

1 **Title**

2 Developing Ocean Climate Change Indicators for the North-central California Coast and Ocean

4 **Authors**

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24 **Abstract**

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

44 **Keywords**

45 climate change, indicators, co-production, management, Greater Farallones National Marine Sanctuary,
46 marine protected areas

48 **1. Introduction**

49 A broad scientific consensus has emerged that climate change is impacting ocean ecosystems on both
50 global and regional scales due primarily to human activities (e.g., Stocker et al., 2014 and references
51 therein; US EPA, 2016; USGCRP, 2017). These impacts, which include changes in ocean circulation,
52 atmospheric conditions, and land runoff into oceans, are well documented and
53 expected to continue and strengthen as emissions of carbon dioxide and other
54 anthropogenic greenhouse gases increase (Stocker et al., 2014 and references therein).
55 How these changes will alter coastal and marine
56 ecosystems on regional and local scales is less understood, yet many management actions
57 occur at these smaller scales.
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68 **1.1 Climate Indicators: The Need, Role, and Process for Development**

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71 The north-central coast of California stretches from Point
72 Año Nuevo to Point Arena and includes the ocean shorelines of the San Francisco
73 metropolitan area (Figure 1). This oceanic region has exhibited marked physical and
74 biological variations (e.g., physical changes in sea level, temperature, and nutrient
75 content, and biological changes in productivity and species abundance on
76 seasonal to decadal timescales) (Largier et al., 2010), indicating the
77 sensitivity of this ecosystem to climate change. While improved models and nested
78 downscaling may contribute to greater insight about and attribution for some physical and biological
79 changes in the region, changes at local scales and in complex marine ecosystems may be best estimated
80 from direct observation. However, directly monitoring the myriad of processes and components that
81 may respond to climate change is seldom feasible in these ecosystems. Instead, key indicators can be
82 effectively measured and interpreted as an index of change. In this way, indicators document responses
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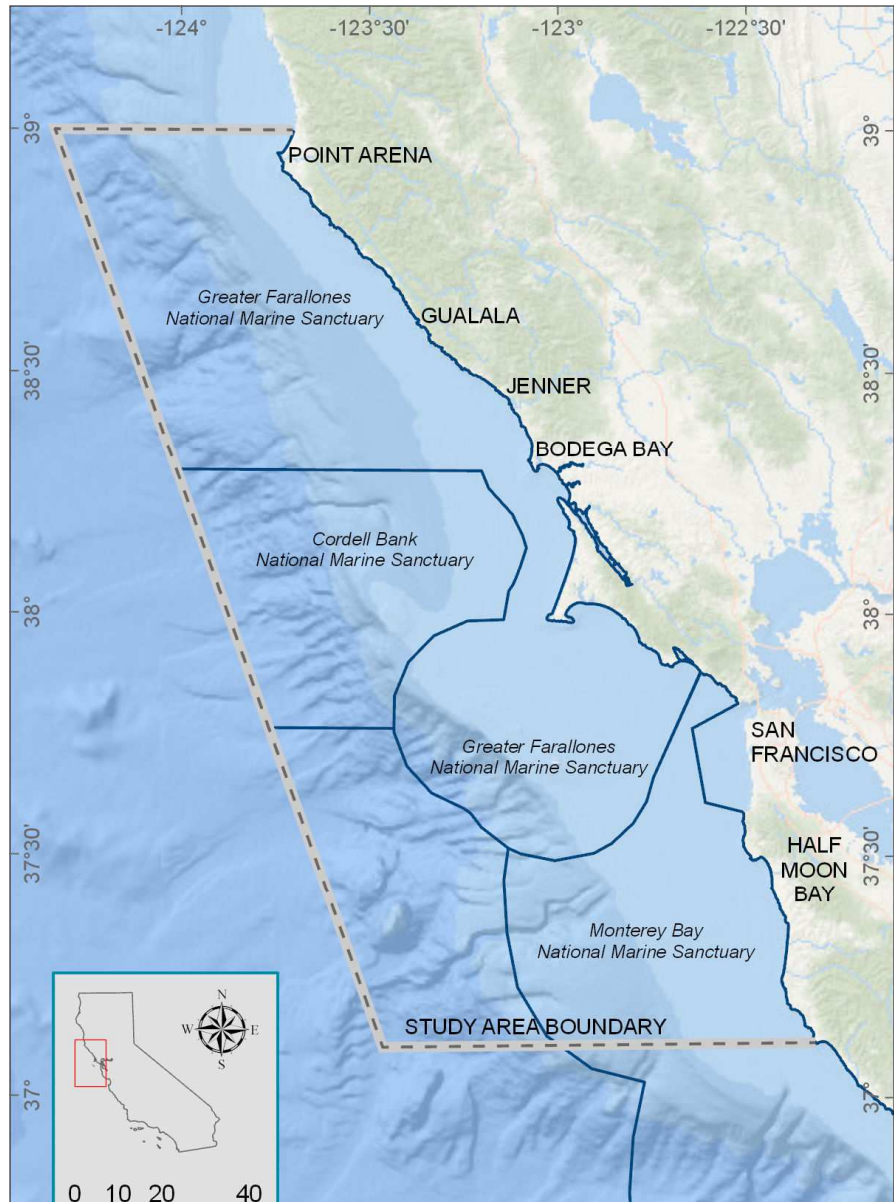


Figure 1: Map of the Ocean Climate Indicators Project study region (bold solid line) and boundaries of Greater Farallones National Marine Sanctuary, Cordell Bank National Marine Sanctuary, and Monterey Bay National Marine Sanctuary (shaded areas).

NOTE: color image for online only.

96 of an ecosystem to change, either confirming or refuting modeled projections of change. Such indicators
97 can be used to monitor climate change at regional and sub-regional scales, and can inform future
98 management and policy decisions.
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100 Indicators have been developed and used at a range of scales, including on a national scale by the
101 National Oceanic and Atmospheric Administration (NOAA), the Environmental Protection Agency (EPA)
102 (US EPA, 2016), the National Park Service (NPS), and the National Aeronautics and Space Administration
103 (NASA); for the State of California by the California Office of Environmental Health Hazard Assessment
104 (OEHHA) (Mazur and Milanes, 2009; OEHHA, 2018); for the individual estuaries in the EPA’s Climate
105 Ready Estuaries program; and for the San Francisco Bay (San Francisco Estuary Program (SFEP), 2011).
106 Other individual indicators exist in the region, and their focus is often on indexing specific aspects of the
107 physical environment such as wind, water temperature, and sea level (Griggs et al., 2017), or tracking
108 changes in single species such as Cassin’s auklet (Wolfe et al., 2009), Dungeness crab, and salmon (e.g.,
109 Myrick et al., 2004). Synthetic indicators also exist, although they often focus on different spatial scales
110 and are specific to physical processes (e.g., the Bakun upwelling index (Bakun, 1973), the Nutrient
111 Upwelling Index (García-Reyes et al., 2014), and the Multivariate Ocean-Climate Indicator (MOCI)
112 (Sydeman et al., 2014)). Our project was the first effort to develop a regionally-scaled, comprehensive
113 set of physical and biological indicators of climate change in the north-central coast of California.
114

115 Although science has been a critical factor in natural resource management, it is often used less than
116 desired owing to a lack of ready data/information. Our goal with this project was to improve the role of
117 science in the decision-making process for managing the natural resources of the region in relation to
118 potential impacts from climate change.
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120 This paper focuses on the process used to develop climate indicators for the north-central California
121 coast and ocean, which included best professional judgment (BPJ) and was grounded in the approach
122 taken by the National Research Council (NRC 2000). One important aspect of the indicator selection
123 process was the active engagement of managers and scientists from beginning to end. This continuity is
124 a key theme in our work and a critical component of the success of this collaborative indicator
125 development process. Because of this engagement, the selected indicators were valued both by
126 managers, who needed actionable information on the presence and impacts of climate change in the
127 region, and scientists, who best understood system functioning.
128

129 **1.2 Overview of the study region**

130 The region under consideration in this study (Figure 1) is often referred to as the “greater Gulf of the
131 Farallones,” indicating the coupling between the Gulf of the Farallones proper (which extends from
132 Point Reyes to Point Año Nuevo) and waters to the north and south. Part of the California Current
133 Ecosystem (Bakun, 1973; Chavez and Messie, 2009), this region is valued for its rich ecological diversity
134 that includes gray, blue, fin, sperm, and humpback whales; Steller sea lions; wintering shorebirds,
135 seabirds, and waterbirds; nesting seabirds like Cassin’s auklet; fish including rockfish, halibut, and
136 endangered coho salmon; and habitat-forming species like California mussel, eelgrass, and bull kelp
137 (GFNMS, 2014 and references therein).
138

139 While large-scale California Current processes dominate offshore, the dominant process over the shelf
140 and closer to the shore is wind-driven upwelling (Largier et al., 1993). Strongest in spring and summer,
141 upwelling brings cold, nutrient-rich waters into the well-lit surface layers (García-Reyes and Largier 2010,
142 2012; García-Reyes et al., 2014). The ensuing high rates of photosynthesis support high levels of
143 biological productivity through multiple trophic levels, resulting in rich and diverse ecological

144 communities (Chavez and Messie, 2009; Bakun et al., 2010; Largier et al., 2010). Outflow from San
145 Francisco Bay is also an important contributor to productivity in the Gulf of the Farallones proper due to
146 nutrients and organic matter from rivers and seasonal streams (GFNMS, 2014). Extensive fisheries,
147 tourism, and marine recreation add to the region’s economic value (e.g., Kildow and Colgan, 2005; SFEP,
148 2011).

149
150 The climate of the region is Mediterranean, with warm dry summers and cool wet winters. The region is
151 subject to the time varying effects of prominent Pacific climate fluctuations, including the El
152 Niño/Southern Oscillation (Rasmussen and Wallace, 1983) and the Pacific Decadal Oscillation (Trenberth,
153 1990; Trenberth and Hurrell, 1994; Largier et al., 2010).

154
155 A network of over 12,000 square miles of contiguous national marine sanctuaries (NMS) has been
156 established from central to north-central California by NOAA, with an additional 2,770 square-miles
157 added in 2015. From south to north, these sanctuaries are: Monterey Bay (MBNMS), Greater Farallones
158 (GFNMS; formerly Gulf of the Farallones), and Cordell Bank (CBNMS) national marine sanctuaries. The
159 north-central coast and ocean region that bounds this study includes GFNMS and CBNMS in their
160 entirety and the northern portion of MBNMS (Figure 1). The National Marine Sanctuary Act affords
161 these sanctuaries the authority to “provide comprehensive and coordinated management to protect the
162 ecologically and economically important waters that they encompass” (GFNMS, 2014). While the
163 sanctuary’s mission motivated the project, other local, state, and federal agencies and research
164 scientists seek to study and protect these economically and ecologically important waters. These
165 synergistic interests encouraged broad regional support and engagement in the effort.

166 167 **1.3 Climate change in the study region**

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

178 179 **1.4 The Ocean Climate Indicators Project**

180 Marine resource managers at GFNMS proposed that reducing non-climate stressors on the region’s
181 ecological systems could help those ecosystems adapt to climate change and increase ecosystem
182 resilience. To achieve this, GFNMS recognized a need for more up-to-date, detailed, scientifically
183 rigorous, and regionally specific information about the impacts of climate change on the north-central
184 California coast and ocean, in order to support “climate-smart” conservation, defined as, “the
185 intentional and deliberative consideration of climate change in natural resource management, realized
186 through forward-looking goals and linking actions to key climate impacts and vulnerabilities” (Stein et al.,
187 2014).

188
189 To help meet this goal, GFNMS and the US Geological Survey (USGS) Western Ecological Research Center
190 established and led the Ocean Climate Indicators Project, in partnership with a steering committee that

191 included research ecologists, biologists, and physical oceanographers from the University of California
192 Davis (UCD), UCD Bodega Marine Laboratory (BML), and Scripps Institution of Oceanography (SIO).
193 The project was successful in 1) engaging the regional scientific and management community, as
194 demonstrated by the robust participation of over 50 scientists and managers from universities and
195 research institutions, non-governmental organizations (NGOs), and federal and state agencies
196 representing a range of disciplines and mandates; and 2) in developing indicators and a monitoring plan
197 that could be readily adopted by the GFNMS Advisory Council and used by GFNMS staff and managers,
198 who are currently working to secure resources to implement them. Beyond climate change, the
199 indicators provide insights about other short and long timescale variability and can thus inform both
200 short and long timescale management decisions
201

202 Here, we discuss the process developed and implemented to create the ocean climate indicators and
203 monitoring plan, and consider the strengths and weaknesses of our approach. The project followed a
204 novel approach that utilized a BPJ process and the indicator selection criteria presented by the NRC
205 (2000). We believe this process can serve as a scalable approach for other efforts to integrate science
206 and management in developing indicators and other products that can be quickly utilized by natural
207 resource managers. BPJ processes, like the one described in this paper, can bring together the
208 perspectives of scientific, resource management, and community experts and reflect a range of
209 priorities and types of knowledge. The novel process described here also strengthens connections
210 between scientists and decision makers in the context of environmental resource management. At the
211 same time, the indicators themselves can provide a good starting point for similar studies in regions
212 around the world, particularly those in similar upwelling-dominated systems.
213

214 **2. Methods**

215 **2.1 Selecting the ocean climate indicators**

216 The indicator selection process was derived from the idea that global climate change drives regional
217 environmental change, which in turn can cause biological changes in an ecosystem. Indicators were
218 divided into two groups: physical indicators that index the changing regional environment and include
219 measures of physical condition such as air or sea surface temperature; and biological indicators that
220 index the changing ecosystem and include measures of key components such as phytoplankton
221 abundance, percent cover of benthic species, or seabird abundances. Socioeconomic climate change
222 indicators were beyond the scope of this project. It is important to note that factors other than climate
223 change, including climate fluctuations like the El Niño Southern Oscillation and the Pacific Decadal
224 Oscillation, management decisions, policies, and local human activities may also affect the indicators.
225

226 The indicator selection process detailed in the NRC publication, *Ecological Indicators for the Nation* (NRC,
227 2000), formed the foundation for the process developed in the Ocean Climate Indicators Project. The
228 steering committee modified and adapted the NRC's procedure to reflect the regional scale of this
229 project and the desire for both physical and biological indicators, and to meet the needs and priorities of
230 GFNMS and other regional managers and scientists.
231

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

- 235 1. Feasibility of measuring the indicator;
 - 236 2. Ability of the indicator to index key phenomena; and
 - 237 3. Relevance of the key phenomena to the broader issue of concern.
- 238

239 These three criteria guided the indicator selection process.

240
241 The BPJ expert judgement process has been used in assessments of ecosystem condition and indicators
242 (Borja and Dauer, 2008; Weisberg et al., 2008; Teixeira, 2010; Murray et al., 2017). Utilizing a suitable
243 and representative set of knowledgeable and experienced experts in a structured BPJ process is one way
244 to quickly link the need for information with the current understanding about the biophysical system.
245 One risk of following a BPJ approach is the potential for biased judgments from participants. We
246 attempted to minimize this risk by providing a structured process that was responsive to feedback and
247 grounded in clearly-defined questions (Burgman et al., 2011). In addition, we assembled a set of over 50
248 professionals that included researchers with expertise in the physical and biological aspects of each of
249 the habitats in the region, as well as managers from a range of state and federal agencies with
250 jurisdiction in the region. We pursued this approach because it is quicker and less constrained by the
251 state of modeling competency, and more inclusive of phenomena and opportunities (e.g., Weisberg et
252 al., 2008; OST, 2013).

253
254 **2.1.1. Indicator Selection Process Step 1 – Literature Review**

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

264
265 **2.1.2 Indicator Selection Process Step 2 – Developing Indicator Selection Criteria**

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

273
274 The criteria (Table 1) focused on a potential indicator’s response to climate change and potential to
275 generate actionable information for managers, temporal and spatial scale, statistical properties (e.g.,
276 accuracy, sensitivity, and precision), reliability, availability of sufficient data on an indicator, and
277 necessary skills to collect indicator data (i.e., feasibility of monitoring routinely over a sustained period
278 of time). Additional assessment questions (Table 1) focused on the availability of existing data and need
279 for new data, and costs, benefits, and cost-effectiveness of monitoring an indicator.

280

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?

<ul style="list-style-type: none"> • 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)? <p>Temporal and spatial scales of applicability:</p> <ul style="list-style-type: none"> • Can indicator detect changes at appropriate temporal and spatial scales? <p>Statistical properties of indicator data:</p> <ul style="list-style-type: none"> • 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? <p>Reliability</p> <ul style="list-style-type: none"> • Has past experience with indicator demonstrated its reliability? • If not, is there other historical evidence that is reliable? <p>Data requirements:</p> <ul style="list-style-type: none"> • 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? <p>Necessary skills:</p> <ul style="list-style-type: none"> • Can the indicator be easily monitored without extensive training, or does it require specialized knowledge?
<p>Additional Indicator Assessment Questions</p> <p>Data requirements:</p> <ul style="list-style-type: none"> • 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? <p>Costs, benefits, and cost-effectiveness:</p> <ul style="list-style-type: none"> • 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?

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

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2.1.3 Indicator Selection Process Step 3 – Applying the Indicator Selection Criteria



286
 287 *Figure 2: (Left) Candidate physical (top) and biological (bottom) ocean climate indicators included in the Indicator Survey.*
 288 *(Right) Additional candidate physical (top) and biological (bottom) ocean climate indicators suggested by the 48 Indicator*
 289 *Survey respondents.*

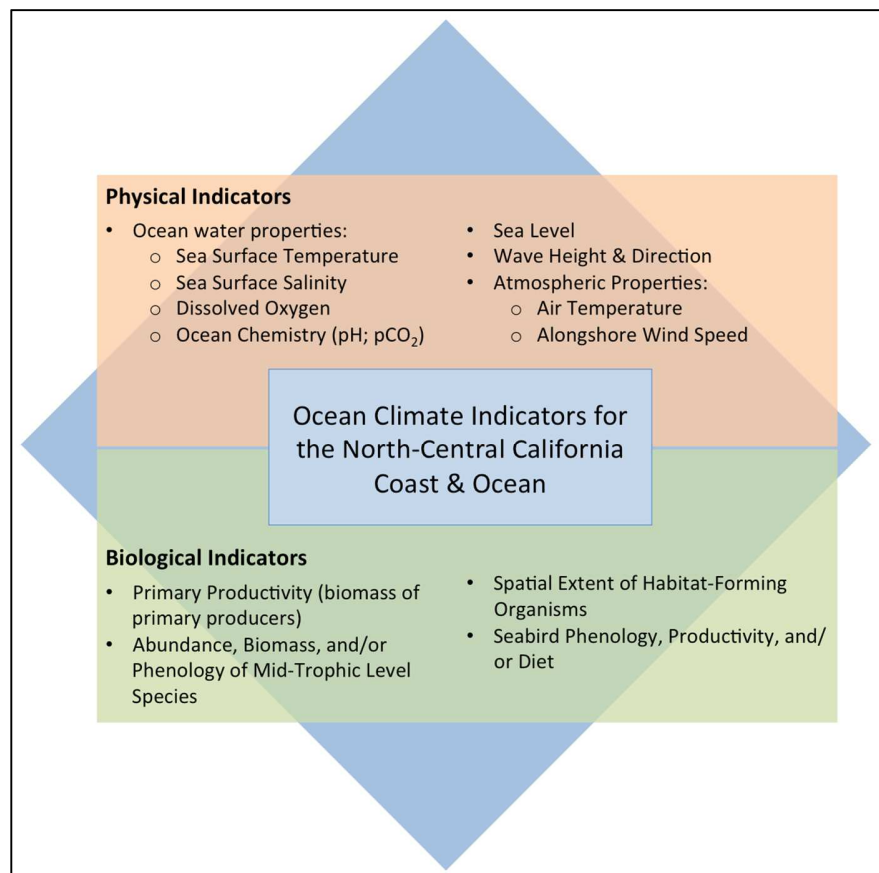
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291
 292 The project steering committee used the indicator selection criteria to reduce the large set of 91
 293 potential ocean climate indicators to a smaller set of 11 physical and 12 biological candidate indicators
 294 (Figure 2). The candidate indicators were then evaluated by 48 invited regional research scientists and
 295 managers from 26 academic institutions, NGOs, and federal and state agencies through an Indicator

296 Survey. These invited researchers and managers were specifically selected due to their expertise in the
297 study region.

298
299 The Indicator Survey assessed how well each candidate indicator met the selection criteria. Individuals
300 participating in the indicator selection survey came mostly from academia (15), NGOs (13), and federal
301 government (18), with fewer individuals from state government agencies (four) and private
302 organizations (one) also represented. The expertise of these individuals was balanced between physical
303 and biological components of the region's ecosystems and survey respondents were invited to self-
304 select whether they provided input on biological indicators, physical indicators, or both.

305
306 The Indicator Survey results (Figure 2), in turn, provided a starting point for discussions at a subsequent
307 Indicators Selection
308 Workshop where 36
309 experts, all of whom had
310 participated in the survey,
311 focused their efforts on
312 narrowing the list of
313 candidate indicators from
314 those that already had
315 broad support according to
316 the survey. At the
317 workshop, each of four
318 breakout groups created a
319 set of recommended
320 indicators. Breakout
321 groups considered a range
322 of criteria including ease of
323 measurement, cost, and
324 the ability to easily
325 interpret the results of
326 indicator monitoring. The
327 full group then discussed
328 each breakout group's
329 results, and any indicators
330 recommended by at least
331 three out of the four



332 breakout groups were
333 taken to be broadly
334 recommended and
335 adopted. The final list of
336 selected physical and biological indicators is provided in Figure 3. During the workshop, the GFNMS
337 Superintendent also provided management context for the project to help underscore the value of
338 participating in the indicator selection process.

Figure 2: Final adopted physical (top) and biological (bottom) ocean climate indicators for the North-central California coast and ocean.

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340 **2.2 Developing the Ocean Climate Indicators Monitoring Inventory and Plan**

341 **2.2.1 Formation of the Indicators Working Group**

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

349
350 The Indicators Working Group consisted of 13 regional scientists and managers who were previously
351 engaged in the project, including several members of the GFNMS Advisory Council and the project
352 steering committee. The GFNMS and CBNMS Superintendents also provided key expertise on sanctuary
353 priorities. Collectively, the working group members and supporting sanctuary staff had scientific
354 expertise on all of the ocean climate indicators, and represented state and federal agencies with
355 jurisdiction in the region.

356 357 **2.2.2 Process of the Indicators Working Group**

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

368 369 **3. Results**

370 **3.1 Ocean Climate Indicators**

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

376
377 The physical ocean climate indicators include: sea surface temperature; sea surface salinity; dissolved
378 oxygen; ocean chemistry (as measured through pH and pCO₂); sea level; wave height and direction; air
379 temperature; and alongshore wind speed (Figure 3). These indicators are intended to provide
380 information about changes in upwelling, water transport, habitat suitability, water quality, primary
381 productivity, runoff, nutrient content, and ocean acidification.

382
383 The biological ocean climate indicators include: primary productivity (particularly the biomass of primary
384 producers); the abundance, biomass, and/or phenology (e.g., timing of regular life events) of mid-
385 trophic level species; the spatial extent of habitat-forming organisms; and seabird phenology,
386 productivity, and/or diet (Figure 3). They are intended to provide information about the health of key
387 trophic levels in the food web, the potential for harmful algal blooms, changes in habitat availability, and
388 potential mismatches in species phenology. The Indicators Working Group later developed a set of focal
389 species for each of these biological ocean climate indicators (Figure 4). Because many of the indicators

390 may influence other properties or processes within the system (e.g., changes in sea surface temperature
391 can affect dissolved oxygen and primary productivity), considering all of the indicators is important to
392 establishing a more comprehensive picture of the presence and impacts of climate change in the region.
393

394 **3.2 Ocean Climate Indicators Monitoring Inventory and Plan**

395 The Monitoring Plan includes three main components: an overarching monitoring goal for the indicators
396 and objectives for the indicators to meet that goal; prioritized monitoring recommendations for each
397 indicator; and an inventory of existing monitoring activities for each indicator. Taken together, the
398 Monitoring Plan provides a road map for leveraging existing monitoring activities and prioritizing
399 potential future investments in new or expanded monitoring activities, to efficiently identify and
400 evaluate the impacts of climate change for each habitat in the study region. For each indicator, the
401 Monitoring Plan also includes information about the habitats in which it is most relevant, an overview of
402 measurement techniques recommended by the working group, and example case studies of how it can
403 be used by natural resource managers.
404

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

- 411 1. Determine the status and trends of ocean climate indicators in the region through existing
412 monitoring and by identifying the need and opportunity for new or expanded monitoring.
- 413 2. Assess the vulnerability of specific geographic areas, ecosystems, and ecosystem components
414 within the north-central California coast and ocean region to the impacts of climate change.
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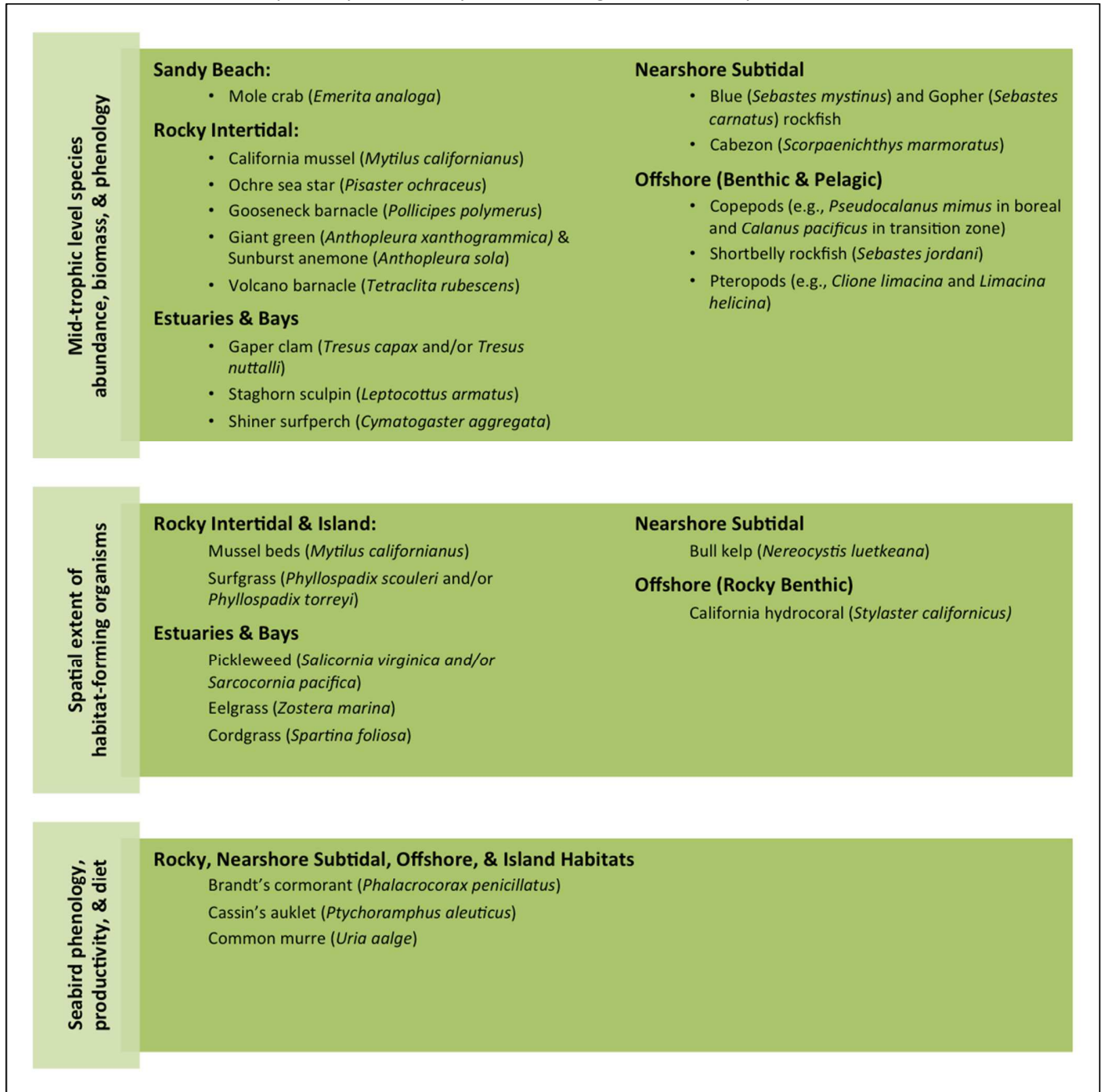
416 In addition, a significant part of the Indicators Working Group’s efforts involved developing monitoring
417 recommendations for each indicator in the Monitoring Plan. While these recommendations differed
418 among indicators, they primarily followed four key themes:

- 419 1. The importance of maintaining indicator monitoring that is already occurring, as this provides
420 scientists and managers with the ability to identify long-term changes in the region.
- 421 2. The utility of expanded and/or new indicator monitoring to fill information gaps.
- 422 3. The key role that the synthesis of existing regional research will play in optimizing monitoring by
423 identifying key indicators or locations.
- 424 4. The need for increased communication among federal, regional, and local government agencies
425 and other scientific organizations to share information, partners, and resources that will aid in
426 assessing and reducing their vulnerability to climate change.
427

428 These recommendations emphasize the importance of continued federal, state, and private investment
429 in monitoring to understand the impacts of climate change in the region. For each monitoring
430 recommendation, the working group also: (i) developed priority levels and the need for additional
431 funding and infrastructure to implement that recommendation; (ii) detailed existing gaps in data and
432 research; (iii) identified current and potential partners; and (iv) provided an estimated timeline for
433 implementation.
434

435 The biological indicators were designed as broad categories; because of this, the working group
436 identified “selected species” in key habitats for three of the four biological indicators using the BPJ
437 approach (Figure 4). “Selected species” were species for which there is a clear, scientifically accepted

438 mechanism for climate change to alter that species' distribution or abundance, and for which
 439 monitoring data is currently available in at least some of the region. The biological indicators are
 440 intended to be evaluated separately in each key habitat, using the selected species.



441
 442 *Figure 4: Selected species for biological ocean climate indicators, for each relevant key habitat within the study region.*

443 **NOTE: Color image for online only.**

444
 445 The working group also developed longer-term recommendations for the ocean climate indicators as a
 446 whole, including the development of a web-based indicator decision support tool that would provide a
 447 simple way for managers and scientists to access processed and interpreted indicator observations and
 448 projections for the region. Finally, the working group provided guidance for reviewing and updating the

449 Monitoring Plan on an annual and 5-year basis, which also involves updating the data sources for each
450 ocean climate indicator, and recommended convening a working group to evaluate the utility and
451 scientific relevance of existing and potential new ocean climate indicators.
452

453 The final Monitoring Plan was adopted by the GFNMS Advisory Council in 2013, and forwarded to
454 GFNMS management to consider how best to integrate its recommendations into the GFNMS
455 Management Plan (GFNMS, 2014) and the program areas of Research and Monitoring, Ecosystem
456 Protection, and Education and Outreach. The strong role that GFNMS played in the organization and
457 implementation of this project helped to ensure that the ocean climate indicators and the Monitoring
458 Plan were relevant to sanctuary management, and that they were presented in a way that maximized
459 their utility to the sanctuary (and to other managers). By convening scientists and managers together,
460 GFNMS ensured project results were scientifically rigorous, as well as applicable to GFNMS and
461 beneficial to other agency management decisions.
462

463 **4. Discussion & Conclusions**

464 The Ocean Climate Indicators Project resulted in the first integrated set of ocean climate indicators and
465 Monitoring Plan specifically developed on a regional scale for the north-central California coast and
466 ocean. Previous indicator development efforts focused on larger geographic scales (US EPA, 2016; Mazur
467 and Milanés, 2009; OEHHA, 2018) or extremely local scales (SFEP, 2011) that were not as directly
468 relevant to managers at GFNMS and elsewhere within the region. The project built upon the broad
469 support of an interdisciplinary group of over 50 regional research scientists and marine resource
470 managers from a range of state, and federal agencies, NGOs, and universities. It had a high level of
471 continued engagement from project partners, and it resulted in indicators that GFNMS is using in their
472 Climate-Smart Conservation Program.
473

474 The project was a novel application of the BPJ approach and the National Research Council's indicator
475 selection criteria (NRC, 2000). It can serve as a scalable model for other efforts to integrate science and
476 management in developing indicators that can be quickly utilized by natural resource managers in the
477 United States and internationally. BPJ approaches like the one described here can bring together the
478 perspectives of scientific, resource management, and community experts to integrate and reflect their
479 priorities and knowledge, all while strengthening connections in the context of environmental resource
480 management. The indicators themselves can also provide a good starting point for similar studies in
481 other regions around the world.
482

483 It is important to acknowledge that institutional buy-in was key to the process, as it enabled continued
484 participation of staff from a broad range of agencies, organizations, and universities. While the project
485 relied on a small number of dedicated, funded staff, the total hours invested among all project
486 participants was quite large. Workshop attendees spent at least 9 hours participating in the Indicator
487 Survey and the Indicator Selection Workshop, while members of the Indicators Working Group spent an
488 additional 25 hours participating in in-person meetings and webinars. These time estimates do not
489 include time spent on meeting preparation, document review, or transportation. In addition, monitoring
490 of all indicators would require substantial coordination of existing monitoring efforts identified in the
491 Monitoring Plan (Duncan et al., 2013) and investment in new ones. However, given the priority that
492 state and federal agencies have placed on understanding the impacts of climate change in the region,
493 there is motivation for cross-agency, cross-institution collaboration to use available data, where possible.
494

495 The scope of this project reflects what was possible within our limited funding and core staff resources.
496 For example, the project resulted in physical and biological indicators, and did not include development

497 of socioeconomic indicators. This conscious limiting of scope allowed us to explore physical and
498 biological indicators in greater detail than we otherwise would have, given the available resources.
499

500 In addition, the indicators were developed through a novel BPJ approach, rather than quantitative
501 assessment of potential indicators. As a result, there is no quantitative confirmation of the skill of these
502 indicators or of their relative importance. Additional resources would need to be secured to conduct a
503 quantitative analysis of the skill and value of these indicators, which could be incorporated as part of a
504 future review of the indicators and Monitoring Plan as recommended by the working group.
505

506 BPJ has been used in several other ecosystem and indicator assessments (Borja and Dauer, 2008;
507 Weisberg et al., 2008; Teixeira, 2010; Murray et al., 2017). Our BPJ approach built on existing research
508 by providing a structured process that was responsive to feedback and grounded in clearly-defined
509 questions (Burgman et al., 2011) in a way that was quicker and less constrained by the state of modeling
510 competency, and more inclusive of phenomena and opportunities (e.g., Weisberg et al., 2008; OST,
511 2013). A more quantitative/objective approach would likely have constrained the range of indicators
512 that could be considered. Our approach provided an opportunity to develop the indicators while
513 working with limited resources, and it supported increasing and continued engagement with the
514 agencies, universities, research institutions, and NGOs that participated in the indicator selection
515 process. It was also more inclusive of the broad range of physical and biological processes that affect the
516 region.
517

518 While the selected indicators may have been biased by the interests of the researchers and managers
519 who participated in this BPJ process, we believe that the large number of project participants from a
520 balanced range of organization types minimized this bias. Future iterations of this process could include
521 an increased number of state agencies to further diversify the range of organizations that were
522 represented. If additional financial and staff resources were available, we could also have pursued a
523 paired approach to indicator selection, using quantitative assessment of available indicator data to
524 inform the selection process.
525

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

528 1. Range of project participants: Because this work relies on a BPJ approach, it was essential that
529 the participating experts have a deep understanding of the region's coastal and ocean
530 environment, and that they represent a broad range of organization types. The project steering
531 committee was careful to include scientists who conducted physical and biological monitoring in
532 the region, who were both experts in their subject areas and also had a broad understanding of
533 the components and connectivity in the ecosystem. Including participants with this level of
534 expertise provided a scientifically-rigorous foundation for this BPJ process.
535

536 2. Engagement of high-level scientists and managers early in the project (including those in the
537 project steering committee) engendered trust from potential partners, encouraged robust
538 participation from a diverse group of physical and biological ocean experts and managers in the
539 region, and gave those experts ownership over the resulting ocean climate indicators. This was
540 particularly important because the project workshops were typically outside of the normal
541 working activities for most agencies. Still, managers at collaborating agencies felt it was
542 important to have representation at these workshops because of the potential long-term
543 benefits to their own natural resource management issues and priorities.

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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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597 **Declaration of Interest**

598 Declarations of interest: none.

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