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Research article

Developing ocean climate change indicators for the north-central California coast and ocean

Benét Duncan[a,1,*], Kelley D. Johnson[a,2], Thomas H. Suchanek[b,c,d,3], Maria Brown[a], John L. Largier[c,e]

[a] Greater Farallones National Marine Sanctuary, 991 Marine Drive, The Presidio, San Francisco, CA, 94129, USA
[b] U.S. Geological Survey (USGS) Western Ecological Research Center, California State University, 3020 State University Drive, Sacramento, CA, 95819, USA
[c] UC Davis Bodega Marine Laboratory, P.O. Box 247, Bodega Bay, CA, 94923-0247, USA
[d] Department of Wildlife, Fish and Conservation Biology, University of California, One Shields Avenue, Davis, CA, 95616, USA
[e] Department of Environmental Science and Policy, University of California, One Shields Avenue, Davis, CA 95616, USA

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ABSTRACT

The Ocean Climate Indicators Project, developed for the Greater Farallones National Marine Sanctuary (GFNMS), yielded the first set of physical and biological ocean climate indicators specifically developed for the north-central California coast and ocean region, which extends from Point Arena to Point Año Nuevo and includes the ocean shorelines of the San Francisco metropolitan area. This case study produced a series of physical and biological indicator categories through a best professional judgment (BPJ) process with an interdisciplinary group of over 50 regional research scientists and marine resource managers from a wide range of state and federal agencies, NGOs, and universities. A working group of research scientists and marine resource managers used this set of ocean climate indicators to develop the Ocean Climate Indicators Monitoring Inventory and Plan. The Plan includes monitoring goals and objectives common for eight physical and four biological indicators; specific goals for each indicator; monitoring strategies and activities; an inventory of available monitoring data; opportunities for expanding or improving existing or new monitoring approaches; and case studies with specific examples of the indicators' utility for natural resource management and basic scientific research. Beyond developing indicators that support effective science-based management decisions, this scalable process established and strengthened mutually beneficial connections between scientists and managers, resulting in indicators that had broad support of project participants, were quickly adopted by the GFNMS, and could be used by managers and scientists from this region and beyond.

1. Introduction

A broad scientific consensus has emerged that climate change is impacting ocean ecosystems on both global and regional scales due primarily to human activities (e.g., Stocker et al., 2013 and references therein; US EPA, 2016; USGCRP, 2017). These impacts, which include changes in ocean circulation, atmospheric conditions, and land runoff into oceans, are well documented and expected to continue and strengthen as emissions of carbon dioxide and other anthropogenic greenhouse gases increase (Stocker et al., 2013 and references therein). How these changes will alter coastal and marine ecosystems on regional and local scales is less understood, yet many management actions occur at these smaller scales.

1.1. Climate indicators: the need, role, and process for development

The north-central coast of California stretches from Point Año Nuevo to Point Arena and includes the ocean shorelines of the San Francisco metropolitan area (Fig. 1). This oceanic region has exhibited marked physical and biological variations (e.g., physical changes in sea level, temperature, and nutrient content, and biological changes in productivity and species abundance on seasonal to decadal timescales)

* Corresponding author.
E-mail address: benet.duncan@colorado.edu (B. Duncan).
[1] Present Address: Western Water Assessment, Cooperative Institute for Research in Environmental Sciences (CIRES), University of Colorado Boulder, 216 UCB, Boulder, CO 80309-0216 USA.
[2] Independent Consultant (formerly K. Higgason, Greater Farallones National Marine Sanctuary).
[3] Current Affiliation: UC Davis Bodega Marine Laboratory and UC Davis Department of Wildlife, Fish and Conservation Biology

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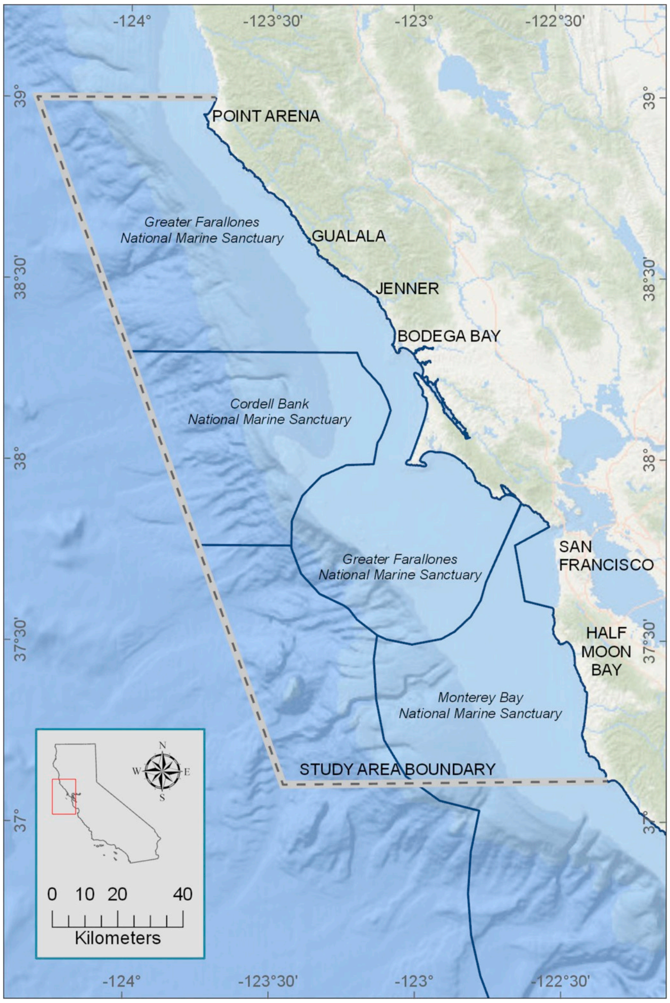

Fig. 1. Map of the Ocean Climate Indicators Project study region (bold solid line) and boundaries of Greater Farallones National Marine Sanctuary, Cordell Bank National Marine Sanctuary, and Monterey Bay National Marine Sanctuary (shaded areas).

(Largier et al., 2010), indicating the sensitivity of this ecosystem to climate change. While improved models and nested downscaling may contribute to greater insight about and attribution for some physical and biological changes in the region, changes at local scales and in complex marine ecosystems may be best estimated from direct observation. However, directly monitoring the myriad of processes and components that may respond to climate change is seldom feasible in these ecosystems. Instead, key indicators can be effectively measured and interpreted as an index of change. In this way, indicators document responses of an ecosystem to change, either confirming or refuting modeled projections of change. Such indicators can be used to monitor climate change at regional and sub-regional scales, and can inform future management and policy decisions.

Indicators have been developed and used at a range of scales, including on a national scale by the National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA) (US EPA, 2016), the National Park Service (NPS), and the National Aeronautics and Space Administration (NASA); for the State of California by the California Office of Environmental Health Hazard Assessment (OEHHA) (Mazur and Milanes, 2009; OEHHA, 2018); for the individual estuaries in the EPA's Climate Ready Estuaries program; and for the San Francisco Bay (San Francisco Estuary Program (SFEP), 2011). Other individual indicators exist in the region, and their focus is often on indexing specific aspects of the physical environment such as wind, water temperature, and sea level (Griggs et al., 2017), or tracking changes in single species such as Cassin's auklet (Wolfe et al., 2009), Dungeness crab, and salmon (e.g., Myrick and Cech, 2004). Synthetic indicators also exist, although they often focus on different spatial scales and are specific to physical processes (e.g., the Bakun upwelling index (Bakun, 1973), the Nutrient Upwelling Index (García-Reyes et al., 2014), and the Multivariate Ocean-Climate Indicator (MOCI) (Sydeman et al., 2014). Our project was the first effort to develop a regionally-scaled, comprehensive set of physical and biological indicators of climate change in the north-central coast of California.

Although science has been a critical factor in natural resource management, it is often used less than desired owing to a lack of ready data/information. Our goal with this project was to improve the role of science in the decision-making process for managing the natural resources of the region in relation to potential impacts from climate change.

This paper focuses on the process used to develop climate indicators for the north-central California coast and ocean, which included best professional judgment (BPJ) and was grounded in the approach taken by the National Research Council (NRC 2000). One important aspect of the indicator selection process was the active engagement of managers and scientists from beginning to end. This continuity is a key theme in our work and a critical component of the success of this collaborative indicator development process. Because of this engagement, the selected indicators were valued both by managers, who needed actionable information on the presence and impacts of climate change in the region, and scientists, who best understood system functioning.

1.2. *Overview of the study region*

The region under consideration in this study (Fig. 1) is often referred to as the "greater Gulf of the Farallones," indicating the coupling between the Gulf of the Farallones proper (which extends from Point Reyes to Point Año Nuevo) and waters to the north and south. Part of the California Current Ecosystem (Bakun, 1973; Chavez and Messié, 2009), this region is valued for its rich ecological diversity that includes gray, blue, fin, sperm, and humpback whales; Steller sea lions; wintering shorebirds, seabirds, and waterbirds; nesting seabirds like Cassin's auklet; fish including rockfish, halibut, and endangered coho salmon; and habitat-forming species like California mussel, eelgrass, and bull kelp (GFNMS, 2014 and references therein).

While large-scale California Current processes dominate offshore, the dominant process over the shelf and closer to the shore is wind-driven upwelling (Largier et al., 1993). Strongest in spring and summer, upwelling brings cold, nutrient-rich waters into the well-lit surface layers (García-Reyes and Largier, 2010, 2012; García-Reyes et al., 2014). The ensuing high rates of photosynthesis support high levels of biological productivity through multiple trophic levels, resulting in rich and diverse ecological communities (Chavez and Messié, 2009; Bakun et al., 2010; Largier et al., 2010). Outflow from San Francisco Bay is also an important contributor to productivity in the Gulf of the Farallones proper due to nutrients and organic matter from rivers and seasonal streams (GFNMS, 2014). Extensive fisheries, tourism, and marine recreation add to the region's economic value (e.g., Kildow and Colgan, 2005; SFEP, 2011).

The climate of the region is Mediterranean, with warm dry summers and cool wet winters. The region is subject to the time varying effects of prominent Pacific climate fluctuations, including the El Niño/Southern Oscillation (Rasmusson and Wallace, 1983) and the Pacific Decadal Oscillation (Trenberth, 1990; Trenberth and Hurrell, 1994; Largier et al., 2010).

A network of over 12,000 square miles of contiguous national marine sanctuaries (NMS) has been established from central to north-central California by NOAA, with an additional 2770 square-miles added in 2015. From south to north, these sanctuaries are: Monterey Bay (MBNMS), Greater Farallones (GFNMS; formerly Gulf of the

Farallones), and Cordell Bank (CBNMS) national marine sanctuaries. The north-central coast and ocean region that bounds this study includes GFNMS and CBNMS in their entirety and the northern portion of MBNMS (Fig. 1). The National Marine Sanctuary Act affords these sanctuaries the authority to "provide comprehensive and coordinated management to protect the ecologically and economically important waters that they encompass" (GFNMS, 2014). While the sanctuary's mission motivated the project, other local, state, and federal agencies and research scientists seek to study and protect these economically and ecologically important waters. These synergistic interests encouraged broad regional support and engagement in the effort.

1.3. Climate change in the study region

Recognizing that global climate change has the potential to alter the local and regional climate, the GFNMS and CBNMS advisory councils established a joint working group to identify potential climate change impacts on the region. A summary report developed by the working group, *Climate Change Impacts: Gulf of the Farallones and Cordell Bank National Marine Sanctuaries* (Largier et al., 2010), highlighted changes of a high probability and/or a high threat to the sanctuaries. These included: sea level rise; shoreline erosion; changes in temperature (cooling of upwelled waters and warming of island and mainland habitats); changes in land runoff; ocean acidification; and a northward shift in the distribution of some species including Humboldt squid, volcano barnacle, and bottlenose dolphins (Largier et al., 2010, and references therein). More recent work has also identified lower oxygen zones as another key change in the region (Sievanen et al., 2018).

1.4. The Ocean Climate Indicators Project

Marine resource managers at GFNMS proposed that reducing non-climate stressors on the region's ecological systems could help those ecosystems adapt to climate change and increase ecosystem resilience. To achieve this, GFNMS recognized a need for more up-to-date, detailed, scientifically rigorous, and regionally specific information about the impacts of climate change on the north-central California coast and ocean, in order to support "climate-smart" conservation, defined as, "the intentional and deliberative consideration of climate change in natural resource management, realized through forward-looking goals and linking actions to key climate impacts and vulnerabilities" (Stein et al., 2014).

To help meet this goal, GFNMS and the US Geological Survey (USGS) Western Ecological Research Center established and led the Ocean Climate Indicators Project, in partnership with a steering committee that included research ecologists, biologists, and physical oceanographers from the University of California Davis (UCD), UCD Bodega Marine Laboratory (BML), and Scripps Institution of Oceanography (SIO).

The project was successful in 1) engaging the regional scientific and management community, as demonstrated by the robust participation of over 50 scientists and managers from universities and research institutions, non-governmental organizations (NGOs), and federal and state agencies representing a range of disciplines and mandates; and 2) in developing indicators and a monitoring plan that could be readily adopted by the GFNMS Advisory Council and used by GFNMS staff and managers, who are currently working to secure resources to implement them. Beyond climate change, the indicators provide insights about other short and long timescale variability and can thus inform both short and long timescale management decisions.

Here, we discuss the process developed and implemented to create the ocean climate indicators and monitoring plan, and consider the strengths and weaknesses of our approach. The project followed a novel approach that utilized a BPJ process and the indicator selection criteria presented by the NRC (2000). We believe this process can serve as a scalable approach for other efforts to integrate science and management in developing indicators and other products that can be quickly utilized by natural resource managers. BPJ processes, like the one described in this paper, can bring together the perspectives of scientific, resource management, and community experts and reflect a range of priorities and types of knowledge. The novel process described here also strengthens connections between scientists and decision makers in the context of environmental resource management. At the same time, the indicators themselves can provide a good starting point for similar studies in regions around the world, particularly those in similar upwelling-dominated systems.

2. Methods

2.1. Selecting the ocean climate indicators

The indicator selection process was derived from the idea that global climate change drives regional environmental change, which in turn can cause biological changes in an ecosystem. Indicators were divided into two groups: physical indicators that index the changing regional environment and include measures of physical condition such as air or sea surface temperature; and biological indicators that index the changing ecosystem and include measures of key components such as phytoplankton abundance, percent cover of benthic species, or seabird abundances. Socioeconomic climate change indicators were beyond the scope of this project. It is important to note that factors other than climate change, including climate fluctuations like the El Niño Southern Oscillation and the Pacific Decadal Oscillation, management decisions, policies, and local human activities may also affect the indicators.

The indicator selection process detailed in the NRC publication, *Ecological Indicators for the Nation* (NRC, 2000), formed the foundation for the process developed in the Ocean Climate Indicators Project. The steering committee modified and adapted the NRC's procedure to reflect the regional scale of this project and the desire for both physical and biological indicators, and to meet the needs and priorities of GFNMS and other regional managers and scientists.

Much has been written about indicator development across systems and disciplines (e.g., Hammond et al., 1995; NRC, 2000; Walz, 2000; Levin et al., 2010), often suggesting that indicators can be identified based on three key criteria:

1. Feasibility of measuring the indicator;
2. Ability of the indicator to index key phenomena; and
3. Relevance of the key phenomena to the broader issue of concern.

These three criteria guided the indicator selection process.

The BPJ expert judgement process has been used in assessments of ecosystem condition and indicators (Borja and Dauer, 2008; Weisberg et al., 2008; Teixeira et al., 2010; Murray et al., 2016). Utilizing a suitable and representative set of knowledgeable and experienced experts in a structured BPJ process is one way to quickly link the need for information with the current understanding about the biophysical system. One risk of following a BPJ approach is the potential for biased judgments from participants. We attempted to minimize this risk by providing a structured process that was responsive to feedback and grounded in clearly-defined questions (Burgman et al., 2011). In addition, we assembled a set of over 50 professionals that included researchers with expertise in the physical and biological aspects of each of the habitats in the region, as well as managers from a range of state and federal agencies with jurisdiction in the region. We pursued this approach because it is quicker and less constrained by the state of modeling competency, and more inclusive of phenomena and opportunities (e.g., Weisberg et al., 2008; OST, 2013).

2.1.1. Indicator selection process step 1 – literature review

The indicator selection process began with an extensive review of available peer reviewed scientific and gray literature about climate change indicators, ecosystem health indicators, and the impacts of climate change on the study region. This review identified several existing climate change indicator efforts at the national level (e.g., Karl et al., 2009; Blunden and Arndt, 2012, EPA, 2016), California State climate change indicators (Mazur and Milanes, 2009; OEHHA, 2018), and regional climate change indicators outside of the study region (e.g., SFEP, 2011). We used this review to develop a description of the key biota in the study region that provided a foundation of understanding about the region, a conceptual model of the processes by which climate change could impact the region, and a set of 91 potential ocean climate indicators (Duncan et al., 2013).

2.1.2. Indicator selection process step 2 – developing indicator selection criteria

The project steering committee worked closely with the GFNMS manager to develop a set of high-priority climate-related management questions, with the understanding that optimal indicators would address as many of these as possible. We used these priority management questions to develop indicator selection criteria and additional assessment questions that assessed how well potential indicators met the priority management questions and how scientifically sound they were (Table 1). The selection criteria used the peer-reviewed criteria presented in NRC (2000) as a starting point and reflected the management priorities identified by GFNMS.

The criteria (Table 1) focused on a potential indicator's response to climate change and potential to generate actionable information for managers, temporal and spatial scale, statistical properties (e.g., accuracy, sensitivity, and precision), reliability, availability of sufficient data on an indicator, and necessary skills to collect indicator data (i.e., feasibility of monitoring routinely over a sustained period of time). Additional assessment questions (Table 1) focused on the availability of existing data and need for new data, and costs, benefits, and cost-effectiveness of monitoring an indicator.

Table 1
Indicator selection criteria and additional assessment questions used during the indicator selection process.

Indicator Selection Criteria
General Importance:
•Does indicator tell about changes in important attributes due to changes in climate?
•Will changes in the indicator result in an identifiable change in the system?
•Can it inform direct or indirect actions by sanctuary management?
•Is the indicator compatible with those being developed by other groups in the region?
•Is it based on the GFNMS ecosystem description (see above)?
Temporal and spatial scales of applicability:
•Can indicator detect changes at appropriate temporal and spatial scales?
Statistical properties of indicator data:
•Is the available indicator data good enough in accuracy, sensitivity, precision, and robustness?
•Is it insensitive to changes in monitoring technology?
•Can it detect signals above “noise” of other environmental variation?
Reliability:
•Has past experience with indicator demonstrated its reliability?
•If not, is there other historical evidence that is reliable?
Data requirements:
•Does enough information exist to develop reliable indicator measurements?
•Can new information be collected to develop reliable indicator measurements?
•What is required for indicator to detect a trend?
•Would another dataset provide sufficient information about this indicator? That is, are proxies available?
Necessary skills:
•Can the indicator be easily monitored without extensive training, or does it require specialized knowledge?
Additional Indicator Assessment Questions
Data requirements:
•What new data, if any, needs to be collected to monitor the indicator?
•Are historical datasets available for this indicator?
•Where is existing indicator available? Can we use it?
Costs, benefits, and cost-effectiveness:
•What are the clear benefits of using this indicator?
•What are the costs of obtaining data for the indicator?
•Do the benefits of using this indicator exceed the cost of obtaining data?

2.1.3. Indicator selection process step 3 – applying the indicator selection criteria

The project steering committee used the indicator selection criteria to reduce the large set of 91 potential ocean climate indicators to a smaller set of 11 physical and 12 biological candidate indicators (Fig. 2). The candidate indicators were then evaluated by 48 invited regional research scientists and managers from 26 academic institutions, NGOs, and federal and state agencies through an Indicator Survey. These invited researchers and managers were specifically selected due to their expertise in the study region.

The Indicator Survey assessed how well each candidate indicator met the selection criteria. Individuals participating in the indicator selection survey came mostly from academia (15), NGOs (13), and federal government (18), with fewer individuals from state government agencies (four) and private organizations (one) also represented. The expertise of these individuals was balanced between physical and biological components of the region's ecosystems and survey respondents were invited to self-select whether they provided input on biological indicators, physical indicators, or both.

The Indicator Survey results (Fig. 2), in turn, provided a starting point for discussions at a subsequent Indicators Selection Workshop where 36 experts, all of whom had participated in the survey, focused their efforts on narrowing the list of candidate indicators from those that already had broad support according to the survey. At the workshop, each of four breakout groups created a set of recommended indicators. Breakout groups considered a range of criteria including ease of measurement, cost, and the ability to easily interpret the results of indicator monitoring. The full group then discussed each breakout group's results, and any indicators recommended by at least three out of the four breakout groups were taken to be broadly recommended and adopted. The final list of selected physical and biological indicators is provided in Fig. 3. During the workshop, the GFNMS Superintendent also provided management context for the project to help underscore the value of participating in the indicator selection process.

2.2. Developing the Ocean Climate Indicators Monitoring Inventory and Plan

2.2.1. Formation of the Indicators Working Group

The steering committee identified the need for a monitoring inventory and plan that contained detailed monitoring recommendations for the indicators and a summary of each indicator and associated existing monitoring. The GFNMS Advisory Council approved the formation of an expert working group - the Indicators Working Group - to develop such a product. This approval of the Indicators Working Group was key to advancing the project because it provided a formal pathway for project collaborators to inform the Advisory Council (and, by extension, the sanctuary) of the ocean climate indicators’ monitoring needs.

The Indicators Working Group consisted of 13 regional scientists and managers who were previously engaged in the project, including several members of the GFNMS Advisory Council and the project steering committee. The GFNMS and CBNMS Superintendents also provided key expertise on sanctuary priorities. Collectively, the working group members and supporting sanctuary staff had scientific expertise on all of the ocean climate indicators, and represented state and federal agencies with jurisdiction in the region.

2.2.2. Process of the Indicators Working Group

The Indicators Working Group convened a series of five meetings to

Fig. 2. (Left) Candidate physical (top) and biological (bottom) ocean climate indicators included in the Indicator Survey. (Right) Additional candidate physical (top) and biological (bottom) ocean climate indicators suggested by the 48 Indicator Survey respondents.

develop the *Ocean Climate Indicators Monitoring Inventory and Plan* (the "Monitoring Plan") (Duncan et al., 2013). The meetings focused on establishing overarching monitoring goals and objectives for the full set of indicators, and for each indicator, developed: (i) monitoring strategies and activities; (ii) an inventory of available monitoring data; (iii) opportunities for expanding or improving existing monitoring or establishing new monitoring; (iv) case studies with specific examples of the indicators' utility for managers; and (v) “selected species” for each biological indicator using the BPJ approach. All final goals and objectives were reached by agreement of the full group. The final plan was adopted by the GFNMS Sanctuary Advisory Council and reviewed by three regional experts through the formal US Department of Interior's USGS peer-review process.

3. Results

3.1. Ocean climate indicators

The indicator selection process resulted in a final set of eight physical and four biological ocean climate indicators for the north-central California coast and ocean region, with the biological indicators representing key ecosystem components (Fig. 3). As described above, these indicators represented the broad agreement of the interdisciplinary group of scientists and managers who participated in the indicator selection process, through both the Indicator Survey and the Indicator Selection Workshop.

The physical ocean climate indicators include: sea surface temperature; sea surface salinity; dissolved oxygen; ocean chemistry (as measured through pH and pCO_2); sea level; wave height and direction; air temperature; and alongshore wind speed (Fig. 3). These indicators are intended to provide information about changes in upwelling, water transport, habitat suitability, water quality, primary productivity, runoff, nutrient content, and ocean acidification.

The biological ocean climate indicators include: primary productivity (particularly the biomass of primary producers); the abundance, biomass, and/or phenology (e.g., timing of regular life events) of mid-trophic level species; the spatial extent of habitat-forming organisms; and seabird phenology, productivity, and/or diet (Fig. 3). They are intended to provide information about the health of key trophic levels in the food web, the potential for harmful algal blooms, changes in habitat availability, and potential mismatches in species phenology. The Indicators Working Group later developed a set of focal species for each of these biological ocean climate indicators (Fig. 4). Because many of the indicators may influence other properties or processes within the system (e.g., changes in sea surface temperature can affect dissolved oxygen and primary productivity), considering all of the indicators is important to establishing a more comprehensive picture of the presence and impacts of climate change in the region.

3.2. Ocean Climate Indicators Monitoring Inventory and Plan

The Monitoring Plan includes three main components: an

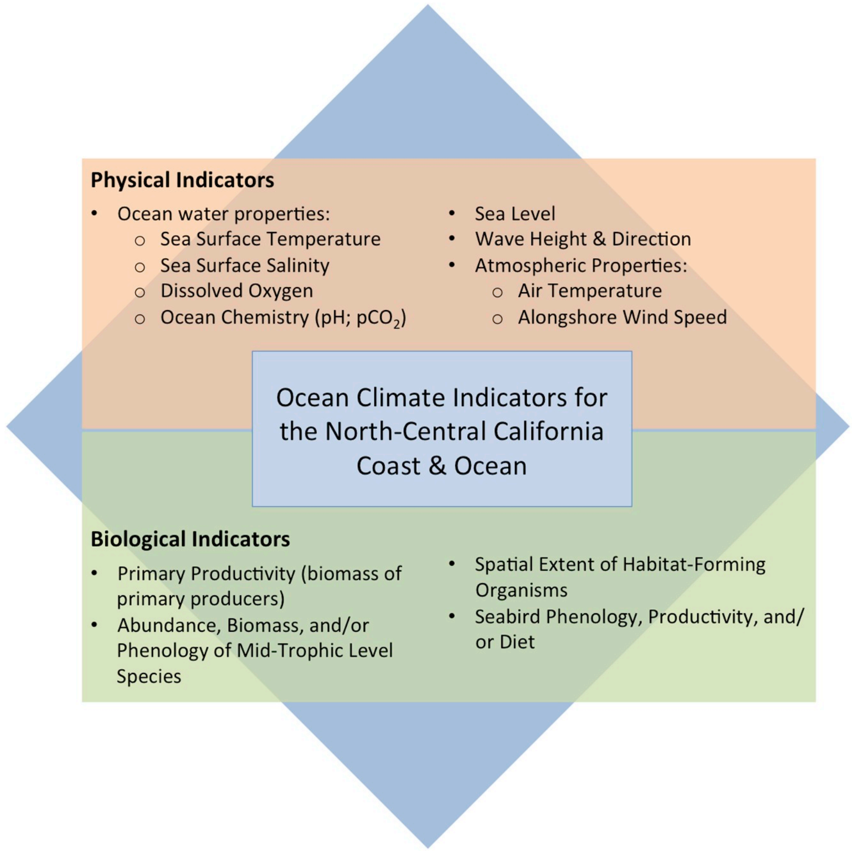

Fig. 3. Final adopted physical (top) and biological (bottom) ocean climate indicators for the North-central California coast and ocean.

overarching monitoring goal for the indicators and objectives for the indicators to meet that goal; prioritized monitoring recommendations for each indicator; and an inventory of existing monitoring activities for each indicator. Taken together, the Monitoring Plan provides a road map for leveraging existing monitoring activities and prioritizing potential future investments in new or expanded monitoring activities, to efficiently identify and evaluate the impacts of climate change for each habitat in the study region. For each indicator, the Monitoring Plan also includes information about the habitats in which it is most relevant, an overview of measurement techniques recommended by the working group, and example case studies of how it can be used by natural resource managers.

To provide context for the indicators and help guide implementation of the Monitoring Plan, the overarching monitoring goal developed by the working group was: “To promote comprehensive and coordinated management of marine resources by increasing understanding of the ecological impacts of climate change on the north-central California coast and ocean region, through the monitoring and evaluation of physical and biological ocean climate indicators”. To help meet this goal, the working group developed two major objectives:

1. Determine the status and trends of ocean climate indicators in the region through existing monitoring and by identifying the need and opportunity for new or expanded monitoring.
2. Assess the vulnerability of specific geographic areas, ecosystems, and ecosystem components within the north-central California coast and ocean region to the impacts of climate change.

In addition, a significant part of the Indicators Working Group's efforts involved developing monitoring recommendations for each indicator in the Monitoring Plan. While these recommendations differed among indicators, they primarily followed four key themes:

1. The importance of maintaining indicator monitoring that is already occurring, as this provides scientists and managers with the ability to identify long-term changes in the region.
2. The utility of expanded and/or new indicator monitoring to fill information gaps.
3. The key role that the synthesis of existing regional research will play in optimizing monitoring by identifying key indicators or locations.
4. The need for increased communication among federal, regional, and local government agencies and other scientific organizations to share information, partners, and resources that will aid in assessing and reducing their vulnerability to climate change.

These recommendations emphasize the importance of continued federal, state, and private investment in monitoring to understand the impacts of climate change in the region. For each monitoring recommendation, the working group also: (i) developed priority levels and the need for additional funding and infrastructure to implement that recommendation; (ii) detailed existing gaps in data and research; (iii) identified current and potential partners; and (iv) provided an estimated timeline for implementation.

The biological indicators were designed as broad categories; because of this, the working group identified “selected species” in key habitats for three of the four biological indicators using the BPJ approach (Fig. 4). “Selected species” were species for which there is a clear, scientifically accepted mechanism for climate change to alter that species’ distribution or abundance, and for which monitoring data is currently available in at least some of the region. The biological indicators are intended to be evaluated separately in each key habitat, using the selected species.

The working group also developed longer-term recommendations for the ocean climate indicators as a whole, including the development of a web-based indicator decision support tool that would provide a

Fig. 4. Selected species for biological ocean climate indicators, for each relevant key habitat within the study region.

simple way for managers and scientists to access processed and interpreted indicator observations and projections for the region. Finally, the working group provided guidance for reviewing and updating the Monitoring Plan on an annual and 5-year basis, which also involves updating the data sources for each ocean climate indicator, and recommended convening a working group to evaluate the utility and scientific relevance of existing and potential new ocean climate indicators.

The final Monitoring Plan was adopted by the GFNMS Advisory Council in 2013, and forwarded to GFNMS management to consider how best to integrate its recommendations into the GFNMS Management Plan (GFNMS, 2014) and the program areas of Research and Monitoring, Ecosystem Protection, and Education and Outreach. The strong role that GFNMS played in the organization and implementation of this project helped to ensure that the ocean climate indicators and the Monitoring Plan were relevant to sanctuary management, and that they were presented in a way that maximized their utility to the sanctuary (and to other managers). By convening scientists and managers together, GFNMS ensured project results were scientifically rigorous, as well as applicable to GFNMS and beneficial to other agency management decisions.

4. Discussion & conclusions

The Ocean Climate Indicators Project resulted in the first integrated set of ocean climate indicators and Monitoring Plan specifically developed on a regional scale for the north-central California coast and ocean. Previous indicator development efforts focused on larger geographic scales (US EPA, 2016; Mazur and Milanes, 2009; OEHHA, 2018) or extremely local scales (SFEP, 2011) that were not as directly relevant to managers at GFNMS and elsewhere within the region. The project built upon the broad support of an interdisciplinary group of over 50 regional research scientists and marine resource managers from a range of state, and federal agencies, NGOs, and universities. It had a high level of continued engagement from project partners, and it resulted in indicators that GFNMS is using in their Climate-Smart Conservation Program.

The project was a novel application of the BPJ approach and the National Research Council's indicator selection criteria (NRC, 2000). It can serve as a scalable model for other efforts to integrate science and management in developing indicators that can be quickly utilized by natural resource managers in the United States and internationally. BPJ approaches like the one described here can bring together the perspectives of scientific, resource management, and community experts to integrate and reflect their priorities and knowledge, all while strengthening connections in the context of environmental resource management. The indicators themselves can also provide a good starting point for similar studies in other regions around the world.

It is important to acknowledge that institutional buy-in was key to the process, as it enabled continued participation of staff from a broad range of agencies, organizations, and universities. While the project relied on a small number of dedicated, funded staff, the total hours invested among all project participants was quite large. Workshop attendees spent at least 9 h participating in the Indicator Survey and the Indicator Selection Workshop, while members of the Indicators Working Group spent an additional 25 h participating in in-person meetings and webinars. These time estimates do not include time spent on meeting preparation, document review, or transportation. In addition, monitoring of all indicators would require substantial coordination of existing monitoring efforts identified in the Monitoring Plan (Duncan et al., 2013) and investment in new ones. However, given the priority that state and federal agencies have placed on understanding the impacts of climate change in the region, there is motivation for cross-agency, cross-institution collaboration to use available data, where possible.

The scope of this project reflects what was possible within our limited funding and core staff resources. For example, the project resulted in physical and biological indicators, and did not include development of socioeconomic indicators. This conscious limiting of scope allowed us to explore physical and biological indicators in greater detail than we otherwise would have, given the available resources.

In addition, the indicators were developed through a novel BPJ approach, rather than quantitative assessment of potential indicators. As a result, there is no quantitative confirmation of the skill of these indicators or of their relative importance. Additional resources would need to be secured to conduct a quantitative analysis of the skill and value of these indicators, which could be incorporated as part of a future review of the indicators and Monitoring Plan as recommended by the working group.

BPJ has been used in several other ecosystem and indicator assessments (Borja and Dauer, 2008; Weisberg et al., 2008; Teixeira et al., 2010; Murray et al., 2016). Our BPJ approach built on existing research by providing a structured process that was responsive to feedback and grounded in clearly-defined questions (Burgman et al., 2011) in a way that was quicker and less constrained by the state of modeling competency, and more inclusive of phenomena and opportunities (e.g., Weisberg et al., 2008; OST, 2013). A more quantitative/objective approach would likely have constrained the range of indicators that could be considered. Our approach provided an opportunity to develop the indicators while working with limited resources, and it supported increasing and continued engagement with the agencies, universities, research institutions, and NGOs that participated in the indicator selection process. It was also more inclusive of the broad range of physical and biological processes that affect the region.

While the selected indicators may have been biased by the interests of the researchers and managers who participated in this BPJ process, we believe that the large number of project participants from a balanced range of organization types minimized this bias. Future iterations of this process could include an increased number of state agencies to further diversify the range of organizations that were represented. If additional financial and staff resources were available, we could also have pursued a paired approach to indicator selection, using quantitative assessment of available indicator data to inform the selection process.

Three broad lessons emerged from this work that can be applied to any indicator development process and to broader science-management integration efforts:

1. Range of project participants: Because this work relies on a BPJ approach, it was essential that the participating experts have a deep understanding of the region's coastal and ocean environment, and that they represent a broad range of organization types. The project steering committee was careful to include scientists who conducted physical and biological monitoring in the region, who were both experts in their subject areas and also had a broad understanding of the components and connectivity in the ecosystem. Including participants with this level of expertise provided a scientifically-rigorous foundation for this BPJ process.
2. Engagement of high-level scientists and managers early in the project (including those in the project steering committee) engendered trust from potential partners, encouraged robust participation from a diverse group of physical and biological ocean experts and managers in the region, and gave those experts ownership over the resulting ocean climate indicators. This was particularly important because the project workshops were typically outside of the normal working activities for most agencies. Still, managers at collaborating agencies felt it was important to have representation at these workshops because of the potential long-term benefits to their own natural resource management issues and priorities.
3. At the same time, we believe that responsiveness to participants' questions, concerns, and suggestions at the Indicator Selection Workshop and working group meetings helped to foster respect among participants, which encouraged ongoing participant engagement throughout this project. This engagement built new and strengthened existing relationships with scientists and managers that can carry forward into future efforts to update the indicators as scientific understanding grows and management priorities evolve. It also helped managers to be confident in the ocean climate indicators and the Monitoring Plan and encouraged broader acceptance of the results beyond the project participants. Future BPJ processes could include surveys to test and quantify these impacts.

GFNMS management and staff established the Ocean Climate Indicators Project, contributed their perspectives through the GFNMS priority management questions, and provided technical expertise at workshops and meetings. As a result, the ocean climate indicators and the Monitoring Plan were tailored to meet the goals of GFNMS. This management participation also helped to ensure that the report was developed in a way that followed established National Marine Sanctuary protocols. External partners were engaged and participated throughout the process, which ensured that others benefited from the results of the project and could apply information where relevant to their separate planning processes.

The data, recommendations and protocols identified in the Monitoring Plan stand as a resource for ongoing assessments of marine resources within GFNMS and CBNMS. These are represented by studies in ongoing projects such as the Applied California Current Ecosystem Studies partnership, which monitors Ocean Climate Indicators during 3-4 cruises per year (Elliott and Jahncke, 2017) and the GFNMS Climate Action Plan that characterizes climate impacts and vulnerabilities to Sanctuary resources (GFNMS, 2016).

4.1. Conclusions

Collaboratively designed and implemented processes can play an important role in developing robust science-management integration products that are well regarded and valuable to both science and management audiences, thereby supporting effective science-based decisions. Such processes also establish and strengthen mutually beneficial connections between scientists and managers that can support the design of future research and monitoring projects to inform difficult management decisions in response to climate change.

As a next step to this foundational work, GFNMS and project partners collaborated on the Climate-Smart Adaptation Project for the north-central California coast and ocean (Hutto, 2016). The goal of that project is to enable marine resource managers to respond to, plan, and manage for the impacts of climate change on habitats, species, and ecosystem services within the region by utilizing expert-driven, scientifically sound vulnerability assessments to develop prioritized, stakeholder-led adaptation strategies. Specifically, the project sought to integrate climate-smart adaptation into existing management frameworks, and provide guidance to help ensure long-term viability of the habitats and resources that natural resource agencies are mandated to protect. GFNMS and its partners will use the ocean climate indicators to help monitor the effectiveness of these adaptation strategies and other management efforts.

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Declarations of interest

None.

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Appendix A. Supplementary data

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