PREDICTING THE CALIFORNIA CURRENT SYSTEM: SYMPOSIUM OF THE 2014 CALCOFI CONFERENCE

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The California Current system (CCS) extends from British Columbia to Baja California. The southern end of the CCS has been observed by CalCOFI[1] for more than 66 years. What will the CCS be like in the coming decades and beyond? How well can the CCS, or parts of it, be forecast on the scale of days to seasons and predicted on the scale of climate change? How will warming, stratification, acidification, and deoxygenation affect the CCS? Our ability to inform management and policy decisions depends on answers to such questions. The Symposium of the 2014 CalCOFI Conference was planned to address these issues. Presentations included hindcasting and prediction of the California Current using statistical and dynamical models, ranging from physics to fishers, and including the atmosphere and ocean. Model types included general circulation models, regional models, Atlantis-type models, and hybrid models including fish and humans.

Dunne et al. used the GFDL's Earth System Model[2] (ESM). A key question was how to bridge scales, from global, which is coarse in resolution but inclusive in processes, to regional, which has the desired resolution but excludes interactions with other regions and the earth. Both have inherent biases with regard to Eastern Boundary Currents. Dunne et al. presented results for a 0.1˚ (~10 km) ocean and 50 km atmosphere ESM that includes lower trophic levels. This spatial resolution is necessary to resolve currents in the EBCs, whose lateral dimensions scale with the Rossby radius. Comparsion of EBC temperature and chlorophyll with observations improved markedly from the 1˚ to 0.1˚ models, though challenges remain. The value of ESMs in predicting EBC dynamics was demonstrated by the unexpected result of the predicted influence of distant processes in the NW Pacific on the nitrate concentration of water upwelled in the California Current under a future climate (Rykaczewski and Dunne 2010).

Curchitser et al. addressed this scale issue by combining model types. A multi-scale ocean was incorporated as part of the NCAR CESM[3]. Scales ranged from a 7 km ocean model in the 1˚ CESM (ocean, atmosphere) and from months to 150 years. Not only was the fidelity of the model to observations enhanced in the multiscale model but feedbacks between regional and global models, particularly large-scale perturbations by regional upwelling, were discovered.

Rose et al. focused on End-to-End modeling—from physics to fishers in the California Current and with anchovy and sardine. The Regional Ocean Modeling System (ROMS) was used with ~10 km and daily resolution and ~1000 km and 50 y domain. A distinguishing feature of this effort is the inclusion of an "individual-based, full life cycle anchovy and sardine submodel" and characterizations of predators, including fishing fleets (Rose et al. in press). This model recreates the decadal-scale variation in anchovy and sardine dynamics, giving hope to our ability to predict such dynamics under a future, changed climate.

Edwards et al. hindcast and nowcast the state of the California Current system using the UCSC ROMS 4D-Var model[4]. A key element of this work is the use of data assimilation, i.e., the continuous incorporation of observational data into the model. Resolution is ~10 km and 8d/cycle and domain being waters off California, Oregon, and Washington and 31 years. This model has enabled the evaluation of fundamental physical processes, such as wind-induced upwelling and stratification, to characterize the habitat of rockfish.

Seo et al. focused on the effects of mesoscale SST and surface currents on eddy kinetic energy (EKE) and Ekman pumping. A 7 km regional coupled model showed a 25%–30% dissipation of EKE due to primarily to eddy-wind interactions, showing the need to include high-resolution air-sea coupling in both directions.

Siedlecki et al. focused on seasonal forecasts of ocean conditions that are "testable and relevant to annual management decisions" in the CCS using J-SCOPE[5].

[1]CalCOFI (California Cooperative Oceanic Fisheries Investigations) http://www.calcofi.org/

[2]GFDL ESM (Geophysical Fluid Dynamics Laboratory's Earth System Model) http://www.gfdl.noaa.gov/earth-system-model

[3]UCAR CESM (University Corporation for Atmospheric Research Community Earth System Model) http://www.cesm.ucar.edu/models/ccsm4.0/

[4]UCSC Ocean Modeling and Data Assimilation http://oceanmodeling.ucsc.edu/

[5]J-SCOPE (JISAO Seasonal Coastal Ocean Prediction of the Ecosystem) http://www.nanoos.org/products/j-scope/

Seasonal forecasts are needed for management decisions yet have been largely neglected due to their being between short-term forecasts and long-term predictions. J-SCOPE combines a ROMS model with the NOAA Climate Forecast System (3-dimensional with data assimilation) and a detailed model of dissolved oxygen to hindcast and forecast SST, O_2, and pH locally and regionally. Forecast skill is good to several months. This model is of particular value to inform management decisions in a region with significant climate-related changes in biogeochemistry and ecology, including fisheries and aquaculture.

Kaplan describes the use of the Atlantis[6] End-to-End model in the California Current system. Atlantis is a ROMS-based model with differential equations defining interactions between physical, chemical, and biological, including human, components of a system. It is a highly parameterized model that can be tuned with observations. Resolution is 12-h time steps and domain is the coastal waters of California, Oregon, and Washington.

Ye et al. describe how nonlinear systems do not lend themselves to analysis and prediction using linear models. They show that nonlinear properties of systems, derived from the analysis of time series of system variables, can be used for short-term forecasting, hence management, using equation-free models.

Themes derived from the combined presentations in the Symposium include:

- Scale is important. As Levin (1992) wrote, we perceive "only a low-dimensional slice through a high-dimensional cake" (p. 1945). In general, populations (e.g., of fish) affected by management decisions are at a scale currently resolved poorly in global-scale models. Yet the latter are useful, if not necessary, to inform higher-resolution models, e.g., with boundary conditions. Increasing computing power and new modeling schemes give promise here.
- Two-way coupling is often important.
- Trade-offs and limits exist. Resolution and domain vary inversely. Forecasting and prediction of nonlinear systems may be inherently limited by their chaotic behavior.
- Long-term, continuous observing programs, such as CalCOFI, are necessary to support all modeling efforts to understand and forecast the CCS. Observations are needed to create models and evaluate their predictive skill. Environmental intelligence requires environmental knowledge.
- Communication and collaboration are important, within both the modeling community writ large and between it, those who observe and those who rely on models, particularly to make decisions in management and policy.

Highest priority should be given to enhancing collaboration among governmental agencies and academic institutions. CalCOFI's success is due in large part to the federal (National Oceanic and Atmospheric Administration[7]), state (California Department of Fish and Wildlife[8]) and university (University of California, San Diego's Scripps Institution of Oceanography[9]) partnership of 66 years. The Symposium papers demonstrate the strengths of individual NOAA and academic entities in state-of-the-art prediction of the California Current system. An investment in an enhanced partnership among NOAA line offices, centers and labs and cooperative institutes working on the California Current system would have a high return in regard to informing decisions on management and policy. Such entities include Geophysical Fluid Dynamics Laboratory[10], the Northwest and Southwest Fisheries Science Centers[11,12], the Pacific Marine Environmental Laboratory[13], the Joint Institute for the Study of the Atmosphere and Ocean[14], the Cooperative Institute for Marine Resources Studies[15], and the Cooperative Institute for Marine Ecosystems and Climate[16].

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[6]Atlantis Ecosystem Model http://www.nwfsc.noaa.gov/research/divisions/cb/documents/atlantis_ecosystem_model.pdf

[7]NOAA http://www.noaa.gov/

[8]CDFW https://www.wildlife.ca.gov/

[9]UCSD/SIO https://scripps.ucsd.edu/

[10]GFDL http://www.gfdl.noaa.gov/

[11]NWFSC http://www.nwfsc.noaa.gov/

[12]SWFSC https://swfsc.noaa.gov/

[13]PMEL http://www.pmel.noaa.gov/

[14]JISAO http://www.jisao.washington.edu/

[15]CIMRS http://hmsc.oregonstate.edu/cimrs

[16]CIMEC https://scripps.ucsd.edu/cimec

REPRESENTATION OF EASTERN BOUNDARY CURRENTS IN GFDL'S EARTH SYSTEM MODELS

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ABSTRACT

The world's major Eastern Boundary Currents (EBC) are critically important areas for global fisheries. Computational limitations have divided past EBC modeling into two types: high-resolution regional approaches that resolve the strong mesoscale structures involved; and coarse global approaches that represent the large-scale context for EBCs but crudely resolve only the largest scales of their local manifestation. These latter global studies have illustrated the complex mechanisms involved in the climate change and acidification response in these regions, with the EBC response dominated not by local adjustments but large-scale reorganization of ocean circulation through remote forcing of water mass supply pathways. While qualitatively illustrating the limitations of regional high-resolution studies in long-term projections, these studies lack the ability to robustly quantify change because of the inability of these models to represent the baseline mesoscale structures of EBCs. In the present work, we compare current generation coarse resolution (1°) and a prototype next generation high-resolution (1/10°) Earth System Models (ESMs) from NOAA's Geophysical Fluid Dynamics Laboratory in representing the four major EBCs. We review the long-known temperature biases that the coarse models suffer in being unable to represent the timing and intensity of upwelling-favorable winds. In promising contrast, we show that the high-resolution prototype is capable of representing not only the overall mesoscale structure in physical and biogeochemical fields, but also the appropriate offshore extent of temperature anomalies and other EBC characteristics. In terms of representation of large-scale circulation, results were mixed, with the high-resolution prototype addressing some, but not all, of the biases in the coarse-resolution ESM. The ability to simulate EBCs in the global context at high resolution in global ESMs represents a fundamental milestone towards both seasonal to interannual ecological forecasting and long-term projection of climate, ecosystem, and acidification baselines and sensitivity.

INTRODUCTION

Past work on the sensitivity of the California Current system has shown the potential for large changes in ecosystem state under climate variability and change (Rykaczewski and Dunne 2010) that agree qualitatively with long-term observations from CalCOFI (Bograd et al. 2008). Specifically, GFDL's coarse resolution ESMs projected increased nitrate (NO_3) in the California Current. While temperature and NO_3 are negatively correlated seasonally and interannually, they are positively correlated under climate change. The mechanisms underlying these changes were found to be a combination of poleward migration of the source-water formation region leading to increase in light limitation and preformed nutrient supply combined with an increase in residence time of source waters before upwelling that led to additional accumulation of nutrients before upwelling. This dominance of remote forcing of local California Current changes demonstrated the potentially complex interplay of changes in atmospheric winds and heat fluxes, stratification, ventilation, and water mass pathways modulating the biogeochemical response. Even excluding global climate change driven components of variation, EBCs are exposed to a suite of forcing modes, including: the seasonal cycle driving pressure gradients and winds; remote interannual forcing like El Niño Southern Oscillation, Pacific Decadal Oscillation, and North Pacific Gyre Oscillation; mesoscale eddies (100–150 days, 30–50 km); squirts, fronts, and jets (e.g., topographic forcing); weather (days to weeks); and the diurnal sea breeze (diurnal, few km scale). Perhaps most challenging, the observed pattern of natural upwelling and intensification of coastal chlorophyll, remineralized nutrients, hypoxia, and associated acidification is coherent all along the EBC, but restricted to 10–100 km from the coast (e.g., Feely et al. 2008). This broad combination of challenges has motivated further work in global-scale Earth System Modeling to retain the inclusion of basin-scale climate change mechanisms while addressing limited resolution of coastal dynamics within coarse-resolution global ESMs.

The nature of this challenge is daunting. While ocean observations indicate a strong role for mesoscale (10–100 km scale) variability, Earth System modelers do not have access to computers powerful enough to develop models to resolve these scales in global imple-

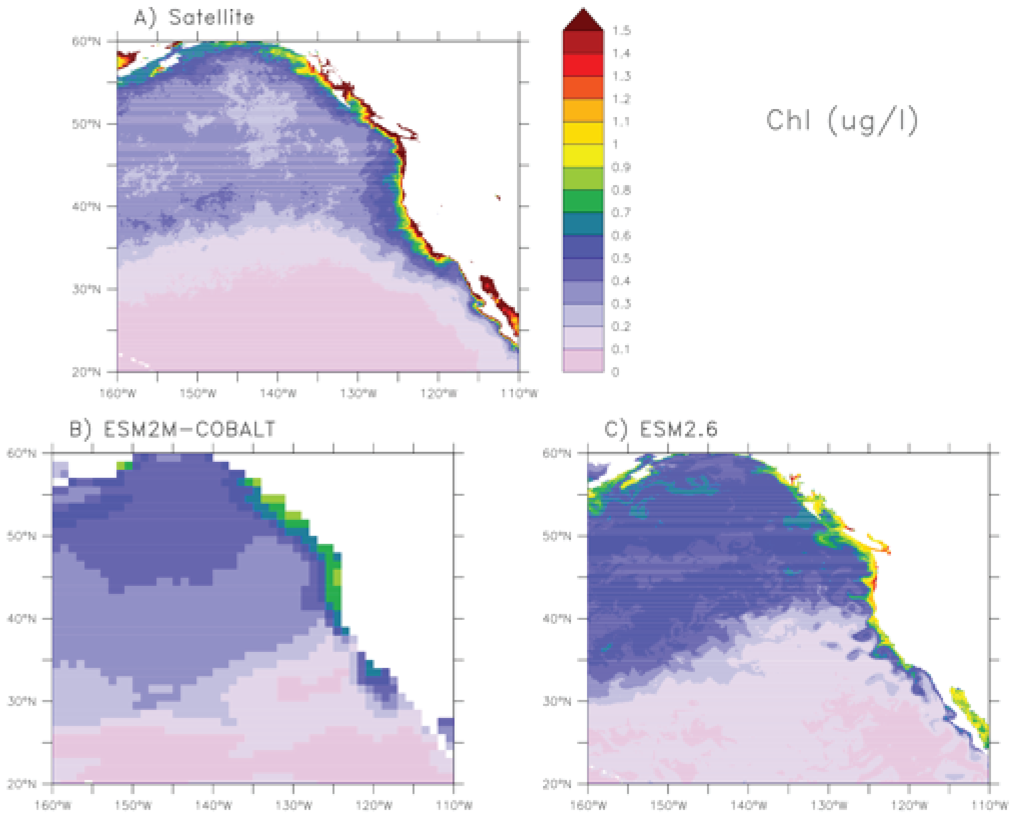

Figure 1. Comparison of surface chlorophyll from SeaWiFS satellite observations (top; http://oceandata.sci.gsfc.nasa.gov/SeaWiFS/Mapped/Monthly/9km/) with coarse, 1˚ resolution COBALT in ESM2M (bottom left; Stock et al. 2014) and 1/10˚ resolution COBALT in ESM2.6 (bottom right; present study).

mentations; the current generation ~1˚ ESMs have considerable regional process-level and fidelity biases. This implies that they commonly misrepresent phenomena such as the position and variability of the major current structures, the scales of either coastal and curl-driven upwelling, topographic and land-sea atmospheric interactions, and mechanistic ecological interactions. At least 1/10˚ resolution is necessary to resolve the Rossby radius of mesoscale eddies in the mid to high latitudes where these phenomena modulate the connection between the ocean surface and interior. Finally, adding biogeochemical tracers is computationally expensive, about 10%–20% per tracer over that of temperature and salinity alone. Overall, while the 1˚ ESM takes about 1.6 hours to run a year on 432 cores, the full 1/10˚ takes about 60 hours to run a year on 15,744 cores—an increase of over a thousand-fold in cost. Such simulations are extremely difficult to configure and run and their results more indicative of prototypes than of exhaustively developed and vetted products.

METHODS

To address the challenge of our computational inability to run long simulations of comprehensive biogeochemical and ecological models at high global resolution, we considered a suite of models assessing sensitivity across three dimensions of potential efficiency: biogeochemical comprehensiveness, spatial resolution, and simulation time. We compared a hierarchy of biogeochemical comprehensiveness including: CMIP5 GFDL Earth System Models which used Tracers of Ocean Phytoplankton with Allometric Zooplankton version 2 (TOPAZv2); the next generation Carbon Ocean Biogeochemistry and Lower Trophics (COBALT); the simplified Biogeochemistry with Light, Nutrients and Gas (BLING; Galbraith et al. 2012); and even further reduced mini-BLING with only dissolved inorganic carbon, phosphate, and oxygen. In the spatial resolution dimension, we compare mini-BLING and COBALT at 1˚ (ESM2M; Dunne et al. 2013) and 1/10˚ (Delworth et al. 2013; Griffies et al. 2015) ocean resolution for baseline simulation characteristics and fidelity. In the simulation time dimension, we compared ESM2M TOPAZ long spin-up with short spin-up to assess the role of equilibration, and compared historical/future simulation (240 years) with the shorter, idealized 1%CO2/yr to doubling perturbation (80 years) to assess the role of perturbation timescale to biogeochemical response. The analysis described herein focuses on the baseline simulation characteristics of the short simulation combining the comprehensive COBALT ecosystem model with the highest spatial resolution climate simulation (~1/10 degree ocean, 50 km atmosphere). We refer to this model as ESM2.6.

GFDL's current ESM2M and ESM2G are publicly available as part of CMIP5. They use Tracers of Ocean Phytoplankton with Allometric Zooplankton version 2 (TOPAZv2) to simulate a coupled suite of multi-elemental mechanisms controlling the ocean carbon cycle. This, in turn, is done through their interacting cycles that incorporate allometric, optimal allocation, and ballast theory through global process-level calibration and distributional biogeochemical validation. Taking TOPAZ as it's starting point, GFDL's next generation biogeochemistry enhances representation of ecosystem structure towards improvement of resolution of energy flows through the planktonic food web and more robust applications, meeting NOAA's stewardship mandate for Living Marine Resources. This model, Carbon Ocean Biogeochemistry and Lower Trophics (COBALT; Stock and Dunne 2010; Stock et al. 2013), increases the number of zooplankton types from 1 to 3 and adds explicit bacteria with a considerable augmentation of theoretical and observational justification for structural and parameter decision making.

RESULTS

The sensitivity to resolution at higher comprehensiveness is illustrated for the California Current EBC in Figure 1. Comparison of 1˚ and 1/10˚ resolutions in the most comprehensive COBALT model demonstrates vast improvement in the ability to represent the ecological response to mesoscale dynamics. Most striking is the improved ability to represent high chlorophyll associated with mesoscale upwelling and transport along the northern portion of the California Current upwelling region. In addition, there are improvements in the representation of the transition between mesotrophy in the offshore subpolar gyre and oligotrophy in the offshore subtropical gyre (blue to purple in fig. 1). Furthermore, the high-resolution model captures modes of mesoscale variance within the subpolar gyre that the coarse model is incapable of generating.

The relative ability of these models to represent the patterns of depressed temperature and elevated chlorophyll associated with EBC upwelling is shown more quantitatively in Figure 2. While the 1˚ resolution model (red) struggles to capture the signature of upwelling at all latitudes, ESM2.6 captures both the quantitative depression of temperature at the coast and the spatial scale of return to open ocean conditions offshore (top panel of fig. 2). However, those offshore temperatures tend to be too warm in both models to a similar extent. In

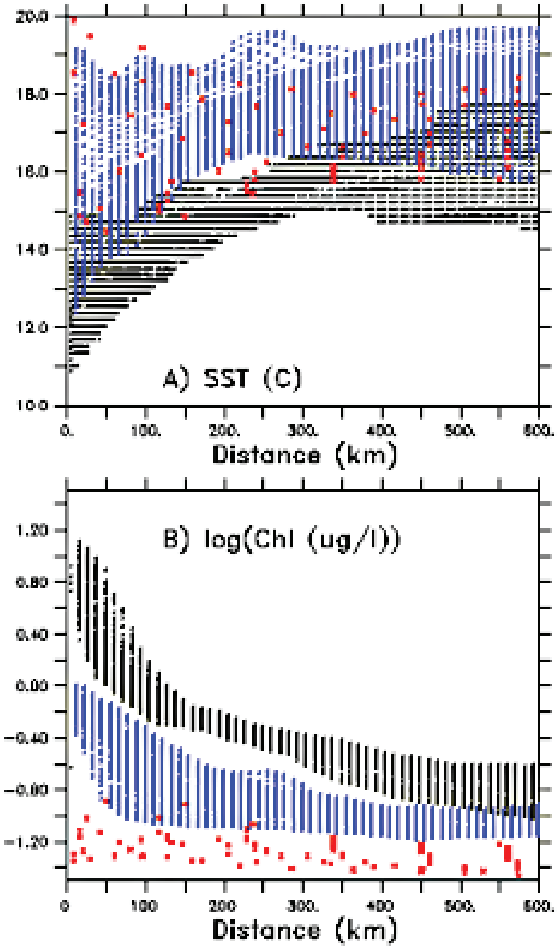

Figure 2. Comparison of Satellite Observations (Black), with coarse, 1˚ resolution COBALT in ESM2M (red; Stock et al. 2014) and 1/10˚ resolution COBALT in ESM2.6 (red; present study) for sea surfaces temperature (C; top; http://www.nodc.noaa.gov/SatelliteData/pathfinder4km/) and log(chlorophyll µg/l) (bottom; http://oceandata.sci.gsfc.nasa.gov/SeaWiFS/Mapped/Monthly/9km/). The number of points in each case reflects the pixel resolution in each case—similar for ESM2.6 and the satellite observations, but considerably lower in the 1˚ resolution model.

terms of chlorophyll, ESM2.6 exhibits both similarly vast improvement in the qualitative structure nearshore and marked improvement offshore, but the highest values of chlorophyll in ESM2.6 (about 1.2 µg/l; <0.1 after the log transform in fig. 2) remain an order of magnitude lower than satellite observations, which exceed 10 µg/l (>1 after the log transform in fig. 2).

Overall, we consider these extremely exciting results and are highly confident that future high-resolution models will be vastly more applicable to living marine resource applications when computational capacities allow full implementation. While these models are revolutionary in representing various aspects of mesoscale dynamics as they may impact ecosystems on the global scale, many challenges remain. One of these challenges is that the high-resolution model retains much of the large-scale biases seen in the coarse-resolution model. A second challenge is that while higher resolution improved representation of areas with peak chlorophyll values about 1.2 μg/l, satellite and field observations commonly exceed 10 μg/l chlorophyll in blooms. Whether this lack of ecological dynamism captured in ESM2.6 is related to a lack of physical dynamics of fronts and other submesoscale phenomena, to lack of pelagic ecological biodiversity—particularly with respect to coastal diatoms, or related to a lack of representation of coastal and benthic interactions—is a focus of current and future work.

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REGIONAL CLIMATE MODELING IN THE CALIFORNIA CURRENT SYSTEM

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BACKGROUND

Though global climate models can represent many identifiable features of the climate system, they also suffer from significant localized biases. Climate model biases are not uniform over the globe. For example, in the ocean, modeled sea surface temperature (SST) errors are often largest along the continental margins. Many coupled climate models generate very large SST biases in the coastal upwelling regions of the California Current system (CCS), the Humboldt Current System (HCS), and the Benguela Current System (BCS), where simulated mean SSTs are much warmer than observed. The NCAR-CCSM3 (spectral atmosphere) used in IPCC-AR4 was no exception, with biases in excess of 3˚C in all three regions. Furthermore, these SST biases have significant remote effects on surface and subsurface temperature and salinity, and on precipitation and hence atmospheric heating and circulation (Collins et al. 2006). Large and Danabasoglu (2006) showed, in particular, with observed SSTs imposed along the BCS coast in an otherwise freely-evolving CCSM3 simulation there are significant improvements in precipitation in the western Indian Ocean, over the African continent, and across the Equatorial Atlantic. Imposed SSTs along the HCS coast reduce precipitation in the so-called double Intertropical Convergence Zone (ITCZ) region of the south tropical Pacific.

These errors often coincide with regions of importance to oceanic ecosystems and nearby human populations. In the Intergovernmental Panel on Climate Change Fourth (IPCC-AR4) Working Group 1 Assessment Report, where the reliability of the models used to make projections of future climate change is assessed, Randall et al. (2007) discuss the many improvements and the strengths of the current generation of coupled models of the physical climate system, but they also highlight a number of remaining significant model errors. Furthermore, they state, "The ultimate source of most such errors is that many important small-scale processes cannot be represented explicitly in models, and so must be included in approximate form as they interact with larger-scale features." Some of the reasons given for the deficiencies are limited computer power, data availability, and scientific understanding. Conversely, regional models have shown significant skill in modeling coastal processes (e.g., Curchitser et al. 2005; Powell et al. 2007; Combes et al. 2009; Veneziani et al. 2009a,b). This creates the opportunity to develop multi-scale numerical solution schemes that adapt the resolution in specific areas of interest, such as the California Current system.

Coastal winds in the latest CCSM4 with a 2˚ resolution (finite volume) atmosphere produce even larger SST biases than were apparent in CCSM3, despite many improvements to the physical model components. Improving the coastal winds by increasing the atmospheric resolution to 1˚ however, significantly reduces the coastal SST biases. The implication is that the further reductions in the SSTs required to eliminate the coastal biases under present day conditions will likely also need to come from improvements to the ocean physics and the upwelling of cold water in particular. These improvements must be realized before the regional biogeochemistry and ecosystem models can be expected to behave accurately because of the sensitivity to temperature and the critical importance of upwelled nutrients for biological processes.

In order to address the above issues we developed a new multi-scale ocean as part of the U.S. National Center for Atmospheric Research Community Earth System Model (NCAR-CESM). The new composite ocean consists of the global Parallel Ocean Program (POP) and the Regional Ocean Modeling System (ROMS). The new composite ocean is connected to the rest of the CESM climate model through a modified flux coupler.

RESULTS FROM THE MULTI-SCALE COUPLED MODEL

In order to test and demonstrate the capabilities of the multi-scale climate model, we have been carrying out a series of simulations where the northeast Pacific upwelling region is solved using a high-resolution (7 km) ocean within a global (1˚) model and a 1˚ atmosphere. Sea ice is solved on the ocean grid and the land surface model on the atmospheric grid. The CESM is initialized from a spun-up climatology and time-stepped

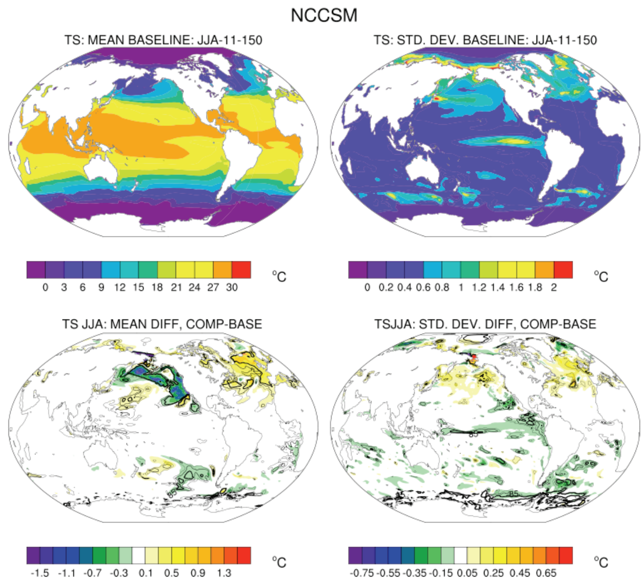

Figure 1. Mean and standard deviation for the summer months of both the control and composite simulations. Thick black lines indicate 95% confidence level using the T- and F-test for the mean and deviation, respectively. Note both the local and remote effects caused by the perturbation that results from resolving the upwelling signal in the northeast Pacific region.

for 150 years. This simulation is then compared to a control run without the high-resolution ocean. The new multi-scale ocean is able to resolve the upwelling that is mostly missing from the global simulations, and this has a significant effect on the regional wind patterns.

Figure 1 shows the surface sea temperature and standard deviation for summer months (June–August) of the control simulation and the corresponding anomalies with the composite model for the last 140 years of simulation. The thick black lines outline regions of 95% confidence based on T- and F-tests for the mean and standard deviations, respectively. The temperature anomaly plot shows the local cooling effect that results from resolving the upwelling in the northeast Pacific and also remote effects in the Atlantic ocean. Significant, and robust, effects are also seen in other variables such as tropical precipitation and sea level pressure.

SUMMARY

A new multi-scale capability was developed by merging a global ocean and a regional ocean model within a global climate model. The goal was to address some of the biases exhibited by low-resolution global models in regions with implications for marine ecosystems. Long integrations show that this configuration is able to address some of these regional biases. Furthermore, by preserving the feedbacks between the regional and global climate models we are able to study upscaling effects that arise from the regionally introduced perturbations. In the case presented here we see effect as far afield as the North Atlantic Ocean. Further studies are proceeding by studying the effects of resolving other major upwelling regions as well a new study in a western boundary current region where global models also show sea surface temperature biases. Future plans include adding a biogeochemistry model to this configuration in order to study the role of upwelling regions in the global CO_2 cycles.

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END-TO-END MODELING OF SARDINE AND ANCHOVY IN THE CALIFORNIA CURRENT SYSTEM

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End-to-end models are receiving increasing attention as a quantitative tool for investigating marine ecosystem responses to climate variation and fisheries management. End-to-end models typically combine submodels of physics (hydrodynamics), lower trophic levels (nutrient-phytoplankton-zooplankton, NPZ), and upper trophic levels (fish, birds, fishers) into a single modeling framework (Plagányi 2007). Such models are attractive because they can simulate a wide variety of effects, including ecosystem responses to interannual environmental variation, changes in fishing, and episodic and long-term trends in climate conditions. Our focus in this paper is on the development of an end-to-end model (climate to fish to fishers), using the sardine-anchovy system of the California Current (CC). The sardine-anchovy low-frequency population cycles have been studied for decades (Lluch-Belda et al. 1989). We focus here on how interannual variation in environmental conditions affected the decadal cycles in sardine and anchovy populations.

Our end-to-end model is 3-dimensional, time-varying, and multispecies, and consists of four coupled submodels: hydrodynamics, Eulerian nitrogen-phytoplankton-zooplankton (NEMURO NP_2Z_3), an individual-based full life cycle anchovy and sardine submodel, and an agent-based fishing fleet submodel (Rose et al. 2015). All submodels were coded within the ROMS community software package, and used the same resolution spatial grid and were all solved simultaneously to allow for possible feedbacks among the submodels. A historical simulation of 1959-2008 was performed (fig. 1) that showed a switch from anchovy dominance to sardine dominance in the mid-1990s. A more in-depth analysis of the causes for the population cycles in the historical simulation is reported in Fiechter et al. (2015). Results illustrate how slightly different temperature and diet preferences between sardine and anchovy can lead to their different responses to environmental variability. Simulated adult population fluctuations were associated with age-1 growth (via age-2 egg production) and prey availability for anchovy, while they depended primarily on age-0 survival and temperature for sardine.

Our analysis demonstrates that the technology is available for developing and using 3-dimensional fully-coupled multispecies end-to-end models. We conclude with a discussion about the prospects for using such end-

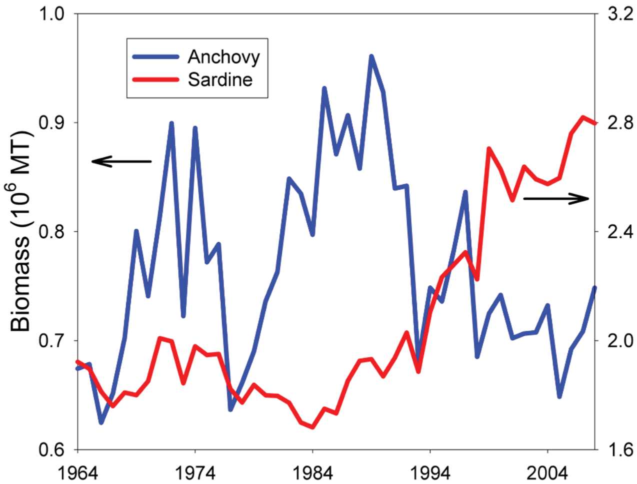

Figure 1. Annual values on January 1 of age-1 and older simulated biomasses of anchovy and sardine in the historical simulation.

to-end models for strategic and tactical predictions. The time is now for development and testing of these end-to-end models so we are ready with models of sufficient and documented confidence for wide-spread usage within the next decade.

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HINDCASTING AND NOWCASTING THE PHYSICAL AND BIOLOGICAL STATE OF THE CALIFORNIA CURRENT SYSTEM

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Assessing the past or present state of the ocean and predicting its future state are challenging enterprises. Observing activities are expensive, and as a result the ocean is woefully undersampled relative to important scales of variability spanning several orders of magnitude (from meters to hundreds of kilometers) in space and hours to decades in time. Numerical ocean models offer a relatively inexpensive alternative to observational sampling, and provide fully 4-dimensional representation of ocean fields and governing processes to better understand field distributions and changes. Yet numerical ocean models offer imperfect representations of nature for many unavoidable reasons, including errors in model initial conditions, forcing fields, model parameterizations, and discretization of the model on a finite grid. In ocean state estimation modelers use methods of data assimilation to rigorously adjust control variables (e.g., model initial conditions or forcing fields) to reduce discrepancies between model fields and observations (Edwards et al. 2015).

The widely-used Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams 2005) includes an advanced 4-dimensional variational data assimilation capability (Moore et al. 2011a) that has been applied in various California Current system configurations. The UC Santa Cruz Ocean Modeling Group implementation consists of a domain extending from 30˚N to 48˚N (Baja California, Mexico, to near Puget Sound, Washington) and offshore to 134˚W, resolved at 1/10 degree, with 42 terrain-following levels spanning the water column (Broquet et al. 2010, Moore et al. 2011b, 2013). Experience assimilating a variety of physical data types has shown that the system produces ocean state estimates with reduced root-mean-square error of both assimilated and unassimilated observations relative to unconstrained model output (Broquet et al. 2009). Forecast-like calculations in which the final state of one assimilation cycle is used as an initial state for an unconstrained forecast indicate that model skill is sustained beyond the period of assimilation alone.

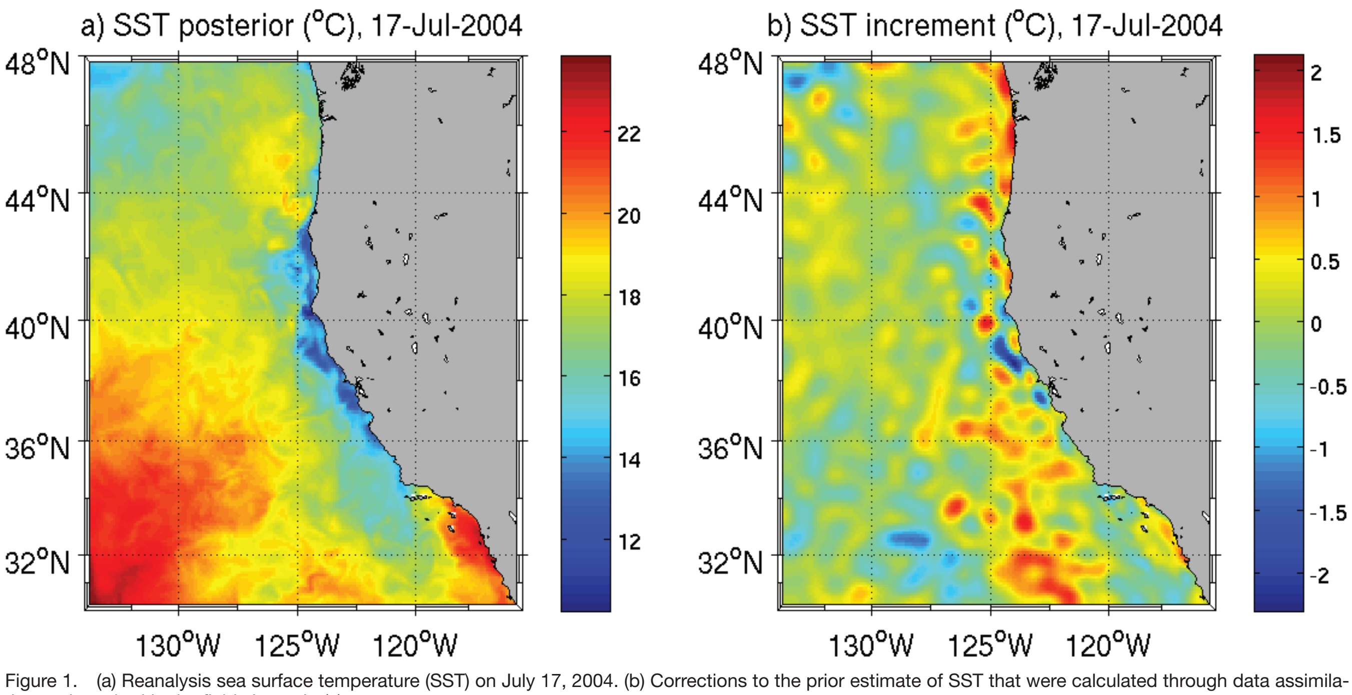

Figure 1. (a) Reanalysis sea surface temperature (SST) on July 17, 2004. (b) Corrections to the prior estimate of SST that were calculated through data assimilation and resulted in the field shown in (a).

A set of data assimilative reanalyses using the UCSC ROMS 4D-Var configuration has been calculated for the CCS (Neveu et al. 2015; Crawford et al. 2015). This product assimilated sea surface temperature (SST) from multiple satellite platforms, satellite-derived sea surface height, and in situ hydrography from various sources in a series of 8-day cycles extending from 1980 to 2010. Lateral boundary conditions were derived from the SODA global ocean state estimate (Carton and Giese 2008). Surface forcing was provided by a combination of CCMP winds (Atlas et al. 2011) and other atmospheric fields from the ERA40 (Källberg et al. 2004) and ERA-Interim (Dee et al. 2011) products. This model output represents a best estimate 31-year, hindcast of the physical state of the California Current, and is served by the UC Ocean Modeling Group for analysis (http://oceanmodeling.ucsc.edu).

Example output from a reanalysis assimilation cycle is shown in Figure 1. SST on this date exhibits cold upwelled water along the central California coast, with warm water bathing the Southern California Bight. Largely mesoscale corrections to a prior estimate, ranging up to about 2 degrees, result in this posterior state estimate.

This set of reanalyses has several applications that may be of interest to the CalCOFI community. It can be used for evaluation of fundamental physical processes. For example, upwelling within the CCS is challenging to observe directly, and in the absence of other information, a coastal upwelling index based on Ekman theory is often used as a proxy (Bakun 1973). The reanalyses reveal that modeled upwelling transport is reasonably approximated by the upwelling index north of about 39°N, but is poorly represented south of this latitude (fig. 2; Jacox et al. 2014). Actual upwelling transport differs from Ekman transport in regions where cross-shore geostrophic transport encounters the coastal boundary (Marchesiello and Estrade 2010). Reduction of the reanalyses into empirical orthogonal functions reveals anomalous nearshore upwelling transport whose principal component relates to large-scale climate indices such as the NPGO and PDO (Jacox et al. 2014).

Ocean state estimates can also be used to provide context for fisheries studies. Schroeder et al. (2014) evaluated the reanalyses against data collected from the NMFS Rockfish Recruitment and Ecosystem Assessment Surveys. That study identified correlations between biological stocks (juvenile rockfish and krill) and physical variables from the reanalyses such as the depth of the 26.0 kg/m^3 isopycnal surface.

Ocean data assimilation is increasingly becoming a routine activity in global and many regional ocean environments. To date, however, most research has focused on physical data assimilation in which ocean currents, temperature, salinity, and sea surface height are constrained by observations. Exciting developments are underway to extend this capability to biogeochemical variables. The UC Santa Cruz Ocean Modeling Group has implemented a form of 4D-Var that accounts for the differing statistics of ecosystem variables relative to physical variables. Chlorophyll in the ocean has been shown to be better represented by lognormal statistics than by Gaussian distributions (Campbell 1995). The coupled physical-biogeochemical assimilation system incorporates surface chlorophyll, and offers considerable promise for hindcasting and nowcasting the combined physical and lower trophic level biological ocean state (Song et al. in prep.).

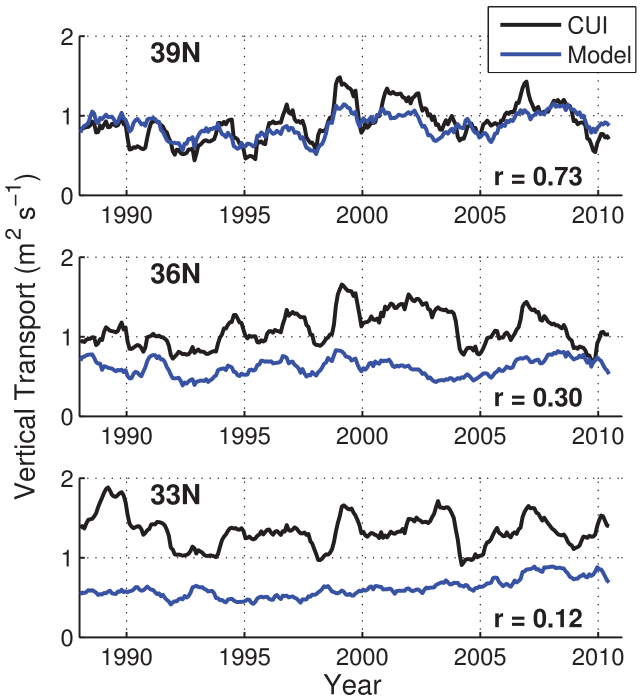

Figure 2. 12-month running means of upwelling estimates from the NOAA Coastal Upwelling Index (CUI, black) and the ROMS-CCS model (blue) of Moore et al. (2013). Model transports are integrated from the coast to 200 km offshore, averaged over 3° of latitude for consistency with the CUI, and calculated as transport across a depth level of 40 m. Adapted from Jacox et al. (2014).

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EFFECT OF EDDY-WIND INTERACTION ON EKMAN PUMPING AND EDDY KINETIC ENERGY: A REGIONAL COUPLED MODELING STUDY FOR THE CALIFORNIA CURRENT SYSTEM

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The California Current system (CCS) is characterized by the energetic summertime mesoscale and filamentary eddies with typical anomalies in sea surface temperature (SST) and surface current exceeding 2˚C and 0.5 cms^{-1}, respectively. Recent satellite observations show that both SST and surface current at oceanic mesoscales significantly influence the Ekman pumping velocity, suggestive of a subsequent dynamical feedback effect on the eddy energetics. The extent to which this mesoscale coupling is important for the Ekman pumping and the eddy kinetic energy (EKE) budget in the CCS is the focus of this study.

A series of the 7 km SCOAR regional coupled model simulations is carried out, in which the effects of mesoscale SST and mesoscale surface current are selectively removed in the formulation of surface wind stress. This is achieved by invoking an interactive spatial smoother, which removes oceanic structures with scales smaller than 300 km from the wind stress calculation. The total summertime Ekman pumping velocity is explained largely by two terms having comparable magnitudes: the linear Ekman pumping resulting from the curl of wind stress and the nonlinear Ekman pumping due to the gradient of surface vorticity by mesoscale current. The Ekman pumping due to the mesoscale SST through the linear relationship between the wind stress curl and the crosswind SST gradient is comparatively small. The simulated summertime EKE level in the CCS is reduced by ~30% (fig. 1) when the mesoscale eddies are allowed to influence the wind stress, and this reduction is almost entirely due to the effect of mesoscale current.

Examination of the upper ocean EKE budget terms shows that the dissipation of the EKE results mainly from the increased surface drags associated with a stronger correlation between the eddy-induced current and the wind stress. The change in SST climatology in the CCS is a resulting response from the offshore temperature advection by the mean and eddy currents of the upwelled water over the shelf. The magnitude of the mean SST change is greater with the mesoscale current than the mesoscale SST. Overall, the demonstrated importance of the eddy-wind interactions via mesoscale surface current suggests that the high-resolution ocean and coupled modeling studies over the energetic (sub) mesoscale variability and transient mixed layer fronts need to evaluate the dynamics and impact of small-scale air-sea coupling via surface current.

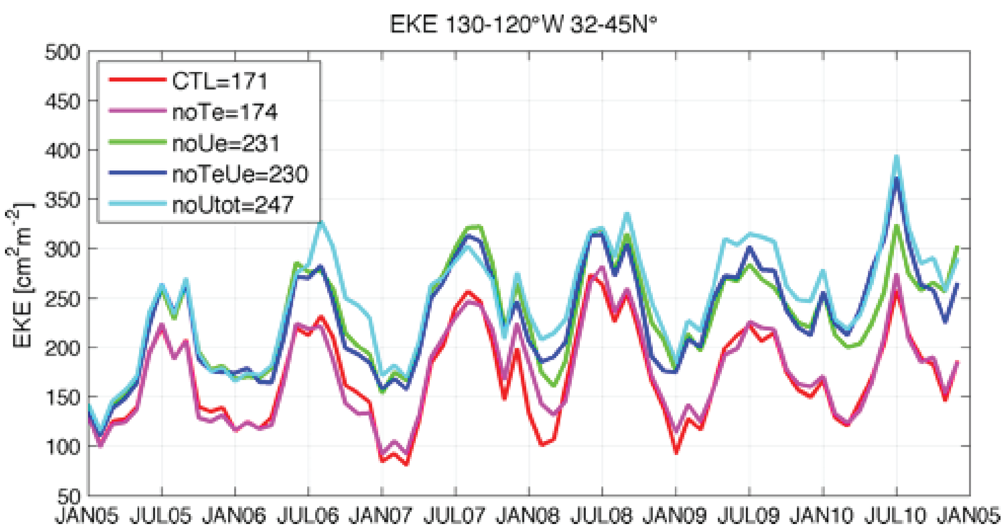

Figure 1. Eddy kinetic energy (EKE) for simulated surface currents in the five model cases averaged over each month of the year from 2005–10. Red is for full coupling. Purple is for no mesoscale SST coupling in wind stress. Green is for no mesoscale current coupling in wind stress. Dark blue is for no mesoscale SST or current coupling in wind stress. Light blue is for no ocean (mesoscale and large-scale) current coupling in wind stress. Allowing mesoscale eddies to affect the wind stress coupling reduces EKE by 25%–30%, while mesoscale SST coupling has very small effects on EKE.

PREDICTING HYPOXIA AND OCEAN ACIDIFICATION OF THE COASTAL WATERS OF THE CCS: WHAT DO WE KNOW AND WHAT CAN WE EXPECT?

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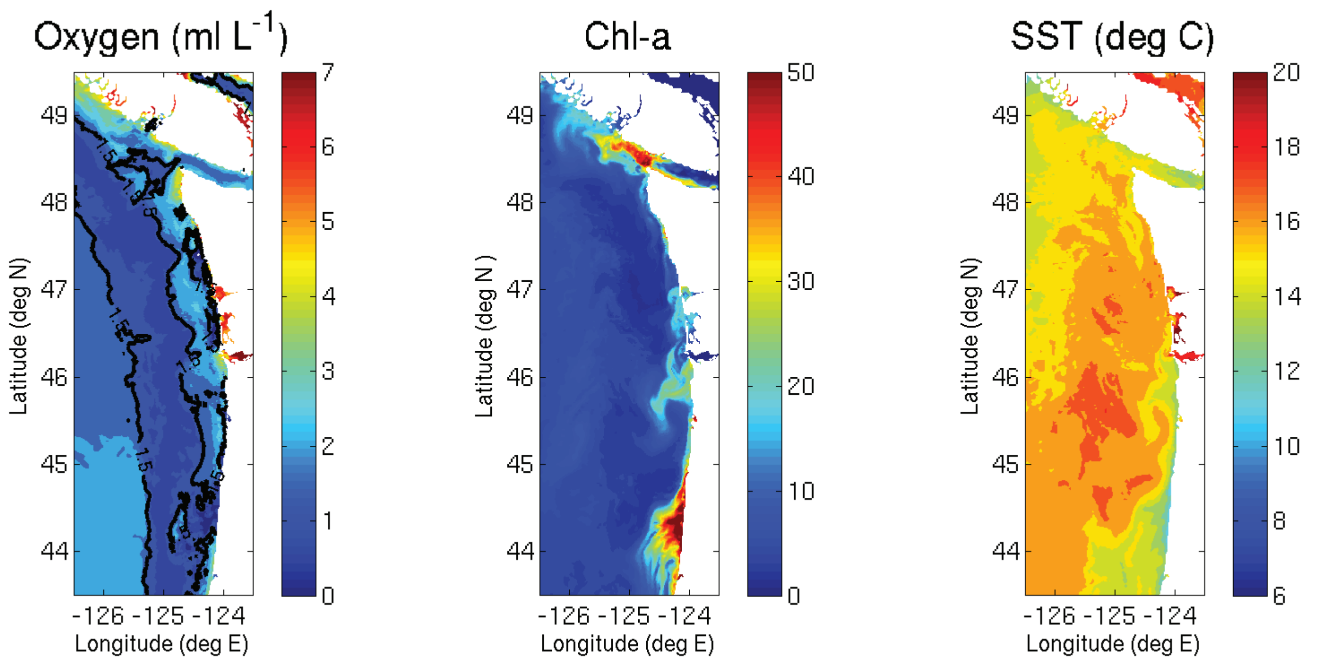

Figure 1. Study region for the J-SCOPE forecast system model. Maps of bottom oxygen (left), chlorophyll (middle, µg/l), and SST from the April 2013 forecasts of August, 2013.

Predictions of ocean acidification and hypoxia were incorporated into the IPCC report (2013) for the first time last year, and forecasts on shorter time scales have now been developed in the California Current system. High-resolution, regional, hindcast models capable of simulating hypoxia and ocean acidification events exist and provide the foundation for forecasting efforts. To build a forecast system, the necessary ingredients include a real-time observational network, a validated down-scaled hindcast simulation for the region complete with biogeochemistry, a region with predictive skill in both winds and SST, and an identified group of stakeholders with products designed in mind for them. Here, we use ROMS as the link from short-term, large-scale, climate forecasts to ecological processes relevant to the California Current Integrated Ecosystem Assessment. Our overarching goal is to provide short-term (six to nine month) forecasts of ocean conditions that are testable and relevant to annual management decisions for biological components in the California Current Integrated Ecosystem Assessment (CCIEA) (Levin and Schwing 2011). Regional hindcast models have been developed to understand the dynamics on the shelf with success, such that biogeochemical models can be designed and linked to them as well (Liu et al. 2009; MacCready et al. 2009; Banas et al. 2009; Sutherland et al. 2011; Giddings et al. 2014; Davis et al. 2014; Siedlecki et al. 2015). Ocean models have advanced in their ability to simulate, or hindcast, spatial structures, seasonal variability, and interannual variability when the forcing is known. JISAO's Seasonal Coastal Ocean Prediction of the Ecosystem (J-SCOPE) is a combination of the Regional Ocean Modeling System (ROMS; Haidvogel et al. 2008) with a detailed oxygen model (Siedlecki et al. 2015) and large-scale predictions from NOAA's Climate Forecast System (CFS) (Saha et al. 2006, 2010; Wen et al. 2012). CFS provides skillful predictions for the region in terms of winds and SST. The CFS is currently being run operationally by NOAA/NCEP/CPC for seasonal weather prediction. In the case of J-SCOPE, NANOOS, the Pacific Northwest regional component of US IOOS, provides the access point to the J-SCOPE seasonal forecasts (http://www.nanoos.org/products/j-scope/), as well as a portal for real-time regional observations. Additionally NANOOS brings linkage to and feedback from resource managers and other stakeholders with interest in the J-SCOPE forecast information. Finally, the CCIEA has partnered with us to advise on the developing product. Through comparisons of model hindcasts and re-forecasts for 2009 and 2013 with local observations, predictive capabilities have been examined for SST, oxygen, and pH. Challenges in forecasting seasonally in the coastal environment include prediction of the fall transition, radiation biases, and the ability of the large-scale model to predict the frequency of relaxations events. Results for the years tested suggest J-SCOPE forecasts had skill on the timescales of a few months.

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END-TO-END MODELING TO PREDICT GLOBAL CHANGE EFFECTS IN THE CALIFORNIA CURRENT ECOSYSTEM

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End-to-end models of marine ecosystems couple climate, oceanography, food webs, and fisheries (Travers et al. 2007). These kinds of large-scale approaches are necessary to understand the cumulative and synergistic impacts of global change and the implications of marine management. End-to-end models of the California Current, such as Atlantis (Kaplan et al. 2013) and the NEMURO plankton-sardine model (Fiechter et al. 2014) simulate mechanisms of ecological interactions and are mainly of use for decadal time scales, and in these ways differ from some other marine forecasting techniques presented in this CalCOFI symposium and elsewhere. The oceanographic features of end-to-end models are often directly driven by simulations of ocean physics (Curchitser et al. 2005) and increasingly by projections of the ocean and atmosphere under climate change (Dunne et al. 2012).

End-to-end models can play a predictive role, ranking management options and investigating scenarios and hypotheses regarding how global change will unfold. Approximately five years ago, Rose and colleagues (2010) urged "restraint in using end-to-end models in a true forecasting mode." Five years later, end-to-end models have advanced substantially, as evidenced by both basic research and fisheries management applications. End-to-end models can now meet higher standards for model review, fitting, and consideration of uncertainty. One example was a recent multiday review of the California Current Atlantis model, conducted by external reviewers and members of the Pacific Fishery Management Council's Scientific and Statistical Committee[1]. The review included consideration of model calibration, fits to history, uncertainty, and parameter sensitivity.

End-to-end models have already provided some simple predictions of climate change impacts in the California Current (Kaplan et al. 2010; Ainsworth et al. 2011). Additionally, they have been used to predict food web impacts of fisheries, fishery management actions, and harvest of forage stocks (Kaplan et al. 2012, 2013). These efforts using the California Current Atlantis model are now being refined to provide improved spatial and taxonomic resolution of the biology, and more detailed projections of oceanography under climate change. Finally, California Current Atlantis model results have been applied to strategic management questions in the context of an Environmental Impact Statement for groundfish fisheries (Pacific Fishery Management Council and National Marine Fisheries Service 2014).

In conclusion, end-to-end models such as the California Current Atlantis model can be used to predict food web impacts of fisheries; these efforts depend on collaboration with field-based programs such as CalCOFI. Predictions of global change are possible and are improving and depend on collaboration with oceanographic research groups. End-to-end models are not tactical tools, and are not intended for short-term predictions (e.g., annual decision cycles). However, strategic management advice from end-to-end models is appropriate for a variety of ecosystem-based management needs, for instance within fishery management plans, fishery ecosystem plans, and cumulative impacts assessments.

[1]**http://www.nwfsc.noaa.gov/research/divisions/cb/ecosystem/marineecology/aem.cfm**

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PREDICTING THE FUTURE IN A NONLINEAR WORLD

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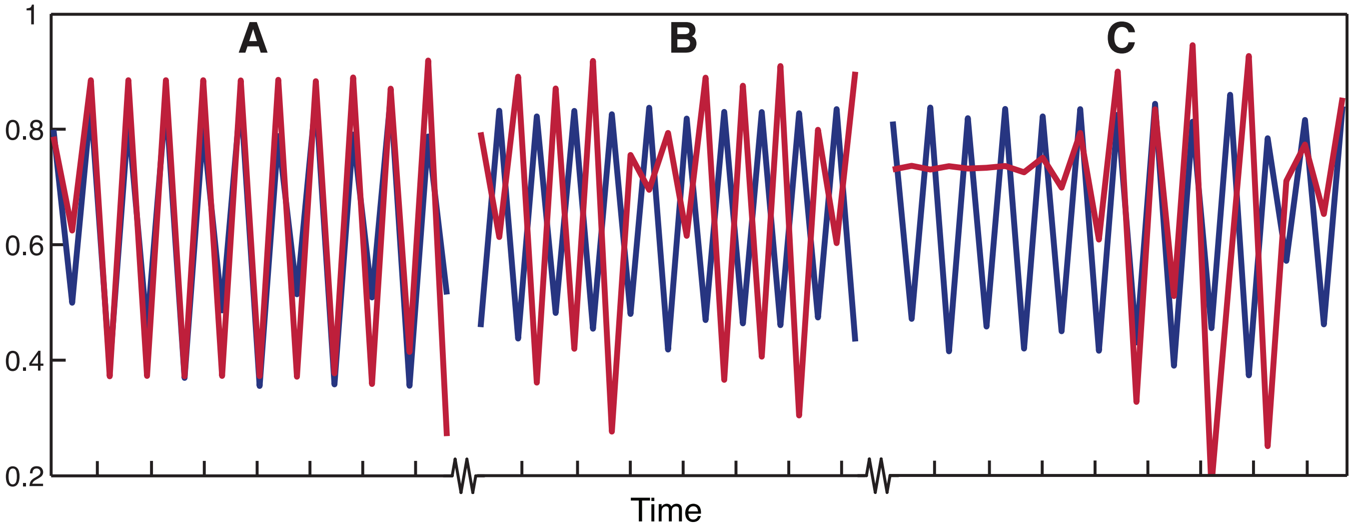

Figure 1. (From Sugihara et al. 2012). Correlations between variables (red and blue) can be ephemeral in nonlinear systems. In panel A, the two variables appear correlated, but in panel b, the variables appear anti-correlated. In panel c, and over longer time periods, there is no correlation, even though the system is dynamically coupled. See Sugihara et al. 2012 for model details and parameters.

Complex nonlinear dynamics are a general characteristic of ecosystems and a challenge for scientists who seek to understand, model, and manage them. These complex dynamics can result from the interaction between endogenous feedbacks, external forcing, and noise (i.e., stochasticity) and can lead to gradual shifts, switching between alternative stable states, deterministic chaos, mirage correlations, and critical transitions. Although the presence of nonlinear, state-dependent behavior means that it may not be possible able to predict the exact state of ecosystems 10–50 years from now, there remains a need for analytical tools that can address the nonlinear behaviors of real ecosystems. Such tools are important to produce accurate forecasts in the short-term, to understand key ecological mechanisms, and to enable adaptive management strategies that remain robust in response to such phenomena as climate change and invasive species.

A fundamental problem with traditional modeling approaches is that they are based on parametric equations, which represent very specific hypotheses about system behavior that can be difficult to justify (Wood and Thomas 1999). Moreover, these models often make simplifying assumptions (e.g., that systems are at equilibrium, different interactions are linearly separable) that do not line up with the known nonlinear reality. Consequently, these models can lack the flexibility to predict future behavior even when they are able to fit the observed data. For example, in nonlinear systems, correlations between variables may not be detectable even if they are dynamically coupled (fig. 1). Thus, variables can appear correlated for the duration of a research study, but this correlation may vanish even though the dynamics have not changed.

One alternative to conventional parametric models is the framework of Empirical Dynamic Modeling (EDM), which does not assume any particular set of equations for the relationships between variables, but instead reconstructs behavior directly from time series data. EDM is based on Takens' Theorem (Takens 1981) and the method of time delay embedding (Packard et al. 1980), which enables it to describe dynamical relationships that are too complex or subtle to capture in a simple set of equations. A brief description of the methods can be found in this short animation: http://simplex.ucsd.edu/EDM_101_RMM.mov.

In addition to the basic methodology of EDM, different techniques have been developed that extend the approach for specific applications: testing for the influence of exogenous factors (Dixon et al. 1999; Deyle et al. 2013), identifying causal interactions (Sugihara et al. 2012; Clark et al. 2015), and even leveraging data from ecological or spatial replicates (Hsieh et al. 2008; Clark et al. 2015). Here, we describe the usage of EDM in two real-world examples of ecological forecasting: (1) identification of a causal linkage between sea surface temperature and Pacific sardine populations in the California Current system and (2) an investigation into the influence of environmental variability on Fraser River sockeye salmon recruitment.

Sea Surface Temperature and Pacific Sardine in the California Current Ecosystem

There has been a long-standing question about whether fluctuations in forage fish abundance are environmentally driven. A well-known example is found in the case of Pacific sardine (*Sardinops sagax*) in the California Current Ecosystem. In California, the Pacific sardine fishery was a rare example of management that explicitly considers environmental conditions. The rationale for this policy was based on work by Jacobson and MacCall (1995), which reported a significant relationship between sea surface temperatures (SST) and recruitment. However, several more recent studies that reanalyze the relationship using newer data have brought the correlation between SST and recruitment into question. The conclusions depend on both the temperature measures examined and the fitting methodology employed (McClatchie et al. 2010; Lindegren and Checkley 2013; Jacobson and McClatchie 2013).

This conundrum can be resolved by using EDM. From a nonlinear perspective, the lack of a significant correlation does not necessarily indicate a lack of causality. Indeed, an analysis of this system using the method of convergent cross mapping (CCM) revealed that information about sea surface temperature (SST) was encoded in sardine time series, suggesting an effect of SST on sardine populations (Sugihara et al. 2012). However, a bottom-line test of whether temperature should be considered for management purposes is if temperature measurements can actually improve forecasts of sardine abundance.

Using EDM models with different environmental measures included as additional coordinates, we found that several temperature variables (SIO pier temperature and the Pacific Decadal Oscillation) did significantly improve forecasts (Deyle et al. 2013). These results provide confirmation that environmental factors do contain information (beyond that of the biological time series) useful for prediction, but to different degrees depending on the variable. Thus, for management purposes, it makes sense to include as robust a measure as possible of the relevant ecosystem affecting Pacific sardines. Indeed, the latest revision to management, by the Pacific Fishery Management Council, establishes harvest control guidelines that respond to a temperature index derived from CalCOFI data, thought to be a better indicator of whether conditions are beneficial or detrimental for recruitment.

Environmental Influences on Fraser River Sockeye Salmon

A similar question of environmental drivers involves sockeye salmon from the Fraser River system in British Columbia, Canada. Early work on this system found that the productivity of these salmon was related to ocean regimes (Beamish et al. 1997) and recent studies suggested that anomalous oceanic conditions experienced by juvenile salmon were responsible for extreme recruitment in 2009 and 2010 (Thomson et al. 2012). However, explicit incorporation of environmental factors into extensions of the standard Ricker model have, to date, produced no significant improvement in actual forecasts (MacDonald and Grant 2012).

Using time series of salmon abundance and the same environmental variables tested in official forecast models, we applied the equation-free framework of EDM, and found that forecasts were significantly improved by the inclusion of environmental factors for the 9 historically most abundant stocks (Ye et al. 2015). In conjunction with the lack of improvement in conventional fisheries models, these results suggest that the interaction between environment and Fraser River sockeye salmon is state-dependent, and therefore not readily encapsulated in simple mechanistic equations (i.e., the extended Ricker stock-recruitment model).

More generally, we note that, although simple parametric models may work over short time periods, such models need to be constantly refit (e.g., an analysis by Beamish et al. 2004 showing better fits of the simple Ricker model when data are partitioned by climate and ocean regimes, a Kalman-filter based approach from Peterman et al. 2000 wherein the Ricker model parameters undergo random drift). Consequently, when the system enters a new state where relationships change, the models will lack predictive power. Moreover, such models are unsatisfactory from a scientific perspective, because they do not explain actual ecological mechanisms—instead the models track the nonlinear behavior of the system phenomenologically as if it were random and therefore do not predict.

CONCLUSIONS

These examples demonstrate the utility of EDM as a data-driven approach for understanding and predicting the future in a nonlinear world. As a general framework, current methods (e.g., CCM, simplex projection) only address certain basic applications, but further developments will continue to bridge the gap between theory and practical usage. As a result, there is a huge potential for increasing use of the EDM framework in situations where parametric models are currently the norm. In addition to the situations described above, where the advantages of EDM for understanding nonlinear behavior are clear, we also note that the ability of EDM models to evolve with new data means that it is inherently more flexible than fixed model structures. Consequently, it is an ideal tool for adaptive prediction in systems changing due to climate change, human impacts, or other unknown factors.

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