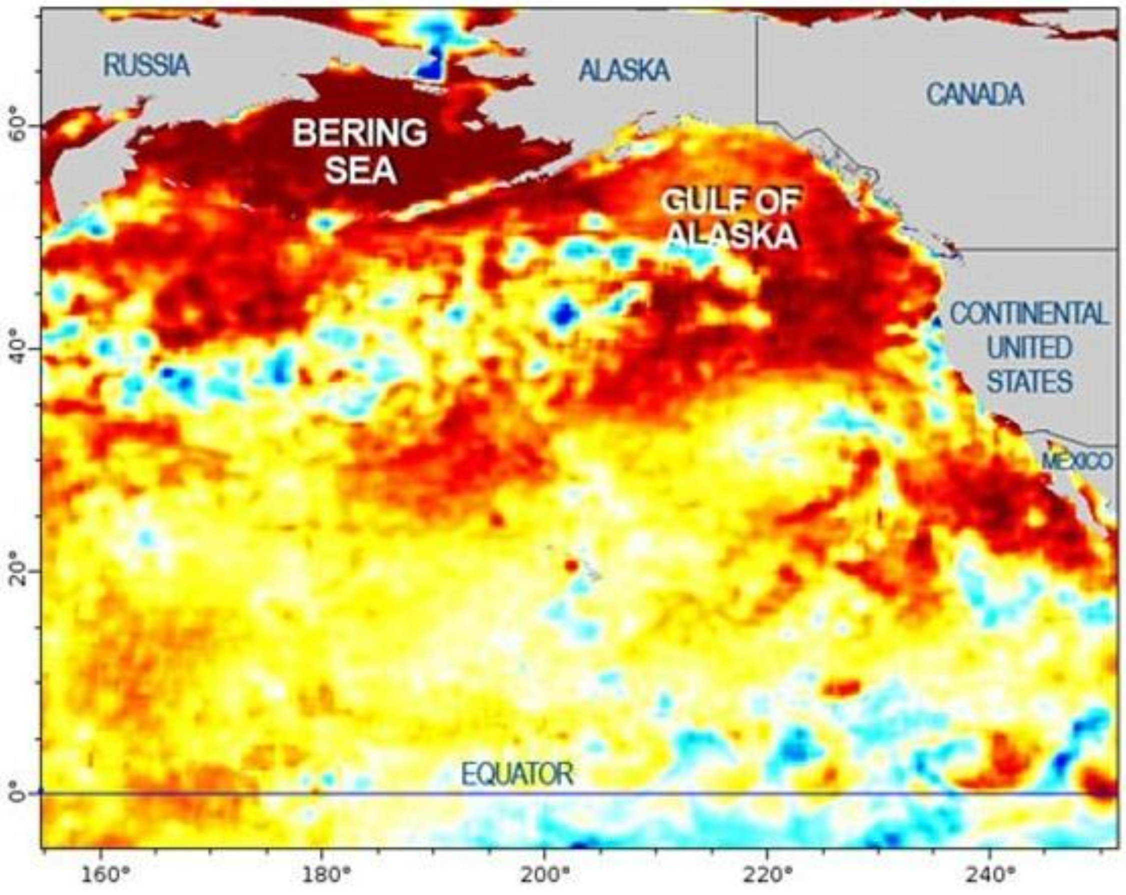
Bayesian autoregressive regression model:

$$abundance_{t+1} \sim abundance_t + \ s(borealization\_trend_t) + \varepsilon$$

Conditional effect of borealization: Posterior mean with 80 / 90 / 95% credible intervals



Attribution of extreme temperatures since 2014



8. THE HIGH LATITUDE MARINE HEAT WAVE OF 2016 AND ITS IMPACTS ON ALASKA

John E. Walsh, Richard L. Thoman, Uma S. Bhatt, Peter A. Bieniek, Brian Brettschneider, Michael Brubaker, Seth Danielson, Rick Lader, Florence Fetterer, Kris Holderied, Katrin Iken, Andy Mahoney, Molly McCammon, and James Partain

The 2016 Alaska marine heat wave was unprecedented in terms of sea surface temperatures and ocean heat content, and CMIP5 data suggest human-induced climate change has greatly increased the risk of such anomalies.

chapter 10

THE RECORD LOW BERING SEA ICE EXTENT IN 2018: CONTEXT, IMPACTS, AND AN ASSESSMENT OF THE ROLE OF ANTHROPOGENIC CLIMATE CHANGE

Richard L. Thoman Jr., Uma S. Bhatt, Peter A. Bieniek, Brian R. Brettschneider, Michael Brubaker, Seth L. Danielson, Zachary Labe, Rick Lader, Walter N. Meier, Gay Sheffield, and John E. Walsh

Record low Bering Sea sea ice in 2018 had profound regional impacts. According to climate

Progress in Oceanography 186 (2020) 102393

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journal homepage: www.elsevier.com/locate/pocean

ELSEVIER

Evaluating ecosystem change as Gulf of Alaska temperature exceeds the limits of preindustrial variability

Michael A. Litzow[a,*], Mary E. Hunsicker[b], Eric J. Ward[c], Sean C. Anderson[d], Jin Gao[c,e], Stephanie G. Zador[f], Sonia Batten[g], Sherri C. Dressel[h], Janet Duffy-Anderson[f], Emily Fergusson[i], Russell R. Hopcroft[j], Benjamin J. Laurel[k], Robert O'Malley[l]

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RESEARCH

OCEAN TEMPERATURE

High-impact marine heatwaves attributable to human-induced global warming

Charlotte Laufkötter[1,2*], Jakob Zscheischler[1,2], Thomas L. Frölicher[1,2]

Marine heatwaves (MHWs)—periods of extremely high ocean temperatures in specific regions—have occurred in all of Earth's ocean basins over the past two decades, with severe negative impacts on marine organisms and ecosystems. However, for most individual MHWs, it is unclear to what extent they have been altered by human-induced climate change. We show that the occurrence probabilities of the duration, intensity, and cumulative intensity of most documented, large, and impactful MHWs have increased more than 20-fold as a result of anthropogenic climate change. MHWs that occurred only once every hundreds to thousands of years in the preindustrial climate are projected to become decadal to centennial events under 1.5°C warming conditions and annual to decadal events under 3°C warming conditions. Thus, ambitious climate targets are indispensable to reduce the risks of substantial MHW impacts.

that equals or exceeds the duration, intensity, and cumulative intensity of the observed MHW in preindustrial and present-day model simulations. These probabilities are denoted by $P^{duration}_{present-day}$, $P^{intensity}_{present-day}$, $P^{cumulativeintensity}_{present-day}$, $P^{duration}_{preindustrial}$, $P^{intensity}_{preindustrial}$, and $P^{cumulativeintensity}_{preindustrial}$, respectively.

Here, we explicitly take changes in the frequency of heatwaves as well as changes in the duration, intensity, or cumulative intensity of heatwaves into account (see materials and methods). Our approach builds on the work of Stott *et al.* (*28*) and Oliver *et al.* (*6*) but with several modifications. In contrast to most previous attribution studies, we specifically calculate the occurrence probabilities of heatwaves as opposed to the probabilities of ex-

Fraction of Attributable Risk (FAR)

$$\text{FAR} = 1 - \frac{\text{preindustrial probability}}{\text{current probability}}$$

FAR = 0 → equally likely with / without human influence

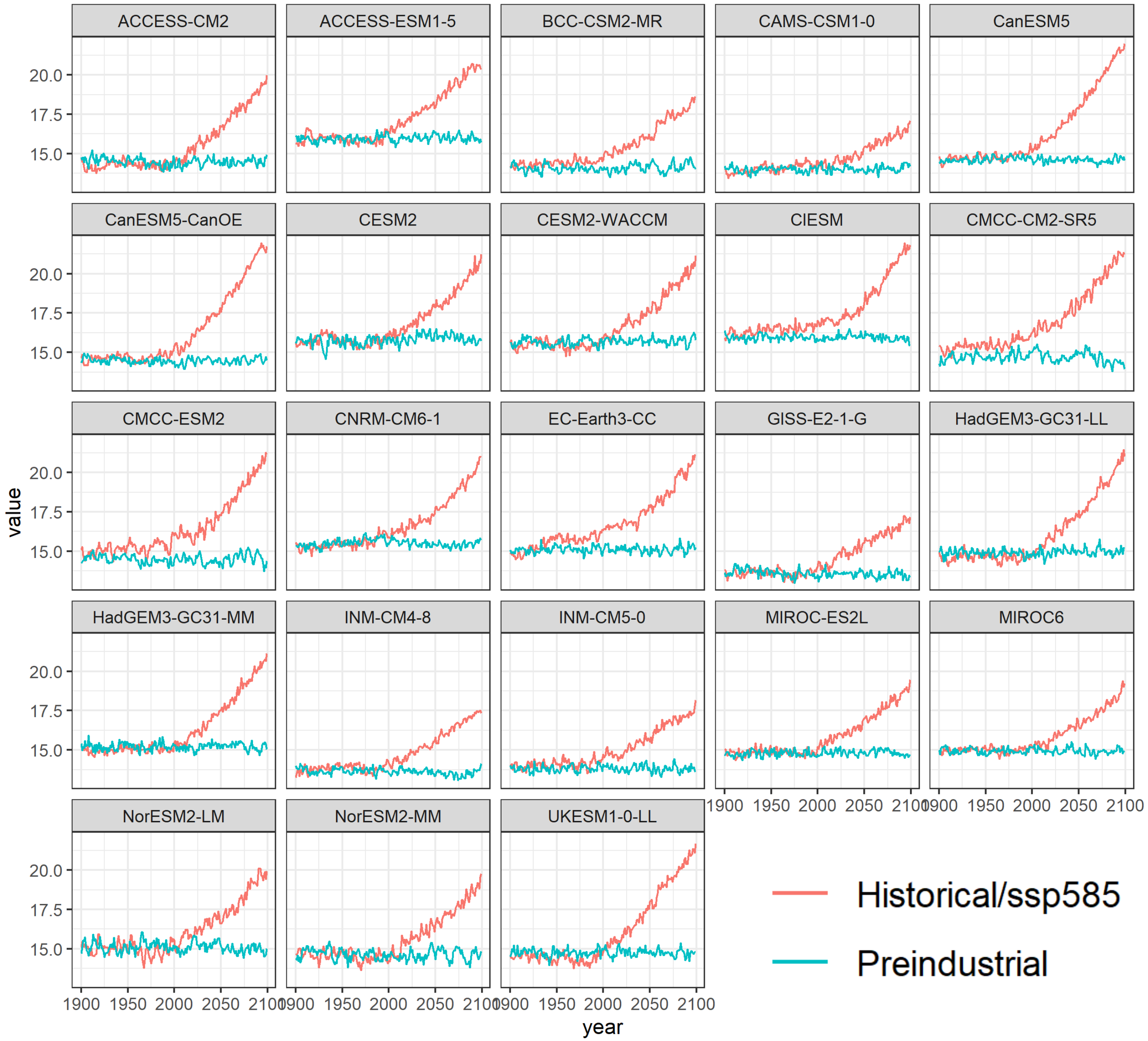
FAR = 0.5 → twice as likely with human influence

FAR = 1 → only possible with human influence

<u>23 CMIP6 models</u>

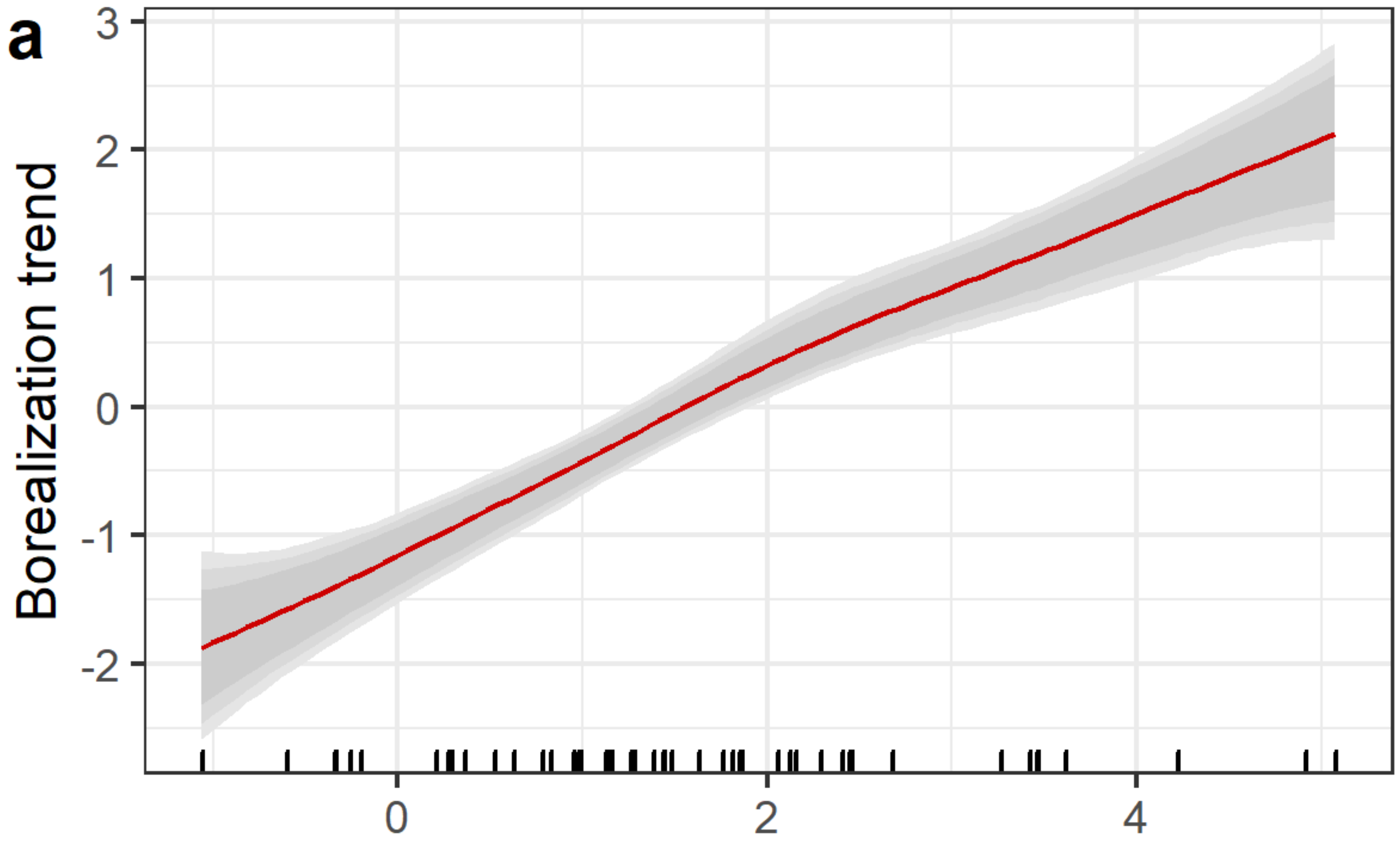
- Weighted for each region (bias, autocorrelation, low-frequency prediction)
- Corrected for differences in climate sensitivity and predicted warming rate (~~model democracy~~)

North Pacific sea surface temperature



Borealization maps onto annual sea surface temperature

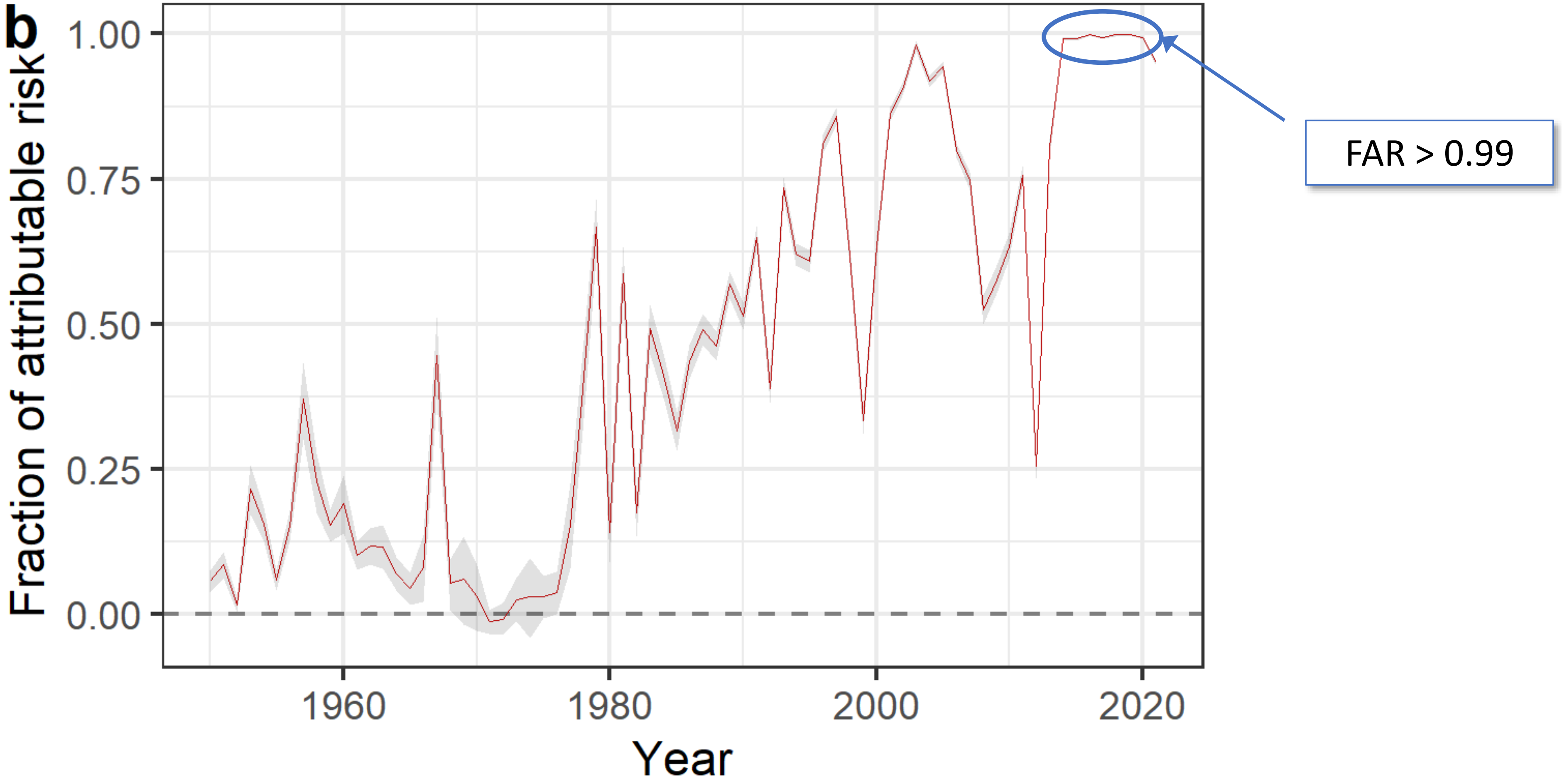
Posterior mean with
80 / 90 / 95%
credible intervals



SST anomaly wrt 1854-1949

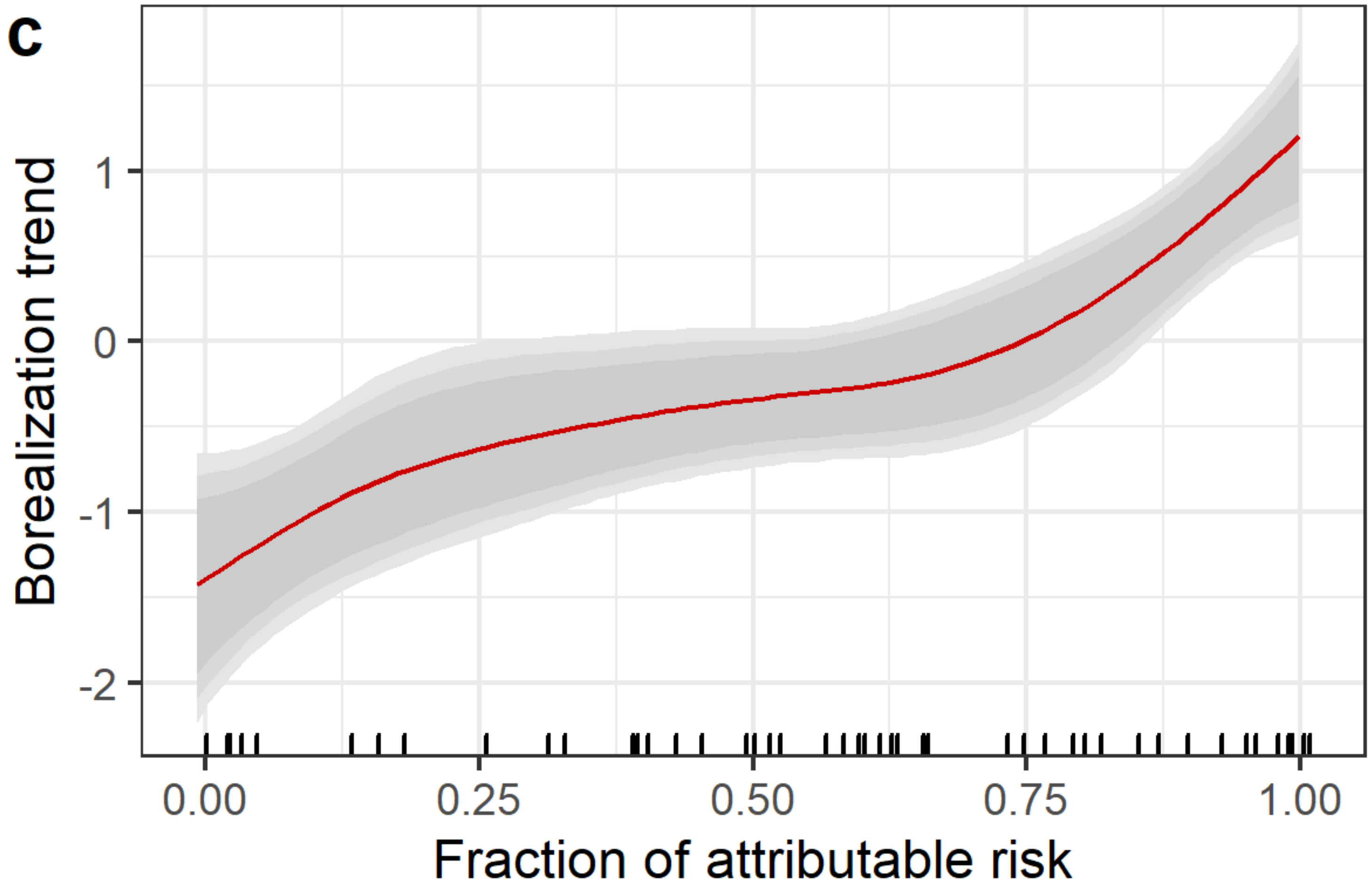
Recent Bering Sea SST extremes are human-caused

Posterior mean with
95%
credible intervals



Rapid borealization events occur during human-caused SST extremes

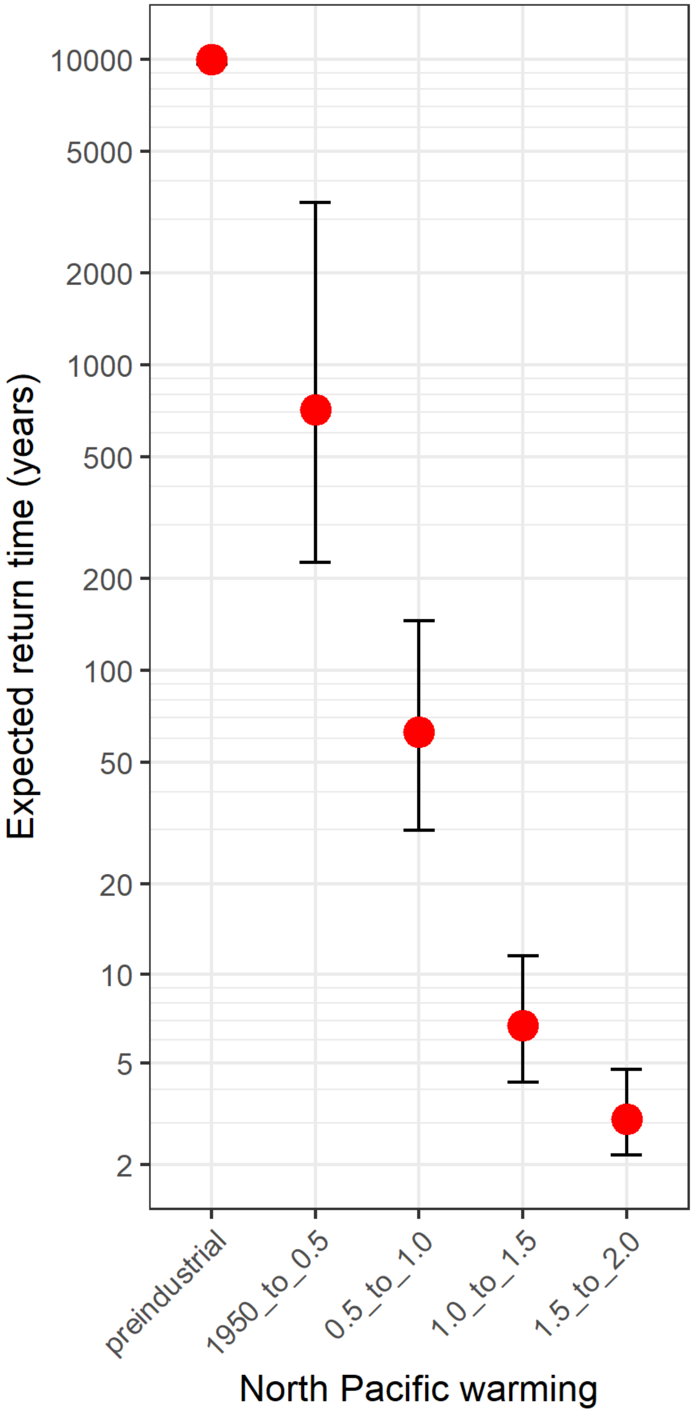
Posterior mean with
80 / 90 / 95%
credible intervals



4. Project borealization

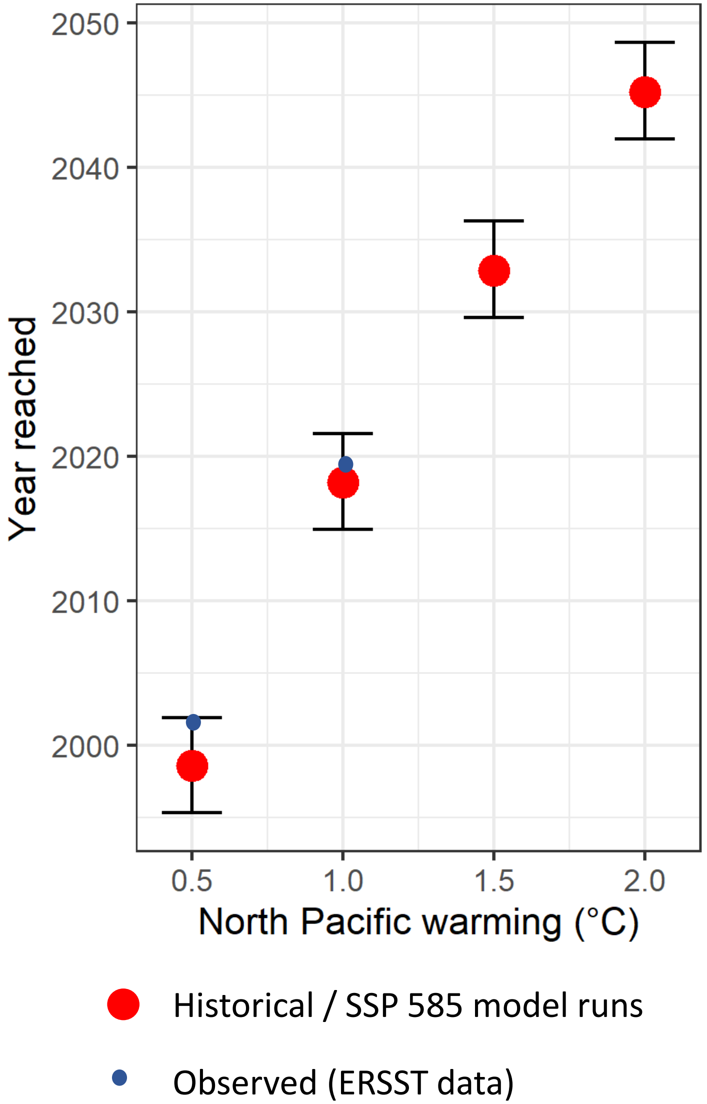
Expected return time for SST anomalies ≥ 2016, 2018-2020 values

(high borealization years)



Posterior means with 95% credible intervals

Observed & projected North Pacific warming rate



Conclusions

- The southeast Bering has rapidly borealized since 2016
- Strong evidence for negative impacts on snow crab
  - *A priori* expectation for ice-associated species
  - Proposed mechanisms map onto borealization
  - Statistical support
- Strong support for human role in borealization
- Probability of borealization *already* increased; *projected* to continue
- Recent M is the most probable value for projections
- M has an anthropogenic component:

  "non-fishing mortality" rather than "natural mortality"
- Northern Bering important for longer-term health of the fishery