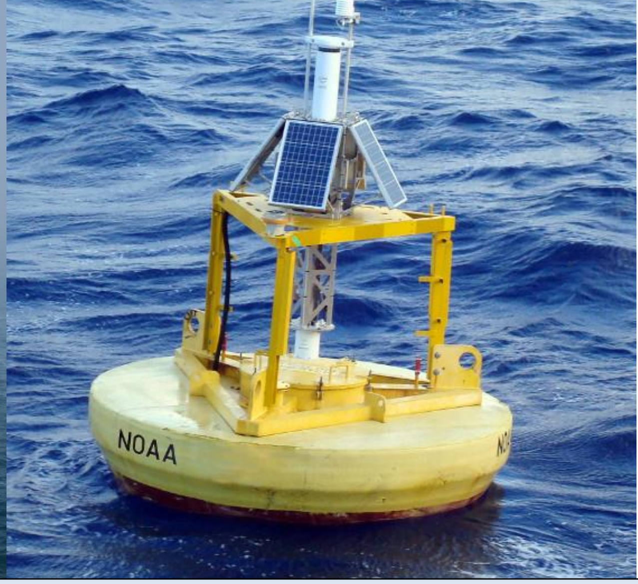

Meeting Coastal Information Needs through Tailored Scientific Assessment

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Meeting Coastal Information Needs in Weather and Climate through Tailored Scientific Assessment

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Policy Program Study

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Executive Summary

Weather, water, and climate issues underpin virtually every aspect of society. Although all communities face multiple complex challenges and opportunities relating to weather, water, and climate, coastal communities are often at the forefront. Coasts are valuable resources that support numerous ecological, social, and economic systems around the United States and the world; however, they are subject to increasing levels of disruption and risk due to ongoing and interconnected changes in climate and human development.

Driven by advances in Earth system observations, science, and services (OSS), as well as technological developments, weather, water, and climate information is increasingly available and reliable. However, for this information to most effectively support the long-term resilience of coastal communities it must also be actionable. As such, there is a tremendous opportunity to employ science more effectively by focusing on stakeholder needs and the decisions those stakeholders must make in the near term and by bringing communities into the process of advancing and applying scientific understanding.

In this study, part of an ongoing pilot program on actionable scientific assessment, we identify three overarching findings and four key areas of information needs applicable to coastal resilience-related decision-making. These findings stem from dialogues with decision makers, resilience practitioners, information providers, and other stakeholders from two U.S. coastal regions—the Gulf of Maine and the Gulf of Mexico—along with additional analysis.

Findings:

- Individuals of all backgrounds and levels of engagement with climate change discourse may benefit from weather and climate information;
- The resilience challenges faced by coastal communities are inherently location-specific; local-scale information is generally necessary but not sufficient to address these challenges. Contextualization as well as appropriate technical support are each vital to the uptake and use of data and other information resources;
- Partnerships of all types, including those between local, regional, state, and federal levels of government and those between public, private, academic, and non-governmental organizations, are a necessary mechanism to support coastal communities in addressing decision making challenges and advancing resilience efforts.

Key information needs:

- *Information to improve the prediction of impacts from hazards such as sea level rise and flooding events, and their interactions.* How should prioritization of targets for relocation, protection, restoration, or acquisition take place? How should a community update its building codes or infrastructure design standards to account for changes in climate?

- *Information to understand and communicate the value of marine processes and ecosystem services*. How will local ecosystem changes affect marine industries? What are the thresholds and tipping points beyond which key species cannot thrive?
- *Information to enable the holistic evaluation of adaptation efforts*. Which measures or practices should a community invest in to maximize resilience? What are the costs (environmentally, socially, and economically) of doing nothing? When and how should a community consider managed retreat?
- *Information to enable visualization*. What might the coast look like in 10, 20, 50, or 100 years? How can communities communicate their visions of the future and collaborate to produce innovative solutions?

Future weather and climate science is likely to be well equipped to provide decision makers with increasingly local information relating to a number of coastal issues, including evaluation of the benefits of adaptation measures such as nature-based solutions; physical, chemical, or biological thresholds and tipping points; and improved prediction of impacts from complex problems. However, delivering this information effectively will almost certainly depend on breaking down traditional disciplinary silos and including insights from throughout the social sciences. Assessments might also utilize a range of timescales in order to promote visualization efforts and present information in a common format to promote inter-municipal collaboration and partnership at all scales.

The complexity of the decision-making landscape means that it is unlikely that any one climate assessment will be able to address the needs of all parties in a municipality or region. A suite of assessments may aid in minimizing uncertainty across the spectrum of decision-relevant values within coastal communities, and, indeed, for all communities and information sectors. However, it is also important for these assessments to work as part of an iterative process. Although "perfect" information will never be available for decision making, a feedback loop between researchers and communities can help create increasingly better assessments and prioritize community action (i.e., which topics of interest are likely to be further informed by future research and which are currently at the limits of scientific knowledge).

Long-term resilience will almost certainly depend on collaboratively filling in knowledge and communication gaps both within and beyond Earth system OSS, in conjunction with broadly available financial and technical support. Federal agencies such as NOAA can continue to promote publicly available datasets and help develop cross-agency standards for processes such as benefit–cost analysis that play a large role in community decision making. Additionally, dedicated collation of available public tools into an easily navigable format, such as an interactive guide, may help less-experienced users target the climate information most applicable to their specific circumstances. Other information providers, particularly those in the private, academic, or nonprofit sectors, have the potential to play a key role in decision support through interpreting information or providing clearinghouses for best or promising practices. In the face of a deluge of climate information and an expanding climate workforce, organizations such as the American Meteorological Society (AMS) may play a role through helping to ensure that the information and models offered to decision makers is credible, for example by developing a program to certify climate information providers.

1. Introduction

1.1 Background

All communities face multiple complex challenges and opportunities relating to weather, water, and climate (WWC). Weather, water, and climate issues underpin virtually every aspect of society, from agriculture and energy to health and transportation, influencing long-term planning efforts as well as everyday actions (Higgins and Miller 2019). As a result, accessible and reliable weather, water, and climate information—driven by advances in Earth system observations, science, and services (OSS)—is increasingly beneficial to modern decision making. However, information is only as good as its use: for WWC information to most effectively support community needs, it must also be actionable.

To support their constituents both current and future, governments and institutions at all levels may use OSS to update regulations and ordinances, guide major public investments, manage existing vulnerabilities, and respond to emerging risks across the spectrum of social and economic sectors. Such efforts are all the more urgent as the impacts of climate change—from the availability of physical resources to the timing and intensity of natural hazards—unfold across the nation and the world. Coastlines and oceans in particular are subject to increasing levels of disruption and risk due to ongoing and interconnected changes in climate and human development (AMS Policy Program 2017; U.S. Global Change Research Program 2018). As risks to the coasts—and the numerous ecological, social, and economic systems they support—arise or increase in magnitude, decisions involving coastal regions and communities are more important than ever before.

1.2 Scientific assessments

Collaborative assessment efforts such as the U.S. National Climate Assessment (NCA) or reports from the Intergovernmental Panel on Climate Change (IPCC) integrate and evaluate scientific findings to determine the current state of knowledge on climate-relevant topics, including mitigation and adaptation. These assessments project major trends and provide tools for decision makers to consider potential climate impacts on environments, infrastructure, and people. However, there is a growing appetite for subnational assessments that build upon this foundation to tailor projections and analyses for specific local or decision contexts (Kirchhoff et al. 2019; Holmes et al. 2020). Scientific assessments are more likely to succeed when founded in trust and community engagement (Higgins and Miller 2019); as a result, there is a critical opportunity to develop a stakeholder-driven assessment process where key weather- and climate-relevant decision points are identified up front to more effectively deliver usable information that supports these key decisions.

1.3 Study approach

This AMS Policy Program study represents a pilot project to provide actionable information for decision-making through the tailored and targeted assessment of weather and climate science for key decisions. As coastal communities are at the forefront of many climate issues, this study focuses on assessing decision support needs relating to coastal resilience. The term "resilience" is used broadly here to mean the ability—of individuals, communities, physical or social infrastructure, or the environment—to adapt to changing conditions and withstand or recover quickly from disruption. However, different people, organizations, or communities may define resilience differently depending on specific contexts or goals.

To provide additional focus throughout the assessment process, the study considers two locations in the United States where coastal resilience is a prominent concern: the Gulf of Maine and the Gulf Coast. Each region represents a diversity of environmental and community types, risks faced, and available resources and capacities; together, they provide a snapshot of the range of issues faced by coastal communities throughout the country. This study is primarily based on dialogues with information providers and information users from both regions which took place virtually during 2020 and 2021, along with additional research and analysis. Existing stakeholder network organizations—such as NOAA's Regional Integrated Sciences and Assessments (RISA) networks, climate change resilience managers, and boundary organizations that provide climate services to local communities—informed these efforts and facilitated dialogues with information users. The participants and discussions drew on federal agencies, state and local government, academic institutions, non-governmental organizations, and the private sector.

Discussion centered around five key topics: 1) challenges and opportunities relating to climate and resilience within the region; 2) major decisions that could be additionally informed by climate information; 3) how information might be provided most effectively for decision-making purposes; 4) how to ensure equitable access to and benefits from information; and 5) timescales that would be most useful to target when providing information.

2. Overview of focus regions

The profiles presented here outline the natural and human landscapes, major vulnerabilities, and governance structures and collaborative efforts within the two focus regions.

2.1 The Gulf of Maine

The Gulf of Maine is a semi-enclosed sea in the North Atlantic Ocean spanning 36,000 square miles of water and 7,500 miles of coastline (Gulf of Maine Council on the Marine Environment 2010). It is bordered by the U.S. states of Maine, New Hampshire, and Massachusetts, as well as the Canadian provinces of New Brunswick and Nova Scotia. The Gulf is characterized by its cold, nutrient-rich waters, powerful tides, and complex geomorphology, which together make the Gulf one of the world's richest marine ecosystems (East Coast Aquatics 2011).

The Gulf of Maine watershed is home to approximately 10.8 million people, with over two-thirds of those who reside in the region living and working in the coastal zone (Schauffler 2013). The majority of the region is suburban or rural and projected population growth is modest; however, fueled by an influx of tourists and seasonal residents, development along the coast is expanding rapidly (Schauffler 2013).

Much of the historic settlement in the Gulf of Maine grew around the fishing industry and fishing continues to play a vital economic and cultural role in the region. Today, commercial fisheries in the watershed generate approximately 900 million to 1.3 billion U.S. dollars annually, with an additional $240 million coming from aquaculture (Gulf of Maine Council on the Marine Environment 2018). Key commercial species include the American lobster, rock crab, sea scallop, soft-shell clam, Atlantic herring, and various groundfish. Local communities along the Gulf are additionally supported by a host of coastal activities and industries including tourism, recreation, and marine transportation.

The Gulf of Maine region faces numerous threats to the resilience of its communities and ecosystems. Waters in the Gulf of Maine are warming faster than 99 percent of the world's oceans, with marine heatwaves increasingly prevalent (Pershing et al. 2015). Atmospheric temperatures are increasing as well, influencing growing seasons, spring streamflow, and the development of storms. Coastal flooding is a major concern: rising sea levels, along with changes in patterns of precipitation, tides, and storm surge, act individually and in conjunction to influence the frequency and intensity of flooding events. Other water-related issues include coastal and ocean acidification as well as pollution from agricultural or storm runoff. Warming, acidification, and other changes in ocean conditions are also likely to alter species and habitat distributions within the region, including those of keystone economic and ecological species. A further threat to the livelihoods of many along the Gulf is the disappearance or disrepair of working waterfronts, vital infrastructure that is increasingly under threat from development pressures in addition to storm surges and sea level rise. This loss of access to the waterfront impacts the financial security of communities where poverty is often already high, and is often seen by residents as detrimental to community culture and history (Coombs 2020).

Multiple organizations are involved in Gulf of Maine issues and governance. The Gulf of Maine Council on the Marine Environment (GOMC) supports collaborative management in the region through partnership between the state and provincial governments of the five Gulf jurisdictions, federal agencies, and First Nations, tribal, and non-governmental organizations. While there is currently no established NOAA RISA network in the Gulf of Maine, the individual states (Maine, Massachusetts, and New Hampshire) each have active Sea Grant programs that support research on coastal issues and work on the ground with communities in the region. Numerous programs and initiatives on both sides of the border—including public, private, academic, and nonprofit groups—are also actively working on coastal issues in the Gulf. Many of these groups have come together to form regional climate networks, such as the New Hampshire Coastal Adaptation Workgroup (NHCAW) and Maine Climate Change Adaptation Providers Network

(CCAP). The Gulf of Maine 2050 International Symposium hosted in 2019 by GOMC, the Gulf of Maine Research Institute (GMRI), and the Huntsman Marine Science Centre (HMSC), convened leaders from along the Gulf to identify priorities and strategies for regional resilience.

2.2 The Gulf Coast

The Gulf of Mexico is an ocean basin encompassing 600,000 square miles of the western Atlantic Ocean and bordered by the United States, Mexico, and Cuba. The U.S. portion of the Gulf of Mexico coastline (a.k.a. the Gulf Coast) spans 1,630 miles and includes the states of Texas, Louisiana, Mississippi, Alabama, and Florida; its watershed drains 33 major rivers across 31 U.S. states, including the Mississippi River (EPA 2020).

Over 60 million people live in the U.S. Gulf Coast region and the population is expected to increase by 14 million by 2030 (Gulf of Mexico Alliance 2016). The region is racially and culturally diverse with an economy highly dependent on the coast and wetlands, which support a number of major marine industries. Commercial fishing includes shrimp, oysters, crab, and fin fish, while oil and gas deposits have made the region the center of the nation’s petrochemical industry (NOAA 2011). Seven of the top ten busiest ports in the United States are on the Gulf Coast, facilitating the import and export of both domestic and foreign goods. Tourism and recreation stemming from the Gulf’s warm climate and coastal resources are also strong economic drivers in the region. However, poverty is prevalent across the Gulf states, with Mississippi and Louisiana having some of the highest rates of poverty in the nation (Benson 2020).

Storms and flooding are a major issue along the Gulf Coast. The region is highly vulnerable to tropical cyclone activity, which can result in catastrophic damage to lives and property. Hurricanes Katrina (2005) and Harvey (2017), both of which made landfall on the Gulf, jointly hold the current record for costliest Atlantic hurricane at $125 billion (in unadjusted U.S. dollars) each in damages (NOAA 2020). The burdens of these events are disproportionately distributed, with communities of color and low-income communities tending to suffer more intense damage while also being less likely to fully recover before the next emergency. Storms and sea level rise exacerbate the erosion of marshes, swamps, bayous, and barrier islands; the disappearance of these wetlands throughout the Gulf Coast drastically impacts native species and increases the vulnerability of coastal communities to storm surge and high speed winds. The construction of levees along the lower Mississippi River and the development of low-elevation areas have left Louisiana in particular vulnerable to erosion due to the loss of sediment deposition, as well as to flooding from levee overtopping or other breaches. Another ongoing concern throughout the Gulf Coast is poor water quality as a result of agricultural runoff, harmful algal blooms (HABs), bacterial pollution, and petrochemical pollution. A hypoxic “dead zone”—caused by excess nutrient pollution and often exacerbated by major weather events—develops annually in the Gulf, placing stress on marine life and the industries which depend on it. Decades of land and resource loss are keenly felt by the region’s tribal communities, many of which are not recognized by the U.S. federal government and are therefore ineligible for federal funding and services as their ancestral lands erode.

A major collaborative effort to improve the environmental and economic health of the Gulf of Mexico is the Gulf of Mexico Alliance (GOMA), a regional ocean partnership between the five Gulf States and federal agencies, academic organizations, businesses, and other nonprofit groups in the region. Also working in the region are four Sea Grant programs (for Florida, Louisiana, Texas, and Mississippi/Alabama), which together have helped form a Climate and Resilience Community of Practice, and the Southern Climate Impacts Planning Program (SCIPP), a RISA team that covers Louisiana and Texas. Following the 2010 Deepwater Horizon oil spill, a variety of organizations and programs, including the British Petroleum (BP)-funded Gulf of Mexico Research Initiative (GoMRI) and the National Academies' Gulf Research Program (GRP), were created to better understand the impacts of petroleum pollution, restore the health of the Gulf, and prepare Gulf communities for the future.

3. Findings

Although coastal resilience is a widespread goal, the variation seen in the pathways to pursue it reveals the complexity of the decision-making landscape as well as the uses and limitations of scientific information. We identify three overarching findings relating to the opportunities and challenges of using weather and climate information within coastal communities. We also assess the state of knowledge for four key climate-relevant decision points identified by decision makers from both the Gulf of Maine and Gulf Coast regions.

3.1 Opportunities and challenges

3.1.1 There is an opportunity to recontextualize who makes use of weather and climate information.

Users of climate information within coastal communities take many forms: town coastal director, city sustainability officer, regional planner, floodplain manager, town councilor, aquaculture farmer, flood insurance advisor, homeowner. The diversity of potential end users means that even within a single community there are innumerable ways in which information might be adapted for different decision purposes. Each user has specific priorities that reflect the unique needs, interests, and capacities of their community or sector. Individual sectors such as fishing, tourism, or recreation often present their own discrete needs that factor into those of the community as a whole. A lobstering town in rural Downeast Maine has different decision priorities than a major economic hub like Boston; municipalities in the central and western Gulf Coast, where the petrochemical industry is most concentrated, may prioritize their energy infrastructure differently than those in the east.

Users also have varying levels of engagement with climate change discourse. Generally, anyone can agree that long-term strength and resilience are properties for their community to aspire to. However, community members might hesitate to specifically relate resilience goals to anthropogenic climate change as a result of skepticism or a fear of politicization. Some users consequently prefer to describe their employment of climate information in terms of specific projects with immediately visible effects on the community. For example, it might be challenging to reach consensus on sea level rise as a broad issue, but acting to address a particular flood-prone parking lot may find more ready agreement. As a result, information providers might be most effective in serving communities by focusing on the end uses of climate information within a community while avoiding discourse on the underlying causes of climate change. An end-use-focused approach might also serve to raise awareness of the value of climate information as a tool among those who otherwise might not have considered it as such.

3.1.2 The resilience challenges faced by coastal communities are inherently location-specific; downscaled information is generally necessary but not sufficient to address these challenges.

Climate information is broadly used within communities to 1) understand existing conditions, 2) consider future scenarios and hazards, or 3) determine the costs and benefits of potential actions. Although not always available, particularly in areas with low population density, the value of high-resolution downscaled or localized information in these instances is well established. Technological advances, such as artificial intelligence (AI) and an increasing number of sensors and other sources of data (e.g., the Internet of Things), have the potential to continue improving the provision of location-specific information and trends.

However, it must be noted that information is only one piece of the decision landscape. Many coastal communities are small and chronically under-resourced. Limited staff, time, and finances restrict how well these communities are able to apply existing information to fit local decision contexts or source new information to fill in knowledge gaps. Tools intended to navigate publicly available datasets—when they exist—are not always readily accessible or built for use by non-experts, leaving potentially helpful information out of reach for many. For example, NOAA's Local Climate Analysis Tool (LCAT),[1] which provides local and regional information on climate variability and change, is publicly available but primarily targeted towards technical users from NOAA, members of other government agencies, and academic partners. The increasing number of available tools from across sectors can create additional hurdles for potential users. As such, access to resources and technical support is a key determinant of a community's ability to incorporate climate information, regardless of scale, in the realization of their needs and priorities.

3.1.3 Partnerships of all types are a necessary mechanism to support coastal communities in addressing decision making challenges and advancing resilience efforts.

In the face of wide-ranging information and resource needs, coastal communities can benefit from sustained partnerships across different groups, scales of organization, and disciplines. At the federal level, NOAA's Sea Grant programs and RISA teams, the U.S. Geological Survey (USGS) Climate Adaptation Science Centers, and the U.S. Army Corps of Engineers (USACE) Silver Jackets are examples of extant partnerships designed to connect coastal decision makers to knowledge, tools, and technical support. These initiatives provide on-the-ground support for locally defined issues (such as flood risk reduction, habitat restoration, or fisheries management) and, though sometimes limited in capacity, tend to be highly trusted by communities as the result of extended outreach and relationship-building efforts.

Many state or county agencies, nonprofit organizations, academic institutions, and private businesses also provide planning assistance and other services that support the resilience of coastal communities and their residents. For example, the Massachusetts Municipal Vulnerability Preparedness (MVP) Program, a partnership between the state, local governments, and nonprofit organizations, provides support for Massachusetts communities to complete vulnerability assessments and develop resiliency plans. The program has been highly successful, with $44 million invested and 312 municipalities enrolled in the program since its establishment in 2017 (Massachusetts Executive Office of Energy and Environmental Affairs 2020).

While the resilience challenges faced by coastal communities are inherently location-specific, they often include broadly similar issues to those faced by neighboring communities. As such, inter-municipal partnerships are crucial, including those which extend beyond the coastline and into the surrounding watershed. Regional planning organizations (such as Planning Commissions or Councils of Governments) are one such form of inter-municipal partnership where regional communities can share experiences, studies, and tools to build a collective knowledge base or pool resources to address common or cross-jurisdictional issues such as land use, water and wastewater systems, or transportation planning. Multi-organizational partnerships can be highly effective at addressing collective needs that span jurisdictions. For example, to help Gulf Coast resilience practitioners address the common concern of navigating a multitude of climate tools, the Northern Gulf of Mexico Sentinel Site Cooperative, Gulf of Mexico Climate Resilience Community of Practice, and Gulf of Mexico Alliance Resilience Team partnered to create Gulf TREE, an interactive tool-selection guide.[2]

Accounting for the needs, responsibilities, and jurisdictions of different partners in a way that maximizes the use of limited resources can be a significant obstacle to effective coastal risk management and community engagement with resilience efforts. While communities might ideally make use of the assessments and solutions put out by other communities, this is complicated by communities not necessarily being mapped for the same data elements or lacking technical mechanisms or standards to integrate database usage. Even when municipal governments are in a position to share best practices with each other, other relevant groups, such as tribal organizations, may struggle to get their observations recognized at the policy level. As a result, while partnerships can empower communities to effectively make use of information when it exists or to obtain usable information and other resources for themselves when necessary, stakeholder-focused scientific assessments in turn may help empower partnerships by providing a common foundation to foster and sustain collaboration.

3.2 Key information needs

Although not all issues faced by coastal communities can be addressed by additional information, stakeholders within the two focus regions identified several key areas where additional information would be valuable to support decisions relating to coastal resilience. Supporting questions may fall within the framework of these broad areas, as demonstrated by the example questions below.

3.2.1 Information to improve the prediction of impacts from complex and interacting problems such as sea level rise, flooding events, and other hazards

One of the greatest challenges faced by coastal communities is the growing threat from hazards such as sea level rise, sunny day flooding, storm surge, and precipitation. These hazards often act in conjunction to increase the risk to populations, property, and infrastructure; however, information can be sparse regarding these interactions and their outcomes. As decisions are increasingly made about when and how to bolster infrastructure, evacuate populations, or buy out property, access to information that links multi-variable forecasts of nature to real world impacts is needed for all communities.

Key questions: How should prioritization of targets for relocation, protection, restoration, or acquisition take place? How should a community update its building codes or infrastructure design standards to account for changes in climate?

State of knowledge

While a number of services, including NOAA's Digital Coast, may help decision makers model the impact of various coastal hazards, the most actionable predictions of coastal hazard impacts will likely need to integrate an increasing number of variables. At present, however, the level of information available to describe impacts at the regional or local level can differ greatly by hazard—in turn complicating attempts to understand their potential interactions. Advances in artificial intelligence (AI) and machine learning (ML) are likely to aid future understanding of the interactions among different processes and the prediction of their impacts at increasingly detailed scales.

Sea level rise is one of the most prominent consequences of climate change. Longitudinal sea level measurements are readily available from tide gauges and satellite altimeters, enabling the identification of trends at both the global and local level. As such, both absolute (i.e., global) and relative sea level rise are highly researched areas, although relative sea level rise (RSLR) tends to be of greater interest to coastal planners due to its impact on the frequency and severity of tidal flooding. For almost all future global mean sea level rise scenarios, RSLR is projected to be greater than the global average along both the Gulf of Maine and the western Gulf Coast, as the result of the withdrawal of fossil fuels and groundwater (Gulf Coast) and the slowing of the Gulf Stream (Gulf of Maine) (Sweet et al. 2017; Chisholm et al. 2021). However, advances in WWC science will continue to refine RSLR projections based on global and regional trends including oceanographic factors (e.g., circulation patterns), the melting of land-based ice, and vertical land movement. There are multiple tools for decision makers to explore projections of sea level rise at various scales, such as the NOAA Digital Coast Sea Level Rise Viewer,[3] NASA Sea Level Projection Tool,[4] Climate Central Coastal Risk Screening tool,[5] and the GMRI Maine-specific sea level scenario map.[6]

Many localities currently rely on **rainfall** estimates produced by NOAA (a.k.a. Atlas 14) to inform flood maps and infrastructure design guidelines. However, this information is sometimes decades out of date and does not currently include projections of future conditions such as extreme weather events. Although some communities are able to fund their own updated rainfall estimates, which may incorporate future climate projections, not all can afford to do so. Regional-level precipitation patterns are difficult to project because they are affected by global circulation patterns in addition to temperature (Shepherd 2014). For the Gulf of Maine region, there is high confidence that there will be significant future increases in extreme precipitation events; however, there is less confidence surrounding the projected amounts of precipitation from these events (Chisholm et al. 2021). Similarly, trends in precipitation for the Gulf Coast region are not as apparent as trends in temperature (Jiang and Yang 2012).

In addition to improved rainfall projections, advances in WWC science may also be used to improve **inundation** mapping at the community level. Determining how water flows throughout an area is a key mechanism through which to determine areas of vulnerability from storm tides, nuisance flooding, or storm runoff. For example, the town of Truro, MA, in collaboration with the National Weather Service (NWS), created a local elevation profile using a combination of lidar, field observation, and past storm tide records. The terrain mapping in conjunction with real-time coastal storm forecasting has improved the implementation of storm preparedness and response measures in advance of storm tides—in turn minimizing disruption, damage, post-storm cleanup efforts, and cost (Borrelli et al. 2017).

Tides have a strong influence on coastal flooding; however, the degree of their influence can be highly variable as the result of interannual and lunar cycles. Additionally, regional-scale variation in tides may be driven by changes in ocean depth, shoreline position, sea ice, ocean stratification, and radiative forcing (Baranes et al. 2020). While tides are in general largely predictable, WWC science can be used to better determine regional tidal variation, which can in turn be used to inform projections of sea level rise. In the Gulf of Maine, the tidal nodal cycle has been predicted to be 18.6 years long and at a point where its forcing is counteracting the sea-level-rise-induced increase in flood hazard; however, after the cycle reaches its minimum in 2025, hazardous flooding is likely to accelerate in the region (Baranes et al. 2020).

Wind direction and speed are massively important in coastal regions, due to their impact on wave dynamics and storm surge. Moreover, high incidences of extreme wind speeds have the potential to exceed current building design standards and lead to damage (Cui and Caracoglia 2016). Climate change may increase the intensity of extreme weather events (i.e., tropical cyclones) along the coasts and, consequently, wind speeds. One model indicates that current design wind speeds are likely to be exceeded more frequently in the U.S. Northeast, including the Gulf of Maine, and that larger extreme events should be expected (Mudd et al. 2014). However, developing appropriate designs that reflect the entire risk from extreme weather events, including both wind and water hazards, necessitates further exploration of the interactions between wind and wave action and consideration of local bathymetry.

Prioritizing targets for community action also necessitates improved integration of existing **adaptation measures** into WWC projections, including how they might fare against various local climate impacts. For example, while porous pavements or retention ponds may work to reduce local stormwater runoff, groundwater rise resulting from sea level rise may reduce the drainage capacity of these measures, leaving communities still vulnerable to precipitation-based flooding (Davtalab et al. 2020). Although tools such as the NOAA Coastal Flood Exposure

Mapper enable exploration of some protective features, such as wetlands, they often lack integration of local projects as well as how adaptation measures may relate to critical facilities or vulnerable populations. However, this is an active area of study with organizations such as the First Street Foundation working to incorporate local adaptation features into a property-level flood modelling process in order to provide a more accurate picture of risks.

3.2.2 Information to understand and communicate changes to marine processes and ecosystem services

While there are many definitions of "ecosystem services", we use it here to refer to the benefit provided to humans by the natural environment, which may consist of provisioning, regulating, supporting, or cultural services (Millennium Ecosystem Assessment 2005). Ecosystem services are the lifeblood of coastal communities, providing food, protection from extreme weather events, climate regulation, air and water purification, and numerous other physical and economic benefits. However, as the climate changes so too does the functionality of oceanic and coastal ecosystems. These changes, whether physical, chemical, or biological, may disrupt the specific conditions needed for industries such as fishing or recreation and therefore ultimately impact how communities make decisions about development or whether businesses choose to move into a region. As a result, an understanding of regional ecosystem processes and interactions, particularly within marine systems, in the context of a changing climate is vital.

Key questions: How will local ecosystem changes affect marine industries? How many leases or permits should a government issue for fishing or aquaculture? What are the thresholds and tipping points beyond which key species cannot thrive?

State of knowledge

The Gulf of Maine and Gulf Coast are each dynamic systems influenced by natural variation as well as anthropogenic factors. Ocean temperatures, salinity, ocean acidification, and water quality are all areas of particular interest due to their potential impacts on habitat and species distribution, as well as the phenology of marine life. As a result, they are generally well monitored through satellite data and sea-based sensors from organizations including NASA, NOAA, and the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS). However, advances in weather and climate information are likely to help further link local physical, chemical, and biological processes and shine light on how each of these processes might vary with the climate.

At present, it is well understood that sea surface temperatures in the Gulf of Maine are highly variable as a result of the convergence of two currents: the Labrador Current, which carries cold fresh water south from the Arctic Ocean, and the Gulf Stream, which brings warm salty water north from the Gulf of Mexico. However, the Gulf of Maine has shown a steady trend toward warming, with the past decade standing as its warmest on record, and has additionally seen prolonged periods of extreme temperatures (i.e., marine heatwaves) (GOMC 2010; Pershing et al. 2015; Bricknell et al. 2020). The distribution and phenology of local marine life is likely to shift considerably as a result of the coupling of higher average sea surface temperatures with hotter and more frequent extremes and increasing levels of acidification. These conditions may create an inhospitable environment for species such as Atlantic cod, northern shrimp, or right whales (Meyer-Gutbrod et al. 2021), disrupting the industries that depend upon them. In particular, the populations of *Calanus* species are predicted to decline in the Gulf of Maine under multiple representative concentration pathway (RCP) climate scenarios; the loss of these keystone zooplankton is likely to have detrimental effects throughout the entire food web (Grieve et al. 2017). Species such as American lobster, longfin squid, black sea bass, Atlantic mackerel, or silver hake may appear in northern waters at increasing rates, creating new opportunities for fishermen. However, so too might invasive European green crabs. Five-to-ten-year assessments are needed to determine with more confidence whether observed changes are the result of variability or long-lasting trends.

The Gulf of Mexico, which carries warm waters from the Caribbean via the Loop Current, has also displayed multidecadal variability alongside an overall warming trend since 1901 (Allard et al. 2016). Warming waters are likely to negatively impact the suitability of the Gulf as a spawning ground for species such as the bluefin tuna, with areas with high probabilities of larval occurrence predicted to decrease by 93 to 96 percent by the end of the century (Muhling et al. 2011). Mangrove forests along the Gulf Coast may migrate northwards, replacing salt marshes and in turn affecting fish and wildlife habitat, nutrient processing, and food web interactions (Osland et al. 2018). It is currently not well understood how the various forcings on sea surface temperatures in the Gulf of Mexico differ by location and season (Allard et al. 2016). As such, future research is likely to focus on better understanding causes of variability such as the Atlantic multidecadal oscillation (AMO). While some analysis finds the AMO comprises both natural and anthropogenic forcing and may be currently in a cool phase (Enfield et al. 2009; Frajka-Williams et al. 2017), recent research has suggested that there is no evidence for the AMO being an oscillation or cycle at all (Mann et al. 2021).

Ocean acidification is the result of at least two factors: increasing carbon dioxide levels in the atmosphere and more intense and frequent rain events. As carbon dioxide levels increase in the air, the ocean absorbs more carbon dioxide from the atmosphere which in turn causes the pH of the sea water to decrease (acidify). The Gulf of Maine may be particularly sensitive to watershed influences on ocean acidification due to tidal mixing and local processes near the coast (Siedlecki et al. 2021). Conversely, the Gulf of Mexico is less vulnerable to acidification despite runoff from the Mississippi River due to its high buffering capacity (Wang et al. 2013). However, more information is needed about how regional acidification affects organisms at different life stages.

The frequency, duration, intensity, and range of harmful algal blooms (HABs) is a burgeoning area of scientific research. As HABs can influence shellfish toxicity, their presence necessarily halts the harvesting of shellfish and may affect site investments for years to come. Information regarding HAB outbreaks is available through sources such as the National Centers for Coastal Ocean Science (NCCOS), which operates a HAB Forecasting Branch to output remote sensing products. HAB forecasts are available daily for the Gulf of Mexico and a weekly dashboard is available to model *Alexandrium catenella* cell concentration in the Gulf of Maine, although a variety of other HABs that are less well monitored can also occur in the region.[7] NCCOS also hosts the Prevention, Control, and Mitigation of HABs (PCMHAB) program, which promotes research to assess the socioeconomic impacts of HABs as well as the development of management strategies.

3.2.3 Information to enable the holistic evaluation of adaptation efforts

Coastal communities must weigh many approaches and options as they work to advance their needs and objectives. Decisions are made based on numerous factors, including an outcome's monetary cost (or perception of that cost), number of people served, area of impact, or opportunity costs, among others. Benefit–cost analysis (BCA) is often a key tool when determining the value of a climate mitigation or adaptation action, particularly when seeking funding from federal agencies such as USACE, FEMA, or HUD. However, the portrayal and calculation of the costs and benefits of different outcomes can be unclear or limited in scope. Existing BCA frameworks differ between agencies, may favor certain project types, and often struggle to quantify ancillary benefits of a project, such as flood mitigation infrastructure with related ecological or public health benefits. A lack of integration means that evaluation processes tend to focus on the immediate economic cost of adaptation efforts, feeding into a culture of "pay to fix" as opposed to emphasizing the value of stability or the cost of doing nothing. Moreover, although the integration of adaptation measures into community planning efforts have the potential to save money in the long term, different measures may have different levels of return for different communities due to variation in geographical location and other physical or social circumstances. As a result, there can be high levels of uncertainty within a community surrounding the best choice (or choices) for investment.

Holistic, discipline-spanning explorations of different outcomes are needed, including the potential social and economic impacts on a community, such as effects on tourism, fishing, or real estate. Predictions on these factors are inherently less certain than predictions of physical phenomena (e.g., sea level rise). However, information that clearly communicates the range of potential costs and benefits (both direct and ancillary) of different resilience options will allow communities to more effectively evaluate options based on their priorities, needs, resources, and goals. As some investments may have relatively high costs in the short term but lower operational or maintenance costs in the long term, holistic evaluations might optimally present outcomes on a range of timescales. Moreover, incorporating social science perspectives on the complex relationship between cultural heritage and climate is necessary in order to understand the variety of potential responses to climate change and increase local engagement with resilience efforts. This may be particularly essential when considering charged topics such as buyouts or large-scale retreat.

Key questions: Which measures or practices should a community invest in to maximize resilience? What are the costs (environmentally, socially, economically) of doing nothing? When and how should a community consider managed retreat?

State of knowledge

Scientific knowledge might better inform evaluation of adaptation efforts through improved understanding of the costs and benefits of measures or practices not currently well represented by traditional BCA tools. For example, nature-based solutions (NbS) are gaining traction as potential investments for communities along both the Gulf of Maine and the Gulf Coast. These adaptation measures focus on the protection, restoration, or management of ecological systems and encompass a wide spectrum of interventions, such as living shorelines, oyster reef restoration, or bioretention. NbS present an opportunity to simultaneously address multiple resilience goals, such as habitat creation, protection from storm surges, and carbon sequestration. However, successful implementation is highly context-specific and can be slow to accrue benefits. As a result, there is currently limited information on the long-term outcomes of local nature-based interventions, particularly in coastal environments (Chausson et. al. 2020). Some nature-based options, such as the restoration of eelgrass beds, are likely to themselves be sensitive to changes in climate, furthering uncertainty as their deployment as a local solution for issues such as poor water quality or shoreline erosion. Coastal communities may therefore be discouraged from pursuing NbS in favor of hardened infrastructure, the benefits of which are generally more readily quantifiable.

Because NbS is a growing area of study, it can be expected that future scientific work will be able to provide more detailed explorations of the costs and benefits of NbS and other solutions for coastal regions. For NbS in particular, this may include regular monitoring of NbS implemented in coastal regions or analysis of the cost-effectiveness of coastal NbS compared to or in conjunction with alternative solutions (including gray infrastructure) as the climate changes. In addition, in order to achieve truly holistic evaluation of these efforts, further work is needed to reflect broader social and ecological issues such as land rights and biodiversity tradeoffs (Price 2021). As the state of knowledge advances, decision makers may find reputable information through tools such as the NOAA Green Infrastructure Effectiveness Database.[8] The database is designed to be accessible to a broad audience by providing a range of literature sources and the ability to filter results by infrastructure technique, hazard type, geography, or study scale. While there are gaps in the currently available literature coverage, particularly for the Gulf of Maine north of Massachusetts, updates to the database are likely to increasingly provide relevant regional and local guidance on the use of green infrastructure as a response to a changing climate.

It is also likely that long-term resilience for coastal communities will involve retreat as a strategy. While managed retreat has historically been seen as a stark and binary issue (i.e., whether to migrate an entire community or not), it is increasingly being considered as merely one option within a portfolio of potential solutions that might be deployed at a variety of scales and at different times. For example, the town of Scituate, MA is currently conducting a feasibility study for managed retreat in its Peggotty Beach area while the state of Louisiana is working with parishes to develop a classification system for risks and when those risks might necessitate resettlement. Existing science can offer projections as to when a location might become physically uninhabitable (e.g., entirely submerged) or a practice physically unsustainable (e.g., the collapse of a fishery). However, determining a community's circumstances for or manner of retreat runs into the limits of what weather or climate science alone can readily provide. Rising insurance costs or loss of property tax revenue, as well as struggles to maintain roads, utilities, or services in the face of repetitive damage, are likely to influence consideration of coastal retreat well before a threshold of habitability based on top-down modeling is reached. This gray area is where the incorporation of social sciences into weather and climate science is particularly important, so as to enable communities to consider retreat on their own terms. Progress is being made in this regard: Horton et al. (2021) have proposed a framework to integrate bottom-up and top-down approaches to assessing human habitability, explicitly considering social dimensions such as local culture and heritage alongside metrics such as salinization of groundwater or permanent inundation. However, data are often missing on how inequities in agency and justice interact with exposure to hazards to shape prospects and options.

3.2.4 Information to enable visualization

There is often uncertainty about what the future of the coast might look like for a particular community, which in turn impacts how the community plans and makes long term decisions. This uncertainty may surround potential climate impacts, as well as legal frameworks or funding mechanisms that might help or hinder change. Consequently, community members may struggle to visualize and situate themselves within different possible future scenarios. Will the shore feature fortified structures or a living coastline? Who will access the waterfront and how? How will people make a living?

Improved visualization of possible coastal scenarios may help inform compelling and positive community-driven narratives about the future. This optimism in turn may have a motivating factor, leading to long-term resilience decisions having increased buy-in from community members.

Key questions: What might the coast look like in 10, 20, 50, or 100 years? How can communities communicate their visions of the future and collaborate to produce innovative solutions?

State of knowledge

Climate information is currently often used to inform coastal flooding scenarios, which are conveyed to users through tools such as NOAA's Coastal Flood Exposure Mapper.[9] However, additional efforts may be needed to visualize risks and vulnerabilities in ways that users find both understandable and relatable. High water mark projects, such as those in Rockingham County, NH, or Orange Beach, AL, or king tide projects document elevation and causes of flooding at key locations within a community in order to aid contextualization of past and future risk. Decision makers also commonly cite a desire for a dynamic tool along the lines of "Google Streetview for flooding" that users of all backgrounds would be able to use to explore potential changes to their neighborhoods. This situation is where collaborations with the private sector might excel—indeed, private sector solutions have been used to model impacts and vulnerabilities to critical infrastructure resulting from different inundation scenarios. For example, the Boston Water and Sewer Commission partnered with a civil engineering firm to develop a model that could juxtapose rainfall amounts with different levels of sea level rise to explore how much more significant flooding might become over time. The model also incorporated a custom flooding results viewer with 360-degree photographic renderings of landmark locations throughout the city to clearly illustrate potential flooding within streets and against buildings that viewers would easily recognize.

Currently available scientific information, in conjunction with perspectives from social sciences and the arts, can also help communities depict their visions of what is needed to thrive in different climate futures. The nonprofit Island Institute has helped Maine communities such as the island town of Vinalhaven create interactive story maps in order to help residents visualize the impacts of different climate futures.[10] This effort included community-defined issues such as the potential property tax burden on residents and impacts to the working waterfront, ferry service, and road infrastructure. As a result, the town has been able to incorporate these threats into the ongoing story of the community when planning for the future.

4. Conclusions for developing actionable scientific assessments

Ultimately, an ideal scientific assessment for coastal resilience would enable decision makers and their constituents to know their range of responses for a given situation and the potential outcomes of each option. Abstract notions of degrees of warming or inches of sea level rise over the next century do not necessarily inform a community what actions should be taken in the present to avoid or reduce risks. As such, the actionability of climate information depends on how well it can be situated within local contexts. This may be accomplished in part through the provision of localized and downscaled information, as well as through tools that enable the integration of multiple hazard variables. Future weather and climate science is likely to be well equipped to provide decision makers with increasingly local information relating to a number of coastal issues, including evaluation of the benefits of adaptation measures such as NbS; physical, chemical, or biological thresholds and tipping points; and improved prediction of impacts from complex problems. However, delivering this information effectively will almost certainly depend on breaking down traditional disciplinary silos and including insights from throughout the social sciences. Assessments might also utilize a range of timescales in order to promote visualization efforts and present information in a common format to promote inter-municipal collaboration and partnership at all scales.

The complexity of the decision-making landscape means that it is unlikely that any one climate assessment will be able to address the needs of all parties in a municipality or region. A suite of assessments may aid in minimizing uncertainty across the spectrum of decision-relevant values within coastal communities, and, indeed, for all communities and information sectors. However, it is also important for these assessments to work as part of an iterative process. Although "perfect" information will never be available for decision making, a feedback loop between researchers and communities can help create increasingly better assessments and prioritize community action (i.e., which topics of interest are likely to be further informed by future research and which are currently at the limits of scientific knowledge).

As climate-relevant information and products are currently highly decentralized, further conversation will likely be needed as to which groups might optimally provide which services, either individually or in collaboration, to ensure accessibility. Long-term resilience will almost certainly depend on collaboratively filling in knowledge and communication gaps both within and beyond Earth system OSS, in conjunction with broadly available financial and technical support. Federal agencies such as NOAA can continue to promote publicly available datasets and help develop cross-agency standards for processes such as BCA that play a large role in community decision making. Additionally, dedicated collation of available public tools into an easily navigable format, such as an interactive guide, may help less-experienced users target the climate information most applicable to their specific circumstances. Other information providers, particularly those in the private, academic, or nonprofit sectors, have the potential to play a key role in decision support through interpreting information or providing clearinghouses for best or promising practices. In the face of a deluge of climate information and an expanding climate workforce, organizations such as AMS may play a role through helping to ensure that the information and models offered to decision makers is credible, for example by developing a program to certify climate information providers.

This study is part of an ongoing pilot program to provide actionable information for decision making through tailored and targeted climate assessments. The AMS Policy Program will continue to promote actionable scientific assessments to support decision making within other sectors of society and help scientists incorporate the information needs of users in future efforts to advance Earth System OSS.

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[1] https://lcat.nws.noaa.gov/
[2] http://www.gulftree.org/
[3] https://coast.noaa.gov/digitalcoast/tools/slr.html
[4] https://sealevel.nasa.gov/ipcc-ar6-sea-level-projection-tool
[5] https://coastal.climatecentral.org/
[6] https://www.gmri.org/stories/gulf-maine-explained-sea-level-rise/
[7] https://coastalscience.noaa.gov/research/stressor-impacts-mitigation/hab-forecasts
[8] https://coast.noaa.gov/gisearch
[9] https://coast.noaa.gov/floodexposure
[10] https://islandinstitute.maps.arcgis.com/apps/MapJournal/index.html?appid=7f1cf3b3f8a243bdb9393a87397aacae

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Appendix

List of experts who contributed to this study in alphabetical order. The organizations represent the primary employers at the time of the interview/presentation.

Brian Ambrette – Maine Governor's Office of Policy Innovation and the Future
Susie Arnold – Island Institute
Sam Belknap – Island Institute
Sebastian Belle – Maine Aquaculture Association
Kristina Boburka – Town of San Padre Island, TX
Gayle Bowness – Gulf of Maine Research Institute (GMRI)
Kyle Boyd – City of Scituate, MA
Dan Burger – National Academies of Sciences, Engineering, and Medicine
Jamie Carter – NOAA
Doug Christel – NOAA Greater Atlantic Regional Fisheries Office (GARFO)
Amy Clement – University of Miami
Renee Collini – Northern Gulf of Mexico Sentinel Site
Monique Coombs – Maine Coast Fishermen's Association
Melissa Daigle – LA Sea Grant
Sherry Godlewski – NH DES
Julia Godtfredsen – City of Newburyport, MA
Kristen Grant – ME Sea Grant
Kristin Greger – City of Biloxi, MS
Adrianne Harrison – NOAA
Anne Herbst – Metropolitan Area Planning Council
Kirsten Howard – NH DES
Shannon Hulst – Barnstable County, MA
Nathan Johnson – Ocean Renewable Power Company
Shirley Laska – Lowlander Center
Sharai Lewis-Gruss – First Street Foundation
Abigail Lyon – Piscataqua Region Estuaries Partnership
Heather McElroy – Cape Cod Commission
Gabe McPhail – Town of Vinalhaven, ME
Ellen Mecray – NOAA
Christian Miller – Mobile Bay National Estuary Program
Troy Moon – City of Portland, ME
Richard Moss – Scan Network
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Andy O'Neill – USGS
Mark Osler – NOAA
Lucy Perkins – City of South Portland, ME
Kristina Peterson – Lowlander Center
Emily Rabbe – Lincoln County Regional Planning Commission
Chris Rea – National Academies of Sciences, Engineering, and Medicine
David Reidmiller – Gulf of Maine Research Institute (GMRI)
CJ Reynolds – Tampa Bay Regional Planning Council
Cassaundra Rose – Maine Governor's Office of Policy and the Future
Joe Rossi – Know Flood
Anne-Marie Runfola – Stellwagen Bank
Abbie Sherwin – Southern Maine Planning and Development Commission

Adam Sobel – Columbia University
Heidi Stiller – NOAA
Amanda Stoltz – USGS
Theresa Torrent – Maine Coastal Program
Amanda Torres – City of Rockport, TX
Jody Thompson – Mississippi–Alabama Sea Grant Consortium
Wendell Verret – Port of Delcambre
Meredith White – Mook Sea Farm
Lisa Wise – NH Sea Grant
Bob Wood – Downeast Fisheries Partnership