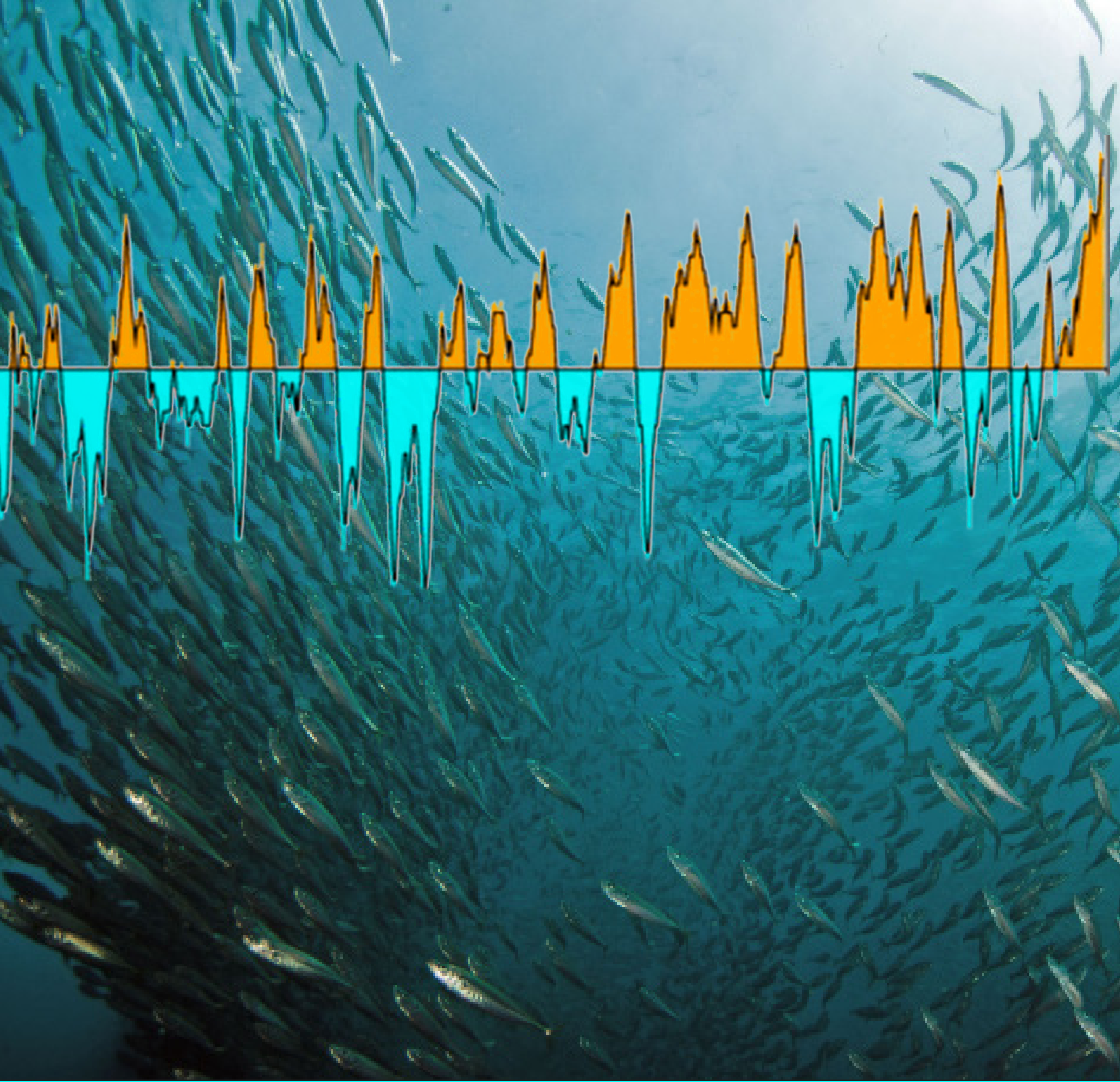

FORECASTING ENSO IMPACTS ON MARINE ECOSYSTEMS OF THE US WEST COAST

A Joint US CLIVAR and OCB Workshop
August 10-11, 2016
San Diego, California

FORECASTING ENSO IMPACTS ON MARINE ECOSYSTEMS OF THE US WEST COAST

Workshop Report

Prepared by:
Emanuele Di Lorenzo (Georgia Tech, co-chair)
Art Miller (University of California, San Diego/Scripps Institution of Oceanography, co-chair)
Clarissa Anderson (University of California, Santa Cruz)
Kris Karnauskas (University of Colorado)
Julie Keister (University of Washington)
Nate Mantua (NOAA Pacific Marine Environment Laboratory)
Mark Ohman (University of California, San Diego/Scripps Institution of Oceanography)
Aneesh Subramanian (Oxford University)

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EDITORS

Heather Benway (OCB), Mike Patterson (US CLIVAR), Kristan Uhlenbrock (US CLIVAR)

BACK COVER IMAGE

Group photo of workshop participants (Credit: Kristan Uhlenbrock)

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EXECUTIVE SUMMARY & CHALLENGES

The El Niño-Southern Oscillation (ENSO) has clear and predictable impacts on the physics, biology, and chemistry of the US West Coast eastern boundary upwelling system - one of the most productive marine ecosystems in the world and is a primary source of ecosystem services for the US (e.g., fishing, shipping, and recreation).

A collaborative and interdisciplinary workshop on "Forecasting ENSO impacts on marine ecosystems of the US West Coast" in August 2016 in La Jolla convened scientists and managers with expertise on the topic from the US Climate Variability and Predictability (CLIVAR), Ocean Carbon Biogeochemistry (OCB), National Oceanic and Atmospheric Administration (NOAA) Fisheries, North Pacific Marine Science Organization (PICES), and International Council for the Exploration of the Seas (ICES) communities.

The goal of this workshop was to develop a strategy for connecting ENSO physical climate forecasts to marine ecosystem forecasts along the US West Coast, in particular the California Current System (CCS).

The CCS marine ecosystem response to ENSO has been well-observed and documented since the early 1950s with a rich set of physical, biological, chemical, and fisheries data collected systematically. This record provides an understanding of the ENSO-related ecosystem drivers in this region (e.g., changes in sea surface temperature (SST), upwelling, alongshore and cross-shore transport, productivity, oxygen, and pH). A combination of different drivers control key biotic ecosystem indicators or specific marine populations (e.g., zooplankton, krill, squid), which can be targeted for forecasting. The selection of biotic indicators depends on the needs and interests of local stakeholders and managers, and is an area that needs further attention and a broader engagement beyond the science community.

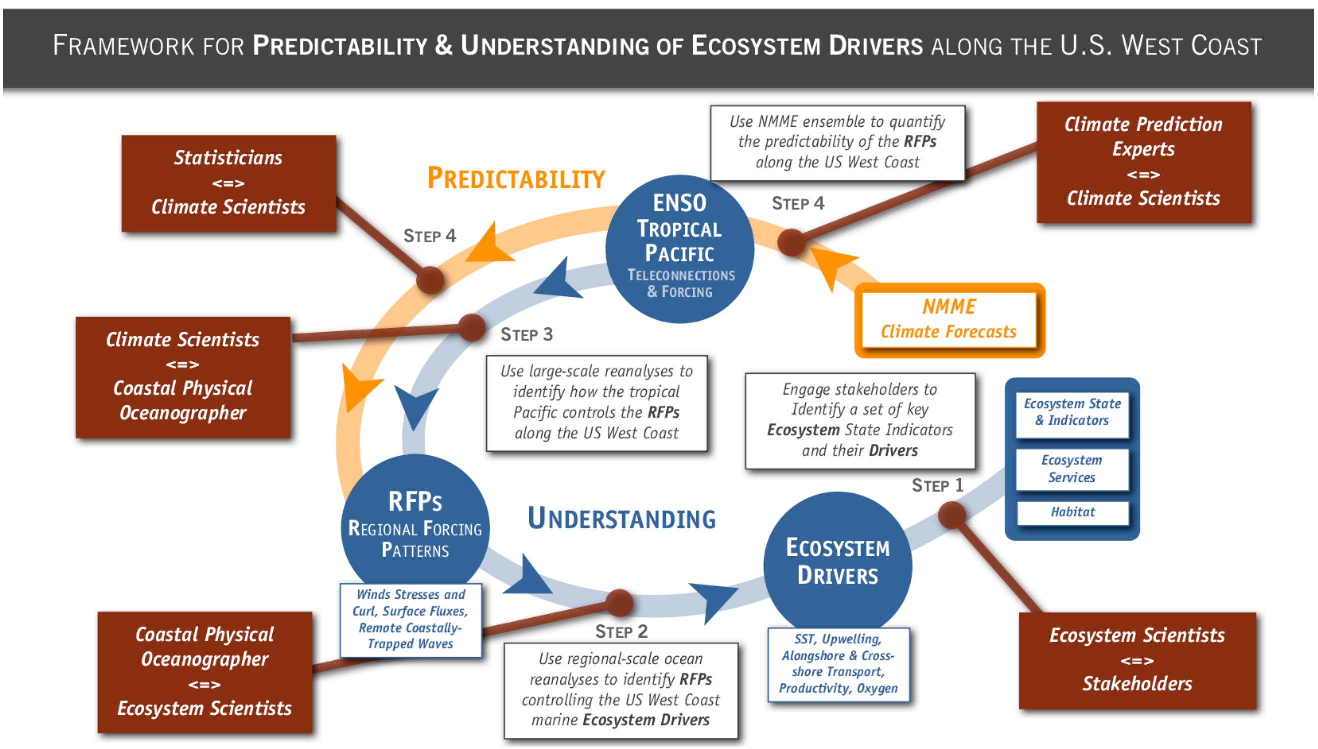
Given the key role that known marine ecosystem drivers play in the management of marine ecosystems and the services they provide, we have outlined a four-step strategy to better understand and quantify the ENSO-related predictability of marine ecosystems along the US West Coast (Schematic 1), including the physical drivers of the marine ecosystem and the biotic responses to these drivers.

1. Engage stakeholders to identify a set of key ecosystem state indicators (e.g., primary production, krill or copepod abundance, market squid biomass, kelp forest biomass) that are relevant for management and monitoring, and their drivers such as changes in sea surface temperatures (SSTs), upwelling, alongshore & cross-shore transport, and oxygen.
2. Use a high-resolution ocean reanalysis to determine the association between local ecosystem drivers and regional forcing patterns (RFPs) (e.g., wind stress and curl, surface fluxes, remote coastally trapped waves) and local ecosystem drivers.

3. Objectively identify the tropical SST and related patterns that optimally force the RFPs along the US West Coast region, using available long-term, large-scale reanalysis products.
4. Quantify the predictability of the RFPs, and estimate their prediction skill at seasonal, interannual, and decadal timescales.

While the goal of steps 1-3 is to understand the dynamic basis for predictability (blue path in Schematic 1), step 4 aims to quantify the predictability of the RFPs (orange path in Schematic 1), and can be implemented using the output of multi-model ensemble forecasts such as the North America Multi-Model Ensemble (NMME) or by building efficient statistical prediction models. Quantitative analysis and modeling of biological responses to physical drivers, and dependence upon biotic initial conditions, will be pursued concurrently with the development of the physical forecast framework and will include the additional tasks:

1. Develop quantitative relationships between selected ecosystem indicators and key physical drivers.
2. Embed these relationships into coupled biophysical models, focusing on regions within the CCS, where empirical validation data are available.
3. Develop diagnostic metrics for biotic initial conditions (e.g., predator/prey populations) that will strongly influence the outcome of forecast models.



Schematic 1. ***Framework for understanding and predicting ENSO impacts on ecosystem drivers***. *Blue path shows the steps that will lead to **Understanding** of the ecosystem drivers and their dependence on tropical Pacific anomalies. Orange path shows the steps that will lead to quantifying the **Predictability** of marine ecosystem drivers along the US West Coast that are predictable from large-scale tropical teleconnection dynamics.*

Breaking down the ecosystem prediction effort in a multi-step approach enables different layers of engagement and collaboration of a diverse set of experts that includes climate scientists, statistician and prediction experts, coastal physical oceanographers, marine ecologists, stakeholders, and managers (red panels in Schematic 1). A more detailed explanation of this strategy and framework is contained in Section 3.

The implementation of this coupled biophysical forecast framework will provide the basis for conducting experimental forecasts in conjunction with existing efforts through the US West Coast coastal ocean observing network, which already possesses key observational and modeling infrastructure in some regions. Accelerated interaction among physical, biological, and chemical oceanographers will facilitate quantitative descriptions of key processes and mechanisms, through which the drivers lead to defined responses in marine ecosystem processes and key populations. Such efforts should leverage the existing Long Term Ecological Research (LTER) sites, NOAA regional observing networks, and other existing observational and modeling programs focused on the US West Coast.

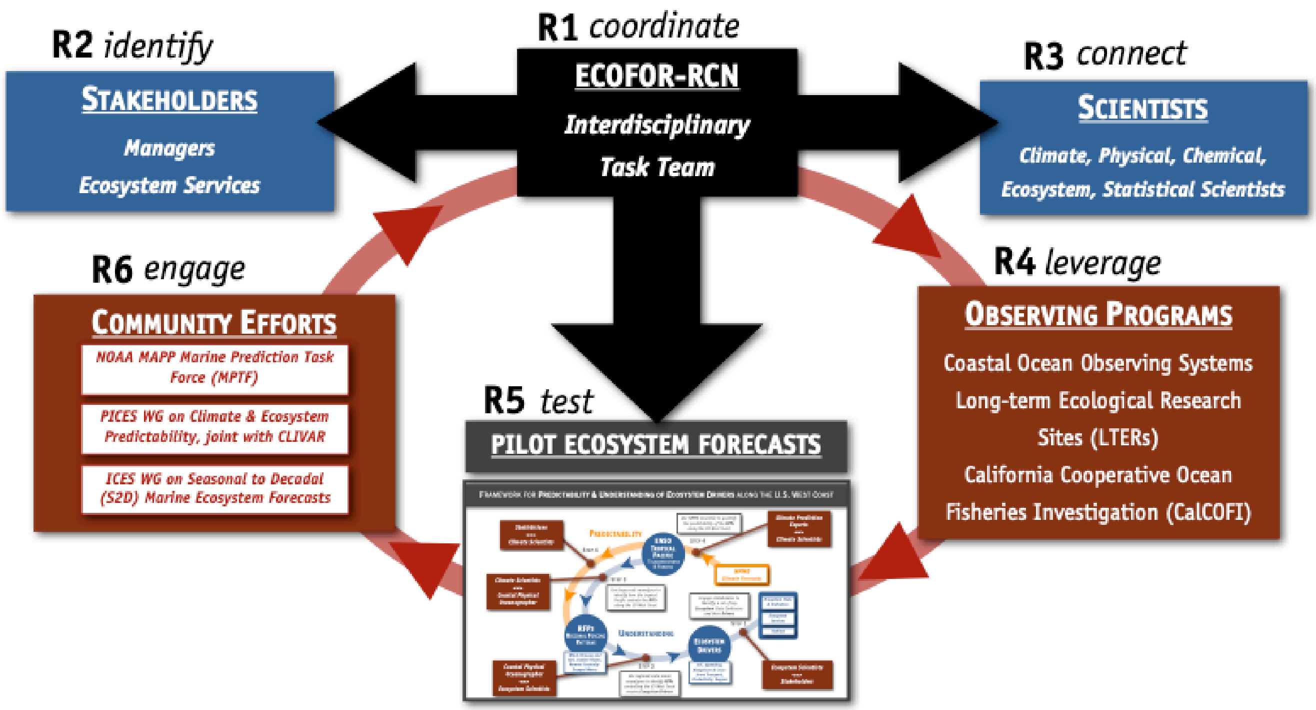
A detailed summary of the workshop results and discussion was completed for the Winter 2017 editions of the US CLIVAR and OCB publications, including a webinar on Forecasting ENSO impacts on marine ecosystems along the US West Coast.

Recommendations

Discussions from the workshop clearly showed the need for a more synergistic approach towards applying the ecosystem forecast framework for the US West Coast. It was recognized that there would be value in putting together an **ECOlogical FORcast Research Coordination Network (ECOFOR-RCN)** that would **coordinate** efforts (recommendation **R1**, Schematic 2) towards the development and testing of a pilot ecological forecasting system/portal for the US West Coast (recommendation **R5**, Schematic 2). Specifically, the ECOFOR-RCN would work towards (1) **identifying** key stakeholders and managers that would serve as end-users and provide important feedback on the target indicators to forecast (recommendation **R2**); (2) **connecting** scientists who bring synergistic expertise (e.g., climate, physical and chemical oceanography, marine ecosystem dynamics, statistics) to the implementation of the ecosystem forecasting framework (Schematic 1); (3) **leveraging** existing coastal observing programs (e.g., COOS and LTERs) as infrastructure for collecting "real-time" physical, chemical and biological data streams and for establishing the basis for an operational pilot forecasting system portal (recommendation **R3**, Schematic 2); and finally (4) **engaging** international community efforts in the area of ecological forecasts to share experiences and best practices (recommendation **R6**, Schematic 2).

R1. Establish an ECOlogical FORcast Research Coordination Network (ECOFOR-RCN)

Developing an operational ecological forecasting system for the US West Coast will require synergies across a broad spectrum of stakeholders and expert groups, including decision makers, managers, and observational and monitoring programs. For this reason, establishing an ECOlogical FORcast Research Coordination Network (ECOFOR-RCN), following the model of the National Science Foundation, is a promising avenue to coordinate all of the different components that are required to establish the basis for a future US West Coast operational ecological forecasting system to aid real-time information for decision makers and a variety of end users (e.g., fisheries). The activity of the RCN is instrumental for implementing the other recommendations that resulted from the workshop, which are discussed below and summarized in the introduction.



Schematic 2. *Recommendations from the US CLIVAR workshop on ENSO ecological forecasting.*

R2. Identify managers and stakeholders to engage in interdisciplinary dialogue with scientists

An integral step towards a well-designed operational ecosystem forecast is the identification of end users who will benefit from the forecast products and can advise on the ecological indicators that should be targeted as priorities in the forecast. The selection of the indicators and the identification of the key stakeholders, decision makers, and end users will largely dictate the methodologies used for the forecast and the development of appropriate "forecast delivery" apps and portal. The ECOFOR-RCN can help identify and connect the different end users with a network of scientists from different background to promote the interdisciplinary dialogue for designing an operational forecasting system.

R3. Connect a diverse set of expertise towards developing ecological forecasting methodologies

Developing and implementing the approaches and modeling methods required for an operational ecological forecasting system requires coordination among climate scientists, statistician and prediction experts, coastal physical oceanographers, marine ecologists, stakeholders, and managers (red panels in Schematic 1). Connecting these different groups and organizing a set of synergistic tasks towards the creation of a pilot forecasting systems is one of the objectives of the ECOFOR-RCN.

R4. Leverage coastal ocean observing networks to integrate ecosystem forecasts

Regional ocean observing systems are ideal testbeds for investigating our ability to capture the local and regional effects of ENSO. The NOAA vision for a national unified Earth system modeling system proposed in 2017 seeks a product-driven strategy aimed at seasonal and subseasonal forecasts. The ability to predict the physical and ecosystem impacts of ENSO on the US West Coast from a system of interconnected and coupled community models is aligned with these national goals, but we need clearly defined pathways for integration into ocean observing systems. A task force has already been proposed to the Interagency Ocean Observation Committee (IOOC) to explore the representation and integration of models and observations from open ocean observing to the regional observing systems along the US West Coast. This kind of bridge is crucial for understanding ecosystem structure/dynamics in the California Current System on interannual to multi-decadal timescales.

R5. Establish and test a multi-institution and inter-agency pilot ecosystem forecast test case

While the long-term goal is to develop operational ecological forecasts, in practice there is a need to develop a pilot ecosystem forecast system that could inform the development and implementation of longer-term efforts. For such a pilot case study, we anticipate that a framework for forecasting ENSO impacts on the marine ecosystem off the US West Coast will depend upon: (i) global climate forecast systems, which provide forecasts at lead times up to ~1 year of atmospheric conditions (e.g., winds, heat fluxes), as well as the physical and biogeochemical ocean state; (ii) high-resolution regional ocean models that are forced by global climate models but are able to resolve important fine-scale dynamics (e.g., upwelling, coastal wave propagation, riverine input) off the west coast; and (iii) dynamical or statistical models that relate the physical/biogeochemical environment to the response of marine species targeted for prediction. In order to develop such a framework, we recommend working backwards – i.e., (1) quantify biological responses to regional forcing, (2) relate the regional forcing to basin-scale (especially ENSO) variability, and (3) determine the predictability of the teleconnections between the basin-scale forcing and the regional response. A significant body of work has already been established on points (1) and (2), and efforts are underway on (3). Development of a marine ecosystem forecasting system should be carried out using hindcasts/reforecasts and long-term biological data sets. Testing the forecasting framework will require long-term operational support as well as continued ocean observations to address non-stationarity in ecological responses to environmental forcing.

R6. Engage with national and international ecosystem forecasting efforts

Advances in forecasting the response of marine ecosystems to climate forcing functions such as El Niño are progressively gaining more attention among national and international organizations and managers. In the scientific community there are several ongoing efforts within PICES and ICES like the ICES Working Group on Seasonal-to-Decadal (WGS2D) prediction of marine ecosystems and Joint PICES/CLIVAR Working Group on Climate and Ecosystem Predictability (CEP). There are also important examples of science networks working closely with fisheries communities and other stakeholders in developing products (successful examples from Australia) and within the NOAA MAPP Marine Prediction Task Force (MPTF).

1 MOTIVATIONS & OBJECTIVES

The US West Coast eastern boundary upwelling system supports one of the most productive marine ecosystems in the world and is a primary source of ecosystem services for the US (e.g., fishing, shipping, and recreation). Long-term historical observations of physical and biological variables in this region have been collected since the 1950s, leading to an excellent foundation for understanding the ecosystem impacts of dominant climate fluctuations such as the El Niño-Southern Oscillation (ENSO). In the northeast Pacific, ENSO impacts a wide range of physical, biogeochemical, and biological processes, including temperature, stratification, winds, upwelling, and primary and secondary production. The El Niño phase of ENSO, in particular, can result in extensive geographic range displacements and altered catches of fishes and invertebrates. We also anticipate effects on vertical and lateral export fluxes of carbon and other biologically important elements. Despite empirical observations and understanding of the coupling between climate and marine ecosystems along the US West Coast, there has been no systematic attempt to use this knowledge to forecast marine ecosystem responses to individual ENSO events. While ENSO forecasting has become routine in the climate community, forecasting the impacts of ENSO on ecosystems and their services has received limited attention. This becomes especially important in light of the strong 2015-16 El Niño and the climate model predictions that ENSO extremes may become more frequent. Responding to this capability gap, we organized a workshop with the central goal to develop a framework for using ENSO forecasts to predict changes in the marine ecosystem off the US West Coast.

The workshop convened 50 participants comprising (1) biologists with expertise in ecosystem responses to physical climate forcing, (2) physical climate scientists with expertise in predicting and understanding ENSO and its impact on the physical state of the Northeast Pacific, (3) fisheries management specialists with operational responsibilities for marine resource and fisheries assessments, and (4) agency managers from sponsoring programs that have invested in projects to advance our understanding of ENSO-ecosystem interactions. Eleven participants, or 22% of the attendees, were early career scientists and students. Target organisms ranged from plankton to exploitable species that are regulated by federal and state agencies. Regions of interest included coastal waters of California, Oregon, Washington, and Alaska, as well as Mexico and Canada, which are oceanographically and ecologically connected regions. Participants discussed and identified the predictable components of the physical climate system that can be used to predict key aspects of the ecosystem on monthly, seasonal, and multi-season timescales. Surprisingly, this aspect of the predictability of ENSO has not been exploited in real-time ecosystem forecasts, so the time is ripe to pursue and develop this agenda in a practical context.

In addition to identifying practical applications of using ENSO forecast to predict ecosystem changes, meeting participants also identified a set of research priorities and challenges needed to fill the gaps in our understanding of ecosystem predictability and our ability to implement real-time ecosystem forecasting along the US West Coast, leveraging existing observational platforms with the coastal observing systems and the long-term ecological research (LTER) site.

2 SESSION SUMMARY PRESENTATIONS

The workshop was organized around five thematic sessions that were aimed at developing the scientific basis for forecasting the response of key ecosystem indicators to ENSO forcing (blue path in Figure 1). With this in mind, Session 1 focused on identifying the regional mechanisms that impact ecosystem indicators used to evaluate ecosystem functions and monitor ecosystem services, and Session 2 focused on understanding how ENSO and its different expressions (e.g., diversity) modify regional drivers. Sessions 3 and 4 (on the orange envelope in Figure 1) focused on reviewing the type of dynamical and empirical models that can be used to develop a pilot operational ecological forecasting system for the US West Coast and identify the required data streams, an initial set of ecological indicators to forecast, sources of uncertainty, and communication strategies. Lastly, Session 5 (red block in Figure 1) reviewed how synergies with ongoing international efforts can accelerate the development of a pilot forecasting system. Each session included two or three invited presentations to summarize the current state of understanding and inform 45-90 minutes discussions among participants. Key points are highlighted here. Full presentations are posted for download on the workshop website.

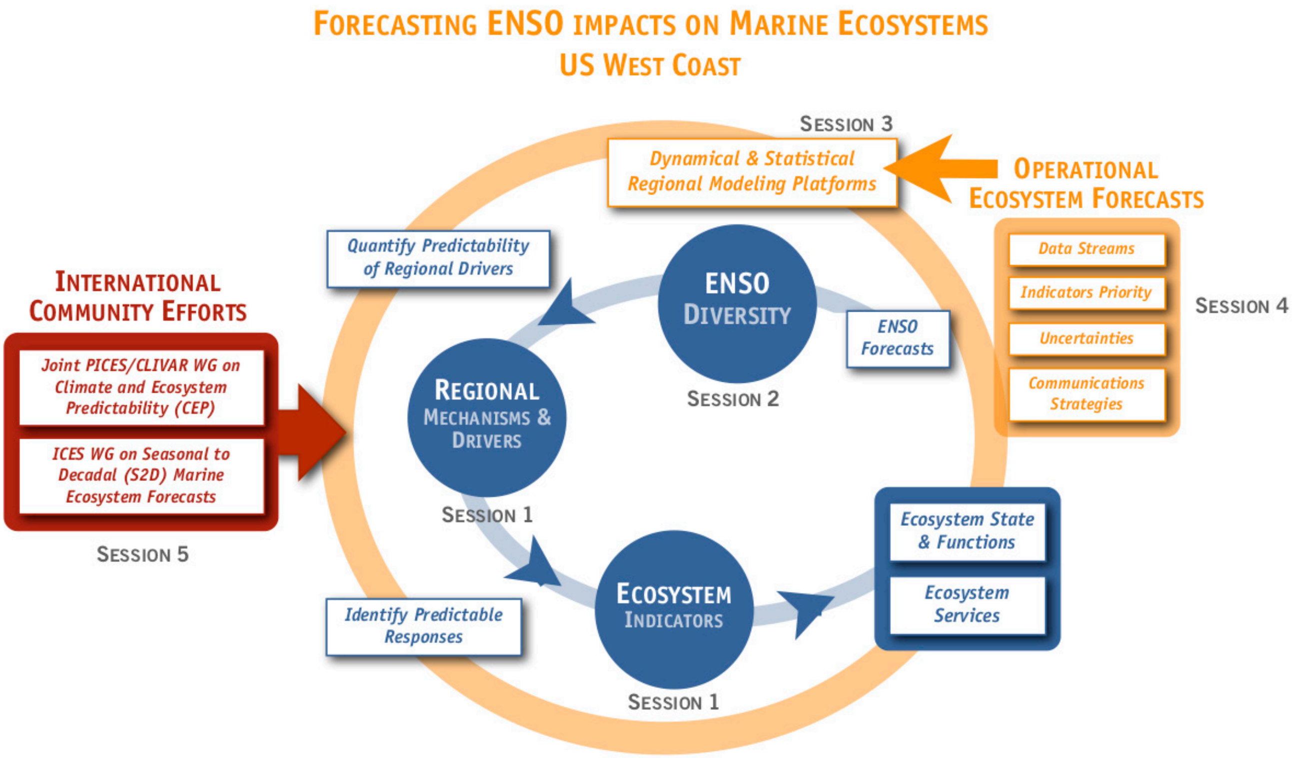


Figure 1. *Summary of the workshop sessions and their goals (blue text boxes)*

Session 1: Regional mechanisms impacting key ecosystem indicators

The goal of this session was twofold: (1) to identify a set of key ecosystem indicators that characterize the ecosystem state, both in terms of ecosystem functions and management of ecosystem services, and (2) to identify the regional processes (physical effects, bottom-up, and top-down) that generate predictable responses in the ecosystem state variables used to define the ecological indicators.

S1.1 California Current ecosystem indicators and their sensitivity to ENSO (Garcia-Reyes)

In the California Current, a large number of physical and biological indicators spanning a wide range of processes and trophic levels have been developed to describe the responses of marine ecosystems to climate anomalies. To adequately describe the ecosystem response to El Niño (or any) events, however, we need to identify indicators that are sensitive to the changes associated with El Niño events, either directly or indirectly. In the California Current region, this is complicated because many environmental parameters (i.e., temperature, sea level, winds) are synchronized in their response to anomalies in the climate forcing, as demonstrated by synthetic multivariate indicators like the Multivariate Ocean Climate Indicator (MOCI; Sydeman et al. 2014; Garcia-Reyes and Sydeman 2017).

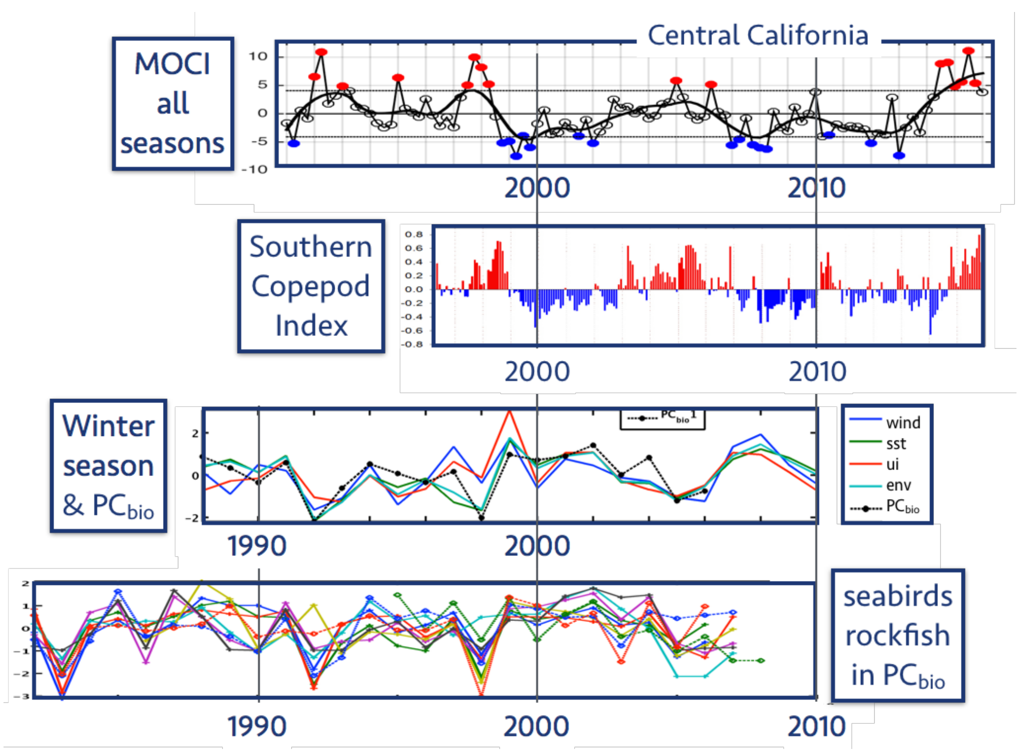


Figure 2. *Top panel: Multivariate Ocean Climate Indicator (MOCI) for central California, synthesizing seasonal values of sea level, sea surface temperature, alongshore wind stress, sea level pressure, air temperature, upwelling index and climate indices (Farallon Institute). Second panel: Biomass anomalies of the Southern Copepod Index (NOAA Northwest Fisheries Science Center). Third panel: Winter mode of variability (principal component analysis) of buoy alongshore wind, SST, upwelling index, and all combined (env) along central and northern California, along with leading mode of variability on biological indicators (PCbio; García-Reyes et al. 2013; 14). Bottom panel: Time series of biological indicators in PCbio, including Farallon Institute's seabird lay-dates and reproductive success and rockfish growth chronologies (García-Reyes et al. 2013; 14).*

Moreover, different ecosystem populations respond differently to varying seasonal conditions. While lower trophic levels (e.g., copepods, krill) generally have a more rapid and direct response to environmental variability, including El Niño, across all seasons, upper trophic levels may respond to variability during a particular season, as determined by food availability. For example, rockfish growth and the Common Murre's productivity relate to winter conditions, while Pacific sardine recruitment, salmon growth, and auklet productivity relate best to summer conditions. Since winter variability is strongly related to ENSO, ecosystem indicators that are sensitive to winter conditions would appear to be the most sensitive to ENSO-related variability (Figure 2).

These results point to the importance of developing indicators of the regional physical processes that impact ecosystems rather than relying on large-scale multivariate indices alone (see next section).

S1.2 Physical processes impacting ecosystem indicators in the CCS (Jacox)

*The content of this session summary is included in an article for the US CLIVAR Variations Winter 2017 edition, entitled **Dominant physical mechanisms driving ecosystem response to ENSO in the California Current System** (Jacox et al. 2017).*

ENSO is a dominant driver of interannual variability in the physical and biogeochemical state of the northeast Pacific, and consequently exerts considerable control over the ecological dynamics of the CCS. In the CCS, upwelling is the proximate driver of elevated biological production, as it delivers nutrients to the sunlit surface layer of the ocean, stimulating growth of phytoplankton that form the base of the marine food web. Much of the ecosystem variability in the CCS can therefore be attributed to changes in bottom-up forcing, which regulate biogeochemical dynamics through a range of mechanisms. Of particular relevance to ENSO-driven variability are the influences of surface winds (which drive upwelling and downwelling), remote oceanic forcing by coastal wave propagation, and alongshore advection. While the relative importance of these individual forcing mechanisms has long been a topic of study, there is general consensus on the qualitative nature of each, and we discuss them in turn below.

One of the canonical mechanisms by which ENSO events generate an oceanographic response in the CCS is through modification of the surface winds and resultant upwelling. During El Niño, tropical convection excites atmospheric Rossby waves that strengthen and displace the Aleutian low, producing anomalously weak (strong) equatorward (poleward) winds, which in turn drive anomalously weak (strong) upwelling (downwelling) through modification of cross-shore Ekman transport near the surface (Alexander et al. 2002; Schwing et al. 2002). This tropical-extratropical communication through the atmosphere has been given the shorthand name "atmospheric teleconnection." When equatorward winds are anomalously weak, as they were for example during the 2009-2010 El Niño (Todd et al. 2011), there is a twofold impact on the nutrient flux to the euphotic zone, and consequently the potential primary productivity. First, weaker winds produce weaker coastal upwelling; independent of changes in the nutrient concentration of upwelling source waters, a reduction in vertical transport translates directly to a reduction in vertical nutrient flux. Second, the nutrient concentration of source waters is altered by the strength of the wind; weak upwelling draws from shallower depths than strong upwelling, and the water that is upwelled is relatively nutrient poor. Both of these effects tend to limit potential productivity during El Niño. Conversely, La Niña events are associated with anomalously strong equatorward winds, vigorous coastal upwelling, and an ample supply of nutrients to the euphotic zone. However, winds that are too strong can also export nutrients and plankton rapidly offshore, resulting in relatively low phytoplankton biomass in the nearshore region (Figure 3).

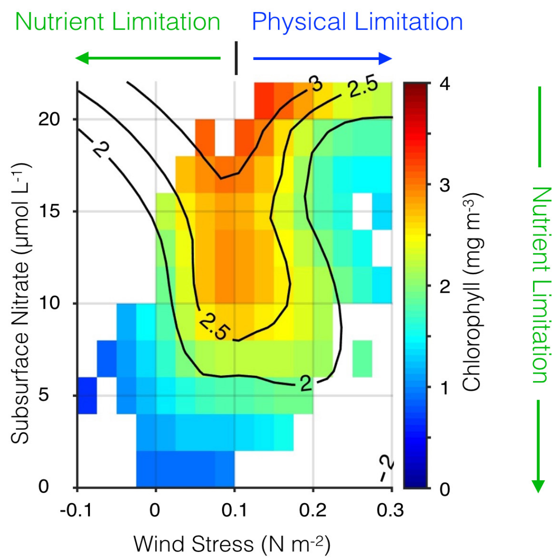


Figure 3. *Surface chlorophyll plotted as a function of alongshore wind stress and subsurface nitrate concentration in the central CCS. Wind stress is from the UC Santa Cruz Regional Ocean Modeling System CCS reanalysis (oceanmodeling.ucsc.edu), nitrate comes from the CCS reanalysis combined with a salinity-temperature-nitrate model developed with World Ocean Database data, and chlorophyll is from the SeaWiFS ocean color sensor. Surface chlorophyll is highest when winds are moderate and subsurface nutrient concentrations are high. Phytoplankton biomass can be hindered by weak upwelling, nitrate-poor source waters, or physical processes (subduction or rapid offshore advection of nutrients and/or phytoplankton, light limitation due to a deep mixed layer) driven by strong winds.*

Remote ocean forcing

As the atmospheric teleconnection transmits tropical variability to CCS winds, an oceanic teleconnection exists in the form of coastally trapped waves that propagate poleward along an eastern ocean boundary and thus approach the CCS from the south (Enfield and Allen 1980; Meyers et al. 1998; Strub and James 2002). During an El Niño, these waves tend to deepen the pycnocline and nutricline, which renders upwelling less effective at drawing nutrients to the surface, and therefore limits potential productivity. While coastally trapped waves that reach the CCS may originate as far away as the equator, topographic barriers exist, notably at the mouth of the Gulf of California (Ramp et al. 1997; Strub and James 2002) and at Point Conception. Since coastally trapped waves that reach a particular location in the CCS can be generated by wind forcing anywhere along the coast equatorward of that location, the oceanic teleconnection may be thought of as an integration of wind forcing experienced along the equator and all the way up the coast to the CCS. Efforts to separate the effects of local wind forcing from coastally trapped waves are complicated by the strong correlation of alongshore wind along the coast, the fast poleward propagation speed of coastally trapped waves, and the fact that both produce similar effects during canonical El Niño and La Niña events. The 2015-16 El Niño is one example where warm water and deep isopycnals were observed in the southern CCS despite anomalous upwelling favorable winds locally (Jacox et al. 2016b). In this case the local winds may have worked to dampen the influence of the oceanic teleconnection (Frischknecht et al. 2016).

Alongshore transport
Anomalous alongshore transport has on several occasions been implicated in major ecosystem change in the CCS. In the case of anomalous advection from the north, such as that observed in 2002 (Freeland et al. 2003), the CCS is supplied by cold, fresh, and nutrient-rich subarctic water that can stimulate high productivity even in the absence of strong upwelling. Conversely, anomalous advection of surface waters from the south, such as that observed during the 1997-98 El Niño (Bograd and Lynn 2001; Lynn and Bograd 2002; Durazo and Baumgartner 2002), may amplify surface warming and water column stratification, exacerbating nutrient limitation and biological impacts associated with the atmospheric and oceanic teleconnections.

The poleward flowing California Undercurrent (CUC) may also be modulated by ENSO variability. In particular, there is evidence that strong El Niño events can intensify the CUC (Durazo and Baumgartner 2002; Lynn and Bograd 2002; Gomez-Valdivia et al. 2015), which transports relatively warm, salty, and nutrient rich water along the North American coast from the tropical Pacific as far north as Alaska (Thomson and Krassovski 2010). Anomalously warm salty water was observed on subsurface isopycnals in the southern CUC during 2015-2016 (Rudnick et al. 2017), suggesting anomalous advection from the south. It is unclear whether coastal upwelling can reach deep enough during El Niño events to draw from the CUC, but if so the CUC intensification could be a mechanism for modifying upwelling source waters and partially mitigating the previously described impacts on nutrient supply.

Finally, in addition to influencing the ecosystem through bottom-up forcing, anomalous surface and subsurface currents can directly influence the ecological landscape by transporting species into the CCS from the north, south, or west. For example, positive phases of ENSO and the Pacific Decadal Oscillation (PDO) are associated with higher biomass of warm-water 'southern' copepods, while negative phases of ENSO and the PDO are associated with increases in cold-water 'northern' copepods (Hooff and Peterson 2006). Importantly, northern copepods are much more lipid-rich than southern copepods; thus, changes in the copepod composition alter the energy available to higher trophic levels and have been implicated in changing survival for forage fish, salmon, and seabirds (Sydeman et al. 2011). During El Niño events, the appearance of additional warm water species (e.g., pelagic red crabs) off the California coast has also been attributed to anomalous poleward advection, though further research is needed to support this hypothesis.

S1.3 Remote ocean vs local/regional atmospheric forcing (Miller)

The content of this session summary is included in an article for the US CLIVAR Variations Winter 2017 edition, entitled ***ENSO diversity and its implications for US West Coast marine ecosystems*** *(Capotondi et al. 2017).*

In the CCS, the atmospheric variability that drives key processes such as upwelling, sea surface temperatures, and changes in transport is forced by dynamics that are both local to the North Pacific and teleconnected from the tropical Pacific. In the Northeast Pacific, the two dominant modes of atmospheric variability are associated with a change in the location and/or intensity of the jet stream, which are captured by a shift in the location of the Aleutian Low or an intensification of the gradient between the Aleutian Low and North Pacific High – a mode of atmospheric variability referred to as the North Pacific Oscillation (NPO; Linkin and Nigam 2008). Changes in the AL and the NPO drive recurrent oceanic responses that are captured in the two dominant ocean modes of the Northeast Pacific, namely the Pacific Decadal Oscillation and the North Pacific Gyre Oscillation (Chhak et al. 2009). The AL and NPO wind patterns also have important differences in the way they impact the upwelling favorable winds, with the AL (NPO) dominating the northern (southern) CCS (Di Lorenzo et al. 2008). While part of the variability of the AL and NPO is dominated by regional processes intrinsic to the North Pacific, an important fraction of their variability is controlled by tropical variability and the different expressions of ENSO.

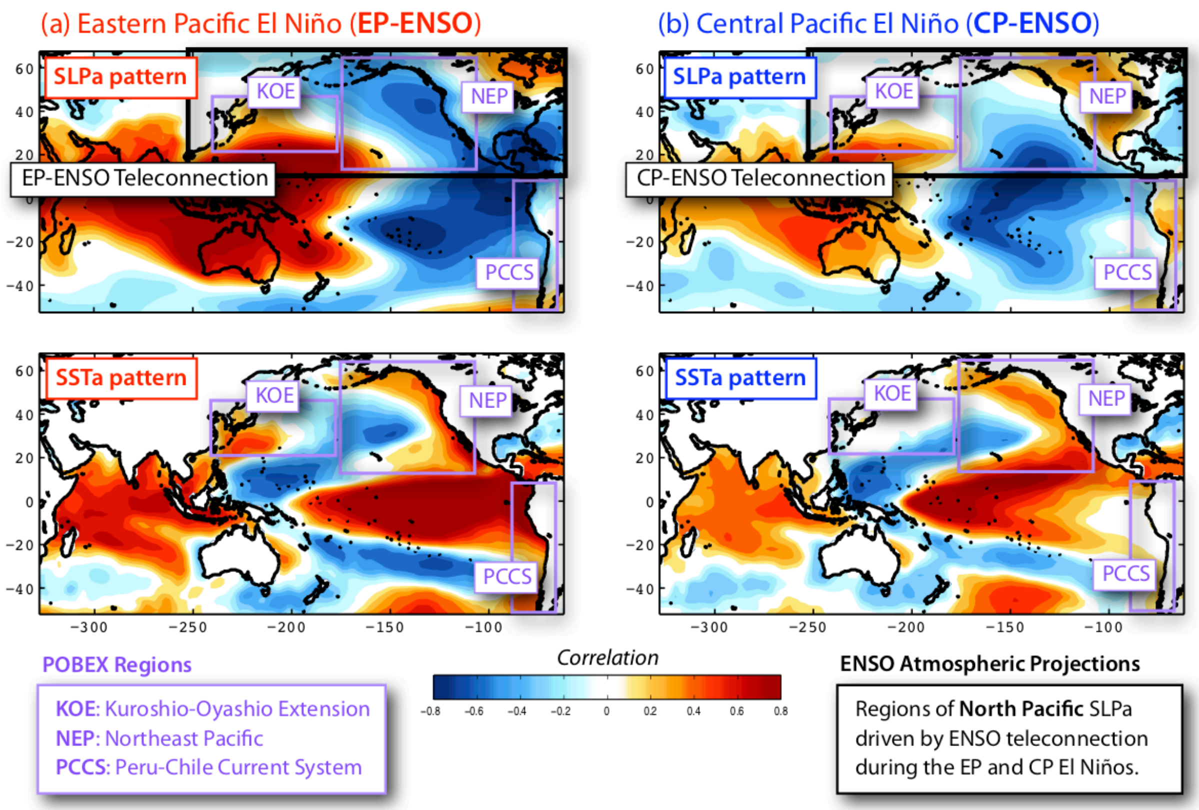


Figure 4. *The flavors of ENSO and their teleconnections over the Northeast Pacific. Sea surface temperature and sea level pressure anomalies during the eastern Pacific or canonical El Niño (panel a) and the central Pacific El Niño (panel b). The black rectangles show the atmospheric projections of a positive ENSO onto the North Pacific atmosphere, also referred to as the ENSO teleconnections. (From Di Lorenzo et al. 2013)*

Equatorial SST anomalies associated with eastern Pacific ENSO influence remote weather and climate through large-scale atmospheric teleconnections. Variations in convection trigger atmospheric stationary Rossby wave trains that alter the Pacific North America Pattern (PNA, Figure 4a, top panel), a mode of North Pacific geopotential height variability, and induce variations in the regional surface atmospheric circulation. In particular, El Niño events are associated with an intensification and southward shift of the AL pressure system (Alexander et al. 2002) and changes in the eastern Pacific Subtropical High, which conspire to weaken the alongshore winds off the US West Coast, resulting in reduced upwelling in the northern and central CCS and warmer SST. These changes associated with the local atmospheric forcing are similar to those induced by coastal Kelvin waves of equatorial origin, making it very difficult to distinguish the relative importance of the oceanic and atmospheric pathways in this region, especially observationally. Furthermore, it has also been recognized that a different expression of ENSO, often referred to as the central Pacific ENSO, also induces an extra-tropical response over the CCS that impacts the NPO atmospheric variability and upwelling in the southern CCS (Figure 4b; Di Lorenzo et al. 2010).

Although these atmospheric teleconnections patterns emerge clearly from statistical analysis of SST and sea level pressure anomalies, large uncertainties exist about the atmospheric midlatitude response to tropical SST anomalies. Results from a recent study based on both observations and climate model ensemble simulations indicate that uncertainties in the sea level pressure response to ENSO arise primarily from atmospheric internal variability rather than diversity in ENSO events (Deser et al. 2017). Thus, the details of the ENSO teleconnections can vary significantly and randomly from event to event, and result in important differences along the California Coast.

A more in-depth description of ENSO diversity and its impacts on the physical and biological characteristics of the CCS is presented in the next section.

Session 2: Impacts of ENSO diversity on ecosystem drivers

Along the US West Coast, ENSO impacts can vary greatly. This reflects the diverse flavors of the tropical expression of ENSO and its teleconnections to higher latitudes. The goal of this session was twofold: (1) to review the different flavors of ENSO impacts on the ocean, atmosphere, and ecosystem state over the North American West Coast, and (2) to examine which aspects of ENSO teleconnections generate predictable responses in ecosystem drivers (e.g., those discussed in session 1).

S2.1 Different types of ENSO variability and teleconnections (Capotondi)

The content of this session summary is included in an article for the US CLIVAR Variations Winter 2017 edition, entitled ***ENSO diversity and its implications for US West Coast marine ecosystems*** *(Capotondi et al. 2017).*

As already noted by Wyrtki (1975), “No two El Niño events are quite alike.” Indeed, ENSO events differ in amplitude, duration, and spatial pattern, and several studies have suggested that such differences may play an important role in ENSO impacts (see Capotondi et al. 2015 for a review). Special emphasis has been given to the location of the maximum equatorial SST anomalies, as this is an aspect that is readily observed and may influence atmospheric teleconnections (Ashok et al. 2007, Larkin and Harrison 2005). Although the longitudinal position of the maximum SST anomalies along the equator varies from event to event in a quasi-continuum fashion, for practical purposes events are often grouped depending on whether the largest anomalies are located in the Eastern Pacific (“EP” events), or in the Central Pacific (“CP” events; see Figure 4). Here we use the relative amplitudes of SST anomalies in the Niño3 (5°S-5°N, 150°W-90°W) and Niño4 (5°S-5°N, 160°E-150°W) regions to classify the events as “EP” or “CP”. Figure 5 shows the equatorial profiles of SST anomalies for the two groups of events in the Simple Ocean Data Assimilation (SODA; Carton and Giese 2008) reanalysis over the period 1958-2007 (Figure 5a) and in 500 years of a pre-industrial control simulation of the National Center for Atmospheric Research (NCAR) Community Climate System Model version 4 (CCSM4; Figure 5b). We notice that there is a large overlap between the two groups of events, which is indicative of the large spread in event longitudinal distribution, although events peaking in the eastern Pacific can achieve larger amplitudes than those peaking in the central

Pacific. This difference in amplitude is not as pronounced in the precipitation profiles (Figure 5c), suggesting that in spite of their weaker SST anomaly signature, CP events may still have a large influence on the atmosphere due to their position in a region of warmer background SST.

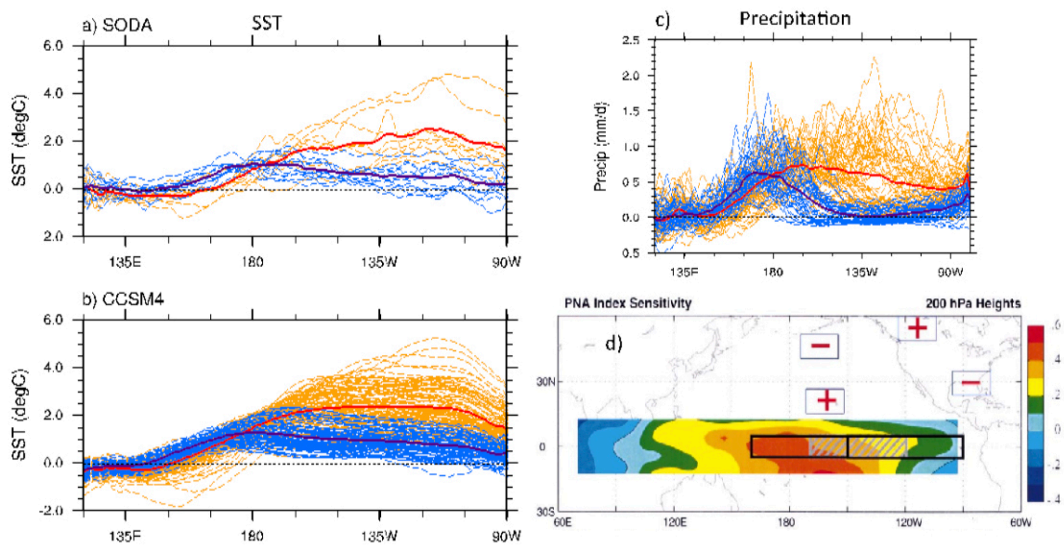


Figure 5. *(a) Equatorial SST anomaly profiles for El Niño events with largest SST anomalies in the Niño-3 region (EP events, thin dashed orange lines) and in the Niño-4 region (CP events, thin dashed blue lines) from the SODA ocean reanalysis over the period 1958-2007. The thick red and blue lines are the composites of the thin orange and blue lines, respectively. b) Same as in a, but for a 500-year pre-industrial simulation of the NCAR-CCSM4 climate model. c) Same as in b, but for precipitation anomalies rather than SST anomalies. The a), b), and c) panels are adapted from Capotondi (2013). d) Tropical SST anomaly pattern, or "sensitivity pattern", that exerts the largest influence on the PNA (the "+" and "-" signs indicate the PNA Highs and Lows as shown in Figure 2), as computed by Barsugli and Sardeshmukh (2002) using ensembles of atmospheric model simulations forced by a set of SST anomaly patches over the tropical Pacific. Panel d) is adapted from Barsugli and Sardeshmukh (2002).*

Impacts of different types of ENSO events

In terms of atmospheric teleconnections, as noted before, "canonical" EP events have been associated with changes in the Aleutian Low, while CP events may produce a strengthening of the second mode of North Pacific atmospheric variability, the North Pacific Oscillation (NPO; Di Lorenzo et al. 2013). AL variability is associated with the Pacific Decadal Oscillation, while the NPO appears to provide the atmospheric forcing for the North Pacific Gyre Oscillation (Di Lorenzo et al. 2008), a mode of variability that is largely correlated with biologically relevant quantities along the west coast of the US However, the event-to-event differences in teleconnections, associated with intrinsic atmospheric variability, may obscure differences in atmospheric response to different event types.

EP and CP events have different subsurface characteristics as well, so that the oceanic pathways between the tropical Pacific and the US West Coast can also be expected to differ in the two cases. While EP events are characterized by large equatorial thermocline anomalies across the basin, which evolve consistently with the recharge oscillator paradigm (Jin 1997), thermocline depth anomalies during CP events tend to be confined in the central part of the basin and do not undergo the large variations associated with the meridional warm water volume transport. As a result, the Kelvin wave signature in the eastern equatorial Pacific, and the resulting amplitude of the coastal Kelvin wave, can be expected to be weaker during CP events. Indeed, a recent study (Fischer et al. 2015) has shown that temperature anomalies (and associated zooplankton composition) in the northern California Current responded very rapidly to EP El Niño events with a peak during boreal winter, but had a delayed response during boreal spring for CP type events. Another compelling example of diversity in ENSO influences is provided by the 2015/16 El Niño. In spite of the magnitude of the event, which was comparable to the previous two extreme events on record, the 1982/83 and 1997/98, the changes in temperature, thermocline/nutricline depth, and alongshore winds associated with this event were much smaller than during the two previous cases (Jacox et al. 2016). These differences are perhaps due to the unique nature of the event, whose spatial pattern has elements of both EP and CP El Niño types, with, in particular, a weaker thermocline depth anomaly in the eastern equatorial Pacific relative to the 1982/83 and 1997/98 cases. The question of whether and how different types of ENSO events have different impacts remains open and is the subject of intense research.

Predicting different types of ENSO events

Several studies have attempted to determine specific precursors for EP and CP type events. SST and wind stress anomalies propagating southwestward from the Southern California coast to the central equatorial Pacific, a pattern known as the “Pacific Meridional Mode” (PMM; Chiang and Vimont 2004) has been suggested as a possible precursor for CP events (Yu et al. 2011; Vimont et al. 2014), while SST and wind stress anomalies extending northward along the coast of South America toward the eastern equatorial Pacific (the “South Pacific Meridional Mode”; Zhang et al. 2014) have been considered as candidate precursors for EP-type events. While these modes of variability do produce initial SST anomalies either in the central or eastern Pacific, these anomalies can propagate along the equator and maximize at a different longitude in the mature phase of the event. For example, the strong 1982/83 EP El Niño developed from anomalous SSTs in the central Pacific in the late spring of 1982, which propagated eastward to achieve their largest amplitude near the South American coast in the following winter (Xue and Kumar 2016). In late spring 2015, on the other hand, anomalies exceeding 2°C appeared in the far eastern Pacific, and then propagated westward to reach their largest amplitude in the central Pacific in winter (Xue and Kumar 2016). While several studies have emphasized SST precursors, thermocline conditions two-seasons prior to the peak of an event appear to play an important discriminating role in the development of the two types of events (Capotondi and Sardeshmukh 2015), with deeper than average initial thermocline conditions in the eastern Pacific favoring EP-type events, and shallower than average eastern Pacific thermocline depth acting as precursor for CP-type events. The results of Capotondi and Sardeshmukh (2015) were obtained using a combination of multiple linear regressions and Linear Inverse Modeling (LIM; Penland and Sardeshmukh 1995), thus objectively providing the initial state that will optimally evolve, two seasons later, in either an EP- or CP-type event.

Given the remaining uncertainties in the exact triggers of ENSO diversity, as well as the large noise level of atmospheric teleconnections, how can we isolate the predictable component of the ENSO influence on the Pacific West Coast physical and biogeochemical conditions? In other words, even if we could perfectly predict ENSO in all its diversity and atmospheric teleconnections, how well could we predict the ecosystem responses? One possible approach is to determine the SST pattern to which a given target quantity (e.g., a mode of atmospheric variability or some local ecosystem forcing function) is most sensitive. The SST anomalies that are most effective in influencing specific “target” regions do not necessarily coincide with the anomalies typical of “canonical” ENSO events (Rasmussen and Carpenter 1982). In fact, as shown by Barsugli and Sardeshmukh (2002), the PNA pattern is particularly sensitive to SST anomalies in the Niño-4 region rather than the Niño-3 region where canonical “EP” events typically peak (Figure 5d). This implies that weaker CP El Niño events may have as large as a projection on the sensitivity pattern as stronger EP events, and be as or more effective in influencing atmospheric teleconnections like the PNA (compare Figs. 5a, b with Figure 5d). Similar sensitivity pattern could be determined for key regional forcing function along the US West Coast region, either using the approach outlined in Barsugli and Sardeshmukh (2002) or through multiple linear regressions as in Capotondi and Sardeshmukh (2015).

In summary, ENSO can provide a large source of potential predictability for the physics and the biology of the US West Coast. However, in light of the large uncertainties associated with ENSO diversity and atmospheric teleconnections, novel approaches need to be developed to isolate the robust predictable components of ENSO influences, and thus provide guidance to prediction development activities.

S2.2 ENSO impacts on ecosystem indicators (Ohman)

This session summary has been converted into articles for the US CLIVAR Variations Winter 2017 edition, entitled ***ENSO impacts on ecosystem indicators in the California Current System*** *(Ohman et al. 2017) and* ***Impact of ENSO on biogeochemistry and lower trophic level response in the California Current System*** *(Anderson et al. 2017).*

Given the complex influence of tropical climate on Northeast Pacific ecosystems, there is significant overlap between ENSO signals and low/high frequency variability of the PDO and North Pacific Gyre Oscillation (NPGO) modes. It is well recognized that this interacting variability drives substantial ecosystem variability across various time and space scales. Large regime shifts in the North Pacific that have reverberated up the ecosystem from physics to fish are recurring patterns now associated with low frequency changes in SST that characterize the PDO (e.g., Mantua et al. 1997).

As discussed by Jacox et al. (2017) there is an expected or canonical set of physical conditions associated with ENSO in the CCS. This physical response to ENSO generally includes: (1) changes to surface wind stress which alters the strength of coastal upwelling and downwelling, (2) remote oceanic forcing by coastally trapped waves that propagate poleward, along the US west coast and modify thermocline depth and coastal stratification, and (3) changes to alongshore advection. The ecological response of the coastal marine environment includes changes to primary production and the community composition of plankton and higher trophic levels that can be directly and more subtly related to these physical factors. Primary production is driven by vertical nutrient flux to well-lit surface waters; nutrient supply is related to upwelling magnitude, upwelling source depth, and nutrient concentrations at the source depth. ENSO-related processes have also been shown to be important for interannual and seasonal variability of oxygen concentrations and carbonate biogeochemistry on Washington and Oregon shelves (Siedlecki et al. 2015). Below, we highlight some of the model and observational studies that have successfully attributed ENSO-like variability to specific impacts on the biogeochemistry and lower-trophic level organisms of the Northeast Pacific and CCS.

Carbon dioxide

Numerical models are widely employed to diagnose climatic forcing of the physical and biogeochemical conditions of the Northeast Pacific. For instance, using a fully-coupled ocean and biogeochemical model, Xiu and Chair (2014) found that after discounting for atmospheric effects, the air/sea flux and resulting pCO2 of sea water in the Pacific was significantly correlated (0.6) to the Multivariate ENSO Index (MEI) with a lag of ten months. Similarly, Wong et al. (2010) found that sea surface pCO2 was significantly correlated with the MEI in the Northeast Pacific. Biogeochemical models of different complexity have also demonstrated the connection between PDO and the interannual variability of air-sea CO2 fluxes (e.g., McKinley et al. 2006). These studies also demonstrate that the different components that control surface ocean pCO2 in the Northeast Pacific respond to PDO with significant amplitudes, but that their combined influence has a relatively small effect on the CO2 fluxes in this region. Xiu and Chai (2014) showed that the dominant variability of pCO2 in the North Pacific is forced by anthropogenic CO2, whereas the dominant mode of variability for air-sea CO2 flux is correlated with the PDO as well as the NPGO.

Nutrients and chlorophyll

In the coastal regions of the Northeast Pacific, such as the CCS, there are significant impacts of ENSO on the nutrient supply due to modifications to upwelling and source waters mentioned above (Jacox et al. 2017). At the peak of the El Niño season in December-January, Frischknecht et al. (2016) found a pattern in the development of chlorophyll events through a modeling study focused on the CCS. Around the onset of the El Niño year, chlorophyll anomalies were consistently low. This pattern was even more pronounced during the spring of the following year. In spring of the second year, i.e., with the onset of the upwelling season, all events shared the development of a strong negative anomaly in chlorophyll. Frischknecht et al. (2016) attributed this phenomenon to a persistent lack of nutrients to support production driven by a combination of physical mechanisms impacting the thermocline detailed in Jacox et al. (2015; 2016), and light limitation at the onset of the upwelling season. Consequently, El Niño events disrupt the biogeochemical cycling in these systems for months, even years, after the event is over. The observations in Oregon from the Newport line in Fisher et al. (2015) detail the nitrate anomalies from 1995 to 2015, and the nitrate anomalies remain negative long after the Niño-3.4 SST anomaly suggested that the event was over. This may contribute to the success surrounding seasonal forecast systems like the University of Washington's Joint Institute for Studies of the Atmosphere and Ocean (JISAO) Seasonal Coastal Ocean Prediction of the Ecosystem (J-SCOPE), where biogeochemical forecasts (bottom oxygen) outperformed physical variables (SST) in terms of predictive skill (Siedlecki et al. 2016).

Oxygen and carbon

The relationship between ENSO and nutrient availability from source waters can be an analogue for oxygen and carbon content. We would expect from observed stoichiometry that when nutrients are low, that oxygen is relatively high and carbon is low. In California, this has been documented: El Niño events correlate to higher oxygen and pH, while La Niña events are correlated with lower oxygen and pH (e.g., Nam et al. 2011). In the northern CCS along the Washington and Oregon coasts, the interannual variability in oxygen content of source waters was correlated to NPGO more than ENSO (Peterson et al. 2013). Consistent with this, oxygen has been increasing since 2010 and aragonite saturation state (a measure of the availability of carbonate ion to calcifying organisms) has been elevated in 2015-2016 relative to year prior in both Oregon and California (McClatchie et al. 2016).

Primary production

As an eastern boundary current, the CCS transports cold, nutrient-rich waters to the surface during seasonal upwelling and is among the most productive in the world in terms of primary production and fisheries. El Niño events generally reduce upwelled nutrients and "upwelling efficacy" (thus, primary production) in the CCS while La Niña often has the opposite effect due to associated increases in the upwelling efficacy (Jacox et al. 2015). In the southern CCS, the 1997/1998 El Niño led to a significant deepening of the nutricline, with the strongest effects along the California Cooperative Oceanic Fisheries Investigations (CalCOFI) Line 80, and a pronounced regional reduction of primary production (Bograd and Lynn 2001). The uptake of Si increased in central California during the onset of the 1997 event, indicating that diatoms were major drivers of the primary productivity prior to the 1998 spring season when overall productivity was reduced in response to density surface adjustments (Shipe and Brzezinski 2003). Interestingly, export ratios of particulate organic carbon and particulate organic nitrogen increased during the period of reduced surface layer productivity in spring 1998, suggesting that export efficiency is not as impacted by ENSO as surface layer primary productivity.

Phytoplankton community composition

Warmer waters and changes in nutrient supply associated with ENSO can lead to phytoplankton community shifts such as an influx of coccolithophores or an increase in harmful algal blooms. The most common harmful algal bloom organism in the CCS is the diatom genus Pseudo-nitzschia. In response to the unprecedented harmful algal bloom of 2015 along the US West Coast that was associated with anomalous warming, McCabe et al. (2016) showed a coherent pattern between the Oceanic Niño Index (ONI), the Pseudo-nitzschia growth rate anomaly determined from temperature-growth relationships, and domoic acid levels in razor clams over a 16-yr period. This relationship with warming temperatures is echoed in a recent study by McKibben et al. (2017) linking warm phases of the PDO and ONI to domoic acid in shellfish in the northern CCS. The toxic blooms off Newport in 2015 were the most prolonged (late-April through October 2015) and among the most toxic observed off Oregon (Du et al. 2015; McKibben et al. 2017). There was, however, no significant correlation between a 15-year record of domoic acid levels from sediment traps in the Santa Barbara Basin and PDO, NPGO, or ENSO, but there was a strong change point in the frequency and toxicity of these blooms after the 1997/1998 ENSO (Sekula-Wood et al. 2011).

Zooplankton community composition

Off the Oregon coast, what has been gleaned from a 21-year time series of fortnightly sampling of hydrography and plankton of shelf and slope waters is that the water masses (and thus the plankton) that dominate shelf and slope waters vary seasonally, interannually, and at decadal scales, making it a simple matter to track the timing of arrival of summer or winter, of ENSO events, and changes in sign of the PDO (Figure 6). On a seasonal basis, during summer, northerly winds drive surface waters offshore (Ekman transport) to be replaced by the upwelling of cold nutrient-rich waters that move onto the continental shelf and fuel massive amounts of primary production. Northerly winds also enhance the southward transport of water (and plankton) from the coastal Gulf of Alaska into the coastal northern CCS, and these species are referred to as 'cold water' or 'northern species.' During winter, the winds reverse and the poleward Davidson current transports warm coastal water from southern California to the northern CCS, bringing with it 'southern species' of plankton. On longer time scales (5-10 years), cold-water, northern copepods are largely replaced by warm-water, southern copepods during El Niño events (Fisher et al. 2015) and during the positive phase of the PDO (Keister et al. 2011). Incorporating the physiological response of these zooplankton groups into biogeochemical/ecosystem models (in addition to the effects of physical transport) will be essential for advancing our predictive capacity of plankton communities in the CCS.

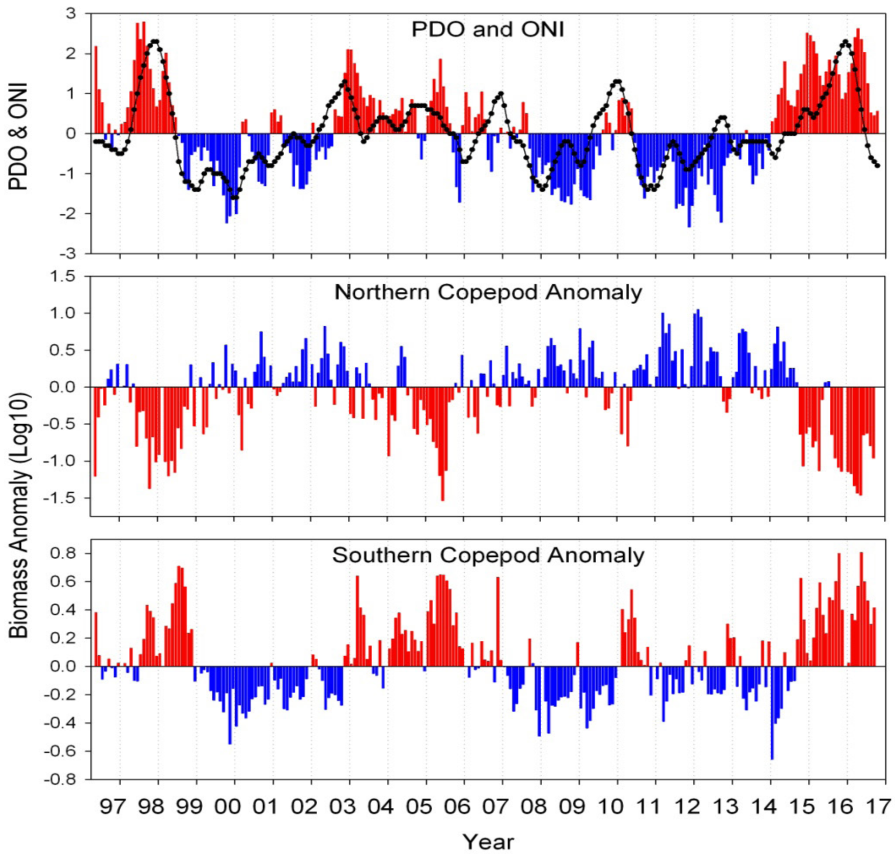


Figure 6. *Monthly time series of the Pacific Decadal Oscillation and Oceanic Niño Index (upper) and monthly-averaged biomass anomalies of northern copepods (middle) and southern copepods (lower). Note the high coherence between the PDO and ONI with the copepod time series – positive anomalies of northern copepods are correlated with negative PDO and ONI; positive anomalies of southern copepods are correlated with positive PDO and ONI.*

S2.3 Coastal ocean response to ENSO, models and observations (Edwards & Rudnick)

This session summary has been converted into an article for the US CLIVAR Variations Winter 2017 edition, entitled ***Dominant physical mechanisms driving ecosystem response to ENSO in the California Current System*** *(Jacox et al. 2017).*

Combining high-resolution ocean models with the long-term observations from the CalCOFI program and the more recent high resolution hydrography from California Underwater Glider Network allows for unprecedented look at the coastal signature of ENSO events. These datasets and others are used to produce a 31 year (1980–2010) sequence of historical analyses of the CCS (Moore et al. 2011; Neveu et al. 2016). The model domain spans the west coast of the United States from 30 to 48°N and 115 to 134°W at 0.1° horizontal resolution with 42 terrain-following levels in the vertical. Surface winds are taken from the European Centre for Medium-range Weather Forecasting (ECMWF) 40 year reanalysis (ERA 40) for 1980–1987 and from the Cross-Calibrated Multiplatform (CCMP; Atlas et al. 2011) wind product for 1988–2010. Heat, freshwater, and radiative surface fluxes are provided by ERA 40 (Uppala et al. 2005) for 1980–2001 and ERA Interim (Dee et al. 2011) for 2002–2010.

ENSO impacts on seasonal timescales

The model analysis period captures 10 El Niños and 10 La Niña events, including the extremes of 1982–1983 and 1997–1998. Figure 7 summarizes the climatological upwelling signature in the central CCS as well as anomalies introduced by El Niño events. In general, El Niño generates a deep pycnocline and weak upwelling (or downwelling), and surface waters carry the signature of a relatively rare and shallow source (note that here the word rare is used in its original meaning as the opposite of dense, or more specifically "having the constituent material or particles loose or not closely packed together; not dense or compact; attenuated" (OED online 2014)). These effects first appear in winter, coincident with maximum tropical SST anomalies associated with the El Niño peak.

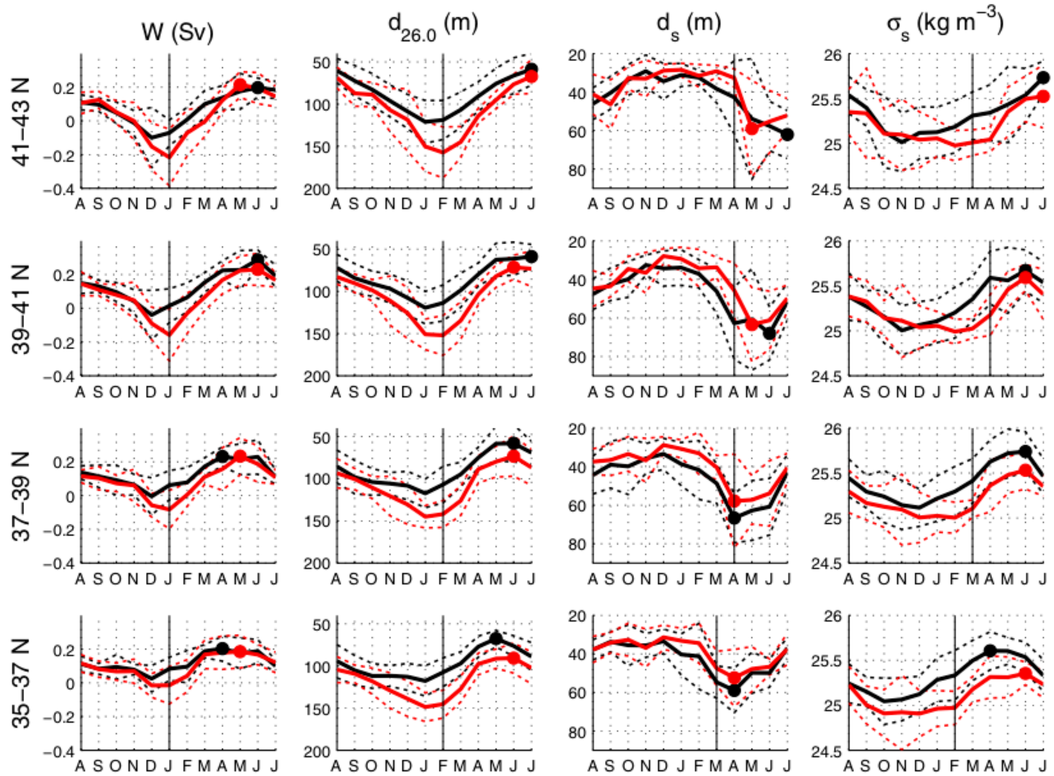


Figure 7. *Monthly climatology of vertical transport (W), pycnocline depth (d26.0), source depth (ds), and source density (sigma) for neutral ONI years (black) and for El Niño years (red) in each 2° latitude bin from 35–43° N. Dotted lines indicate 6 one standard deviation of the values for each month. Colored dots mark upwelling season minima or maxima of each time series. Vertical black lines indicate months of greatest difference between El Niño and neutral years. Note the time axis runs August–July to reflect the typical timing of El Niño events and their impact on coastal upwelling. (From Jacox et al. 2015)*

ENSO impacts on interannual timescales

The impacts of ENSO on upwelling are also evident on interannual scales with a significant lagged response in the CCS that varies between 1-3 months. An analysis of the relation between the ONI and different measures of upwelling suggest that both atmospheric and oceanic teleconnections play an important role (Figure 8). For example, the 1-month lag response in the winds suggest an atmospheric teleconnections, while the 3-month lag response in the source density of the upwelled water suggest an oceanic waveguide ENSO coastal signature.

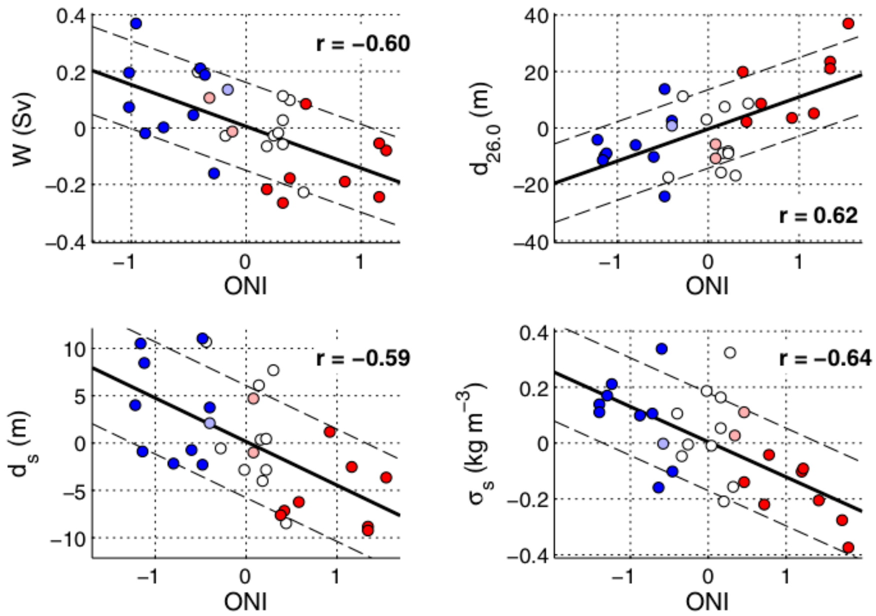


Figure 8. *Upwelling season (March–July) anomalies of vertical transport (W), pycnocline depth (d26.0), source depth, and source density (sigma) plotted against the ONI. W correlates most strongly with the ONI at one month lag, d26.0 and ds lag the ONI by two months, and sigma has a 3 month lag. Therefore, the ONI averaging period is February–June for W, January–May for d26.0 and ds, and December–April for sigma. Dashed lines indicate 6 one standard deviation of the dependent variable. (From Jacox et al. 2015)*

In general, El Niño events produce anomalously weak upwelling and source waters that are unusually shallow, warm, and fresh, while La Niña conditions produce the opposite. Maximum vertical transport anomalies in the CCS occur ~1 month after El Niño peaks in midwinter, and before the onset of the upwelling season. Source density anomalies peak later than transport anomalies and persist more strongly through the spring and summer, causing the former to impact the upwelling season more directly. As nitrate concentration covaries with density in the central CCS, El Niño may exert more influence over the nitrate concentration of upwelled waters than it does over vertical transport, although both factors are expected to reduce nitrate supply during El Niño events. Interannual comparison of individual diagnostics highlights their relative impacts during different ENSO events, as well as years deviating from the canonical response to ENSO variability.

To explore the joint impact of vertical transport and source water composition, Jacox et al. (2015) construct an “Upwelling Efficacy Index” (UEI, Figure 9), defined as the first principal component of the four explanatory variables shown in Figure 8. The UEI captures 84% of the variance in its four constituent variables and correlates with each of them at r ~ 0.9. Inasmuch as density is a proxy for nitrate supply, the UEI is a proxy for nitrate flux during upwelling, which depends on both vertical transport and nitrate concentration in source waters. Negative values of the UEI indicate anomalously low nitrate flux into the mixed layer from below. The UEI better defines a proxy for productivity as evident by the strong correlation with observed CHla (Figure 9).

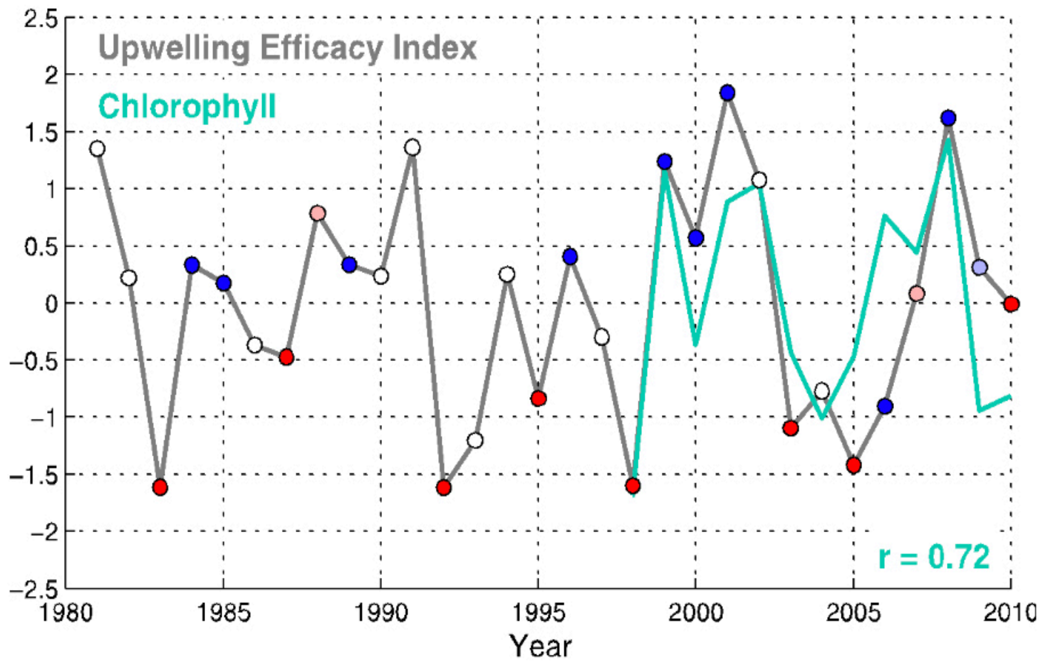


Figure 9. *Time series of the Upwelling Efficacy Index (gray) and SeaWiFS chlorophyll (green). Chlorophyll is averaged from March to July, and over the region 35–43° N and 0–300 km from shore. Red dots are El Niño years, blue dots are La Niña years, and pale red (blue) dots are El Niño (La Niña) years that do not meet our additional criteria of the Oceanic Niño Index – ONI>0 (ONI<0) – for the upwelling season. (From Jacox et al. 2015)*

The 2015-2016 ENSO impacts

While we find strong recurrent associations between ENSO and key upwelling parameters in the CCS, individual events can show non-canoncial responses. The 2015–2016 El Niño is by some measures one of the strongest on record, comparable to the 1982–1983 and 1997–1998 events that triggered widespread ecosystem change in the northeast Pacific. However, its impacts on the physical state of the CCS are weaker than expected based on tropical sea surface temperature anomalies; temperature and density fields reflect persistence of multiyear anomalies more than El Niño. One potentially important difference from the previous strong El Niño is the fact that the 2015-16 event had more of a central Pacific expression with little waveguide activities.

Session 3: Dynamical and statistical modeling for ecosystem forecasts

The goal of this session was to identify a set of modeling platforms that show promise for forecasting ENSO impacts on marine ecosystems. These modeling platforms can be dynamical or statistical, or a combination of both. Participants reviewed the hindcast and predictability potential of existing models, assessed the data needs to make these models operational, and identified new modeling approaches.

S3.1 Biogeochemical models (Siedlecki)

Acidification and deoxygenation in coastal waters are of increasing concern to local fisheries. Many economically or ecologically important species (e.g., oysters, crabs, phytoplankton, zooplankton) in the Pacific Northwest are expected to feel direct effects of ocean acidification. Direct effects have been observed on the $100 million shellfish industry, and additional indirect economic impacts are possible on the finfish industry due to a loss of prey species. The ability to predict the degree of acidification, as well as relevant indices of impact for species of interest, could be of considerable benefit to managers. A seasonal ocean prediction system, the University of Washington's J-SCOPE, has recently been utilized in the coastal waters of the Pacific Northwest (Siedlecki et al. 2016; Kaplan et al. 2016). The goal has been to provide seasonal (six month) predictions of ocean conditions that are testable and relevant to management decisions for fisheries, protected species, and ecosystem health components. The results include integrated ecosystem assessment products (e.g., forecasts of ecological indicators).

J-SCOPE forecasts (2009, 2013-2014) of subsurface ocean conditions have measurable skill on seasonal timescales for variables relevant to management decisions for fisheries, protected species, and ecosystem health (Siedlecki et al. 2016; Figure 10). The skill is greater for subsurface variables like bottom temperature and bottom oxygen, than for SST, but forecasts have skill several months into the future.

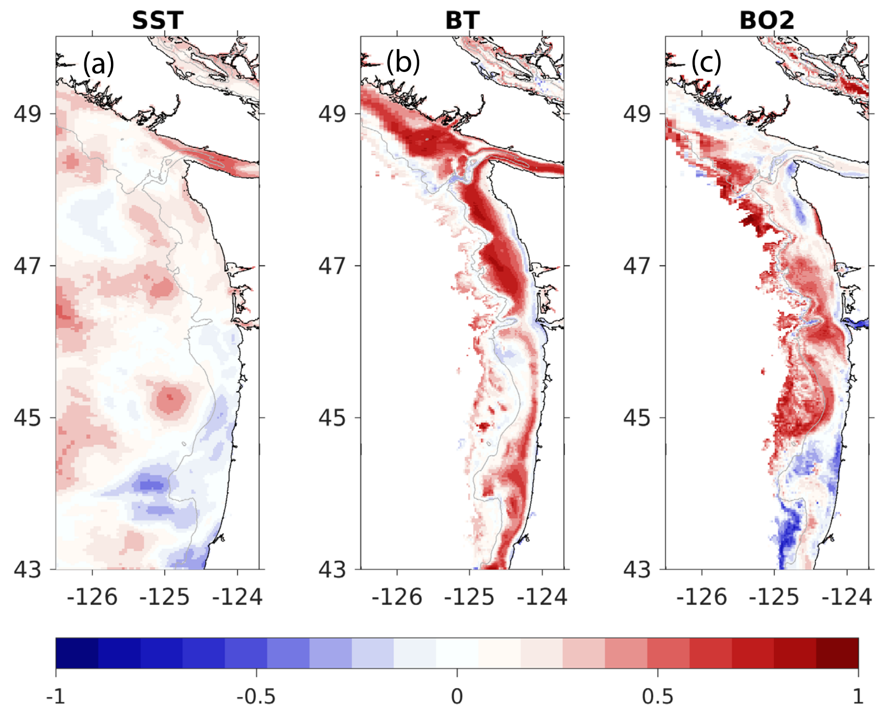


Figure 10. *Plot of model performance comparing forecasted anomalies to hindcasted anomalies, for four forecasts and three ocean conditions. Each map shown represents R, based on six monthly anomaly maps (April, May, June, July, August, September). The comparison demonstrates skill when R > 0.5. Each panel displays a different model field (a) SST, (b) bottom temperature (c) bottom oxygen. All panels highlight the 200-meter isobaths as an indication of the shelf break. (From Siedlecki et al. 2016)*

Forecasting efforts benefit from a relationship with local stakeholders and managers, as well as a real-time observational network (Siedlecki et al. 2016; Hobday et al. 2016). When communicating the forecasts, physical and biogeochemical forecasts need to be placed within the context of the high variability in the region. J-SCOPE has created a climatology (2009-present) of ocean conditions in the region and is now reporting forecasts as anomalies from the climatology. The climatology from the model can also be used to identify regions that regularly experience stressful conditions and potentially influence habitat for species sensitive to those conditions.

The forecasted conditions are most effectively communicated if packaged with end users in mind, like the tuna products displayed on the Northwest Association of Networked Ocean Observing Systems (NANOOS). To that end, J-SCOPE is working toward forecasting indices designed with management in mind, like those variables identified by the California Current integrated ecosystem assessment. Long-term monitoring is essential to establish these relationships between environmental variables and biological indices, but in the absence of data, a well-validated model can be used to expand our records in time and space. If the indices are to be forecasted, Kaplan et al. (2016) found that training the empirical model-based index on the environmental fields from the model rather than observations is instrumental to the success of the index. All models, but especially forecast models, exhibit a bias in some environmental fields. And by training the index on the biased conditions, the forecasted index has more success.

Using J-SCOPE, several species-specific indices with end users in mind are in development: sardines, hake, crab, shellfish, and pteropods. Challenges of this approach include availability of biological datasets for testing, biases of forecast models, and limitations of empirical models for indices (e.g., they solely depend on what you put in them). Sardine habitat was chosen to forecast within J-SCOPE's domain because the northern extent of sardine observations exhibits large interannual variability. This phenomenon is potentially driven by environmental variability and consequently was a perfect candidate for this experiment. For crab and shellfish indices, the scope of seasonal oceanographic forecasts from J-SCOPE is expanded to explicitly include acidification, with new acidification indices from model output relevant to biological impacts (e.g., severity index for shellfish, and a risk habitat for crab megalopae). These indices are being developed in collaboration with local stakeholders and managers.

S3.2 Modeling and forecasting lower trophic level impacts (Rousseaux)

Satellite ocean color missions (i.e., SeaWiFS, MODIS, Suomi-VIIRS) have provided data on global phytoplankton concentrations since 1998. These data have substantially improved our understanding of the drivers and dynamics of chlorophyll, which represents the base of the food web. The assimilation of satellite ocean color data has not only yielded valuable ecosystem information such as phytoplankton diversity, but has also provided a complete global dataset free of gaps, due to clouds and aerosols that are common in individual satellite datasets. While forecast models of physical oceanic and atmospheric conditions have considerably improved over the past few decades and are routinely used to predict ocean state and weather patterns including hurricanes, winds, and other potentially threatening conditions, the forecast of ocean biogeochemistry has been limited in terms of areas and variables forecasted.

The presentation demonstrated how ocean and atmospheric forecast data (wind stress, SST, and shortwave radiation) produced by a forecasting system are used to develop a seasonal biogeochemical forecast (Figure 11). Forecast skills were evaluated using satellite ocean color data in the context of the 2015 El Niño event. The biogeochemical forecast was in agreement with the dynamical conditions in which the increase in central Pacific SST observed during the 2015 El Niño event reversed, and the surfacing of colder water signaled a return to normal or potentially the development of La Niña conditions.

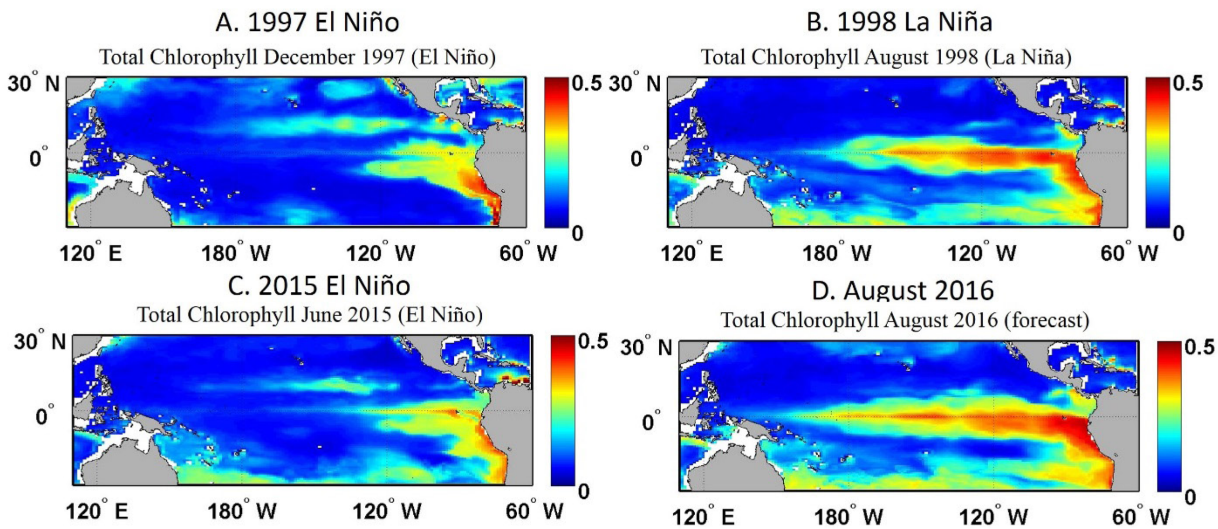


Figure 11. *Spatial distribution of chlorophyll concentration (μg L-1) in (A) December 1997, (B) August 1998, (C) June 2015, and (D) forecast (January 2016) of chlorophyll concentration for August 2016 using the NASA Ocean Biogeochemical Model (NOBM) and the Global Modeling and Assimilation Office forecast.*

While still in its infancy, forecasting of ocean biogeochemistry will have numerous applications. It can, for example, improve fisheries management and offer the potential for strategic rather than reactive marine resource management during these events. Biogeochemical forecasts can also inform monitoring, prediction, and management of harmful algal blooms, as well as much needed support for ocean field campaigns such as NAAMES (North Atlantic Aerosols and Marine Ecosystems Study), Arctic-COLORS (Arctic-Coastal Land Ocean inteRactionS in the Arctic), and EXPORTS (Export Processes in the Ocean from RemoTe Sensing).

S3.3 Modeling and forecasting higher trophic levels and top predators (Hazen)

*The discussions that took place during this session have been summarized in detail in an article entitled **Modeling to aid management of marine top predators in a changing climate** in the Winter 2017 editions of the US CLIVAR and OCB publications (Hazen et al. 2017).*

Highly migratory species are inherently difficult to manage as they cross human-imposed jurisdictional boundaries in the open seas. Top predators face threats such as ship-strike risk and non-target catch (bycatch) in fisheries. Current management approaches use large-scale seasonal closures to avoid bycatch of highly migratory predators, but we also want to explore dynamic ocean management that tracks ocean features in space and time. Since many top predators migrate seasonally across ocean basins, targeted management approaches require an understanding of how distribution and abundance varies with the oceanic environment through time. Given that these data are often sparse and can be collected using a variety of platforms (e.g., fisheries catch, survey data, telemetry studies), an approach that synthesizes across data type would provide a more holistic understanding. This study operationalized the concept of dynamic ocean management for the California drift gillnet fishery, a fishery that targets swordfish, thresher shark, and mako shark, but also can catch a number of species as bycatch, including sea lions, sea turtles, and blue sharks. While still in the formative stage, this tool, termed EcoCast (Figure 12), uses habitat models and risk weightings to estimate catch/bycatch ratios in near time. The EcoCast tool was employed for two years, 2012 (an average year) and 2015 (an El Niño year), to examine how predicted patterns in catch and bycatch change. These approaches could be applied to other migratory species for which telemetry, catch, or survey data are available, and emphasizes the utility of integrating multiple data types for marine conservation and management.

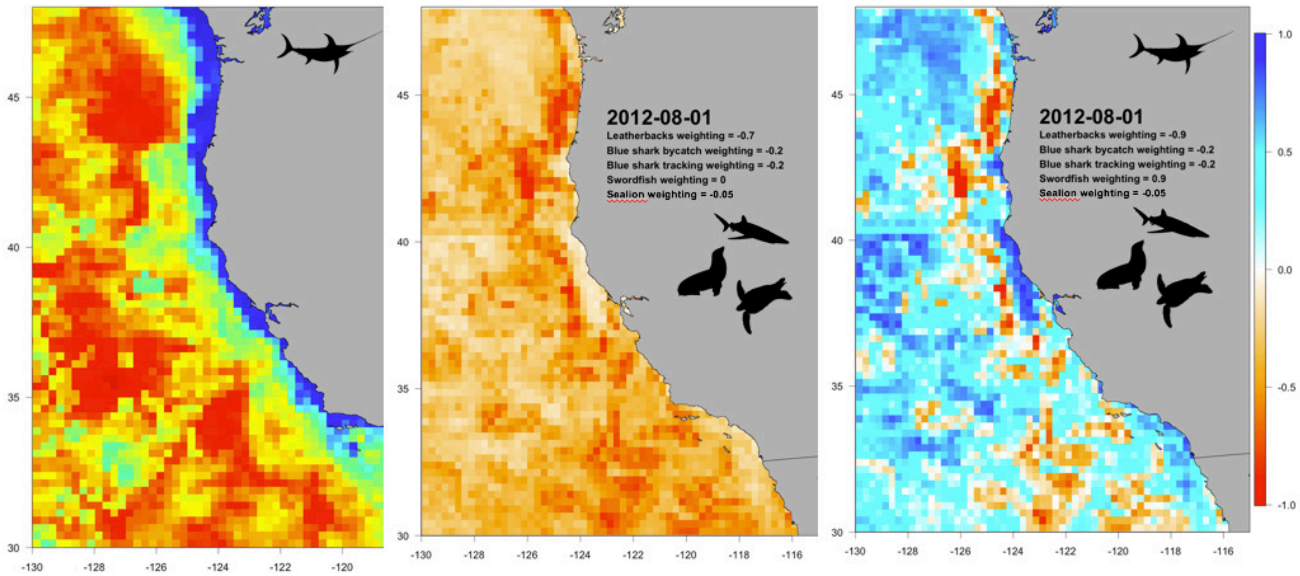


Figure 12. *Example of EcoCast predictions. (Adapted from Hazen et al. 2018)*

Session 4: Data streams and operational ecosystem forecasts

This session was devoted to identifying the technical challenges in implementing an operational forecast of ENSO impacts on marine ecosystems. These challenges include: (1) prioritizing ecological indicators to forecast, (2) obtaining real-time access to the required data streams for the model forecasts and developing new required data streams, (3) providing uncertainty estimates on the forecasts, and (4) developing effective strategies for communicating with stakeholders and the general public.

S4.1 Operational forecasting of ocean conditions from NOAA-NCEP (Wang)

The current NOAA National Centers for Environmental Prediction (NCEP) Climate Forecast System version 2 (CFSv2) forecast is produced daily with four forecast runs covering nine target months and sixteen forecast runs covering forty-five target days. Monthly and seasonal forecast products can be developed based on lagged ensembles of the forecast runs. The forecast is evaluated for the mean sea-level pressure, surface wind stress, and SST. The system has some skill near the US West Coast, as measured with anomaly correlation coefficient, for monthly forecasts with a lead-time of 10-15 days (Figure 13). Seasonal skill is higher in winter/spring than in summer/fall, which likely reflects the seasonality of the ENSO signals, which are stronger in winter/spring than in summer/fall.

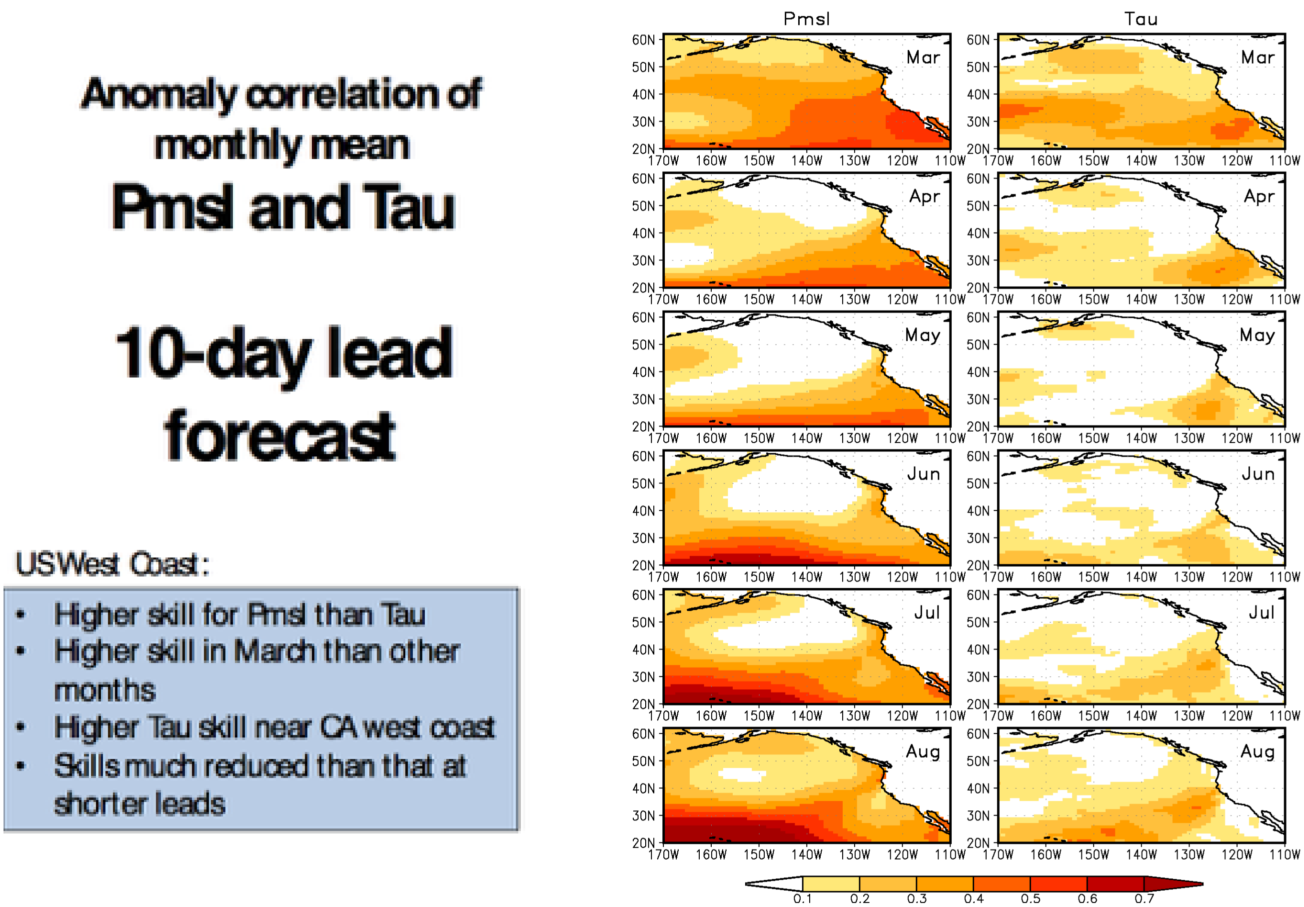


Figure 13. *Example of 10-day lead forecast from the NOAA-NCEP-CFSv2 system for sea level pressure (left column) and upper ocean temperatures (right column).*

S4.2 Data streams for data assimilation and forecasting from the US Navy (Frolov)

The US Navy Earth Systems Prediction Capability (ESPC) is a global coupled high-resolution system for extended range prediction, with plans to implement a seasonal ensemble system for seasonal forecasting. The design of the ESPC ensemble prediction system is similar to the designs of extended range ensembles operated by other National Weather Prediction agencies, and it can serve as a guide for the design of a West Coast prediction system, taking into consideration: (1) the sensitivity of West Coast ecosystem (WCE) forecasts to the exact storm sequences – specifically, is it important to drive the WCE forecasts with a diversity of plausible storm forecasts or is it sufficient to just present the forecast with one plausible realization of storms? – and (2) the sensitivity of WCE forecasts to the internal chaos of the system compared to the uncertainty in the global seasonal forecasts that will drive the system.

S4.3 Ecosystem forecasts (Alexander)

As a first step in the process of ecological forecasting, investigators have explored SST forecasts in large marine ecosystems (LMEs), including the CCS from the coupled climate models in the North American Multi-Model Ensemble (NMME, Kirtman et al. 2014). As in most regions, the ensemble mean monthly SST predictions for the CCS have greater skill than those from most individual models (Figure 14), especially for probability forecasts.

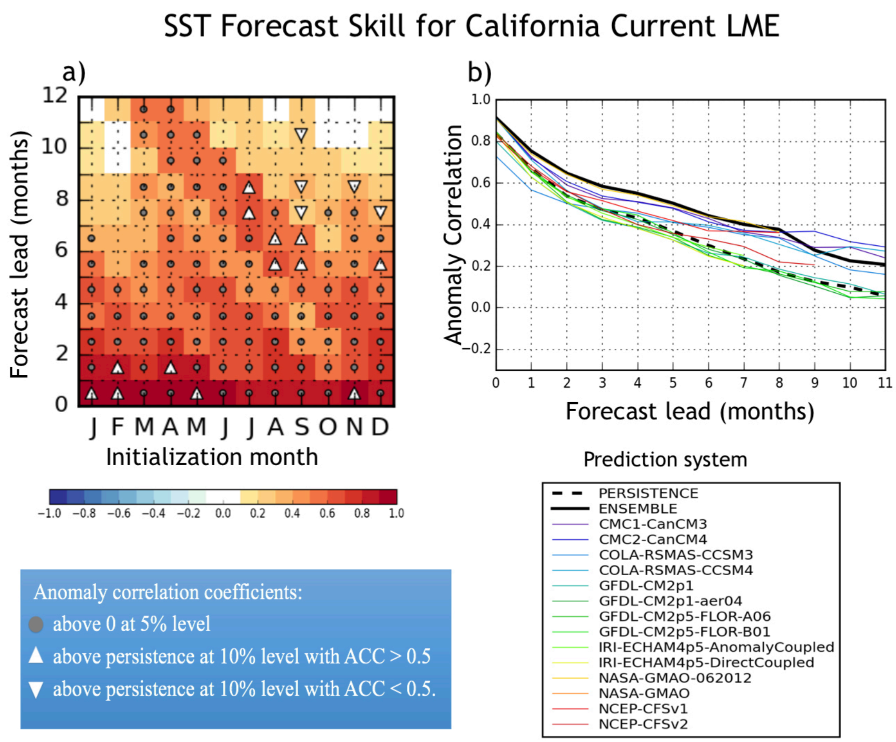


Figure 14. *(a) Anomaly correlation coefficients (AACs) between observations and the multi-model mean monthly forecasts as a function of the initialization month (x-axis) and lead-time (y-axis). Gray dots indicate ACCs significantly above 0 at 5% level, white upward triangles indicate ACCs significantly above persistence at 10% level with ACC>0.5. White downward triangles indicate ACCs significantly above persistence at 10% level with ACC<0.5. b). Average of the ACCs over all 12 initialization months as a function of forecast lead-time (x-axis).*

Several mechanisms that could drive SST predictability in the CCS are explored using the Canadian forecast model (CanCM4), perhaps the most skillful NMME member in the CCS. On seasonal timescales, correlations between SST in the CCS and across the Pacific basin display an ENSO-like spatial pattern. This pattern indicates predictability originating in the northeast Pacific (persistence), as well as in the tropical Pacific (related to ENSO variability). Persistence contributes skill especially at short lead-times. The skill above persistence is concentrated in a band that represents forecasts of February-July SST with lead times >5 months. A simple linear regression analysis using the Niño 3.4 Index suggests that most of the dynamical model skill above persistence is related to predictable evolution of ENSO variability. In other words, model skill appears to derive from persistence plus a predictable local manifestation of tropical temperature anomalies.

Clearly predicting SSTs is just an initial step towards marine ecological forecasts. Nevertheless, SST forecasts have recently been shown to improve predictions of sardine biomass (Tomassi et al. 2016) in the CCS. More direct ecosystem forecasts depend on a number of factors, including: (1) how to (best) downscale the climate model output to regional scales for the CCS and other regions, (2) how to initialize chemical and biological fields, given the lack of data, (3) how to assess forecast skill at sub-seasonal timescales (e.g., predicting the onset of the upwelling season three weeks in advance), and (4) how to characterize uncertainty, especially given the lack of deterministic atmospheric forecast skill beyond two weeks.

S4.4 Seasonal forecasts of ocean conditions in the California Current Large Marine Ecosystem (Tommasi)

*The discussions that took place during this session have been summarized in detail in an article entitled **Seasonal forecasts of ocean conditions in the California Current Large Marine Ecosystem** in the Winter 2017 editions of the US CLIVAR and OCB newsletters (Tommasi et al. 2017).*

Recent advances in ENSO prediction and global dynamical seasonal climate prediction systems have enabled skillful seasonal forecasts of SST anomalies in the CCLME after bias correcting the forecasts to remove model drift (Stock et al. 2015; Jacox et al. 2019; Hervieux et al. 2019). Skill of SST anomaly predictions produced by the National Atmospheric and Oceanic Administration (NOAA) North American Multi-Model Ensemble (NMME) are shown in Figure 15. Skill is evaluated through the anomaly correlation coefficient (ACC) between monthly SST anomalies from retrospective forecasts from 1982 to 2009 and observed SST anomalies. Forecasts are skillful (ACC > 0.6) across initialization months for lead times up to ~4 months. Persistence of the initialized SST anomalies provides much of the prediction skill at these short lead times (Stock et al. 2015, Jacox et al. 2019). Pre-existing temperature anomalies at depth may also provide some predictability. Skillful forecasts of February, March, and April SST extend to lead times greater than 6 months (Stock et al. 2015; Jacox et al. 2019). This ridge of enhanced predictive skill for winter to early spring forecasts is apparent across seasonal forecasting models, and arises from the ability of the prediction systems to capture the wintertime coastal signature of predictable basin-scale SST variations (Jacox et al. 2019, Stock et al. 2015). Specifically, the models can skillfully forecast the predictable evolution of meridional winds during ENSO events and the associated changes in upwelling anomalies and SST in the CCLME (Jacox et al. 2019).

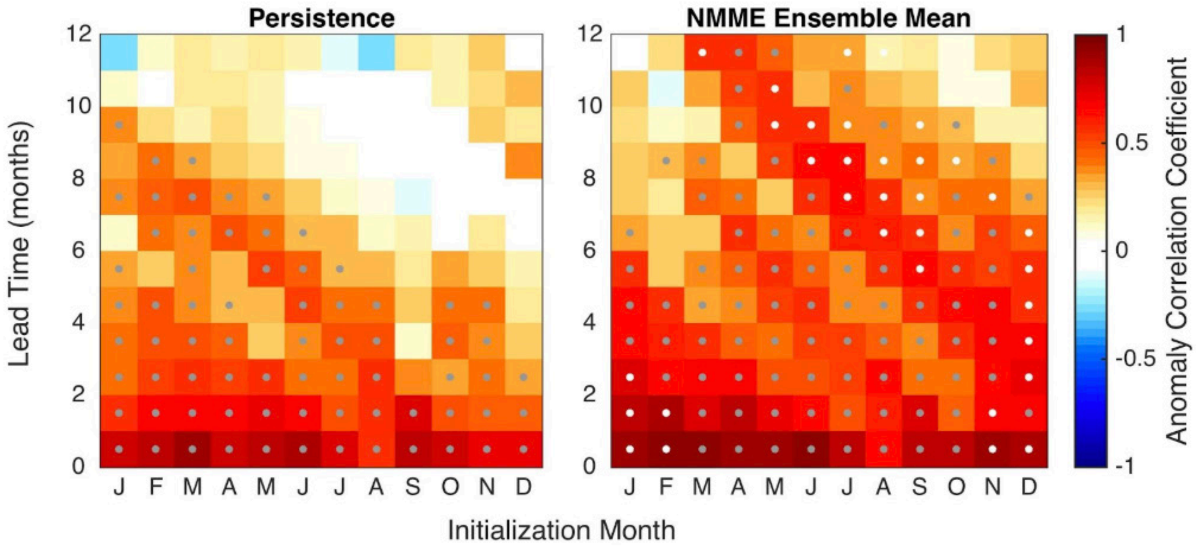


Figure 15. *Anomaly correlation coefficients (ACCs) as a function of forecast initialization month (x-axis) and lead-time (y-axis) for persistence, and the National Atmospheric and Oceanic Administration (NOAA) North American Multi-Model Ensemble (NMME) for the California Current system (US west coast, less than 300 km from shore). Note the ridge of high SST anomaly prediction skill exceeding persistence at long lead-times (4-12 months) for late winter-early spring forecasts. Grey dots indicate ACCs significantly above 0 at a 5% level; white dots indicate ACCs significantly above persistence at a 5% level. (Adapted from Jacox et al. 2019).*

Application of seasonal SST forecasts to inform dynamic management of living marine resources was pioneered in Australia (Hobday et al. 2011), where seasonal SST forecasts are now operationally used to improve the decision making of the aquaculture industry (Spillman and Hobday 2014; Spillman et al. 2015), fishers (Eveson et al. 2015), and fisheries managers (Hobday et al. 2011). Through both increased awareness of climate prediction skill at fishery-relevant scales and of their value to ecosystem based management, such efforts have now begun to expand to other regions (see Tommasi et al. 2017a, and case studies therein). In the CCLME, recent work demonstrates that integration of current March SST forecasts into fisheries models can provide useful information for catch limit decisions for Pacific sardine (i.e., how many sardine can be caught each year) when combined with existing harvest cutoffs (Tommasi et al. 2017b). Knowledge of future SST conditions can improve predictions of future recruitment and stock biomass, and allow for the development of a dynamic management framework, which could increase allowable fisheries harvests during periods of forecasted high productivity and reduce harvests during periods of low productivity (Tommasi et al. 2017b). Hence, integration of skillful seasonal forecasts into management decision strategies may contribute to greater long-term catches than catches set by management decisions based solely on past SST information or on no environmental information at all (Figure 16, Tommasi et al., in press).

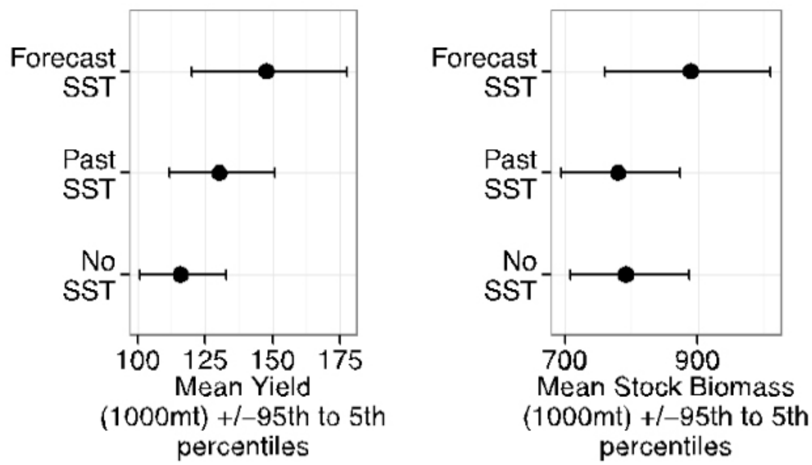


Figure 16. *Mean long-term Pacific sardine catch and biomass following catch limit decisions integrating different levels of environmental information. The catch limit incorporating future SST information reflects the uncertainty of a 2-month lead forecast. (Adapted from Tommasi et al. 2017b)*

Novel dynamical downscaling experiments in the Northern California Current as part of the J-SCOPE project (Siedlecki et al. 2016) show that seasonal climate forecasts may be of potential utility also for dynamic spatial management strategies in the CCLME (Kaplan et al. 2016). Predictions of ocean conditions from a global dynamical climate prediction system (NOAA NCEP CFS) forced the Regional Ocean Modeling System (ROMS) with biogeochemistry to produce seasonal forecasts of ocean conditions, both at the surface and at depth, with measureable skill up to a 4-month lead time (Siedlecki et al. 2016). The downscaling, in addition to enabling forecasts of fishery-relevant biogeochemical variables such as chlorophyll, oxygen, and pH not yet produced by global forecasting systems, resolved the fine-scale physical and ecological processes influencing the distribution of managed species within the CCLME. For instance, high-resolution regional implementations of ROMS are better able to resolve upwelling and coastal waves dynamics (Jacox et al. 2015; Siedlecki et al. 2016), two processes that drive the CCLME response to ENSO variability. Downscaled forecasts also served to develop prototype forecasts of Pacific sardine spatial distribution (Kaplan et al. 2016). Such forecasts have the potential to inform fishing operations and fisheries surveys, and to be considered as a factor in setting the US and Canadian quotas for this internationally shared stock (Kaplan et al. 2016; Siedlecki et al. 2016; Tommasi et al. 2017a).

These CCLME case studies suggest that with recent advancements in state-of-the-art global dynamical prediction systems and regional downscaling models, some skillful seasonal predictions of ocean conditions are possible (Siedlecki et al. 2016; Tommasi et al. 2017a). Seasonal forecast skill may be further improved by better representation in seasonal forecast systems of other potential sources of prediction skill such as ocean eddies and gyre circulations in the extratropics and the basin-wide atmospheric response to SST anomalies in the Kuroshio-Oyashio region (Smirnov et al. 2015). Such skillful seasonal forecasts present opportunities for inclusion in climate-ready management strategies for improved living marine resource management and for better informed industry operations in the CCLME.

3 DEVELOPING AN ECOSYSTEM FORECASTING FRAMEWORK

The joint US CLIVAR/OCB/NOAA/PICES/ICES workshop on Forecasting ENSO impacts on marine ecosystems of the US West Coast (Di Lorenzo and Miller 2017) held in La Jolla, California, in August 2016 outlined a three-step strategy to better understand and quantify the ENSO-related predictability of marine ecosystem drivers along the US West Coast (Figure 17). **The first step** is to use a high-resolution ocean reanalysis to determine the association between local ecosystem drivers and regional forcing patterns (RFPs). The identification of ecosystem drivers will depend on the ecosystem indicators or target species selected for prediction (Ohman et al. 2017). **The second step** is to objectively identify the tropical SST patterns that optimally force the RFPs along the US West Coast region using available long-term large-scale reanalysis products. While the goal of the first two steps is to understand the dynamical basis for predictability (Figure 17, blue path), **the final third step** (Figure 17, orange path) aims at quantifying the predictability of the RFPs, and estimating their prediction skill at seasonal timescales. This third step can be implemented using the output of multi-model ensemble forecasts such as the North America Multi-Model Ensemble (NMME) or by building efficient statistical prediction models such as Linear Inverse Models (LIMs; Newman et al. 2003).

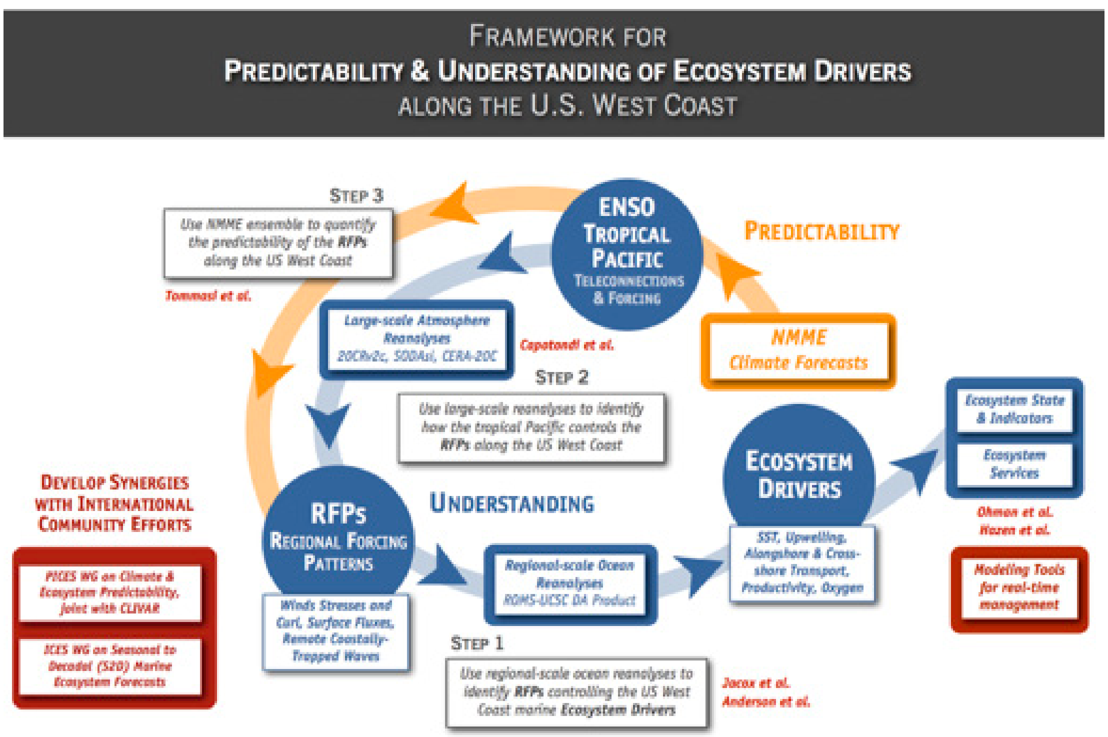


Figure 17. *Framework for understanding and predicting ENSO impacts on ecosystem drivers. Blue path shows the steps that will lead to* **Understanding** *of the ecosystem drivers and their dependence on tropical Pacific anomalies. Orange path shows the steps that will lead to quantifying the* **Predictability** *of marine ecosystem drivers along the US West Coast that are predictable from large-scale tropical teleconnection dynamics.*

Important to the concept of ENSO predictability is the realization that the expressions of ENSO are very diverse and cannot be identified with a few indices (Capotondi et al. 2015; 2017). In fact, different expressions of SST anomalies (SSTa) in the tropics give rise to oceanic and atmospheric teleconnections that generate different coastal impacts in the northeast Pacific. For this reason, we will refer to ENSO as the collection of tropical Pacific SSTa that lead to deterministic and predictable responses in the regional ocean and atmosphere along the US West Coast.

In the sections below, we discuss the elements of the framework for quantifying the predictability of ENSO-related impacts on coastal ecosystems along the US West Coast (Figure 17). Our focus is on the CCS, reflecting the regional expertise of the workshop participants. Specifically, we discuss (1) the ecosystem drivers and what is identified as such, (2) RFP definitions, and (3) the teleconnections from the tropical Pacific and their predictability.

3.1. Identifying ecosystem drivers in the California Current System

The impacts of oceanic processes on the CCS marine ecosystem have been investigated since the 1950s when the long-term CalCOFI time-series program began routine seasonal sampling of coastal ocean waters. The CalCOFI program continues today and has been augmented with several other sampling programs (e.g., the coastal ocean observing network), leading to an unprecedented understanding of how climate and physical oceanographic processes, such as upwelling, drive ecosystem variability and change (e.g., King et al.2011; Ohman et al. 2013; Di Lorenzo et al. 2013).

The dominant physical oceanographic drivers of ecosystem variability occur on seasonal, interannual, and decadal timescales and are associated with changes in (1) SST, (2) upwelling velocity, (3) alongshore transport, (4) cross-shore transport, and (5) thermocline/nutricline depth (Ohman et al. 2017). Ecosystem response to these drivers occurs at multiple trophic levels, including phytoplankton, zooplankton, small pelagic fish, and top predators, and several examples have been identified for the CCS (see summary table below from Ohman et al. 2017). This set of ecosystem drivers and responses emerged from discussions among experts at the workshop.

Table 1. Examples of water column biological processes and organisms known to be affected by El Niño in the California Current System. Columns indicate the type of organism; approximate geographic region and season of the effect; direction of change in response to El Niño; temporal pattern of response (immediate, time-lagged, time-integrated); and the hypothesized oceanographic processes driving the organism response. CCS = California Current System; NCCS, CCCS, and SCCS denote northern, central, and southern sectors of the CCS.

Ecosystem indicator	Region & season	Change during El Niño	Time scale of response	Regional ocean processes
Primary production	Entire CCS winter, spring, summer	Declines	Variable lag; instantaneous or time-lagged	Reduced upwelling, nutrient fluxes; deeper nutricline & weaker winds
Pseudo-nitzschia diatoms; Domoic Acid	Entire CCS spring-summer	Blooms	1-3 month lag	Elevated temp; Altered nutrient stoichiometry
Copepod assemblage	NCCS spring-summer	Warm water species appear	Nearly instantaneous	Poleward advection; reduced upwelling, warmer temp
Subtropical euphausiids	SCCS spring-summer	Increase	Nearly instantaneous; persists beyond Niño event	Poleward advection
Cool water euphausiids	Entire CCS spring-summer	Decrease	Time-lagged	Reduced upwelling; Anomalous advection
Pelagic red crabs	SCCS & CCCS winter, spring, summer	Increase	Nearly instantaneous	Poleward advection
Market squid	CCCS & SCCS winter & spring	Collapse	Instantaneous for distribution; time-lagged for recruitment	Warmer temp/deeper thermocline; reduces spawning habitat
Pacific sardine	Entire CCS winter-spring	Changes in distribution; compression of spawning habitat	Instantaneous for spawning & distribution, recruitment time-lagged, biomass is time-integrated	Wind stress, cross-shore transport
Northern anchovy	CCCS & SCCS winter-spring	Changes in distribution; compression of spawning habitat	Instantaneous for spawning & distribution, recruitment time-lagged, biomass is time-integrated	Reduced upwelling; anomalous advection
Juvenile salmon survival	NCCS spring-summer	Decrease in Pacific NW	Time-integrated	Reduce river flow, decreased food supply in ocean
Adult sockeye salmon (Fraser River)	NCCS summer	Return path deflected northward to Canadian waters	Time-integrated	Ocean temp, including Ekman controls
Warm assemblage of mesopelagic fish	SCCS spring (?)	Increase	Lagged 0-3 months	Poleward and onshore advection
Common murre (reproductive success)	CCCS winter-spring	Decrease	Time-Lagged, time-integrated	Prey (fish) availability; thermocline depth; decreased upwelling?
Top predator reproduction and abundance	Entire CCS	Species-dependent	Time-integrated	Advection of prey, altered temp, upwelling, mesoscale structure
Top predator distribution	Entire CCS	Altered geographic distributions	Instantaneous or time-lagged	Advection of prey, altered temp, upwelling, mesoscale structure

While much research has focused on diagnosing the mechanisms by which these physical drivers impact marine ecosystems, less is known about the dynamics controlling the predictability of these drivers. As highlighted in Ohman et al. (2017), most of the regional oceanographic drivers (e.g., changes in local SST, upwelling, transport, thermocline depth) are connected to changes in large-scale forcings (e.g., winds, surface heat fluxes, large-scale SST and sea surface height patterns, freshwater fluxes, and remotely forced coastally trapped waves entering the CCS from the south). In fact, several studies have documented how large-scale changes in wind patterns associated with the Aleutian Low and the North Pacific Oscillation drive oceanic modes of variability such as the Pacific Decadal Oscillation and the North Pacific Gyre Oscillation (Mantua et al. 1997; Di Lorenzo et al. 2008; Chhak et al. 2009; Ohman et al. 2017; Jacox et al. 2017; Anderson et al. 2017; Capotondi et al. 2017) that influence the CCS. However, these large-scale modes only explain a fraction of the ecosystem's atmospheric forcing functions at the regional scale. Thus, it is important to identify other key forcings in order to gain a more complete mechanistic understanding of CCS ecosystem drivers (Jacox et al. 2014; 2015).

3.2. Connecting to the atmospheric and oceanic regional forcing patterns

The dominant large-scale quantities that control the CCS ecosystem drivers are winds, heat fluxes, and remotely forced coastally trapped waves (Hickey 1979). Regional expressions or patterns of these large-scale forcings have been linked to changes in local stratification and thermocline depth (Veneziani et al. 2009a; 2009b; Combes et al. 2013), cross-shore transport associated with mesoscale eddies (Kurian et al. 2011; Todd et al. 2012; Song et al. 2012; Davis and Di Lorenzo 2015b), and along-shore transport (Davis and Di Lorenzo 2015a; Bograd et al. 2015). For this reason, we define the regional expressions of the atmospheric and remote wave forcing that are optimal in driving (e.g. most efficient in energizing the variability of) SST, ocean transport, upwelling, and thermocline depth as the RFPs. To clarify this concept, consider the estimation of coastal upwelling velocities. While a change in the position and strength of the Aleutian Low has been related to coastal upwelling in the northern CCS, a more targeted measure of the actual upwelling vertical velocity and nutrient fluxes that are relevant to primary productivity can only be quantified by taking into account a combination of oceanic processes that depend on multiple RFPs, such as thermocline depth (e.g., remote waves), thermal stratification (e.g. heat fluxes), mesoscale eddies, and upwelling velocities (e.g., local patterns of wind stress curl and alongshore winds; Gruber et al 2011; Jacox et al. 2015; Renault et al. 2016). In other words, if we consider the vertical coastal upwelling velocity along the northern CCS, a more adequate physical description and quantification would be given from a linear combination of the different regional forcing functions rather than one individual forcing function.

The largest interannual variability in the Pacific that impacts the RFPs is ENSO. The strength of the ENSO signal constitutes the largest source of seasonal (3-6 months) predictability. During El Niño and La Niña, atmospheric and oceanic teleconnections from the tropics modify large-scale and local surface wind patterns and ocean currents of the CCS and force coastally trapped waves.

3.3. Quantifying ENSO teleconnections and potential seasonal predictability of the regional forcing patterns

While ENSO exerts important controls on the RFPs in the CCS, it has become evident that ENSO expressions in the tropics vary significantly from event to event, leading to different responses in the CCS (Capotondi et al. 2017). Also, the CCS is not only sensitive to strong ENSO events but responds to a wide range of tropical SSTa variability that is driven by ENSO-type dynamics in the tropical and subtropical Pacific. For this reason, we define an "ENSO teleconnection" as any RFP response that is linked to ENSO-type variability in the tropics.

ENSO can influence the upwelling and circulation in the CCS region through both oceanic and atmospheric pathways. It is well known that equatorial Kelvin waves, an integral part of ENSO dynamics, propagate eastward along the Equator and continue both northward (and southward) along the coasts of the Americas as coastally trapped Kelvin waves after reaching the eastern ocean boundary. El Niño events are associated with downwelling Kelvin waves, leading to a deepening of the thermocline, while La Niña events produce a shoaling of the thermocline in the CCS (Simpson 1984; Lynn and Bograd 2002; Huyer et al. 2002; Bograd et al. 2009; Hermann et al. 2009; Miller et al. 2015). The offshore scale of coastal Kelvin waves (~100-200 km) decreases with latitude, and the waves decay while propagating northward along the coast due to dissipation and radiation of westward propagating Rossby waves. In addition, topography and bathymetry can modify the nature of the waves and perhaps partially impede their propagation at some location. Thus, the efficiency of coastal waves of equatorial origin in modifying the stratification in the CCS is still a matter of debate. To complicate matters, regional wind variability south of the CCS also excites coastally trapped waves, which supplement the tropical source.

In the tropics, SSTa − associated with ENSO − rearrange tropical convection and excite mid-troposphere stationary atmospheric Rossby waves that propagate signals to the extratropics. These waves are referred to as the atmospheric ENSO teleconnections (Capotondi et al. 2017). Through these atmospheric waves, warm ENSO events favor a deepening and southward shift of the Aleutian Low pressure system that is dominant during winter, as well as changes in the North Pacific Subtropical High that is dominant during spring and summer, resulting in a weakening of the alongshore winds, reduced upwelling, and warmer surface water. These changes are similar to those induced by coastal Kelvin waves of equatorial origin, making it very difficult to distinguish the relative importance of the oceanic and atmospheric pathways in the CCS. In addition, due to internal atmospheric noise, the details of the ENSO teleconnections can vary significantly from event to event and result in important differences along the California Coast (Figure 18).

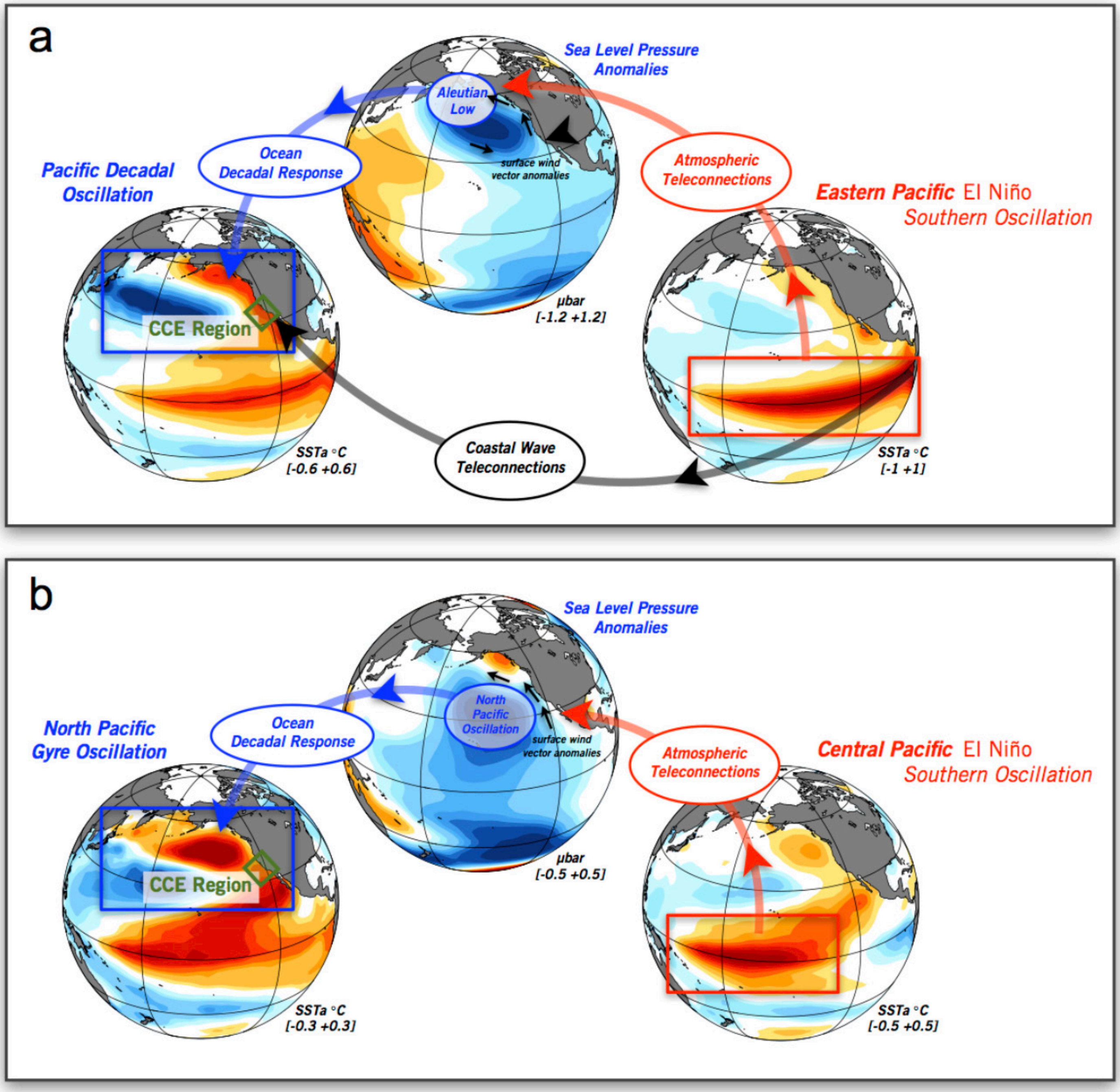


Figure 18. *Schematic of ENSO teleconnections associated with different flavors of tropical SSTa. (a) Atmospheric teleconnections of the canonical eastern Pacific El Niño tend to impact the winter expression of the Aleutian Low, which in turn drives an oceanic SSTa anomaly that projects onto the pattern of the PDO. (b) Atmospheric teleconnections of the central Pacific El Niño tend to impact the winter expression of the North Pacific High, which in turn drives an oceanic SSTa anomaly that projects onto the pattern of the NPGO.The ENSO SSTa maps are obtained by regressing indices of central and eastern Pacific ENSO with SSTa. The other maps are obtained by regression of SSTa/SLPa with the PDO (a) and NPGO (b) indices.*

El Niño events exhibit a large diversity in amplitude, duration, and spatial pattern (Capotondi et al. 2015). The amplitude and location of the maximum SST anomalies, whether in the eastern (EP) or central (CP) Pacific, can have a large impact on ENSO teleconnections (Ashok et al. 2007; Larkin and Harrison 2005). While "canonical" EP events induce changes in the Aleutian Low (Figure 17b), CP events have been associated with a strengthening of the second mode of North Pacific atmospheric variability, the North Pacific Oscillation (NPO; Figure 17a) (Di Lorenzo et al. 2010; Furtado et al. 2012). In addition, it is conceivable that EP events have a larger Kelvin wave signature than CP events, resulting in different oceanic influences in the CCS.

In summary, while ENSO influence on CCS physical and biological parameters is undeniable, several sources of uncertainty remain about the details of that influence. This uncertainty arises in the physical environment on seasonal timescales from many sources, including the diversity of ENSO events, the intrinsic unpredictable components of the atmosphere, and the intrinsic unpredictable eddy variations in the CCS. We also need to distinguish between physically forced ecosystem response versus intrinsic biological variability, which is potentially nonlinear and likely unpredictable. Skill levels need to be quantified for each step of the prediction process (i.e., ENSO, teleconnections, local oceanic response, local ecosystem response) relative to a baseline – for example, the persistence of initial condition, which is also being exploited for skillful predictions of the large marine ecosystem at the seasonal timescale (Tommasi et al. 2017). The target populations should be exploitable species of interest to federal and state agencies that regulate their stocks. Models are currently being developed to use ocean forecasts to advance top predator management (Hazen et al. 2017). The implementation of this framework (Figure 16) for practical uses will require a collaborative effort between physical climate scientists with expertise in predicting and understanding ENSO and biologists who have expertise in understanding ecosystem response to physical climate forcing.

3.4. Partnering with national and international marine ecosystem forecasting efforts

Advances in forecasting the response of marine ecosystems to climate forcing functions, such as El Niño, are progressively gaining more attention in national and international organizations. Here, we report on two efforts that are relevant to the workshop. Partnering with these international activities is identified as a priority for making progress on forecasting ENSO impacts on marine ecosystems of the US West Coast.

Joint PICES/CLIVAR Working Group: Climate and Ecosystem Predictability (Bond)

The North Pacific Marine Science Organization (PICES) Working Groups 27, 28, and 29 on North Pacific Climate (WG27), Regional Modeling (WG29), and Ecosystem Indicators (WG28) ended in 2015. While WG27 has identified and described a series of climate and ecosystem mechanisms that have forecast potentials ranging from 3 months to 10 years, WG28 has developed a set of modeling strategies to simulate these mechanisms at both basin and regional scales over the North Pacific. Complementary to WG27 and WG29, the outcomes of WG28 provide us with a series of key ecosystem indicators that can be connected to climate processes identified by WG27 and modeled by WG29. Furthermore, the activities of WG27 and WG29 strongly leveraged collaborations with CLIVAR by conducting joint sessions and by entraining CLIVAR expertise.

Building on the outcomes of WGs 27, 28, and 29, and the CLIVAR collaborations, a new joint CLIVAR/PICES Working Group on Climate and Ecosystem Predictability (WG-CEP) will use the knowledge gained on the mechanisms of Pacific climate, regional modeling, and ecosystem indicators to develop terms of reference that focus on climate and ecosystem predictions (Figure 19). Establishing this group in collaboration with CLIVAR will allow PICES to integrate CLIVAR expertise and interest in seasonal to decadal predictions.

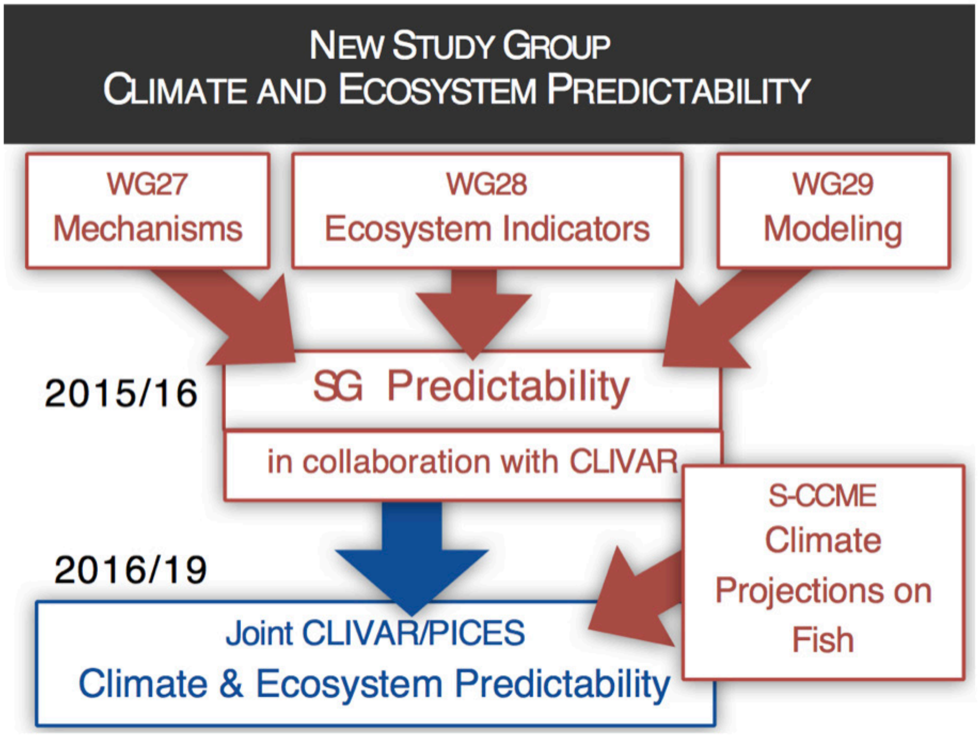


Figure 19. *The objectives of SG-CEP are to (1) synthesize the outcomes and previous knowledge gained through working groups 27, 28 and 29, (2) identify synergies with the ICES/PICES section on climate change and marine ecosystems (S-CCME) and the new ICES Working Group on Seasonal-to-Decadal Prediction, and (3) leverage CLIVAR expertise with the goal of developing the terms of reference for establishing a new joint working group between PICES and CLIVAR on Climate and Ecosystem Predictability. The main goal for establishing this new working group is to allow PICES to identify and quantify the skill of the models in predicting climate-driven variations in marine ecosystems.*

International Council for the Exploration of the Seas (ICES) Working Group: Seasonal-to-Decadal (WGS2D) prediction of marine ecosystems (Payne)

Tremendous advances in oceanographic observing and modeling systems over the last decade have led to dramatic improvements in our ability to predict the ocean. And skillful annual and multi-annual forecasts are now a reality in many regions (e.g., North Atlantic, Stock et al. 2015). However, the logical next step of translating physical environment predictions into predictions about biological outcomes and incorporating this into management remains a challenge. Only 1-2% percent of stocks today incorporate any form of environmental information into their tactical management procedures. Nevertheless, exploiting this predictive skill is emerging as one of the new challenges in marine science and can be seen as a key prerequisite for developing ecosystem-based management.

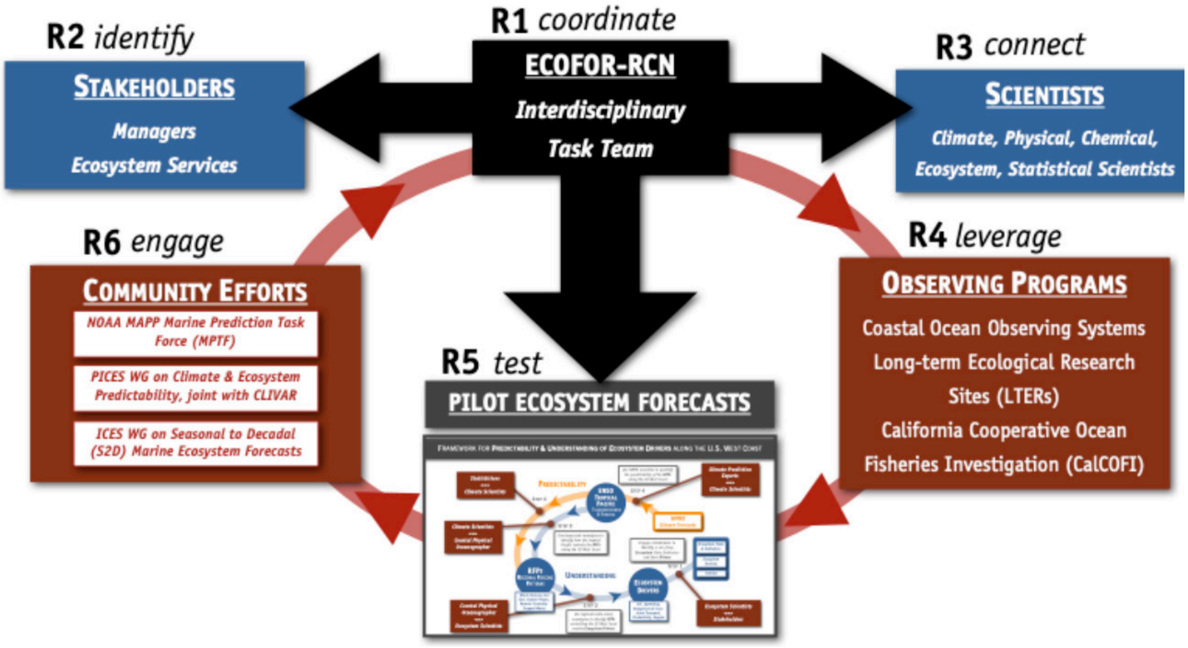
WGS2D aims to take up this challenge. While research has historically focused on recruitment, many other biological responses with management relevance, such as spatial distributions and growth and timing of key events, are also tightly linked to the physical environment and therefore potentially predictable. The group will identify these “low-hanging” and predictable management-relevant biological variables and use them to produce ecological forecast products, which will be delivered in an operational manner for applications that are relevant to ICES efforts. WGS2D will also harness the momentum developing in this research area. The group has already convened a session at the 2016 ICES Annual Science Conference entitled: “Seasonal-to-decadal prediction of marine ecosystems: opportunities, approaches, and applications.”

While these ongoing efforts will benefit the science for developing ecosystem forecasts for the US West Coast, additional synergies must be established in order to advance the scientific understanding and technological basis to make routine ecosystem forecasts. To this end we anticipate that a focused task team of interdisciplinary scientists and stakeholders would be a key step to implement the ecosystem forecasting framework designed during this workshop (see recommendation R6), and to establish synergies with existing efforts within the coastal ocean observing network and the long-term ecological research sites (LTERs).

4 RECOMMENDATIONS

Discussions from the workshop clearly showed the need for a more synergistic approach towards applying the ecosystem forecast framework for the US West Coast. It was recognized that there would be value in putting together an **ECOlogical FORcast Research Coordination Network (ECOFOR-RCN)** that would **coordinate** efforts (recommendation **R1**, Schematic 2) towards the development and testing of a pilot ecological forecasting system/portal for the US West Coast (recommendation **R5**, Schematic 2). Specifically, the ECOFOR-RCN would work towards (1) **identifying** key stakeholders and managers that would serve as end-users and provide important feedback on the target indicators to forecast (recommendation **R2**); (2) **connecting** scientists who bring synergistic expertise (e.g., climate, physical and chemical oceanography, marine ecosystem dynamics, statistics) to the implementation of the ecosystem forecasting framework (Schematic 1); (3) **leveraging** existing coastal observing programs (e.g., COOS and LTERs) as infrastructure for collecting "real-time" physical, chemical and biological data streams and for establishing the basis for an operational pilot forecasting system portal (recommendation **R3**, Schematic 2); and finally (4) **engaging** international community efforts in the area of ecological forecasts to share experiences and best practices (recommendation **R6**, Schematic 2).

R1. Establish an ECOlogical FORcast Research Coordination Network (ECOFOR-RCN)
Developing an operational ecological forecasting system for the US West Coast will require synergies across a broad spectrum of stakeholders and expert groups, including decision makers, managers, and observational and monitoring programs. For this reason, establishing an ECOlogical FORcast Research Coordination Network (ECOFOR-RCN), following the model of the National Science Foundation, is a promising avenue to coordinate all of the different components that are required to establish the basis for a future US West Coast operational ecological forecasting system to aid real-time information for decision makers and a variety of end users (e.g., fisheries). The activity of the RCN is instrumental for implementing the other recommendations that resulted from the workshop, which are discussed below and summarized in the introduction (see description of schematic 2).



Schematic 2. *Recommendations from the US CLIVAR workshop on ENSO ecological forecasting. See text for a description.*

R2. Identify managers and stakeholders to engage in interdisciplinary dialogue with scientists
An integral step towards a well-designed operational ecosystem forecast is the identification of end users who will benefit from the forecast products and can advise on the ecological indicators that should be targeted as priorities in the forecast. The selection of the indicators and the identification of the key stakeholders, decision makers, and end users will largely dictate the methodologies used for the forecast and the development of appropriate "forecast delivery" apps and portal. The ECOFOR-RCN can help identify and connect the different end users with a network of scientists from different background to promote the interdisciplinary dialogue for designing an operational forecasting system.

R3. Connect a diverse set of expertise towards developing ecological forecasting methodologies
Developing and implementing the approaches and modeling methods required for an operational ecological forecasting system requires coordination among climate scientists, statistician and prediction experts, coastal physical oceanographers, marine ecologists, stakeholders, and managers (red panels in Schematic 1). Connecting these different groups and organizing a set of synergistic tasks towards the creation of a pilot forecasting systems is one of the objectives of the ECOFOR-RCN.

R4. Leverage coastal ocean observing networks to integrate ecosystem forecasts

Regional ocean observing systems are ideal testbeds for investigating our ability to capture the local and regional effects of ENSO. The NOAA vision for a national unified Earth system modeling system proposed in 2017 seeks a product-driven strategy aimed at seasonal and subseasonal forecasts. The ability to predict the physical and ecosystem impacts of ENSO on the US West Coast from a system of interconnected and coupled community models is aligned with these national goals, but we need clearly defined pathways for integration into ocean observing systems. A task force has already been proposed to the Interagency Ocean Observation Committee (IOOC) to explore the representation and integration of models and observations from open ocean observing to the regional observing systems along the US West Coast. This kind of bridge is crucial for understanding ecosystem structure/dynamics in the California Current System on interannual to multi-decadal timescales.

R5. Establish and test a multi-institution and inter-agency pilot ecosystem forecast test case

While the long-term goal is to develop operational ecological forecasts, in practice there is a need to develop a pilot ecosystem forecast system that could inform the development and implementation of longer-term efforts. For such a pilot case study, we anticipate that a framework for forecasting ENSO impacts on the marine ecosystem off the US west coast will depend upon: (i) global climate forecast systems, which provide forecasts at lead times up to ~1 year of atmospheric conditions (e.g., winds, heat fluxes), as well as the physical and biogeochemical ocean state; (ii) high-resolution regional ocean models that are forced by global climate models but are able to resolve important fine-scale dynamics (e.g., upwelling, coastal wave propagation, riverine input, etc.) off the west coast; and (iii) dynamical or statistical models that relate the physical/biogeochemical environment to the response of marine species targeted for prediction. In order to develop such a framework, we recommend working backwards - i.e. (1) quantify biological responses to regional forcing, (2) relate the regional forcing to basin-scale (especially ENSO) variability, and (3) determine the predictability of the teleconnections between the basin-scale forcing and the regional response. A significant body of work has already been established on points (1) and (2), and efforts are underway on (3). Development of a marine ecosystem forecasting system should be carried out using hindcasts/reforecasts and long-term biological data sets. Testing the forecasting framework will require long-term operational funding, as well as continued ocean observations to address non-stationarity in ecological responses to environmental forcing.

R6. Engage with national and international ecosystem forecasting efforts

Advances in forecasting the response of marine ecosystems to climate forcing functions such as El Niño are progressively gaining more attention among national and international organizations and managers. In the scientific community there are several ongoing efforts within PICES and ICES like the ICES Working Group on Seasonal-to-Decadal (WGS2D) prediction of marine ecosystems, and Joint PICES/CLIVAR Working Group on Climate and Ecosystem Predictability (CEP). There are also important examples of science networks working closely with fisheries communities and other stakeholders in developing products (successful examples from Australia) and within the NOAA MAPP Marine Prediction Task Force (MPTF).

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Appendix A: Workshop Organizers

Scientific Organizing Committee	Affiliation
Emanuele Di Lorenzo	Georgia Tech, co-chair
Art Miller	University of California, San Diego/ Scripps Institution of Oceanography, co-chair
Clarissa Anderson	University of California, Santa Cruz
Enrique Curchitser	Rutgers University
Kris Karnauskas	University of Colorado
Julie Keister	University of Washington
Nate Mantua	NOAA Pacific Marine Environment Laboratory
Mark Ohman	University of California, San Diego/ Scripps Institution of Oceanography
Aneesh Subramanian	Oxford University
Cisco Werner	NOAA Fisheries

Program Organizing Committee	Affiliation
Heather Benway	OCB Program
Mike Patterson	US CLIVAR
Jill Reisdorf	UCAR
Kristan Uhlennbrock	US CLIVAR

Appendix B: Participants

Name	Affiliation
Albert Hermann	University of Washington
Andrea Ray	NOAA Earth System Research Lab
Aneesh Subramanian	Oxford Universtiy
Antonietta Capotondi	University of Colorado/NOAA ESRL
Art Miller	Scripps Institution of Oceanography
Bill Peterson	NOAA Fisheries
Brian Powell	University of Hawaii
Cecile Rousseaux	NASA Goddard Space Flight Center
Chris Edwards	University of California, Santa Cruz
Cisco Werner	NOAA SWFSC
Clarissa Anderson	UC Santa Cruz
Daniel Rudnick	Scripps Institution of Oceanography
Desiree Tommasi	NOAA GFDL/Princeton University
Dillon Amaya	Scripps Institution of Oceanography
Edgar Pavia	CICESE
Elliott Lee Hazen	NOAA SWFSC
Emanuele Di Lorenzo	Georgia Tech
Fei Chai	University of Maine
Francisco Chavez	MBARI
Jack Barth	Oregeon State University
James Todd	NOAA Climate Program Office
Jill Reisdorf	UCAR
Julie Keister	University of Washington
Kris Karnauskas	University of Colorado
Kristen Davis	University of California, Irvine
Laura Lilly	Scripps Institution of Oceanography
Marisol Garcia-Reyes	Farallon Institute
Mark Ohman	Scripps Institution of Oceanography
Mark Payne	Technical University Denmark
Martin Frischknecht	ETH Zurich, Switerland
Mike Alexander	NOAA Earth System Research Lab
Mike Jacox	UC Santa Cruz/NOAA SWFSC
Mike Patterson	US CLIVAR
Nate Mantua	NOAA Pacific Marine Envirnoment Lab
Nathali Coredero Quiros	Scripps Institution of Oceanography
Nick Bond	University of Washington

Name	Affiliation
Russ Davis	Scripps Institution of Oceanography
Ryan Rykaczewski	University of South Carolina
Sam McClatchie	NOAA SWFSC
Samantha Siedlecki	University of Washington
Sandy Lucas	NOAA Climate Variability & Predictability
Sergey Frolov	Naval Research Lab
Steven Bograd	NOAA SWFSC
Stuart Bishop	University of North Carolina
Tawnya Peterson	Oregon Health & Science University
Ted Strub	Oregon State University
Toby Garfield	NOAA SWFSC
Uwe Send	Scripps Institution of Oceanography
Wanqiu Wang	NOAA Climate Prediction Center
Wei Cheng	Univ of Washington and NOAA/PMEL
Yi Chao	Remote Sensing Solutions

Appendix C: Agenda

Wednesday, August 10, 2016

Time		*Presenter*
08:45	Welcome remarks, overview of the day	Emanuele Di Lorenzo, Georgia Tech Mark Ohman (SIO)
09:00 -12:00	**Session 1: Regional mechanisms**	**Facilitators:** Julie Keister (UW), Nathan Mantua (NOAA)
09:00	Ecosystem indicators	Marisol Garcia-Reyes, Farallon Institute
09:20	Physical processes impacting ecosystem indicators	Mike Jacox, UC Santa Cruz/NOAA Southwest Fisheries Science Center
09:40	Remote ocean vs. local/regional atmospheric forcing	Art Miller, Scripps Institution of Oceanography
10:00	Break	
10:30	Discussion: Session 1	
11:15	Lunch	
13:00 -16:00	**Session 2: ENSO diversity**	**Session 2: ENSO diversity**
13:00	Different types of ENSO variability and teleconnections	Antonietta Capotondi, NOAA Earth System Research Lab
13:20	ENSO impacts on ecosystem indicators	Mark Ohman, Scripps Institution of Oceanography
13:40	Coastal ocean response to ENSO, models and observations	Chris Edwards, UC Santa Cruz & Dan Rud- nick, Scripps Institution of Oceanography
14:00	Discussion: Session 2	
14:45	Break	
15:15	Discussion: Session 2 cont.	
16:00 -17:00	Overview of day 1	Emanuele Di Lorenzo, Georgia Tech & Art Miller, Scripps Institution of Oceanography
17:00	Break for evening social event	Emanuele Di Lorenzo, Georgia Tech & Art Miller, Scripps Institution of Oceanography

Thursday, August 11, 2016

Time		*Presenter*
08:30	Overview of day 2	
08:40 -11:30	**Session 3: Dynamical and statistical modeling for ecosystem forecasts**	**Facilitators:** Clarissa Anderson (UCSC), Brian Powell (U. Hawaii)
08:40	Biogeochemical models	Samantha Siedlecki, U. Washington
09:00	Modeling and forecasting lower trophic impacts	Cecile Rousseaux, NASA Goddard Space Flight Center
09:20	Modeling and forecasting higher trophic levels and top predators	Elliott Hazen, NOAA Southwest Fisheries Science Center
09:40	Statistical methods for ecosystem forecasting	Open discussion
10:00	Break	
10:20	Identifying Ecosystem Indicators sensitive to ENSO	Breakout group discussion
11:30	Lunch	
12:30 -14:30	**Session 4: Data streams and operational ecosystem forecasting**	**Facilitators:** Cisco Werner (NOAA), Jack Barth (OSU)
12:30	Operational forecasting of ocean conditions	Wanqiu Wang, NOAA Climate Prediction Center
12:50	Data streams for data assimilation and forecasting	Sergey Frolov, Naval Research Lab
13:10	Ecosystem forecasts	Mike Alexander, NOAA Earth System Research Lab
13:30	Mechanisms impacting Ecosystem indicators	Open discussion
14:30	Break	
15:00 -17:00	**Session 5: Developing a general ecosystem forecasting framework**	**Facilitators:** Emanuele Di Lorenzo, Georgia Tech & Art Miller, Scripps Institution of Oceanography
15:00	PICES/CLIVAR: Climate and Ecosystem Predictability (CEP)	Nick Bond (NOAA)
15:20	ICES: Seasonal-to-Decadal (S2D) prediction of marine ecosystems	Mark Payne (DTU)
15:40	Final Discussion	Open discussion
16:30	Meeting adjourns	

Appendix D: Products & Dissemination

Below is a set of contributions to the US CLIVAR Variations and OCB News winter 2017 edition that were produced as part of the ENSO workshop discussions and output. Together with the joint newsletter issues, a webinar was also conducted by the workshop organizing committee.

Webinar: Forecasting ENSO impacts on marine ecosystems along the US West Coast

The webinar was held on Wednesday, February 15, 2017 and hosted by US CLIVAR. A link to the complete set of talks is available here.

US CLIVAR Variations and OCB News Winter Editions 2017

A set of articles summarizing the discussions from the workshop are listed below and can be read in full text here on the US CLIVAR and OCB websites.

1. A framework for ENSO predictability of marine ecosystem drivers along the US West Coast (Di Lorenzo and Miller)
2. ENSO impacts on ecosystem indicators in the California Current System (Ohman, Mantua, Keister, Garcia-Reyes, and McClatchie)
3. Dominant physical mechanisms Driving Ecosystem Response to ENSO in the California Current System (Jacox, Rrudnick, and Edwards)
4. ENSO diversity and its implications for US West Coast marine ecosystems (Capotondi, Karnauskas, Miller, and Subramanian)
5. Impact of ENSO on biogeochemistry and lower trophic level response in the California Current System (Anderson, Siedlecki, Rousseaux, Powell, Peterson, and Edwards)
6. Modeling to aid management of marine top predators in a changing climate (Hazen, Alexan-der, Bograd, Hobday, Rykaczewski, and Scales)
7. Seasonal Forecasts of Ocean Conditions in the California Current Large Marine Ecosystem (Tommasi, Jacox, Alexander, Siedlecki, Werner, Stock, and Bond)

https://usclivar.org/meetings/2016-enso-ecosystems

US Climate Variability &
Predictability Program
1201 New York Ave NW, Suite 400
Washington, DC 20005
www.usclivar.org
uscpo@usclivar.org
twitter.com/usclivar

Ocean Carbon & Biogeochemistry Program
Woods Hole Oceanographic Institution
266 Woods Hole Road
Woods Hole, MA 02543
(508) 289-2838
www.us-ocb.org
hbenway@whoi.edu
twitter.com/us_ocb

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