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Ocean and coastal indicators: understanding and coping with climate change at the land-sea interface

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Abstract
The U.S. Exclusive Economic Zone (EEZ) encompasses approximately 3.4 million square nautical miles of ocean and a coastline of over 12,300 miles. Along with the Great Lakes, this vast area generates ~US 370 billion of U.S. gross domestic product, 617 billion in sales and 2.6 million jobs each year. These ocean and coastal ecosystems also provide many important non-market services including subsistence food provisioning, health benefits, shoreline protection, climate regulation, conservation of marine biodiversity, and preservation of cultural heritage. As climatic changes occur, these benefits or ecosystem services may be significantly reduced

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or in some cases enhanced. These services are also under an array of pressures including over-exploitation of natural resources, pollution, and land use changes that occur simultaneously in synergistic, multiplicative, or antagonistic ways. This results in direct and indirect impacts that are often unpredictable across spatial and temporal scales. Here, we discuss a set of indicators designed in close collaboration with the U.S. National Climate Indicators System. Tracking the impacts via indicators will be essential to ensure long-term health of the marine environment and sustain the benefits to stakeholders who depend on marine ecosystem services.

Keywords Ocean indicators · Coastal indicators · Climate change indicators · Global change · Ecosystem services · Human communities · Conceptual models

1 Introduction

Changes in the planet's climate system already affect the structure and function of oceans, coasts, and the communities that depend on them, and these effects are expected to increase substantially with continued climate change (Griffis and Howard 2012; IPCC 2018; Barange et al. 2018; IPCC 2019). Ocean and coastal ecosystems provide a range of important services to billions of people world-wide, playing essential roles in sustainability under nearly all of the United Nations Sustainable Development Goals (SDGs). The effects of climate-related changes such as ocean warming, deoxygenation, acidification, coastal flooding, droughts, rising seas, and extreme weather can be far reaching and unpredictable given the complex relationships between physical, chemical, biological, and human variables within ocean and coastal ecosystems (Doney et al. 2011; Allison and Bassett 2015). There is growing demand for indicators of climate impacts on these ecosystems to help track changes, provide early warnings, reduce impacts, and increase resilience of these valuable systems and the many people, communities, and economies that depend on them. Since 2000, the USA has produced periodic US National Climate Assessments (NCAs) that assess current and future impacts of climate change on the USA. The third NCA process launched development (Kenney and Janetos 2014, Kenney et al. 2016) of a core set of specific indicators (called the National Climate Indicator System (NCIS)) to help establish baselines for understanding how environmental conditions are changing in response to changing climate, assess risks and vulnerabilities, and to help inform resiliency and planning for climate impacts (Melillo et al. 2014; USGCRP Climate Indicators,[1] Kenney et al. 2018). This article describes indicators of ocean and coastal ecosystems that were identified in that process to help track climate-related processes and impacts in these important areas.

The US exclusive economic zone (EEZ) encompasses approximately 3.4 million square nautical miles of ocean and a coastline of over 12,300 miles. Along with the Great Lakes, this vast area generates ~ US$370 billion of US gross domestic product, $617 billion in sales, and 2.6 million jobs each year (NOAA 2019). These ocean and coastal ecosystems also provide many important non-market services including subsistence food provisioning, health benefits, shoreline protection, climate regulation, conservation of marine biodiversity, and preservation of cultural heritage. Ocean systems also provide important climate mitigation and adaptation services (Millennium Ecosystem Assessment (MEA) 2005). For example, the oceans have absorbed 25% of anthropogenic carbon emissions and 84% of the heat since the Industrial Revolution (Levitus et al.

[1] The NCIS information is available at USGCRP (https://www.globalchange.gov/browse/indicators/catalog).

2009; Doney et al. 2020), to the benefit of society though the detriment of the ocean. Coastal vegetation (e.g., mangroves, salt marsh, and seagrass) sequesters and stores more carbon on a per-area basis than terrestrial forests, though it can be released when habitats are degraded or destroyed (Mcleod et al. 2010; Pendleton et al. 2012; Himes-Cornell et al. 2018). Healthy coasts also provide climate adaptation benefits through coastal protection, fisheries productivity for food security, and protecting communities against chronic sea level rise (MEA 2005). However, these services are under multiple pressures including over-exploitation of natural resources, pollution, and land-use changes, with changes in climate patterns and extreme weather adding another layer of complexity. These pressures occur simultaneously in synergistic, multiplicative, or antagonistic ways and result in direct and indirect impacts that are often unpredictable across spatial (e.g., ocean basins to local habitats) and temporal (e.g., centuries to hours) scales (Barbier et al. 2011).

Indicators are frequently used as decision-support tools for monitoring or tracking large-scale systemic changes (e.g., MEA 2005; Halpern et al. 2012; Atkins et al. 2015; Zador et al. 2017), particularly when the object of interest (e.g., ocean health) cannot be measured directly or completely. Unfortunately, indicator systems for oceans and coasts are still nascent in many regions, although significant progress has been made in recent years (for example, see Halpern et al. 2019; NOAA National Marine Ecosystem Status 2020). This paper describes a system of indicators designed to track changes in US ocean and coastal ecosystems that may be correlated with climate change, as part of the larger NCIS. The goal of the NCIS is to create a "system of physical, natural, and societal indicators that communicate and inform decisions about key aspects of the physical climate, climate impacts, vulnerabilities, and preparedness" (Kenney et al. 2016). Its primary purpose is to support the sustained US NCA process (Buizer et al. 2013) by providing long-term, regularly updated information about key impacts in US systems and sectors, including oceans and coasts, that are required by the 1990 Global Change Research Act and are of broad concern to the US public (see Kenney et al. 2018).

The system described here is not the first suite of indicators for ocean and coastal conditions. Others include the MEA (2005), Ocean Health Index (Halpern et al. 2012), Intergovernmental Panel on Climate Change Ocean Systems chapter in the Fifth Assessment Report (Pörtner et al. 2014), US Environmental Protection Agency (EPA) Climate Indicators (2014), Marine Living Planet Index (WWF 2015), and United Nations World Ocean Assessment (WOA 2016). In the USA, indicators of ocean ecosystem condition have been developed for most marine ecosystems to help inform fisheries management and other sectors (Slater et al. 2017). These are some of the much needed efforts to help track and assess the conditions of ocean and coastal ecosystems. While they are useful in assessing changes in ocean and coastal systems related to climate change and other stressors (Halpern et al. 2017, 2019), they were not specifically designed to track the impacts of climate on ocean and coastal ecosystem services including regulatory, supporting, provisioning, and cultural services, as this effort does.

The overall process and decision criteria for the NCIS framework, and the associated guidance on scientific integrity and utility, were provided by the Indicator Working Group established for the third NCA Advisory Committee (Kenney and Janetos 2014). Multiple indicator technical teams were established, based on an ecosystem, region, or crossover topic.[2] Each team was asked to develop a conceptual model, make recommendations for indicators

[2] See list of teams at: http://www.globalchange.gov/engage/process-products/NCA3/technical-inputs.

that could be implemented immediately, and identify research priorities for future indicator development (Kenney and Janetos 2014). Here, we define a conceptual model for indicator selection and recommend specific indicators of ocean and coastal ecosystem function that support the NCIS vision.

The ocean and coastal indicators described here are not meant to be directly causative. Rather, they are based on a new conceptual model of intrinsic connections between climate processes, physical attributes of the ocean itself, living organisms that inhabit the ocean, and people that depend on the ocean and coasts. The model describes, based on existing information and hypotheses, how these indicators interactively support individuals and communities in meeting their social, economic, subsistence, and cultural needs (Fig. 1). Throughout the development process, the Oceans and Coasts Team (Team) emphasized identification of potential indicators with robust science-based connections to anthropogenic climate change and pre-existing time-series monitoring data. The goal was to identify a system that is flexible and scalable such that individuals, communities, and the Nation can follow the indicators to track ecological and societal changes. The indicator system described here can also be used to recognize opportunities to mitigate against some long-term changes and adapt to others, thus reducing impacts and increasing resilience.

2 Development of a conceptual model for oceans and coasts

Ecosystem services are defined very broadly as "the benefits people obtain from ecosystems" (MEA 2005). The conceptual model above (Fig. 1) illustrates the many regulatory services (e.g., climate regulation), supporting services (e.g., primary productivity, habitat), provisioning

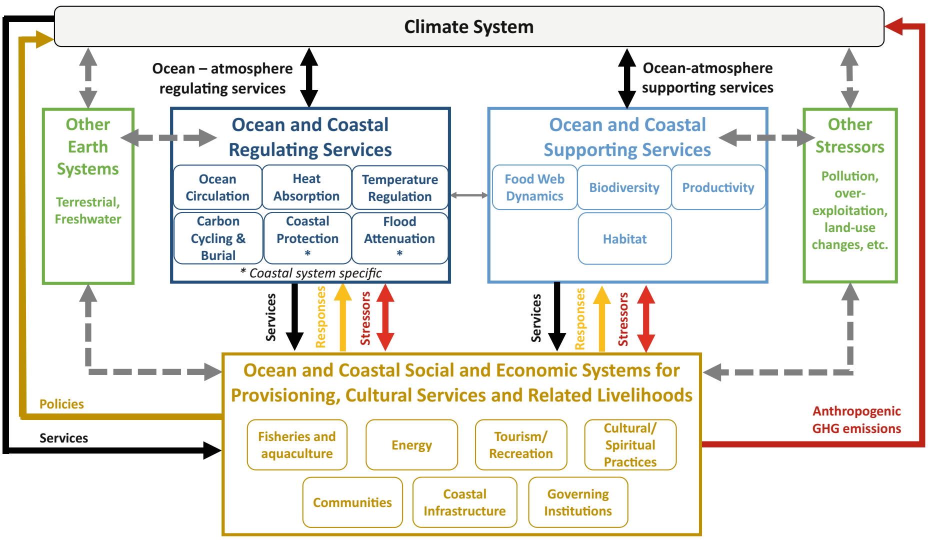

Fig. 1 Conceptual model of climate impacts on ocean and coastal ecosystem services and associated benefits within a global framework *goes approximately here***.** N.B. dashed lines signify relationships between systems and services, and solid lines signify relationships among four main types of services (regulating, supporting, provisioning and cultural). Red lines indicate stressors. Black lines indicate ecosystem services. Gold lines indicate human responses to changes in stressors and/or services

services (e.g., extractive activities such as food fish or energy sources), and cultural services (e.g., native peoples' rituals, multi-generational fishing traditions, and nature tourism) provided by oceans and coasts, as well as highlights economic and cultural livelihoods through ocean-related jobs and activities.

Tracking shifts in ecosystem services related to climate change and the impact of specific interventions is difficult. The benefits and services provided to humans by ocean and coastal ecosystems, human impacts that drive changes to those services, and the measures put in place to maintain benefits and services not only create positive and negative feedback loops, but they also operate in tandem with outside stressors (Fig. 1). For example, human activities resulting in greenhouse gas (GHG) emissions influence the global climate system and exert substantial pressures on the ocean and coastal environment, including a rise in ocean temperatures. As a result, warming oceans may drive poleward shifts in the geographic range of marine fish in search of preferred temperatures (Spencer 2008; Doney et al. 2011; Hare et al. 2016). Consequently, commercial, recreational, and subsistence fishermen who rely on species undergoing range shifts may (1) make spatial adjustments to the areas where they harvest, (2) invest more time and resources traveling farther to conduct fishing activities (using more petroleum products and contributing to increased emissions), (3) switch to a new species (possibly requiring new equipment), or (4) change professions (which goes against strong cultural ties to fishing as not just an occupation, but a way of life) (Link et al. 2015). Thus, climate change may require updating fishery management practices as well as initiating activities designed to mitigate and/or adapt to climate stressors (Howard et al. 2013; Pinsky and Mantua 2014; Selden and Pinsky 2019).

The goal of the NCIS is to identify key points along the ecosystem services pathway that may be impacted by climate change and can provide an early warning of changes to come and, critically, how those changes might reverberate through the other system components (Kenney et al. 2016). Therefore, based on this conceptual model, the Team attempted to identify representative indicators that not only showed changes to specific services and benefits but also the linkages between regulating, supporting, provisioning, and cultural services. We looked for those indicators that could be accurately measured and could function as the "canary in the coal mine" for larger-scale climatic shifts and anticipated changes to ocean ecosystem services.

3 Moving from a conceptual model to indicators

The process and decision criteria for the NCIS, as well as the scientific integrity and utility aspects, were provided by the Indicator Working Group established for the third NCA (Kenney and Janetos 2014). In addition, the Oceans and Coasts Technical Team, composed of academic and government experts, developed 5 core criteria (below) for determining which indicators to advance based on their alignment with the conceptual model and utility for tracking specific services (Kenney et al. 2016):

1. Is the indicator representative of specific climate variable changes and their direct and indirect impacts on the ocean and coastal system?
2. Are the links between the indicator and climate change strongly supported in the peer-reviewed scientific literature? Generally, this evaluation was straightforward for the

regulating services and increased in complexity for supporting services, followed by provisioning and cultural services.

3. Is the indicator scalable (both spatially and temporally)? To generate a list of useful indicators for the NCIS, it was important to consider sub-national, national, and global scales as well as temporal scales ranging from climatic (centuries), to biotic (decades), and to time frames for resource decision-making (1–2 years).
4. Does the proposed indicator system build on or augment existing indicator efforts? We attempted to determine the stability and longevity of each indicator dataset as well as institutional commitment to continue monitoring efforts into the foreseeable future.
5. Will the indicator system communicate climate impacts well to a variety of audiences, and allow easy access to the data behind the indicator? For instance, are there web tools that allow the public to view the data in graphic form? Is the link between each indicator and climate change easy to understand or explain?

4 Recommended indicators of climate-related changes to the ocean and coast

Based on assessment of existing literature, 21 indicators were identified that met the defined criteria, could provide valuable information for tracking large-scale changes to the marine environment, and addressed at least one of the ecosystem service categories within the conceptual model (see Online Resource 1 for basic information on the full set of 21 indicators). These indicators also had potential to provide context for important decisions related to natural resource management, coastal development, tourism and recreation, and human activities within indigenous and other coastal resource-dependent communities. Of the 21 identified indicators, nine (see Table 1) were classified by the Team as operational and ready for inclusion in the pilot NCIS in 2014. The remaining 12 indicators required additional research and/or assessment before they could be considered operational. Some of these indicators have since been updated, expanded, strengthened, and fortified with additional supporting material, such that they are now operational. Of the nine indicators recommended by the Team, four were selected for inclusion in the pilot NCIS: sea surface temperature (SST), arctic sea ice extent, ocean chlorophyll concentration, and sea level rise. For more information on these 4 indicators, please refer to Online Resource 1 and the NCIS website.[3] Here, we will focus on the remaining five indicators that were recommended by the Team for the pilot NCIS. These indicators were not adopted at that time because (1) they were operational but not in a final form ready for inclusion in the pilot or (2) they needed further development and did not then meet the full set of criteria, as described in Kenney et al. (2018).

4.1 Indicators of regulatory services

Oceans and coasts provide regulatory services through their interactions with other earth systems (e.g., freshwater systems, terrestrial systems, climate systems); see Fig. 1. For example, oceans and coasts help to regulate global temperatures and circulation patterns, carbon capture and burial, storm severity, and heat absorption. Indicators of these services were relatively well developed and available compared to other areas. Four of the nine

[3] http://www.globalchange.gov/explore/indicators

Table 1 Ocean and coast indicators recommended for pilot NCIS

Indicator	Ecosystem services and link to conceptual model	Metric selected	Proposed datasets [a]
Sea surface temperature*	Regulating services • Global temperature regulation • Heat absorption	Temperature changes in the top 20 m of the ocean	GHRSST, NESDIS, Global Drifter Program, UK Met Office, IOOS, Coast Watch
Arctic sea ice extent*	Regulating services • Global temperature regulation • Heat absorption	Consistent ice extent and thickness	NSIDC
Sea level rise*	Regulating services • Heat absorption • Flood risk	Regional rates of sea level rise compared to NCA global sea level rise scenarios out to 2100	NOAA CO-OPS long-term tide stations
Aragonite saturation	Regulating services • Carbon uptake	Aragonite saturation state in open ocean marine waters	HOTS, BATS
Ocean chlorophyll concentration* and other primary production	Supporting services • Food web dynamics • Productivity	Chlorophyll concentration and/or phytoplankton abundance and composition	SeaWiFS, MODIS-Aqua, CZCS, MERIS, SeaBASS, NODC
Fish distribution	Supporting services • Food web dynamics • Biodiversity	Mean location of fish landings	NMFS Trawl Surveys, OCEANADAPT (https://www.st.nmfs.noaa.gov/ecosystems/climate/activities/oceanadapt)
Coral thermal stress	Supporting services • Food web dynamics • Biodiversity	SST increases (intensity and duration)	Coral Reef Watch HotSpots, NESDIS
Community climate vulnerability	Provisioning and cultural services, livelihoods National (except Alaska): • Sea level rise risk ME through TX: • Sea level rise risk and affected seafood related businesses ME through NC: • Species vulnerability • Catch composition diversity Alaska:	National (except Alaska): Sea level rise in increments of 1-6 ft ME through TX: Seafood related business in 1-6 ft inundation zones ME through NC: dependence on climate vulnerable species and/or catch composition diversity Alaska:	National: American Community Survey data from the U.S. Census, Custom database based on Coastal Elevation data, NMFS Commercial Landings and Recreational Effort ME through TX: North American Industry Classification System, Custom database based on NOAA High-Resolution Digital Elevation Models from the National Elevation Dataset for Coastal Areas ME through NC: NMFS Commercial Landings Alaska:

Table 1 (continued)

Indicator	Ecosystem services and link to conceptual model	Metric selected	Proposed datasets [a]
	• Sea ice coverage • Erosion risk • Permafrost coverage • Proximity to transition zones	Changes in extent of sea ice, land erosion, permafrost, and transition zones	NOAA Climate Data Center sea ice coverage, University of Alaska Fairbanks Institute of North Engineering permafrost zone GIS layers, US Army Corps of Engineers and State of Alaska Immediate Action Work Group reports on erosion risk
Community Social Well-being	Provisioning and cultural services, livelihoods+ • Social vulnerability • Gentrification pressure vulnerability • Commercial and recreational fishing dependence	Social vulnerability: • Personal disruption • Population composition • Poverty • Labor force structure • Housing characteristics Gentrification pressure Vulnerability: • Retiree migration (except for Alaska) • Urban sprawl (except for Alaska) • housing disruption Fishing dependence: • Commercial/recreational fishing engagement and reliance	American Community Survey data from U.S. Census, NMFS Commercial Landings, NMFS Permits Data, NMFS Marine Recreational Information Program

[a] For more detail on datasets and methods, see Online Resource 1

*These indicators have been adopted for the NCIS and are described here: http://www.globalchange.gov/browse/indicators

+For detail on the construction of these indicators, see Colburn and Jepson (2012), Jepson and Colburn (2013), and Colburn et al. (2017). See also: https://www.fisheries.noaa.gov/national/socioeconomics/social-indicators-fishing-communities-0

Includes the ecosystem services that link indicators to the conceptual model, corresponding metric(s), and recommended dataset(s)—table after Heath et al. (2015)

indicators recommended for inclusion in the pilot NCIS track regulatory services (sea surface temperature, arctic sea ice extent, sea level rise, and aragonite saturation state). Of these, only one (aragonite saturation state) was not included in the pilot NCIS based on the lack of a consistent and more comprehensive monitoring system for tracking changes over time. It is described below.

- Aragonite saturation state provides a measure of ocean acidification (OA), the CO_2 absorption service provided by the oceans (Sabine et al. 2004; Astor et al. 2014). In the open ocean, long-term declines in aragonite saturation state are directly caused by increases in atmospheric CO_2 (Doney et al. 2020). Parameters that determine aragonite saturation values relate to the kinetics of aragonitic calcium carbonate accretion or dissolution; dissolution of aragonite structures exposed to seawater is favored when saturation state values dip below 1. This geological threshold is useful for understanding the implications of changes in ocean carbonate chemistry for living and nonliving calcium carbonate structures, and can also be applied to aragonite saturation state thresholds above 1 for species and/or species groups for which research has defined their sensitivity to changes in carbonate chemistry (e.g., Waldbusser et al. 2015; Bednaršek et al. 2019). Information on species sensitivity to OA conditions documented through laboratory experiments, modeling exercises, and limited field observations indicates that exposure to acidified conditions can increase coral bioerosion, change phytoplankton community composition, reduce recruitment of calcifying organisms, alter development and neurobiology of some fish species, and reorganize ecosystems (Kroeker et al. 2013; Busch and McElhany 2016; Marshall et al. 2017; Doo et al. 2020). These impacts will cascade into the tourism industry (reef diving), commercial fishery production (both bivalves and crustaceans), and subsistence use of reef fish, bivalves, and crustaceans (Doney et al. 2020). Communities where commercial or subsistence fishing depends largely on bivalves or crustaceans will be most heavily impacted (Mathis et al. 2015; Ekstrom et al. 2015). But even smaller levels of dependence on bivalves or crustaceans may be critical to overall economic viability for some fishing communities (Colburn et al. 2016, Hodgson et al. 2018).

4.2 Indicators of supporting services

Oceans and coasts provide supporting services, such as maintenance of biodiversity (at the levels of genes, species, and habitats), ocean and coastal productivity, food web dynamics, and the foundation for healthy conditions in ocean habitats. Three of the nine indicators recommended for inclusion in the NCIS track these supporting services (fish distribution, coral thermal stress, and ocean chlorophyll concentration). Of these, only one (ocean chlorophyll concentration) was included in the pilot NCIS. Here, we describe the two supporting services indicators that were not included in the pilot NCIS but were considered sufficiently operational to be included in subsequent phases of the NCIS.

- Fish distribution tracks changes in the spatial distribution of major US commercial fish stocks over time (Overholtz et al. 2011; Morrison et al. 2015; Hare et al.

2016; OceanAdapt[4]). Using survey data, shifts can be measured as directional changes in range centroids, which have been found to be strongly related to changes in ocean temperature (sensu Pinsky et al. 2013; Thorson et al. 2017). Additionally, life history attributes have been used to classify the potential for fish distributions to shift due to changes in climate (Hare et al. 2016). As fish stock distributions change, the composition of ocean ecosystem communities also changes, thereby affecting predator/prey dynamics and competitive interactions. Impacts on ecosystem communities at local scales will differ, as a range shift can represent a species' disappearance at one end of its range and introduction at the other end. In addition, spatial distances between the new stock range and the fishing communities who target those species may change, affecting the costs of fishing, social networks, and subculture cohesion (Griffis and Howard 2012). Further, many fisheries management efforts include spatial allocations; thus, indicators of fish distribution are of great importance to fishery managers and those who depend on living marine resources for their livelihoods (re. Pinsky and Mantua 2014; Pinsky et al. 2018). This indicator was considered operational and added to the NCIS (renamed USGCRP Indicators Catalog[5]) in 2020.

- Coral thermal stress describes the occurrence, duration, and magnitude of high SST events that can result in coral bleaching (Hoegh-Guldberg 2011; Heron et al. 2015; NOAA Coral Reef Watch[6]). Severe bleaching events can cause impairment or death of organisms and collapse of a charismatic, ecologically, and socioeconomically important ecosystem. Once bleaching is underway, even if heat stress lessens, it can take decades for severely bleached reefs to fully recover, if at all (Robinson et al. 2019). Coral reefs are areas of high biodiversity; they provide significant economic benefits through tourism and recreational and commercial fishing, protect coastlines from storm surges, and are focal points for subsistence fishing. Due to corals' sensitivity to climate change-related temperature increases and ocean acidification (Hoegh-Guldberg et al. 2007; Gattuso et al. 2015, 2018), tracking this indicator may also provide advance warning of climate-related impacts to come (Lough et al. 2018; Robinson et al. 2019). This indicator is considered operational and slated for addition to subsequent iterations of the NCIS.

4.3 Indicators of provisioning and cultural services and related livelihoods

Oceans and coasts provide both provisioning and cultural services. They provide food, such as fish, shellfish, and crustaceans that are also an important feature of ocean-dependent economies. And they provide cultural services in the specific cultural traditions of societies with long fishing traditions, their sense of place, as well as the livelihoods derived from fishing. Fishing, whether commercial or recreational and ocean ecotourism (such as whale watching or visiting beaches) all provide important cultural services. Climate change that impacts fisheries and shorelines will impact provisioning services, cultural services, and related livelihoods. Society can both amplify and mitigate impacts of climate change on oceans and coasts. Two of the

[4] https://toolkit.climate.gov/tool/oceanadapt#

[5] https://www.globalchange.gov/browse/indicators/catalog

[6] https://toolkit.climate.gov/tool/noaa-coral-reef-watch%E2%80%94satellite-monitoring-decision-support-system

nine indicators recommended for inclusion in the pilot NCIS track provisioning and cultural services (community climate vulnerability, community social well-being), but not included. They are described below.

Indicators of cultural services are generally not as well developed as indicators for the other ecosystem services (Hernández-Morcillo et al. 2013) or require nationwide surveys (e.g., Bryce et al. 2016). Here we describe indicators that assess the climate vulnerability and social well-being of coastal communities, especially in relation to fishing. These two indicators are based on community-level data, as it is at the local level that most people directly engage on climate issues (Howard et al. 2013). The social well-being indicators were not initially included in the NCIS because they were not yet available nationally (though they were available for the east coast and in development nationally) and because they did not have a direct link to climate—though more socially vulnerable communities may be less resilient to climate-related (and other) impacts. And the linked climate indicators described below were not yet developed at the time of the first recommendations. Now, however, both the social well-being indicators and two of the climate indicators are available nationally and so ready for inclusion. Additional climate indicators are now available for the east coast, but not yet available nationally. We mention them here, but reserve recommending them until they are developed for the entire USA.

The indicators are complex and composed of multiple indices, based primarily on data from the US Census Bureau and the National Marine Fisheries Service (NMFS). Some are specifically climate-related (Himes-Cornell and Kasperski 2015; Colburn et al. 2016). Others track the social well-being of communities as measured by social vulnerability, gentrification pressure vulnerability, and fishing dependence (Jepson and Colburn 2013, as adapted from Cutter et al. 2008, Jacob et al. 2010, 2012). In general, higher levels of any index may mean lower ability to cope with climate or other impacts. Catch composition diversity is the exception, with lower diversity connoting increased vulnerability. When multiple vulnerabilities combine, communities may be less able to respond to and recover from impacts (Pinsky and Mantua 2014; Thomas et al. 2019). When indicators show increasing vulnerability over time, this is a signal for further investigation.

- Community climate vulnerability includes three sets of indicators. The first set is available nationally (except for Alaska), the second is currently available for subsets of states (though under development elsewhere), and the third is Alaska specific. The nationally applicable indicator is *sea level rise* (SLR) *risk* for US coastal county communities (except for Alaska), which can manifest as salt-water intrusion into water supplies, loss of habitat, and loss or relocation of homes, fishing infrastructure, or fishing-related businesses The set currently available for some states only includes *sea level rise risk and affected seafood businesses* (available Maine through Texas) which specifically maps loss of fisheries infrastructure and two indicators available for Maine through North Carolina. These two are *percent climate vulnerable species*, which tracks the degree of economic risk to communities based on the climate vulnerability of fish species landed, and *catch composition diversity,* which tracks changes in the diversity of species landed in a community—and thus ability to easily switch species if one or more is highly climate vulnerable or moves beyond the range of the local fleet (Colburn et al. 2016). The Alaska-specific indicators are *sea ice coverage*, *erosion risk*, *permafrost coverage*, and *proximity to transition zones* (Himes-Cornell and Kasperski 2015). Together these create an initial set of indices that can predict the vulnerability of US communities to various components of climate change. These indicators are designed to be used in conjunction with the community social vulnerability indicators to assess the vulnerability of communities more broadly.

- Community social well-being indicators assess and track social factors that affect a community's ability to cope with climate or other types of change. Each of these indicators is composed of a set of indices (see Table 1) which are themselves created from NMFS landings data, NMFS recreational fishing effort data, and/or publicly available US Census data. See Jepson and Colburn (2013) for details on construction of the social well-being indicators. There are three sets of indicators: *social vulnerability*, *gentrification pressure vulnerability*, and *fishing dependence*. *Social vulnerability* indicators characterize pre-existing conditions that reflect states of susceptibility to harm, including differential access to resources. For example, a community with high social vulnerability (e.g., high poverty and/or a high cost of housing) could experience a decrease in affordable housing as sea level rises. *Gentrification pressure vulnerability* indicators identify conditions that can affect the viability of commercial and recreational working waterfronts. A community with high gentrification pressure vulnerability (e.g., high number of retirees and/or second homes along the waterfront) could experience lower resilience to sea-level rise and other aspects of climate change. *Fishing dependence* indicators identify the scale of commercial and/or recreational fishing in coastal communities. These indicators measure the importance of fishing in a community relative to all communities in the sample, as well as the importance of fishing within each community. Communities with high dependence on fishing and high social and/or high gentrification pressure vulnerability may be less resilient to the effects of climate change. For example, a community with social well-being vulnerabilities that is traditionally dependent on climate-vulnerable species may be more affected by fishery species range shifts due to climate change (e.g., increasing sea surface temperature, ocean acidification).

The community social well-being indicators identify vulnerable populations that may be less able to withstand and recover from climate change and socioeconomic impacts. These indicators are important because coastal communities and associated coastal and ocean waters hold a vital sense of place (Clay and Olson 2007; Urquhart and Acott 2014; Khakzad and Griffith 2016) and are linked to cultural identity (Clay and Olson 2008; Poe et al. 2014; Donkersloot 2010; Donkersloot et al. 2020; Satterfield et al. 2017) for many long-term residents, and provide food, employment, minerals, shipping, recreation, and cultural and spiritual fulfillment to residents and non-residents alike.

5 Research priorities and next steps

The conceptual framework and indicators highlighted here provide some initial building blocks for a system to track and assess impacts of climate change on US ocean and coastal ecosystems. However, much needs to be done to develop a fully operational system and make it useful (and used) in risk assessment and decision-making. Based on the work of this Team and other efforts (e.g., Selig et al. 2015; DePiper et al. 2017; Halpern et al. 2017), building the needed indicator system will require investments in three key areas: (1) continued monitoring, (2) additional research to improve existing indicators (especially for social and habitat categories, and for data overall at national to regional scales), and (3) research to develop additional indicators to adequately track and communicate climate impacts, risks, vulnerabilities, and preparedness in ocean and coastal systems.

Continue monitoring To be useful, indicators require consistent funding over the long-term for monitoring and assessment. The ability to track trends over time and space is critical to our understanding of rates and directions of change.

Improve existing indicators A useful indicator system for assessing climate change impacts on oceans and coasts will require a number of key steps, including reducing lags between data collection and indicator delivery, improving spatial and temporal representation of indicators, reducing the costs of indicator production (e.g., new analyses or sampling methods), identifying directionality and thresholds, ensuring the indicators have measurable targets (Samhouri et al. 2012), and ensuring that decision-makers have the tools and ability to use the information. For example, the current species distribution indicator tracks shifts in species distributions within fishery survey or governance areas. However, decision-makers also need information on species that are shifting across these boundaries, so incorporating this information into the indicator would increase its utility for management decisions.

Develop new indicators For some desired indicators, data may be available from multiple sources, necessitating research on analytical methods that enable links between climate changes and their impacts, or to improve consistency over space and continuity over time. For others, basic data may not exist at the appropriate spatial or temporal resolution and frequency. For example, recent research has resulted in new ways to characterize and track marine heat waves which could be a useful additional indicator of climate change impacts on ocean ecosystems (Holbrook et al. 2019, 2020; Jacox et al. 2020). Additional research on thresholds or tipping points is also critical to help decision-makers incorporate indicator information into risk assessments and management strategies. Research may be needed to develop efficient and accurate methods for data collection or derivation or synthesis. We recommend continued support for data collection for current indicators, coupled with priority research funding directed toward developing new indicators. Further, it is key to have indicators with strongly supported data streams that are designed to be integrated into existing and planned future management efforts.

The following are some of the prime candidates for new indicators the Team identified based on their linkages to climate-impacts in ocean and coastal systems. They were considered previously, but not included in our list of 21 due to the lack of nation-wide information, and/or monitoring. With additional research, these could be developed into robust indicators.

Subsistence fisheries Subsistence fisheries provide food security and cultural value to coastal communities, and generate revenue for local economies via purchases to support fishing activities and for government agencies via permit fees. Climate change has the potential to alter the abundance and distribution of living marine resources harvested in subsistence fisheries. Currently, data on subsistence fishing are lacking from nearly every region.

Coral reef-related tourism and recreation Healthy coral reef ecosystems support economically and culturally valuable tourism industries. Climate change and ocean acidification will likely reduce the distribution and species diversity of most coral reef ecosystems. Data on social and economic indicators related to coral reef health are needed, as are methods to link social and economic indicators related to tourism and recreation to climate change impacts on coral reefs.

Incidence of *Vibrio* outbreaks in coastal ecosystems *Vibrio* is a genus of bacteria that includes species that cause severe illnesses in humans when infected through ingestion (e.g., shellfish consumption) or direct contact. Because *Vibrio* abundance is strongly linked to coastal water temperatures and salinity, a *Vibrio* indicator would have implications for the Clean Water Act's "fishable, swimmable" mandate and the value of ecosystem services provided by coastal ecosystems. Research and monitoring efforts are needed to directly measure or calculate *Vibrio* abundance in US coastal waters.

Harmful algal blooms Harmful algal blooms (HAB) are becoming more prevalent in coastal areas in their extent and distribution. These blooms are directly influenced by environmental conditions and have implications for human and wildlife health. The variety of HAB species with different environmental characteristics and health impacts mean that multiple strategies for developing indicators are needed. There are a few methods that have been developed, but they have not been comprehensively tested. A program is needed to evaluate and establish robust, reliable, and systematic methods for monitoring changes in the frequency and spatial extent of HABs, and to design an indicator from these data. After determining the appropriate focus, the program would need to collect data from the many state and academic monitoring programs, develop improved sensors for HAB cell and toxin detection, and fill in gaps in existing monitoring programs by including HAB monitoring in the Integrated Ocean Observing System.

Marine mammal morbidity and mortality Recent rise in reports of diseases in marine organisms has raised concerns among scientists, politicians, managers, and the public that ocean health is deteriorating. Since many marine mammal species share the coastal environment with humans, consume the same food, and morbidity and mortality events usually command considerable public attention, marine mammals can serve as effective sentinels for ecosystem change and emerging diseases. Data from existing networks, such as the NOAA National Marine Mammal Stranding Network, can be integrated with other ocean observing systems to understand the impacts of climate disruption on ocean health, reduce public health risks, and ensure sustainable development of coastal and ocean resources.

Shorebird phenology and abundance Many shorebird species use and migrate through a variety of habitats that are likely to be impacted by climate change, from coastal shores and wetlands to arctic tundra. Because these species are dependent on so many different types of habitat, their abundance and phenology are good integrators of global change.

Bottom temperature and/or mixed layer depth Tracking the temperature of the ocean's bottom is necessary for understanding the ocean's heat storage, which in turn is important data for parameterizing and testing climate change models. Collecting these data also will elucidate the depth of the ocean's mixed layer, which influences biological communities and the absorption of carbon dioxide and, thus, ocean acidification. Observing programs need to be expanded to include regular measures of bottom temperature.

6 Conclusions

Developing and tracking indicators of climate change impacts in ocean and coastal ecosystems across the range of ecosystem services are needed to better understand, prepare for, and respond to these changes (see, for example, Link (2005), Levin et al. (2016), Gaichas et al. (2018), Karp et al. 2019, Magel et al. (2020), Doney et al. (2020)). This is an important need in the USA and internationally (e.g., per the U.N. SDGs, the Aitchi Targets[7] and the Paris Agreement[8]), given the global interconnectivity of the oceans. This advanced understanding can help decision-makers at international to local levels assess risks and options to reduce impacts and foster adaptation. For indicator systems such as those proposed for the NCIS to succeed, there must be increased commitment to long-term collection, synthesis, and delivery of physical, chemical, biological, social, economic that is the foundation of indicator systems. Long-term monitoring efforts are critical to tracking impacts, providing early warning of impending changes, and making effective decisions in a changing world.

In the USA and worldwide, there is high and growing demand for information on past, current, and expected future impacts of climate change on human life, food security, livelihoods, and communities. Information on climate impacts in ocean and coastal ecosystems lags many other areas despite the significant ecosystem services provided by these systems. To help advance the NCIS, this paper identifies a conceptual framework and initial suite of indicators that could be used to track impacts of climate change in US ocean and coastal ecosystems, from the physical to the biological to the social and economic. Already, some of the indicators described here are being used to inform fisheries management. For example, the Mid-Atlantic Fishery Management Council (MAFMC) is using some of the biological and social indicators as part of a stakeholder-driven risk assessment to help guide fishery management strategies for current and future conditions (Gaichas et al. 2018). And NMFS scientists are beginning to incorporate some of the biological indicators into the stock assessment advice they provide to Fishery Management Councils (e.g., Karp et al. 2019).

The fact that only a small set of indicators were considered to be at an operational level and ready for inclusion in the pilot NCIS is indicative of the clear need for much more work to be done to develop the full suite of indicators needed to track climate impacts on ecosystem services in these systems. Advances in ocean and coastal indicator systems such as the Ocean Health Index (Halpern et al. 2019) present useful opportunities to help build the NCIS ocean and coastal indicator system. We also recognize the pressing need to improve the synthesis, delivery, and integration of indicator information into decision-making at local to national (and international) scales, beyond simple monitoring and generation of time-series datasets (e.g., Link et al. 2015; Busch et al. 2016). Finally, we recommend continued support for tracking existing indicators and increased funding for developing the new indicators needed to effectively track and respond to climate change impacts on US ocean and coastal systems and the many people, businesses, communities, and economies that depend on them.

7 https://www.cbd.int/sp/targets/

8 https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement

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Authors' contributions Clay: planning and primary writing of paper, led and contributed to overall revisions in response to reviewer comments in round 1 and round 2, submission to journal.

Howard**:** major contribution to overall writing.

Colburn: provided language, data, and data sources for overall human community indicators, led and provided revisions and responses to round 1 reviewer comments on human community indicators overall.

Himes-Cornell: provided language, data, and data sources for Alaska human community indicators, contributed to revisions and responses to round 1 reviewer comments on Alaska human community indicators.

Rumrill: provided language, data, and data sources for bio-physical indicators, provided revisions and responses to round 1 reviewer comments on bio-physical indicators.

Zador: provided language, data, and data sources for bio-physical indicators, provided revisions and responses to round 1 reviewer comments on bio-physical indicators.

Griffis: overall project planning and oversight, contributed to overall revisions and responses to reviewer comments in both round 1 and round 2.

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