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Developing a Social–Ecological–Environmental System Framework to Address Climate Change Impacts in the North Pacific

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"Forecasting and Understanding Trends, Uncertainty and Responses of North Pacific Marine Ecosystems" (FUTURE) is the flagship integrative Scientific Program undertaken by the member nations and affiliates of the North Pacific Marine Science Organization (PICES). A principal goal of FUTURE is to develop a framework for investigating interactions across disciplinary dimensions in order to most effectively understand large-scale ecosystem changes and resulting impacts on coastal communities. These interactions are complex, often nonlinear, occur across a range of spatial and temporal scales, and can complicate management approaches to shared and *trans*-boundary problems. Here, we present a Social–Ecological–Environmental Systems (SEES) framework to coordinate and integrate marine science within PICES. We demonstrate the application of this framework by applying it to four "crisis" case studies: (a) species alternation in the western North Pacific; (b) ecosystem impacts of an extreme heat wave in the eastern North Pacific; (c) jellyfish blooms in the western North Pacific; and (d) Pacific basin-scale warming and species distributional shifts. Our approach fosters a common transdisciplinary language and knowledge base across diverse expertise, providing the basis for developing better integrated end-to-end models. PICES provides the structure required to address these and other multi-national, inter-disciplinary issues we face in the North Pacific. An effective and comprehensive SEES approach is broadly applicable to understanding and maintaining resilient marine ecosystems within a changing climate.

Keywords: North Pacific, North Pacific Marine Science Organization, social–ecological systems, climate change, ocean sustainability

CHALLENGES IN CHARACTERIZING CHANGES IN THE NORTH PACIFIC

Long-term observations of physical and biological properties collected around the North Pacific, coupled with numerical simulations of coupled atmosphere-ocean-ecosystem phenomena, have improved understanding of the drivers of climate variability in the North Pacific and the consequent impacts on marine ecosystems. This body of research has highlighted patterns of climate variability associated with El Niño-Southern Oscillation (ENSO) at interannual scales (e.g., Doney et al., 2012) and the Pacific Decadal and the North Pacific Gyre Oscillations (PDO and NPGO, respectively; Mantua et al., 1997; Di Lorenzo et al., 2008) at decadal to multi-decadal scales. The influence of long-term anthropogenic climate change on the North Pacific basin is increasingly evident (Barange et al., 2016; Holsman et al., 2018). Further, coupled numerical models and continued observations have improved our understanding of the feedbacks and teleconnections among tropical ENSO events and PDO and NPGO patterns in the extratropical North Pacific (Di Lorenzo et al., 2013; Newman et al., 2016), and the sensitivity of such dynamics to anthropogenic climate change continues to stimulate new questions. The desire to understand the basin-scale climate and ocean dynamics, to predict variability in ocean conditions and the consequences of those processes for marine ecosystems and human society, and to communicate scientific understanding to decision makers and the public motivated the development of the intergovernmental North Pacific Marine Science Organization (PICES).

Our understanding of the principal drivers of large-scale climate variability in the North Pacific is quite mature (Box 1; Liu and Di Lorenzo, 2018). However, the mechanisms by which that variability impacts marine ecosystems, at both regional and basin scales and across multiple trophic levels, remains poorly understood. Furthermore, the ways in which human societies respond to these ecosystem fluctuations can be complex and inconsistent, depending on varying regional and national motives and contemporary concerns (Ommer et al., 2011). Interactions among social–ecological systems (SES; Berkes and Folke, 1998), occur across a range of spatial and temporal scales, contributing to the challenges in studying and managing these systems. In the face of a large-scale global driver like climate change, there is a community-wide goal to maintain resilient and sustainable ecosystems, requiring a more complete understanding of climate-driven impacts on marine ecosystems that can inform effective strategies of marine management and governance.

Here, we synthesize recent developments in understanding climate variability in the North Pacific, its ecosystem impacts, and how human societies affect, and are affected by, these environmental and ecological changes. Building from the SES framework, we review the concept of social–environmental–ecological systems (SEES), and describe how a SEES approach has been implemented within the PICES, through its flagship Science Program "Forecasting and Understanding Trends, Uncertainty and Responses of North Pacific Marine Ecosystems" (FUTURE)[1]. To illustrate how PICES addresses complex, multi-dimensional and multi-national issues in the North Pacific, we apply the SEES approach to four case studies in which specific climate drivers have resulted in ecosystem perturbations and responses within human societies. Finally, we review the lessons learned from PICES' approach to understanding climate-ecosystem-human interactions, and identify the key challenges remaining.

The goal of the PICES FUTURE Program is to "understand and forecast the responses of North Pacific marine ecosystems to both climate change and human activities, and to evaluate the capacity and resilience of these ecosystems to withstand perturbations" (PICES, 2016). Specifically, the principal objectives of FUTURE are to:

(1) Increase understanding of climatic and anthropogenic impacts and consequences on marine ecosystems, with continued leadership at the frontiers of marine science;
(2) Develop activities that include the interpretation, clarity of presentation, peer review, dissemination, and evaluation of ecosystem products (e.g., status reports, outlooks, forecasts).

To address objective (1), PICES has outlined a series of research questions (**Appendix 1**) that guide the work of Expert Groups (Sections, Working Groups, Study Groups and Advisory Panels)[2]. To address objective (2), PICES produces a number of products[3] aimed at communicating PICES science to a diverse audience, including the scientific community, marine resource management agencies within the member countries, other international marine science and management organizations (e.g., ICES, RFMOs), and the general public. Given its objectives and legacy of multi-disciplinary research on the North Pacific, PICES, and the FUTURE program in particular, are ideal candidates to explore the many changes taking place in the North Pacific within a SEES approach.

THE NORTH PACIFIC SOCIAL–ECOLOGICAL–ENVIRONMENTAL SYSTEM (SEES)

Largely as a result of the separation of ecological and social sciences in resource management issues (e.g., fisheries), natural and human systems have usually been considered as two separate entities in the marine realm (Berkes, 2011). In this concept, natural systems formed the template within which human systems operated (e.g., Park, 1936), and human systems were seen as drivers and recipients of change from the natural system. About 20 years ago, however, this view began to shift (driven by natural resource challenges and the inability of the previous model to provide lasting, meaningful solutions, e.g., Berkes and Folke, 1998)

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[1] https://meetings.pices.int/Members/Scientific-Programs/FUTURE
[2] http://meetings.pices.int/about/OrganizationStructure
[3] http://meetings.pices.int/publications

toward a concept of a fully coupled and interacting social–ecological system (Perry et al., 2010). Berkes (2011) notes that this concept recognizes the social (human) and ecological (biophysical) subsystems as two equally important parts, which function as a coupled, interdependent, and co-evolutionary system. As described by Berkes (2011, p. 12), "Human actions affect biophysical systems, biophysical factors affect human well-being, and humans in turn respond to these factors".

As the social–ecological system concept has evolved, it has expanded beyond its original common-pool resource management (mostly fisheries) origins. McGinnis and Ostrom (2014) describe how the initial focus involved resource users who extracted units from a resource system, and how these users maintained an overarching governance in the context of related ecological systems and the broader social, political, and economic setting. McGinnis and Ostrom (2014) further propose an expanded social–ecological system framework to guide analysts in many disciplines with studying similar sets of problems. This relies on addressing three questions:

(1) What is the focal level of analysis (e.g., what system, which actors, what governance regime)?
(2) What variables should be measured and how can indicators for these variables be developed and implemented?
(3) How can the results be communicated across diverse research (and management) communities?

PICES has further elaborated these three questions of this social–ecological systems concept to address a variety of coupled marine social and ecological changes in the North Pacific. In particular, PICES has explicitly identified the climate system and its effects on the physico–chemical ocean environment, as necessary to fully understand current changes taking place within the North Pacific, and expressed this as a coupled social–ecological–environmental system (SEES).

The PICES implementation of a North Pacific SEES was designed to identify and understand the linkages between climate forcing, oceanic processes, marine ecosystem responses (at multiple trophic levels and spatial scales), and the human system (**Figure 1**). Within the climate system, we aim to understand the modes of climate variability and change on the basin scale, and how this climate forcing downscales to the coastal domain and to regional scales, which are relevant for the management of marine resources. These climate drivers subsequently impact physical, chemical, and biological processes across a range of spatial and temporal scales, which can collectively affect the functioning and ultimately resilience of marine ecosystems. Climate-driven impacts on the ecosystem can occur at all trophic levels and can alter habitats, species-specific functional responses and population and community structure. At the ecosystem level, these changes can alter overall resilience and shift key thresholds (i.e., tipping points) and ecosystem reference points that are critical for effective management. Thus human societies, which rely heavily on the ecosystem services provided by the ocean, are often negatively impacted by these ecosystem fluctuations. Human activities (e.g., fisheries and aquaculture, shipping) also contribute multiple stressors back onto the ocean and its ecosystems (e.g., harmful algal blooms, invasive species, noise and pollution), thereby linking the human system back to the environmental and ecological dimensions. Finally, to better understand how each of the SEES dimensions varies and interacts requires adequate monitoring and assessment of all of its components, and the subsequent dissemination of data and products.

Within PICES, this SEES approach for the North Pacific accomplishes three goals: (a) it provides a roadmap for initiating interactions amongst PICES Expert Groups and for developing products to fulfill FUTURE's objectives; (b) it identifies critical knowledge gaps that PICES might address through the creation of new Expert Groups; and (c) it facilitates a holistic understanding of how large-scale climate variability and change impacts oceanic and ecosystem processes, and how human societies can manage, mitigate, benefit from, and/or adapt to these changes.

UNDERSTANDING AND SOLUTIONS THROUGH A SEES APPROACH: CASE STUDIES

The SEES approach relies on "embracing reciprocal links among people and nature, and harnessing knowledge from the natural and social sciences" (H. Leslie, pers. comm.; Leslie, 2018). In the North Pacific, PICES has implemented a SEES framework to facilitate bridging scales between local communities and basin scale dynamics, and to better understand complex dynamics that impact its coastal communities (i.e., within member nations). To demonstrate the robustness and utility of this approach, we applied the SEES concept to four "crisis" case studies in the North Pacific.

Case Study 1: Species Alternation in the Western Pacific

Fish species alternation is a classic example of an ecosystem regime shift response to climate change (Alheit and Bakun, 2010). Such an alternation occurred in the western North Pacific following the climate regime shift of 1988–1989 (Zhang et al., 2007; **Figure 2**). The Japanese sardine (*Sardinops melanostictus*) stock was at historic highs (>20 million tons) in the mid-1980s and showed a rapid and continuous decline after 1988 to a level of<1 million tons by the mid-1990s. In the winter of 1982–1983, an altered wind field in the eastern North Pacific induced positive sea surface height anomalies (+SSHA) in the region, which subsequently propagated westward as a Rossby wave (Nonaka et al., 2006) ①. The +SSHA reached the Kuroshio Extension region in 1988, resulting in increased wintertime sea surface temperatures (SST) as the mixed layer depth shoaled (Nishikawa and Yasuda, 2008) ②. These changes in the physical properties in the Kuroshio Extension, the nursery ground of larval and juvenile Japanese sardine, subsequently reduced and changed the timing of regional primary production. The timing of the spring bloom after 1988 was up to 2 months earlier

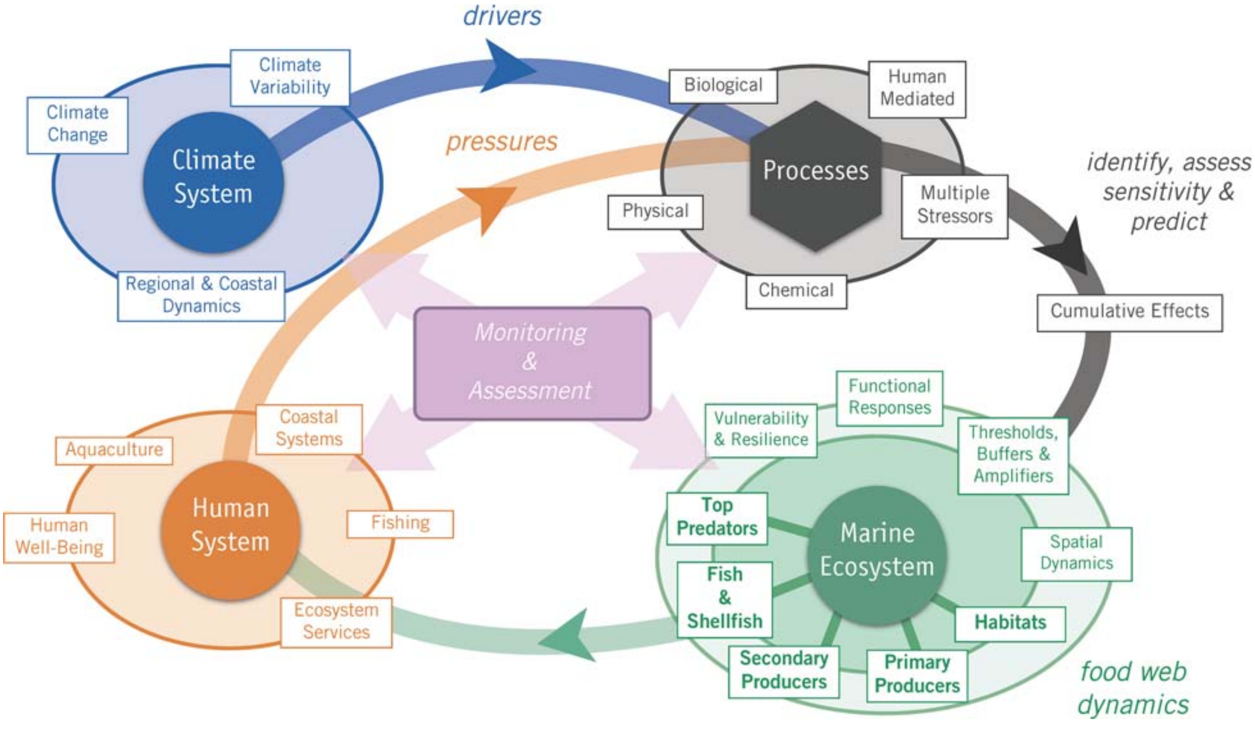

FIGURE 1 | The North Pacific Social–Ecological–Environmental System (FUTURE schematic).

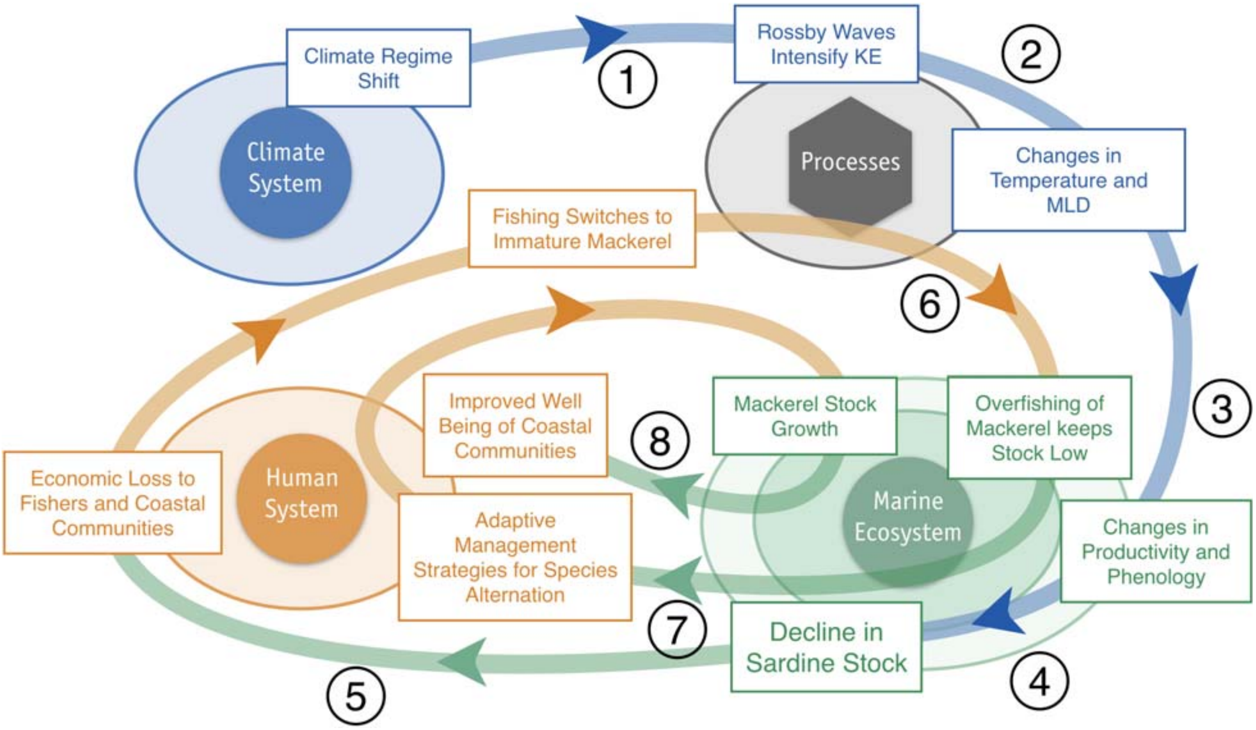

FIGURE 2 | FUTURE SEES case study 1: Species alternation in the western Pacific.

than before (Nishikawa et al., 2011) ③. As a result, Japanese sardine recruitment decreased due to a mismatch between the peak of prey production (February) and the arrival of larval and juvenile sardine (April) ④. By the mid-1990s the stock had collapsed.

Purse seiners and local communities suffered economic losses from the collapse of the Japanese sardine stock ⑤. Most purse seiners had invested in large-scale vessels through the late 1980s, and were unable to pay off loans on those vessels when the sardine catch declined. Local communities also suffered economically because of the small amount of sardine landings used as raw materials for processing. To avoid bankruptcy, purse seiners switched their target catch to immature chub mackerel (*Scomber japonicus*), eventually leading to the overfishing of this stock in the 1990s (Makino, 2011) ⑥. Although there were several strong year classes of chub mackerel during this period, overfishing occurred and resulted in recruitment failure of the spawning population (3 + years) and a drop to low stock levels.

To address these issues, the national government of Japan introduced a "total allowable catch" in 1997, setting an upper limit on chub mackerel total catch. In addition, to protect the strong year classes, the government and purse seiners cooperatively introduced the "Resource Recovery Plan" in 2003 which adaptively controls fishing pressure on immature chub mackerel when a strong year class occurs (Makino, 2018) ⑦. Since adoption of this plan, several strong year classes have been protected thereby allowing the chub mackerel stock to increase to sustainable levels (Yukami et al., 2017). Overall, the economic situation of these Japanese purse seiners and the well-being of their coastal communities have been improved ⑧.

Since these fish species alternations were induced by natural climate variability, it is expected that the regional chub mackerel stock may decline in the future, being replaced by an increasing sardine stock. However, an increased understanding of the dynamics associated with these alternations, from climate regime shifts to fisher behavior and the effects of both governmental and industry interventions, provides an important basis for understanding future changes. Continued monitoring of the physical (environmental) conditions, plankton production and phenology, and larval fish survival in this region will be essential to identify ecosystem change and inform adaptive management strategies for coastal fishers.

Case Study 2: Ecosystem Impact of a Marine Heat Wave in the Eastern Pacific

The northeast Pacific Ocean experienced highly anomalous atmospheric and oceanic conditions during 2014–2016, which was accompanied by significant ecosystem disruptions along the North American West Coast (**Figure 3**). A large warm temperature anomaly (nicknamed "The Blob") developed in the upper ocean during fall 2013, and spread through much of the Gulf of Alaska during the winter of 2013–2014, reaching record-breaking SST anomalies (> 3 SD; Bond et al., 2015; Di Lorenzo and Mantua, 2016; Hobday et al., 2018) ①. The anomaly persisted through the winters of 2014–2015 and 2015–2016, with warm SST anomalies reaching the west coast of North America in spring and summer 2014 and extending from Alaska to Baja California by spring 2015 (Kintisch, 2015; Di Lorenzo and Mantua, 2016).

As these warm near-surface waters were advected to and impacted coastal waters, the enhanced vertical stratification reduced the efficacy of coastal upwelling to supply nutrients to the euphotic zone which negatively impacted coastal productivity ②. The combination of reduced primary productivity and the presence and persistence of unusually warm waters led to significant disruptions in the California Current ecosystem (Cavole et al., 2016), including reduced phytoplankton abundance and production (Du and Peterson, 2018; Gómez-Ocampo et al., 2018), a coastwide toxic algal bloom (McCabe et al., 2016; Ryan et al., 2017), reduced biomass of copepods and euphausiids and high abundance of oligotrophic doliolids (Peterson et al., 2017), the massive mortality of a planktivorous seabird (Jones et al., 2018), and substantial changes in species distributions and community composition across multiple trophic levels (Cavole et al., 2016; Santora et al., 2017; Brodeur et al., 2019) ③.

These ecosystem disruptions had immediate and profound impacts on the human communities that rely on the marine resources of the California Current. The harmful algal bloom led to the closure of lucrative salmon fisheries and changes in the timing of crab fisheries (Cavole et al., 2016) ④. These changes led to disproportionate negative impacts on small-scale fishers and subsequent economic loss to their coastal communities (McCabe et al., 2016) ⑤. The anomalous conditions led to a particularly unfortunate convergence of circumstances leading to higher whale mortality. While the HAB event delayed the opening of the crab fishery, the anomalously warm conditions within the California Current led to a higher proportion of anchovies, a key forage fish, to inhabit nearshore regions where crab pots are typically deployed. Humpback whales, which migrate through the region, foraged further inshore for anchovies just as the crab fishery was opened, leading to a higher number of whale entanglements and mortalities (NOAA Fisheries, 2017) ⑥.

There were important management actions taken to respond to this unprecedented situation. Fishers made requests for a disaster declaration (McCabe et al., 2016), and both State and Federal agencies set up committees of managers, scientists, fishers and NGO representatives to develop adaptive management strategies ⑦. There were changes in marine spatial planning, and an NGO provided funds to the fishing community to pay for removal of derelict fishing gear ⑧. Although the ecosystem response to this large marine heat wave was unanticipated, the human response was relatively quick and likely mitigated some of the more significant negative impacts. Extreme events such as this are projected to become more frequent with climate change (Sydeman et al., 2013; Froelicher et al., 2018), suggesting that a SEES approach such as that applied here can confer resiliency to the human communities that depend on the sea. In particular, monitoring environmental and ecosystem

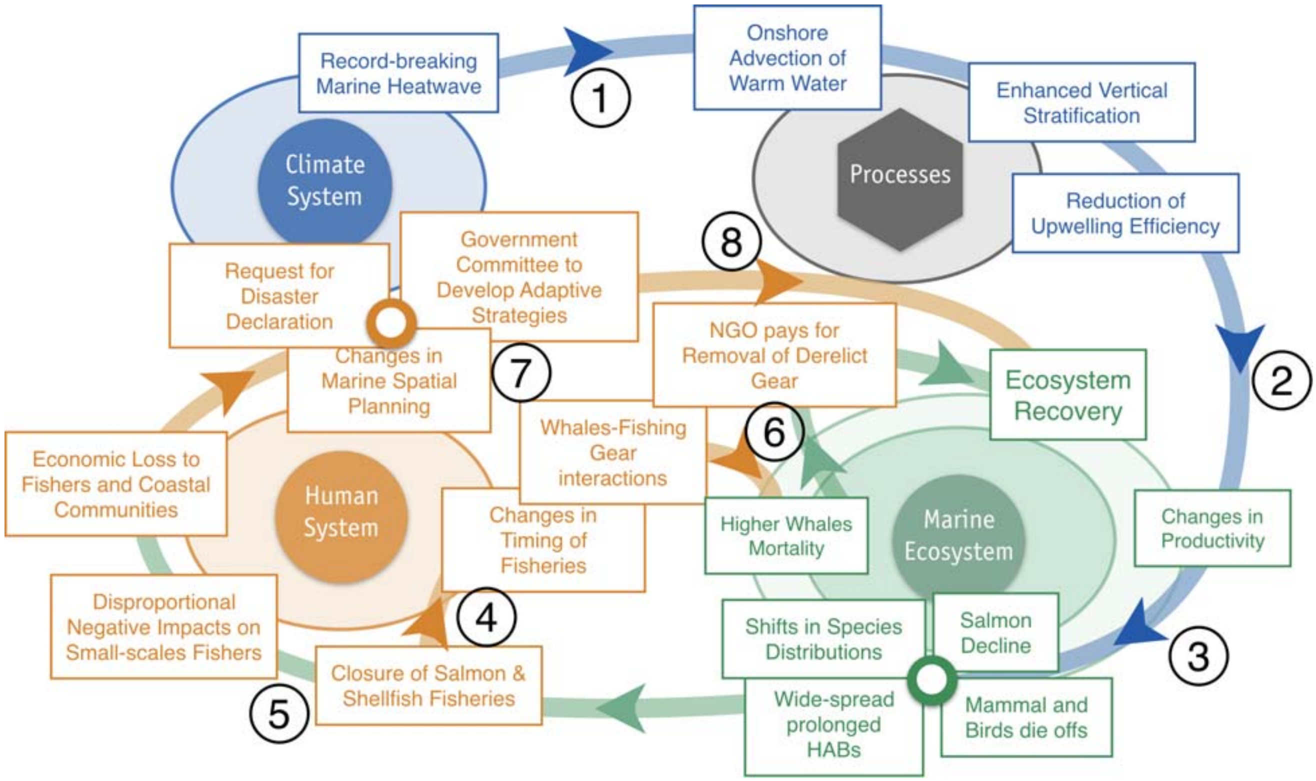

FIGURE 3 | FUTURE SEES case study 2: Ecosystem impact of a marine heat wave in the eastern Pacific.

conditions at sufficient spatial and temporal resolution, as well as human interactions with the ecosystem, will allow relevant stakeholders to respond more efficiently to large-scale perturbations such as these.

Case Study 3: Jellyfish Blooms in the Western Pacific

Coastal marine ecosystems are exposed to multiple anthropogenic stressors that can degrade the ecosystem services in unexpected ways. One such example is large-scale jellyfish blooms which cause economic losses to fishers and coastal communities. These blooms often decrease fish stock biomass, value, and marine recreation while increasing the costs associated with preventing clogging of cooling pipes, including power generating facilities (Uye and Brodeur, 2017). A number of human activities related to coastal development can promote the survival of jellyfish in their early life stages, particularly with newly developed platforms and coastal infrastructure providing more substrate (habitat) for polyp settlement and survival (Duarte et al., 2013; Makabe et al., 2014; **Figure 4**) ①. Eutrophication allows for higher abundances of microzooplankton which are prey for both benthic polyps and planktonic ephyrae, and the resultant hypoxia eliminates predators of polyps while the polyps themselves can tolerate these low oxygen conditions ②. Fishing pressure (pathway #3 in **Figure 4**) can also eliminate predators of ephyrae and small medusae (Shoji, 2008) ③. Finally, a winter warming trend observed in the western North Pacific can accelerate asexual reproduction and polyp growth (Han and Uye, 2010) ④.

These anthropogenically driven environmental changes collectively contribute to an increase in the abundance of jellyfish (Purcell et al., 2007; Richardson et al., 2009). Jellyfish feed on fish larvae and mesozooplankton, which are an important prey for fish and a predator of microzooplankton, so subsequent declines in fish are beneficial for the survival of polyps, ephyrae and medusae – a positive feedback referred to as the "jellyfish spiral" (Uye, 2011). Large jellyfish blooms have occurred more frequently in the western North Pacific in recent years, affecting coastal activities in a number of countries including Japan and the Republic of Korea (**Figure 4**). Blooms of the giant jellyfish *Nemopilema nomurai* occurred frequently after 2000 in the marginal seas of the western North Pacific (Uye, 2008), resulting in substantial economic losses to fishers and coastal communities ⑤. The impact was especially serious for coastal fishers because the presence of giant jellyfish impeded the catch of commercially valuable fish species and decreased fish prices due to reduced catch quality. In response to these blooms, a collaborative international monitoring program was established (Uye and Brodeur, 2017). This program has allowed the size of jellyfish blooms, and their dispersal by ocean currents, to be monitored (Xu et al., 2013; Sun et al., 2015) ⑥. Based on these observations and model simulations, it is now possible to provide early warnings of jellyfish blooms (magnitude, timing) to the fishing community and other stakeholders

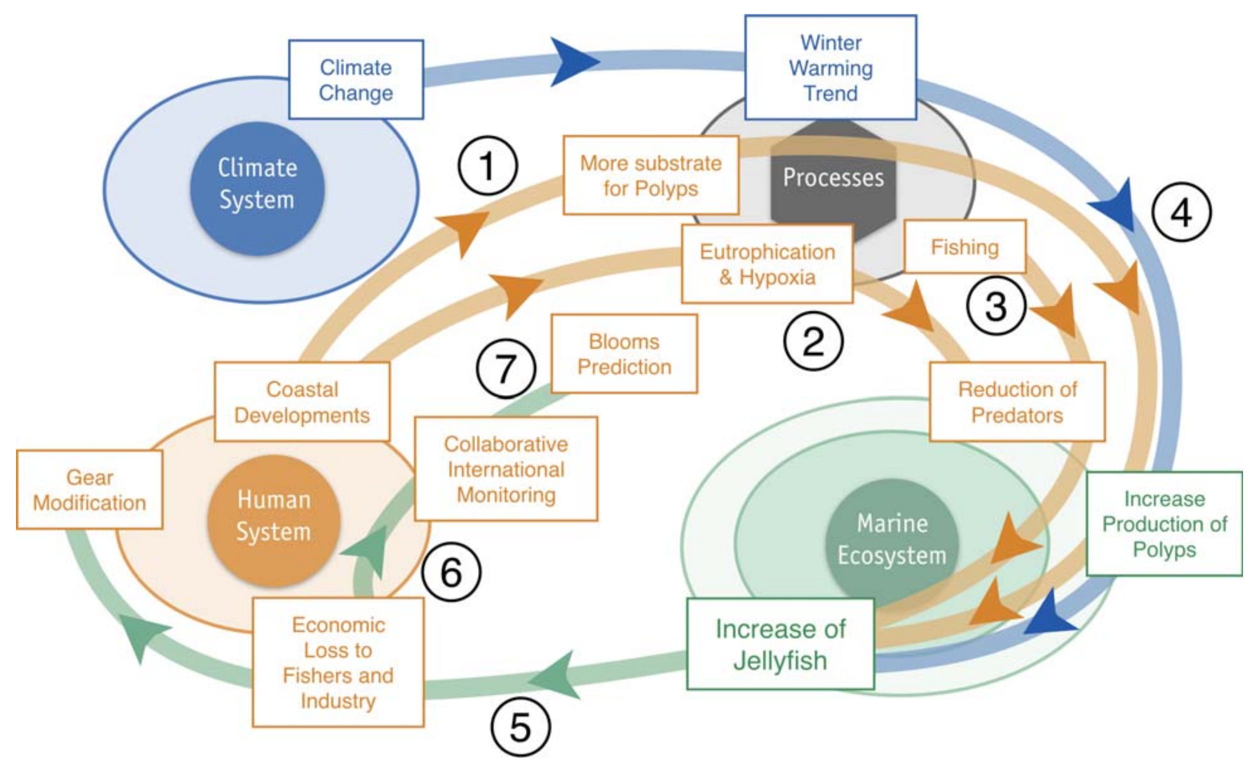

FIGURE 4 | FUTURE SEES case study 3: Jellyfish blooms in the western Pacific.

(Uye, 2014) ⑦. These forecasts are based on early-summer on-deck sightings of young medusae from ferries, allowing fishermen to prepare countermeasures in anticipation of potential jellyfish blooms.

Case Study 4: Warming and Distributional Shifts in Highly Migratory Species

Climate models project a warming of sea surface temperatures of up to 3°C in the North Pacific by the end of the 21st century (Woodworth-Jefcoats et al., 2017) ①. In response to this basin-scale warming, many pelagic fish species are expected to shift their migratory patterns and distributions, both due to physiological constraints and changes in prey distribution (Cheung et al., 2015; Woodworth-Jefcoats et al., 2017; **Figure 5**) ②. In particular, species such as bluefin, yellowfin and albacore tuna are likely to shift their centers of distribution poleward to maintain an optimal thermal environment and to follow shifting prey populations (Hazen et al., 2013) ③. Indeed, during the recent extreme marine heat wave in the eastern North Pacific in 2014–2015, bluefin tuna were observed well north of their typical range, fostering robust recreational fishing opportunities off northern California and Oregon that extended into Washington and British Columbia (Cavole et al., 2016).

These distributional shifts, especially of top predators, will lead to profound changes in the abundance (and possibly distribution) of commercially important fish species that are available to local fishing communities ④, potentially leading to loss of revenue and disruptions in the efficacy of fisheries management protocols (e.g., Pinsky and Fogarty, 2012). Fishing communities that are reliant on particular stocks may face substantial hurdles, as fishing trips increase in distance and expense, and may even cross jurisdictional boundaries. Further, as new species begin to inhabit local waters, they could face over-exploitation if there are insufficient management policies in place to account for the new ecosystem structure. Regardless of how the ecosystem is altered, there will be winners and losers, both in terms of the dominance of particular species and the fishing communities that may or may not be able to adequately respond to these changes (e.g., McIlgorm et al., 2010; Perry et al., 2011) ⑤.

These climate-induced changes in species distribution (e.g., Humboldt squid in the Northeast Pacific; Stewart et al., 2014) raise important policy and management issues. Within the coastal boundaries of the North Pacific, negotiations will be required to sustainably manage *trans*-boundary stocks, especially for emerging *trans*-boundary species. For example, there are negotiations underway between Canada, The United States and Mexico to adapt existing policy and management options to shifting sardine distributions. Similar negotiations are underway between Canada and The United States to consider the poleward shift of albacore tuna populations. In waters beyond national jurisdictions, Regional Fishery Management Organizations (RFMOs, such as the recently established North Pacific Fisheries Commission) will need to account for projected distributional shifts as new policy, regulations and management considerations

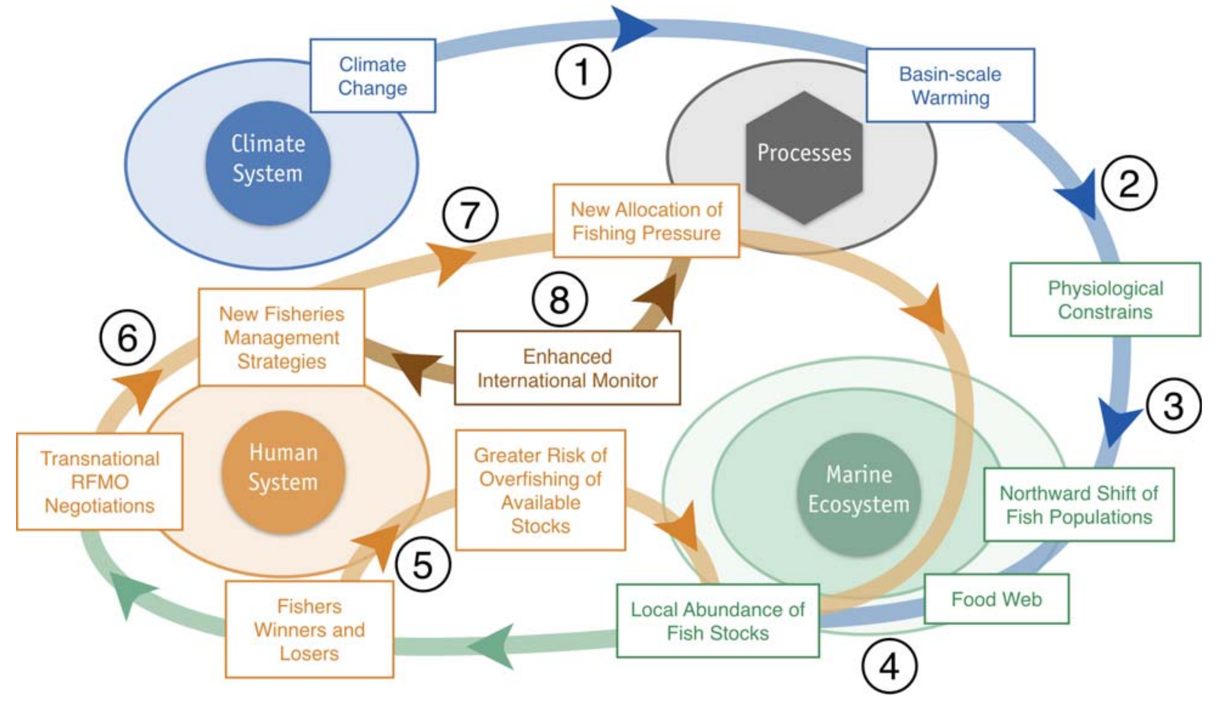

FIGURE 5 | FUTURE SEES case study 4: Warming and distributional shifts in highly migratory species.

are developed ⑥. These new climate-informed management strategies will open new fishing opportunities to nations that fish the North Pacific ⑦. Any efforts to adaptively respond to distributional shifts will also require enhanced monitoring and assessment of the ecosystem, both regionally and basin-wide, which in turn will require international cooperation ⑧. The SEES framework applied here could be instrumental in understanding and forecasting potential interconnections between social and ecological systems.

LESSONS LEARNED AND NEW CHALLENGES

We have implemented a Social–Ecological–Environmental framework to address critical issues of relevance to nations that share North Pacific marine resources, specifically the member nations of PICES, with a focus on climate- and human-induced ecosystem changes that impact coastal communities. This approach has increased capacity for PICES to understand and communicate the processes that link climate variability and change to multi-trophic, multi-scale ecosystem responses, and to more effectively develop strategies to mitigate negative impacts on both our ecosystems and the human communities that depend upon them. PICES has used this approach to identify key linkages (between individual scientists, national and international organizations, and research projects) for enhanced collaborative research, as well as to identify important gaps in research and communication that require attention. Within PICES, our SEES approach has led to the creation of several new multi-national Working Groups that are addressing issues of particular concern, including one comparing thresholds of ecosystem responses within national Exclusive Economic Zones and another aimed at improving short- (seasonal) to long-term (decadal) ecological forecasting[4] on both coastal and basin-wide scales.

We demonstrated our SEES approach by describing the cross-disciplinary linkages associated with four important issues affecting PICES member nations (**Figures 2–5**). Working through these examples has allowed PICES to better address these issues by strengthening communication pathways and focusing limited resources on shared problems, and paves the way for developing end-to-end (physics to humans) models of the system. Although we chose these case studies based on our collective knowledge of the issues, the approach could also be applied in anticipation of other climate-induced impacts (e.g., effects of increased ocean acidification or declining oxygen levels) as well as anthropogenically driven stressor-response cases beyond those associated with climate (e.g., an oil spill, coastal development, etc.). This approach is broadly applicable to other inter-governmental organizations whose mandate is to address issues that transcend national and traditional disciplinary boundaries. A key challenge will be to develop effective means to translate the products of our SEES framework – an improved understanding of the linkages between the climate system, the marine ecosystem, and human communities – to the managers and stakeholders tasked with preparing society for the forthcoming changes.

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[4] https://meetings.pices.int/members/working-groups

DATA AVAILABILITY

No datasets were generated or analyzed for this study.

AUTHOR CONTRIBUTIONS

All authors conceived the manuscript as part of the activities of the PICES FUTURE Scientific Steering Committee. SB wrote the article with contributions from EDL, RP, RR, MM, HS, and TT. All authors provided the edits and comments to the manuscript. EDL developed the FUTURE and case study schematics.

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APPENDIX 1: FUTURE SCIENCE RESEARCH THEMES

(1) What determines an ecosystem's intrinsic resilience and vulnerability to natural and anthropogenic forcing?

    (1.1) What are the important physical, chemical and biological processes that underlie the structure and function of ecosystems?
    (1.2) How might changing physical, chemical and biological processes cause alterations to ecosystem structure and function?
    (1.3) How do changes in ecosystem structure1 affect the relationships between ecosystem components?
    (1.4) How might changes in ecosystem structure and function affect an ecosystem's resilience or vulnerability to natural and anthropogenic forcing?
    (1.5) What thresholds, buffers and amplifiers are associated with maintaining ecosystem resilience?
    (1.6) What do the answers to the above sub-questions imply about the ability to predict future states of ecosystems and how they might respond to natural and anthropogenic forcing?

(2) How do ecosystems respond to natural and anthropogenic forcing, and how might they change in the future?

    (2.1) How has the important physical, chemical and biological processes changed, how are they changing, and how might they change as a result of climate change and human activities?
    (2.2) What factors might be mediating changes in the physical, chemical and biological processes?
    (2.3) How does physical forcing, including climate variability and climate change, affect the processes underlying ecosystem structure and function?
    (2.4) How do human uses of marine resources affect the processes underlying ecosystem structure and function?
    (2.5) How are human uses of marine resources affected by changes in ecosystem structure and function?
    (2.6) How can understanding of these ecosystem processes and relationships, as addressed in the preceding sub-questions, be used to forecast ecosystem response?
    (2.7) What are the consequences of projected climate changes for the ecosystems and their goods and services?

(3) How do human activities affect coastal ecosystems and how are societies affected by changes in these ecosystems?

    (3.1) What are the dominant anthropogenic pressures in coastal marine ecosystems and how are they changing?
    (3.2) How are these anthropogenic pressures and climate forcings, including sea level rise, affecting nearshore and coastal ecosystems and their interactions with offshore and terrestrial systems?
    (3.3) How do multiple anthropogenic stressors interact to alter the structure and function of the systems, and what are the cumulative effects?
    (3.4) What will be the consequences of projected coastal ecosystem changes and what is the predictability and uncertainty of forecasted changes?
    (3.5) How can we effectively use our understanding of coastal ecosystem processes and mechanisms to identify the nature and causes of ecosystem changes and to develop strategies for sustainable use?