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The Surprising Oceanography of the Gulf of Maine

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Cover Page Footnote

Thanks to the individuals, groups, and agencies that have invested in and conducted long-term environmental monitoring in the Gulf of Maine and who have maintained publicly available datasets. Funding was provided by NSF OCE 2049308 and NSF grant #1849227.

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by Nicholas R. Record, Ben Tupper, Johnathan Evanilla, Kyle S. Oliveira, Logan Ngai, Camille H. Ross, and Karen Stamieszkin

ABSTRACT

The oceanography of the Gulf of Maine has recently changed in ways that have not been seen previously, but that are likely to be more common in the future. Because of the rapid rate of change, some view the Gulf of Maine as a window into the ocean's future with the idea that lessons learned can be applied in places that have yet to experience similar rapid changes. Based on a formal statistical definition of oceanographic surprises, the frequency of surprises in the Gulf of Maine is higher and has increased faster than expected even given underlying trends. The analysis suggests that we should expect new kinds of surprises that are characteristically different from previous ones. The implication for policymaking is that in addition to considering long-term environmental changes, it is important to consider scenarios of sudden, unexpected, and potentially extreme environmental changes.

INTRODUCTION

Nothing is so painful to the human mind as a great and sudden change.—Mary Shelley (1818)

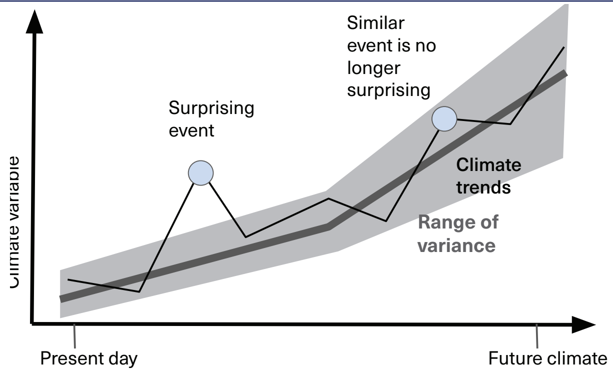
The Gulf of Maine has a history of frequent oceanic change. Oceanographically, it is a young system, emerging from beneath the Laurentide Ice Sheet around the time when humans were developing agriculture in other parts of the world (Shaw et al. 2006), then developing into a productive system that underpinned intensive extractive fisheries over the last several hundred years (Lotze et al. 2022). Because of the foundational oceanographic work done by Henry Bigelow in the early 1900s (Bigelow 1926, 1927), oceanographers have been able to track century-scale changes, such as a yellowing due to changes in dissolved organic matter (Balch et al. 2016) and a shift in the timing of phytoplankton blooms (Record et al. 2019a).

Despite a long history of study, a recent rapid oceanographic shift took the research, resource management, conservation, and industry communities by surprise. This recent shift was notable in that the surface warming rate during the decade beginning in 2004 significantly exceeded anything in the historical record. An analysis of historical temperatures around the globe, going back to 1900, found that decadal warming at this rate had a likelihood of less than 3 in 1,000 (Pershing et al. 2015). While warming has continued, the rate of warming during that decade stands out as extreme given the statistical properties of the temperature record (Witman et al. 2023). The interconnected effects of this event surprised communities around the Gulf of Maine, received attention in a Pulitzer-finalist series of articles (Woodard 2020), and stand out globally as what is referred to as an oceanographic "surprise."

An oceanographic surprise can be defined as "conditions that are unexpected based on recent history" (Pershing et al. 2019: 18378), or as in climate surprises, "a gap between one's expectations about the likely (i.e., plausible) climate and the climate that actually occurs" (Streets and Glantz 2000: 97). There are multiple ways to quantify surprises, but the essence is to quantify how much deviation there is from the expectation that past conditions are indicative of future conditions.

Oceanographic surprises, like *black swan events* (Taleb 2007), come from outside our experience, are difficult to predict, and have outsized effects on society. While we often focus on steady, predictable changes, oceanographic surprises have the potential to influence resources, management, and conservation well in advance of the gradual climate change timeframes that people are accustomed to thinking about (Broecker 1987) (Figure 1). There are interactions between trend (directional change over time) and variance (the range around that trend), where steeper trends can magnify variance, or high variance can overshadow trends, making surprises difficult to track. Oceanographic surprises are likely to shape marine policy in the future, so an understanding of their dynamics and scales can provide a more forward-looking perspective that can help inform

FIGURE 1: **Oceanographic or Climate Surprises**



Note: Thin black line shows a climate variable changing through time, including surprising events; heavy gray line shows long-term trends; gray-shaded area shows typical variance range around the trend, such as a 95% confidence interval. Year-to-year variability around the trend can defy expectations. In this example, an early surprise reaches future climate conditions far in advance of the long-term projection. A similar event that occurs after climate has shifted may no longer be surprising as it is closer to new typical conditions. In many cases, surprises can influence resources, management, and conservation efforts more so than long-term trends.

policy decisions. Partly by their definition—that they defy our experience and prediction—they are difficult to understand. However, a look back at previous oceanographic surprises can provide some insights. Here we reviewed the oceanographic changes that have occurred in the Gulf of Maine and reinterpreted them through the lens of surprises. First, we reviewed the scientific literature to provide an interpretation of what the oceanographic community has viewed as surprising. Second, we compiled historic oceanographic data from the Gulf of Maine at a multidecadal time scale, including physical and biological oceanographic measurements, and analyzed them in the context of a standard statistical definition of oceanographic surprises.

HISTORICAL OCEANOGRAPHIC SURPRISES

We transform the world, but we don't remember it. We adjust our baseline to the new level, and we don't recall what was there.—Daniel Pauly[1]

The Gulf of Maine sits near the confluence of the warmer, saltier Gulf Stream and the cooler, fresher Labrador Current, whose varying relative contributions set up the stratification and oceanographic dynamics of the Gulf's interior (Figure 2). The deep basins are supplied by a current through the Northeast Channel, which is the only deep water opening to off-shelf waters. Surface currents generally flow counter-clockwise around the deep basins, with a strong coastal current flowing east-to-west along the coast of Maine. Additionally, significant seasonal river input and strong tidal currents shape local dynamics.

Over the past millennium, the Gulf of Maine has undergone gradual long-term changes—generally cooling, with variability largely tied to climate oscillations like the Atlantic Multidecadal Oscillation (Whitney et al. 2022). Superimposed on long-term dynamics, there have been occasions of rapid changes that could be viewed as oceanographic surprises, with consequences for humans. Many of these events were better understood after the fact, once the mechanisms had been studied, but at the times of occurrence, they were regarded as surprises. Here we provide a short timeline of recent events that have been treated in the scientific literature as surprising oceanographic events.

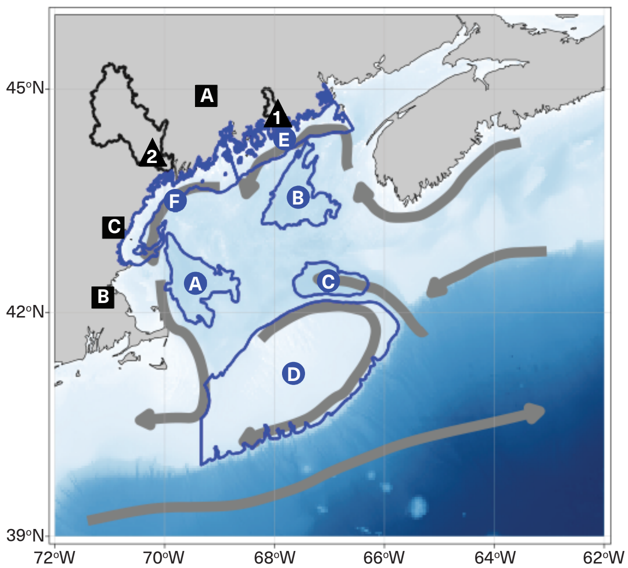
1815—Tambora Eruption

The eruption of Indonesia's Mount Tambora in 1815 led to the coldest year in the recorded history of the northeastern United States due to the global stratospheric spread of sulfate aerosols. The effects on the Gulf of Maine have been reconstructed using historical fish export data, weather readings, dam construction, and town growth chronologies and narrative sources. Winter conditions persisted year-round, with wide-ranging impacts: the cooling of coastal waters, crop failure, livestock death, and famine. The oceanographic changes in the Atlantic possibly lasted close to 10 years (Raible et al. 2016). The effects of coastal dynamics on anadromous fish runs, particularly alewives, contributed to a rapid fishery reorganization, from targeting anadromous fish to targeting pelagic fish. This type of reorganization had taken decades to centuries in Medieval Europe, but took just a few years in coastal Maine. The year 1816 was referred to as the "mackerel year" (Alexander et al. 2017) due to the extreme impacts on fisheries.

1950s—Atlantic Multidecadal Oscillation Warming

The Gulf of Maine experienced a decade of intensified warming from the 1940s into the 1950s before rapid cooling returned temperatures to the background warming trend (Shearman and Lentz 2010; Stearns 1965). This decadal event is generally linked to the Atlantic Multidecadal Oscillation, which tracks a sea surface temperature climate oscillation that has a 60- to 80-year period. This oscillation crested during this shift, and the intensified warming and cooling in the Gulf of Maine was driven by changes in the

FIGURE 2: **Extent of Marine Regions**



Note: Blue circles: (A) Wilkinson Basin (WBN), (B). Jordan Basin (JBN), (C) Georges Basin (GBN), (D) Georges Bank (GBK), (E) Eastern Maine Coastal Current (EMCC), (F) Western Maine Coastal Current (WMCC). Global Historical Climate Network weather stations black squares: (A) Corinna, ME: (B) Durham, NH; (C) Blue Hill Observatory, Milton, MA. US Geological Survey river monitoring stations triangles: (1) Narraguagus River (2) Androscoggin River (respective watersheds outlined in black). Generalized current representations are shown with grey streamlines. Source: Base bathymetry from GEBCO Compilation Group (2023) GEBCO 2023 Grid (DOI: 10.5285/f98b053b-0cbc-6c23-e053-6c86abc0af7b). Marine regional boundaries adapted from https://www.marineregions.org/. Androscoggin River watershed boundary adapted from US Geological Survey, 2019, National Hydrography Dataset (ver. USGS National Hydrography Dataset Best Resolution (NHD) for Hydrologic Unit (HU) 4 -2001 (published 20191002)), https://www.usgs.gov/national-hydrography/access-national-hydrography-products.

Gulf Stream and Labrador Current, which control the proportions of warm-saltier and cool-fresher, respectively, water masses to the region (Petrie and Drinkwater 1993; Friedland and Hare 2007). Trade publications during this decade reflect that fishing communities were surprised by these changes, reporting shifts to new species and occurrences of invasive species (McClenachan et al. 2019). There is some evidence that a similar event occurred in the late 1800s, also tied to the oscillation (Moore et al. 2017).

Late 20th Century—Great Salinity Anomalies

Great Salinity Anomalies are characterized by a large influx of Arctic ice and cold, fresh Labrador Subarctic Slope Water southwestward along the North Atlantic shelf (Greene et al. 2013). This influx of water typically enters the Gulf of Maine and Scotian Shelf regions, flushing out the more temperate, saltier waters typical of the region. There have been three such recorded instances, occurring in 1971–1973, 1982–1985, and 1990–1994 (Belkin 2004).

Each of these events is linked to a minimum in the North Atlantic Oscillation, which tracks an atmospheric climate oscillation. The large changes in temperature and salinity during these events have impacted the ecosystem, largely through increases or decreases in the dominant copepod *Calanus finmarchicus* abundance, which has driven shifts in abundances of fish and calving rates of North Atlantic right whales (Pershing et al. 2005).

2004–2014—Extreme Rapid Warming

The recent decadal warming mentioned earlier was first observed as surface warming in 2012, detected and described using satellite measurements (Pershing et al. 2015) and attributed to a variety of drivers, including climate oscillations and atmospheric warming connected to the Jet Stream (Chen et al. 2014). Later studies traced the origin of the warming back further to 2010, when a step change in deep water entering the Gulf of Maine through the Northeast Channel occurred (Record et al. 2019b). More recent studies traced the origin of the shift back to 2008–2009, to a change in the Gulf Stream near Newfoundland, which then, through a series of oceanographic connections, drove the later increase in warm water entering Northeast Channel (Gonçalves Neto et al. 2023).

The oceanographic change can be seen in its effects on fisheries, though the recent warming is viewed much more negatively by fishing communities than warming was in the mid-1900s (McLenachan et al. 2019). Research has linked warming to declines in cod (Pershing et al. 2015), right whales and their zooplankton prey (Record et al. 2019b), sand lance (Suca et al. 2021), northern shrimp (Richards and Hunter 2021), razorbills and murres (Scopel et al. 2021), blue mussels (Sorte et al. 2017), and in lobster health due to increased epizootic shell disease (Reardon et al. 2018). On the flip side, there have been increases in other species, such as fiddler crabs, longfin squid, and black sea bass (McMahan et al. 2020).

2016–2023—Emerging Phytoplankton Species

Warming events like those in the mid-1900s and early 2000s have largely been associated with the arrival or increases of warm-water species and declines of cold-water species (McClenachan et al. 2019). Since 2016, the oceanography of the Gulf of Maine has been marked by the arrival of potentially harmful algal species that do not appear to track the shifting climate envelope (Record et al. 2021). This includes *Pseudo-nitzschia australis* blooms since 2016 and the arrival of *Karenia mikimotoi* since 2020. In 2022, an unidentified Chrysophyte formed a dense bloom in Casco Bay, and in 2023, *Tripos muelleri* bloomed across the Gulf—both blooms intense enough to potentially cause hypoxic events. While these blooms have surprised communities, industry, and management, it is difficult to put them into historical context because of limited knowledge of past surprising algal blooms.

QUANTIFYING SURPRISES

We need to principally study the rare and extreme events in order to figure out common ones—Nassim Taleb (2007)

The importance of surprises, rather than gradual changes, has been raised in the past (Broecker 1987), and recent work on marine heat waves has provided quantitative approaches for measuring and tracking surprising temperatures in the surface ocean. The Gulf of Maine has a diverse collection of multidecadal time series, ranging from the physics to the biology, so we can use these quantitative tools to look retrospectively at oceanographic surprises in a more holistic way. Our analysis focused on an interannual time resolution, drawing from available multidecadal measurements related to physical and biological oceanography. All data sources are public, and we provide a brief description of each in the accompanying sidebar.

As an orientation to the data, it is useful to examine the relationships between time series. We examined all pairwise correlations, organized based on a multidimensional clustering.[2] Three clear clusters emerged (Figure 3). The largest and tightest cluster contained sea surface temperature time series for all regions, along with the Gulf Stream Index, and the surface chlorophyll metrics over all three basins and Georges Bank. This clustering appeared to show a coherence of the offshore oceanographic dynamics with the Gulf Stream. A second smaller but also tight cluster contained the terrestrial weather station metrics along with the Atlantic Multidecadal Oscillation. The remaining time series were more loosely clustered together and included many of the coastal current associated dynamics: the coastal current chlorophyll metrics, the coastal harmful algal bloom indices, and river discharge. The coastal cluster also included other biological metrics, including phytoplankton color index and the *Calanus* index.

DATA SOURCES FOR TIME SERIES ANALYSIS

Climate indices—Annual climate oscillation indices: the Atlantic Multidecadal Oscillation (AMO), the North Atlantic Oscillation (NAO), Gulf Stream Index (GSI) (Chen et al. 2021).

Sea surface temperature—Sea surface temperature records (SST) from the Optimum Interpolation Sea Surface Temperature (OISST) (Huang et al. 2021) and Extended Reconstructed Sea Surface Temperature (ERSST) (Huang et al. 2017) data products; annual means for the spatial regions in Figure 2.

River discharge—US Geological Survey stream gauge daily discharge, including the Androscoggin (01059000) and Narraguagus (01022500) Rivers (USGS 2016).[4]

Land-based climate records—Global Historical Climatology Network daily records from Durham, NH, Blue Hill Coop, MA, and Corinna, ME (Menne et al. 2010), including annual medians of surface air temperature daily minimum (Tmin) and maximum (Tmax).

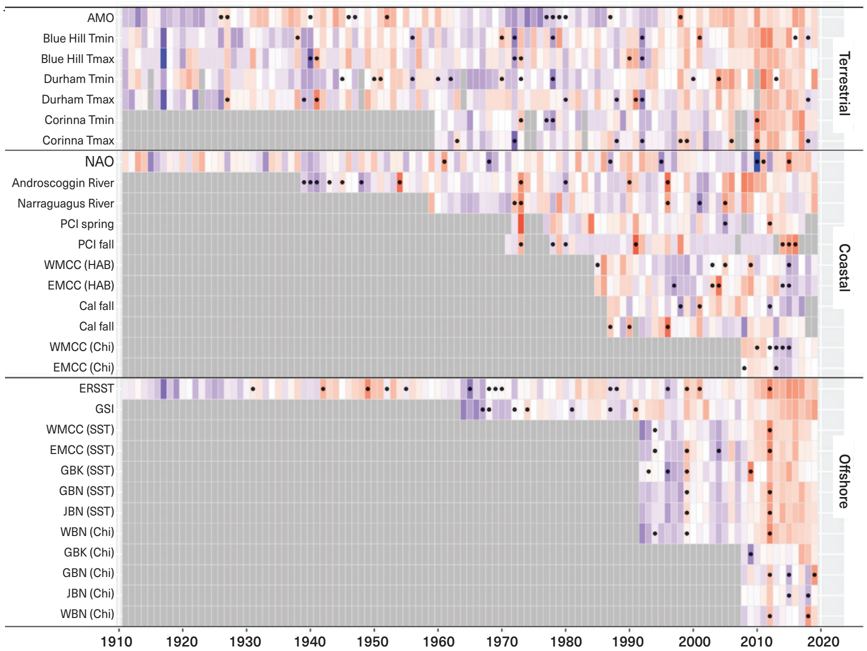
Phytoplankton—Monthly global chlorophyll-a concentration from ocean color satellites (CMEMS 2023), including annual values for the spatial regions outlined in Figure 2; the phytoplankton color index (PCI) from the Gulf of Maine continuous plankton recorder (CPR), including a spring (March–May) and fall (September—November) log-scale anomaly (Record et al. 2019a).

Zooplankton—Index of late-stage *Calanus finmarchicus* from the National Oceanic and Atmospheric Administration (NOAA) Fisheries Ecosystem Monitoring Program (EcoMon) spring (March–May) and fall (September–November) log-scale anomaly for stations > 100m depth.

Algal toxins—Maine Department of Marine Resources paralytic shellfish toxin seasonal severity index, calculated following Anderson et al. (2014).

The tighter linking between the terrestrial and offshore clusters probably suggests the strong role of a temperature driver. The coastal system, while it sits spatially between the land and the offshore, is more loosely connected, likely due to the complexity of the interactions between temperature, river flow, and the dynamics of the coastal current, which is coupled with upstream dynamics connected to the Labrador Current. In many cases, the coastal system was negatively correlated with the broader temperature and offshore dynamics.

FIGURE 3: **Time Series of Surprises across Data Sets**



Note: Each time series is normalized so that color indicates standard deviation from mean (red is positive, blue is negative). Points indicate whether or not a year is surprising based on the deviation-from-trend method described in the text. Terrestrial, coastal, and offshore designations are based on correlation analysis described in the text. Location abbreviations are as in Figure 2.

Surprise Measurements

There are multiple ways to define surprises. In much of the marine heat wave literature, for example, heat waves are defined relative to a deviation from mean conditions and are increasing in frequency as temperature increases (Oliver 2018). However, using this approach, after enough warming, heat waves would become the mean condition (Jacox 2019) and would no longer be surprising. To account for this effect, we used a surprise metric that was based on the deviation from a recent trend.[3] By applying the method consistently to each year in the time series, we can reduce the tendency for retrospective or confirmation biases.

One decision in this type of analysis is the choice of the size of the sliding window. The Gulf of Maine tends to have distinct one- to two-decade shifts (Pershing et al. 2005), and there is evidence that people's perceptions and expectations respond to shifts in the ocean environment at this time scale (McClenachan et al. 2019). This tracks with how the recent decadal change in the Gulf of Maine was surprising across coastal communities and the scientific community. Based on these patterns, a timescale of n = 10–20 years is reasonable.

We ran our analysis across a range of values of n and found that the results were very noisy at n = 10 and converged to a consistent pattern around n = 15–20 years. Results presented here used n = 20 years, but we acknowledge that the timescale at which people are surprised is dynamic and subjective.

A few patterns emerged in the time series of surprises. Surprising events in sea surface temperature, when they occurred, occurred together across regions. However, surprising temperatures in the ocean did not align with surprising temperatures on land. Surface chlorophyll had a coherence similar to ocean temperatures, though with a separation between the offshore regions and the shallower coastal current regions. The 2012 warm event that brought attention to the rapid warming also stood out, with coherent surprising temperature measurements having been followed by surprising events in multiple other metrics. The warming associated with the Atlantic Multidecadal Oscillation in the mid-20th century registered a similar surprise, aligning with the oceanographic (Stearns 1965) and trade (McClenachan et al. 2019) literature, though other metrics were not available for comparison. There did not appear to be a type of surprise (i.e., a cluster of surprising metrics) that occurred more than once, though the limitations in the durations of some time series could be hiding patterns. Notably, surprises occurred throughout all time series in over 10 percent of instances, more than two times the expected frequency of two-sigma events. Since 2012, that percentage rose to 12 percent, and nearly 20 percent for biological variables. The elevated frequency of surprises is consistent with the sea surface temperature patterns in the North Atlantic, where surprises have been occurring more than would be expected, even accounting for the warming trend (Pershing et al. 2019). Among the different time series, those associated with phytoplankton measurements tended to have higher surprise frequencies than the other time series.

THE NEXT SURPRISE

My suspicion is that we have been lulled into complacency by model simulations that suggest a gradual warming over a period of about 100 years. —Wallace S. Broecker (1987)

If we take the premise that surprises—sudden unexpected changes—have outsized relevance to the policy and social spheres, then we have to ask, What will the next surprise be, and when will it occur? There are indications that major oceanographic events could transform ocean dynamics in the coming decades (Ditlevsen and Ditlevsen 2023), and even the recent oceanographic surprises created crises for fisheries (Pershing et al. 2015) and marine mammals (Record et al. 2019). The retrospective look at oceanographic surprises gives us two lessons: (1) surprises are more common than would be expected based on random chance, even if we are taking the trend into account; and (2) each documented surprise looks qualitatively different from previous ones. These lessons point to the conclusion that we should expect new kinds of surprises, and probably soon. Streets and Glantz (2000), in their taxonomy of surprising events, distinguish between two types of surprises. Open surprises, also called *known unknowns*, represent those that we have some understanding of, and for which we have some knowledge of the consequences, but that we can't predict accurately. In the Gulf of Maine, this could include processes like sea level rise or infectious diseases. For sea level rise, for example, we know that there is an on-going climate-driven process occurring, but sea level rise tends to do its damage during sudden events, where the background sea level rise is amplified by the coincidence of a high tide and a storm surge. This type of event can reshape a coastline suddenly and unexpectedly, even when people are aware of the issue. Similarly, we have seen epizootic shell disease influence lobster populations in southern New England, so we have some sense for what the impact would be in the Gulf of Maine, but it can be difficult to predict if or exactly when such an event would occur because of rapid and nonlinear disease dynamics.

Open surprises could also include events like sudden cooling. The long-term warming trend has led to a shifting-baselines type scenario (cf. Pauly 1995), where the recent warm years—at the extreme of the data—are commonplace and no longer surprising. A temporary shift back to historical average (or even slightly above average) conditions could constitute a surprise, catching our management or policy approaches off guard. The cooling in the 1960s, following the warm period, was also regarded with some degree of surprise by the fishing industry at the time (McClenachan et al. 2019). While the prediction of long-term warming of the Gulf of Maine is consistent in models (Saba et al. 2016), the Gulf Stream and Labrador Current are highly dynamic, and the short-term dynamics are more difficult to predict.

The other category of surprise is called closed surprises, sometimes referred to as *unknown unknowns* (Streets and Glantz 2000). Pragmatically, there is a continuum between open and closed surprises. Further along the spectrum toward a closed surprise would be processes like ocean acidification. At present, we are aware that additional carbon dioxide affects the pH of the ocean, which can affect some organisms, but we don't have a sense for what an ocean acidification surprise would look like, we don't know what the chance is of one occurring, and we don't have multidecadal measurements for historical context. Other potential surprises that fall along this spectrum include a thermohaline shutdown (Ditlevsen and Ditlevsen 2023), new invasive, toxic, or hypoxia-inducing algal species (Record et al. 2021), or the collapse of species population levels. In many of these cases, long-term monitoring can help us understand and prepare for surprising events. The multidecadal analysis shown here had to exclude time series that began more recently, but there are monitoring programs that began in the 2000s for which continued investment is needed. These include the buoy system supported by the Northeast Regional Association for Coastal Ocean Observing Systems, the Gulf of Maine North Atlantic Time Series, coastal plankton monitoring supported by the Marine Biodiversity Observation Network, and others. There are also historical measurements of ocean chemistry that extend back many decades (Rebuck and Townsend 2014), but because of gaps, analysis of surprises was not possible. Maintaining and strengthening our long-term monitoring will help improve our understanding of long-term dynamics and give us more opportunity to study surprises.

Of course, it might be impossible to measure and prepare for everything. After all, if we knew something was coming, it wouldn't be a surprise. At the far end of the spectrum of closed surprises, there are the unknown unknowns that we might not even be considering. How can we take this type of surprise into account when considering policy decisions? One approach for preparing for this type of event, and for surprises in general, is the process of foresighting—a multidisciplinary, collaborative brainstorming process that considers potential changes in the climate and environment, technologies and economics, and their interactions in order to plan for and shape the future (Hobday et al. 2020). At the heart of the process is a challenge to the assumption that the future will be like the present or will follow present trends. There is an emphasis on including members of coastal communities, indigenous communities, marine industries, and other invested people in the foresighting process; information provided by these groups can shape the focal questions and spatio-temporal scales of prediction efforts (Record et al. 2022). Broad inclusion is particularly important given the emerging knowledge on climate justice—that those most affected by anthropogenically driven changes are often those least responsible (Dolšak and Prakash 2022; Whyte 2019). This scenario has often played out through surprising events like floods, storms, or wildfires; an equity-centered foresighting approach could address the questions of who is surprised and why and possibly provide solutions that address climate injustices.

Maine has a history of a collaborative approach to policy and management, which is to some degree a response to fisheries collapses of the past (Waller et al. 2023). Historically, most fishery collapses in the Gulf of Maine were not oceanographically driven. But these collapses can also be viewed as ocean surprises with major impacts, and they provide some collective memory and knowledge of how surprises play out in coastal communities. Today, multiple interacting marine uses are converging in the Gulf of Maine, such as rapid aquaculture growth, the development of offshore wind, and traditional and new fisheries, set on a backdrop of long-term environmental trends. Simultaneous with these changes is the increasing appearance of oceanographic surprises that can thwart long-term plans. Understanding gradual changes can help give us direction, but it's often the sudden, unexpected events that force action. We won't be able to prepare for every contingency, but by viewing our history and data through the lens of surprises, rather than only as steady gradual changes, we can imagine policies that better prepare us for the unexpected.

ACKNOWLEDGMENTS

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NOTES

1 https://www.ted.com/talks/daniel_pauly_the_ocean_s_shifting_baseline

2 https://corrr.tidymodels.org

3 For each time point, we fit a linear model to the previous n years, where n is a sliding window representing the period of time on which expectations are based. The surprise metric for the subsequent point is the number of standard deviations off the linear fit. A value of +/- 2 standard deviations represents a surprise. This method is referred to as "betting on the trend" and has been used to define surprising ocean temperatures (Pershing et al. 2019). This is also referred to as a two-sigma event, which has an expected frequency of around once per 20 years. Under this model, an extreme value might be a surprise one year, but as the window slides forward, this new information is incorporated into expectations, so a similar value will be less surprising in subsequent years.

4 https://doi.org/10.3133/gip213

REFERENCES

Alexander, Karen E., William B. Leavenworth, Theodore V. Willis, Carolyn Hall, Steven Mattocks, Steven M. Bittner, Emily Klein, et al. 2017. "Tambora and the Mackerel Year: Phenology and Fisheries during an Extreme Climate Event." *Science Advances* 3(1):e1601635. https://doi.org/10.1126/sciadv.1601635.

Anderson, Donald M., Darcie A. Couture, Judith L. Kleindinst, Bruce A. Keafer, Dennis J. McGillicuddy Jr., Jennifer L. Martin, Mindy L. Richlen, et al. 2014. "Understanding Interannual, Decadal Level Variability in Paralytic Shellfish Poisoning Toxicity in the Gulf of Maine: The HAB Index." *Deep Sea Research Part II: Topical Studies in Oceanography* 103:264–276. https://doi.org/10.1016/j.dsr2.2013.09.018.

Balch, Willam, Thomas Huntington, George Aiken, David Drapeau, Bruce Bowler, Laura Lubelczyk, and Kenna Butler. 2016. "Toward a Quantitative and Empirical Dissolved Organic Carbon Budget for the Gulf of Maine, a Semienclosed Shelf Sea." *Global Biogeochemical Cycles* 30(2): 268–292. https://doi.org/10.1002/2015GB005332.

Belkin, Igor M. 2004. "Propagation of the 'Great Salinity Anomaly' of the 1990s around the Northern North Atlantic." *Geophysical Research Letters* 31:L08306. https://doi.org/10.1029/2003GL019334.

Bigelow, Henry B. 1926. *Plankton of the Offshore Waters of the Gulf of Maine.* Washington, DC: US Government Printing Office.

———. 1927. *Physical Oceanography of the Gulf of Maine.* Washington, DC: US Government Printing Office.

Broecker, Wallace S. 1987. "Unpleasant Surprises in the Greenhouse?" *Nature* 328:123–126. https://doi.org/10.1038/328123a0.

Chen, Ke, Glen G. Gawarkiewicz, Steven J. Lentz, and John M. Bane. 2014. "Diagnosing the Warming of the Northeastern US Coastal Ocean in 2012: A Linkage between the Atmospheric Jet Stream Variability and Ocean Response." *Journal of Geophysical Research: Oceans* 119(1): 218–227. https://doi.org/10.1002/2013JC009393.

Chen, Zhuomin, Young-Oh Kwon, Ke Chen, Paula Fratantoni, Glen Gawarkiewicz, Terrence M. Joyce, Timothy J. Miller, et al. 2021. "Seasonal Prediction of Bottom Temperature on the Northeast US Continental Shelf." *Journal of Geophysical Research:*

Oceans. 126(5): e2021JC017187. https://doi.org/10.1029/2021JC017187.

CMEMS. 2023. *Global Ocean Colour Plankton MY L4 Monthly Observations.* EU Copernicus Marine Service Information. Marine Data Store. https://doi.org/10.48670/moi-00283.

Ditlevsen, Peter, and Susanne Ditlevsen. 2023. "Warning of a Forthcoming Collapse of the Atlantic Meridional Overturning Circulation." *Nature Communications* 14(1): 4254. https://doi.org/10.1038/s41467-023-39810-w.

Dolšak, Nives, and Aseem Prakash. 2022. "Three Faces of Climate Justice." *Annual Review of Political Science* 25:283–301. https://doi.org/10.1146/annurev-polisci-051120-125514.

Friedland, Kevin D., and Jonathan A. Hare. 2007. "Long-Term Trends and Regime Shifts in Sea Surface Temperature on the Continental Shelf of the Northeast United States." *Continental Shelf Research* 27(18): 2313–2328. https://doi.org/10.1016/j.csr.2007.06.001.

Gonçalves Neto, Afonso, Jaime B. Palter, Xiaobiao Xu, and Paula Fratantoni. 2023. "Temporal Variability of the Labrador Current Pathways Around the Tail of the Grand Banks at Intermediate Depths in a High-Resolution Ocean Circulation Model." *Journal of Geophysical Research: Oceans* 128(3): e2022JC018756. https://doi.org/10.1029/2022JC018756.

Greene, Charles H., Erin Meyer-Gutbrod, Bruce C. Monger, Louise P. McGarry, Andrew J. Pershing, Igor M. Belkin, Paula S. Fratantoni, et al. 2013. "Remote Climate Forcing of Decadal-Scale Regime Shifts in Northwest Atlantic Shelf Ecosystems." *Limnology and Oceanography* 58(3): 803–816. https://doi.org/10.4319/lo.2013.58.3.0803.

Hobday, Alistair J., Fabio Boschetti, Christian Moeseneder, Robert L. Stephenson, Cindy Bessey, Catherine M. Bulman, Stephanie Contardo, et al. 2020. "Quantitative Foresighting as a Means of Improving Anticipatory Scientific Capacity and Strategic Planning." *One Earth* 3(5):631–644. https://doi.org/10.1016/j.oneear.2020.10.015.

Huang, Boyin, Chunying Liu, Viva Banzon, Eric Freeman, Garrett Graham, Bill Hankins, Tom Smith, and Huai-Min Zhang. 2021. "Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1." *Journal of Climate* 34:2923–2939. https://doi.org/10.1175/JCLI-D-20-0166.1.

Huang, Boyin, Peter W. Thorne, Viva F. Banzon, Tim Boyer, Gennady Chepurin, Jay H. Lawrimore, Matthew J. Menne, et al. 2017. *NOAA Extended Reconstructed Sea Surface Temperature (ERSST), Version 5.* NOAA National Centers for Environmental Information. https://doi.org/10.7289/V5T72FNM.

Jacox, Michael G. 2019. "Marine Heatwaves in a Changing Climate." *Nature* 571:485–487. https://doi.org/10.1038/d41586-019-02196-1.

Lotze, Heike K., Stefanie Mellon, Jonathan Coyne, Matthew Betts, Meghan Burchell, Katja Fennel, Marisa A. Dusseault, et al. 2022. "Long-Term Ocean and Resource Dynamics in a Hotspot of Climate Change." *Facets* 7:1142–1184. https://doi.org/10.1139/facets-2021-0197.

McClenachan, Loren, Jonathan H. Grabowski, Madison Marra, C. Seabird McKeon, Benjamin P. Neal, Nicholas R. Record, and Steven B. Scyphers. 2019. "Shifting Perceptions of Rapid Temperature Changes' Effects on Marine Fisheries, 1945–2017." *Fish and Fisheries* (6):1111–1123. https://doi.org/10.1111/faf.12400.

McMahan, Marissa D., Graham D. Sherwood, and Jonathan H. Grabowski. 2020. "Geographic Variation in Life-History Traits of Black Sea Bass (*Centropristis striata*) during a Rapid Range Expansion." *Frontiers in Marine Science* 7. https://doi.org/10.3389/fmars.2020.567758.

Menne, Matthew J., Imke Durre, Bryant Korzeniewski, Shelley McNeill, Kristy Thomas, Xungang Yin, Steven Anthony, et al. 2012. Global Historical Climatology Network-Daily (GHCN-Daily), Version 3. NOAA National Climatic Data Center. https://doi.org/10.7289/V5D21VHZ.

Meyer-Gutbrod, Erin L., Charles H. Greene , Kimberley Davies, and David G. Johns. 2021. "Ocean Regime Shift Is Driving Collapse of the North Atlantic Right Whale Population." *Oceangraphy* 34(3): 22–31. https://doi.org/10.5670/oceanog.2021.308.

Moore, G.W.K., J. Halfar, H. Majeed, W. Adey, and A. Kronz. 2017. "Amplification of the Atlantic Multidecadal Oscillation Associated with the Onset of the Industrial-Era Warming." *Scientific Reports* 7:40861. https://doi.org/10.1038/srep40861.

Oliver, Eric C.J., Markus G. Donat, Michael T. Burrows, Pippa J. Moore, Dan A. Smale, Lisa V. Alexander, Jessica A. Benthuysen, et al. 2018. "Longer and More Frequent Marine Heatwaves over the Past Century." *Nature Communications* 9(1):1324. https://doi.org/10.1038/s41467-018-03732-9.

Pauly, Daniel. 1995. "Anecdotes and the Shifting Baseline Syndrome of Fisheries." *Trends in Ecology & Evolution* 10(10): 430. https://doi.org/10.1016/S0169-5347(00)89171-5.

Pershing, Andrew J., Charles H. Greene, Jack W. Jossi, Loretta O'Brien, Jon K.T. Brodziak, and Barbara A. Bailey. 2005. "Interdecadal Variability in the Gulf of Maine Zooplankton Community, with Potential Impacts on Fish Recruitment." *ICES Journal of Marine Science* 62(7): 1511–1523. https://doi.org/10.1016/j.icesjms.2005.04.025.

Pershing, Andrew J., Michael A. Alexander, Christina M. Hernandez, Lisa A. Kerr, Arnault Le Bris, Katherine E. Mills, Janet A. Nye. et al. 2015. "Slow Adaptation in the Face of Rapid Warming Leads to Collapse of the Gulf of Maine Cod Fishery." *Science* 350(6262): 809–812. https://doi.org/10.1126/science.aac9819.

Pershing, Andrew J., Nicholas R. Record, Bradley S. Franklin, Brian T. Kennedy, Loren McClenachan, Katherine E. Mills, James D. Scott, et al. 2019. "Challenges to Natural and Human Communities from Surprising Ocean Temperatures." *Proceedings of the National Academy of Sciences* 116(37): 18378–18383. https://doi.org/10.1073/pnas.1901084116.

Petrie, Brian, and Kenneth Drinkwater. 1993. "Temperature and Salinity Variability on the Scotian Shelf and in the Gulf of Maine 1945–1990." *Journal of Geophysical Research: Oceans* 98(C11): 20079–20089. https://doi.org/10.1029/93JC02191.

Raible Cristoph C., Stefan Brönnimann, Renate Auchmann, Philip Brohan, Thomas L. Frölicher, Hans-F. Graf, and Phil Jones. 2016. "Tambora 1815 as a Test Case for High Impact Volcanic Eruptions: Earth System Effects." *Wiley Interdisciplinary*

Reviews: Climate Change 7(4):569–589. https://doi.org/10.1002/wcc.407.

Reardon, Kathleen M., Carl J. Wilson, Patrick M. Gillevet, Masoumeh Sikaroodi, and Jeffrey D. Shields. 2018. "Increasing Prevalence of Epizootic Shell Disease in American Lobster from the Nearshore Gulf of Maine." *Bulletin of Marine Science* 94(3): 903-921. https://doi.org/10.5343/bms.2017.1144.

Rebuck, N.D., and D.W. Townsend. 2014. "A Climatology and Time Series for Dissolved Nitrate in the Gulf of Maine Region." *Deep Sea Research Part II: Topical Studies in Oceanography* 103:223–237. https://doi.org/10.1016/j.dsr2.2013.09.006.

Record, Nicholas R., William M. Balch, and Karen Stamieszkin. 2019a. "Century-Scale Changes in Phytoplankton Phenology in the Gulf of Maine." *PeerJ* 7:e6735. https://doi.org/10.7717/peerj.6735.

Record, Nicholas R., Peter D. Countway, Kohl Kanwit, José Antonio Fernández-Robledo. 2021. "Rise of the Rare Biosphere: Thinking beyond Climate Envelopes for Forecasting Harmful Algal Blooms." *Elementa Science of the Anthropocene* 9(1): 00056. https://doi.org/10.1525/elementa.2020.00056.

Record, Nicholas R., Johnathan Evanilla, Kohl Kanwit, Craig Burnell, Carmen Cartisano, Bryant J. Lewis, Jill MacLeod, et al. 2022. "Benefits and Challenges of a Stakeholder-Driven Shellfish Toxicity Forecast in Coastal Maine." *Frontiers in Marine Science* 9:923738 https://doi.org/10.3389/fmars.2022.923738.

Record, Nicholas R., Jeffrey A. Runge, Daniel E. Pendleton, William M. Balch, Kimberley T.A. Davies, Andrew J. Pershing, Catherine L. Johnson, Karen Stamieszkin, et al. 2019b. "Rapid Climate-Driven Circulation Changes Threaten Conservation of Endangered North Atlantic Right Whales. *Oceanography* 32(2): 162–169. https://doi.org/10.5670/oceanog.2019.201.

Richards, R. Anne, and Margaret Hunter. 2021. "Northern Shrimp *Pandalus borealis* Population Collapse Linked to Climate-Driven Shifts in Predator Distribution." *PLOS One* 16(7): e0253914. https://doi.org/10.1371/journal.pone.0253914.

Saba, Vincent S., Stephen M. Griffies, Whit G. Anderson, Michael Winton, Michael A. Alexander, Thomas L. Delworth, Jonathan Hare, et al. 2016. "Enhanced Warming of the Northwest Atlantic Ocean under Climate Change." Jo*urnal of Geophysical Research: Oceans* 121(1): 118–132. https://doi.org/10.1002/2015JC011346.

Scopel, Lauren, Antony Diamond, Stephen Kress and Paula Shannon. 2019. "Varied Breeding Responses of Seabirds to a Regime Shift in Prey Base in the Gulf of Maine." *Marine Ecology Progress Series* 626:177–196. https://doi.org/10.3354/meps13048.

Shaw J., D.J.W. Piper, G.B.J. Fader, E.L. King, B.J. Todd, T. Bell, M.J. Batterson, and D.G. Liverman. 2006. "A Conceptual Model of the Deglaciation of Atlantic Canada." *Quaternary Science Reviews* 25(17–18): 2059–2081.

Shearman, R. Kipp, and Steven J. Lentz. 2010. "Long-Term Sea Surface Temperature Variability along the US East Coast." *Journal of Physical Oceanography* 40(5):1004–1017. https://doi.org/10.1175/2009JPO4300.1.

Shelley, Mary W. 1998. *Frankenstein, or, the Modern Prometheus,* the 1818 Text. New York: Oxford University Press.

Sorte, Cascade J.B., Victoria E. Davidson, Marcus C. Franklin, Kylla M. Benes, Meredith M. Doellman, Ron J. Etter, Robyn E. Hannigan, et al. 2017. "Long-Term Declines in an Intertidal Foundation Species Parallel Shifts in Community Composition." *Global Change Biology* 23(1): 341–352. https://doi.org/10.1111/gcb.13425.

Stearns, Franklin. 1965. "Sea-Surface Temperature Anomaly Study of Records from Atlantic Coast Stations." *Journal of Geophysical Research* 70(2):283–296.

Streets, D.G., and M.H. Glantz. 2000. "Exploring the Concept of Climate Surprise." *Global Environmental Change* 10(2): 97–107. https://doi.org/10.1016/S0959-3780(00)00015-7.

Suca, Justin J., David N Wiley, Tammy L Silva, Anna R Robuck, David E Richardson, Sarah G Glancy, Emily Clancey, et al. 2021. "Sensitivity of Sand Lance to Shifting Prey and Hydrography Indicates Forthcoming Change to the Northeast US Shelf Forage Fish Complex." *ICES Journal of Marine Science* 78(3): 1023–1037. https://doi.org/10.1093/icesjms/fsaa251.

Taleb, Nassim Nicholas. 2007. *The Black Swan: The Impact of the Highly Improbable.* New York: Random House.

USGS (US Geological Survey). *2016, National Water Information System data available on the World Wide Web (USGS Water Data for the Nation).* https://doi.org/10.5066/F7P55KJN.

Waller, J., J. Bartlett, E. Bates, H. Bray, M. Brown, M. Cieri, C. Clark, et al. 2023. "Reflecting on the Recent History of Coastal Maine Fisheries and Marine Resource Monitoring: The Value of Collaborative Research, Changing Ecosystems, and Thoughts on Preparing for the Future." *ICES Journal of Marine Science* 80:2074–2086. https://doi.org/10.1093/icesjms/fsad134.

Witman, Jon D., Andrew J. Pershing, and John F. Bruno. 2023. "Smooth and Spiky: The Importance of Variability in Marine Climate Change Ecology." *Annual Review of Ecology, Evolution, and Systematics* 54:129–149. https://doi.org/10.1146/annurev-ecolsys-022323-082123.

Whitney, Nina M., Alan D. Wanamaker, Caroline C. Ummenhofer, Beverly J. Johnson, Nathaniel Cresswell-Clay, and Karl J. Kreutz. 2022. "Rapid 20th Century Warming Reverses 900-Year Cooling in the Gulf of Maine." *Communications Earth & Environment* 3(1):179. https://doi.org/10.1038/s43247-022-00504-8.

Whyte, Kyle. 2019. "Way beyond the Lifeboat: An Indigenous Allegory of Climate Justice." In *Climate Futures: Reimagining Global Climate Justice,* edited by Kum-Kum Bhavnani et al., 11–20. Bloomsbury Publishing.

Woodard, Colin. 2020. "Mayday: Gulf of Maine in Distress." *Portland Press Herald,* September 7, 2020.

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