

Predicting Trophic Interactions and Habitat Utilization in the California Current Ecosystem

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LONG-TERM GOALS

While specifically focusing on trophic interactions affecting habitat utilization and foraging patterns of California sea lions (CSL) in the California Current Large Marine Ecosystem (CCLME), the long-term goal of our modeling approach is to better understand and characterize biological “hotspots” (i.e., the aggregation of multiple marine organisms over multiple trophic levels) off the U.S. west coast and in other regions where similar fully-coupled ecosystem models may be implemented. As such, our research represents a major step towards a predictive model that can provide fundamental knowledge about: (1) the spatial and temporal distribution of key marine organisms over multiple trophic levels, and (2) natural and anthropogenic variability in ecosystem structure and trophic interactions

OBJECTIVES

The main research objective is to quantify habitat utilization and trophic interactions in the CCLME by considering patterns of covariability between environmental variables (e.g., temperature, primary production) and foraging patterns and success of middle (sardine and anchovy) and higher (sea lions) trophic level species. To this end, our numerical experiments are designed to isolate patterns of variability on seasonal to interannual timescales by identifying shifts in habitat utilization (e.g., shelf vs. offshore foraging) in the CCLME during “normal” and “extreme” years.

APPROACH

Our fully-coupled ecosystem modeling framework consists of a lower trophic level ecosystem model (NEMURO) embedded in a regional ocean circulation model (ROMS), and both coupled with a multi-species individual-based model (IBM) for forage fish (sardine and anchovy) and California sea lion. The IBM for sea lion includes bioenergetics and movement components based on available data on their foraging patterns and diet in the CCLME. The numerical experiments with the ecosystem model are designed to identify trophic interactions and habitat utilization on various timescales, including periods of extreme variability (e.g., El Niño, La Niña, delayed upwelling). Our team includes expertise in areas of climate modeling in upwelling regions (E. Curchitser), physical-biological modeling in the CCLME (J. Fiechter and C. Edwards), data assimilation (A. Moore), forage fish ecology (K. Rose) and pinniped ecology (D. Costa). The team also includes a postdoctoral research associate (L. Huckstadt)

working on the bioenergetics and behavior components for the sea lions under the supervision of D. Costa.

WORK COMPLETED

We completed the third year of the project, and our progress to date is on track with respect to the proposed milestones for Year 3. As of 1 September 2015, we have achieved the following main tasks:

- (1) Evaluation of a 50-year simulation of the fully coupled ecosystem model (with sardine and anchovy only) to determine which environmental factors controlled forage fish population dynamics in the CCLME during 1959-2008.
- (2) Implementation of the CSL IBM component in the ecosystem model with full bioenergetics and various movement algorithms, such as kinesis and restricted-neighborhood search.
- (3) Evaluation of a 20-year simulation of the fully coupled ecosystem model (with sardine, anchovy and CSL) to determine how environmental variability and prey availability controlled sea lion habitat utilization and foraging success along central California during 1989-2008.

The completion of task (1) led to the submission of two manuscripts to *Progress in Oceanography* describing the fully coupled ecosystem model framework (Rose et al., 2015) and the environmental factors controlling sardine and anchovy population abundance in the simulation (Fiechter et al., 2014). The completion of tasks (2) and (3) led to presentations at the IMBER 2014 Open Science Conference in the session “End-to-end modelling for research and management” and at the EPOC 2015 Conference in the session “Predictability of biology across different space-time-trophic scales”. A manuscript describing the results from the 1989-2008 simulation is also in preparation.

RESULTS

We ran the fully-coupled ecosystem model from 1988 to 2008 as this particular time period encompasses one of the strongest El Niño events on record in 1997-98, a warm-to-cold PDO regime shift in the late 1990's (Peterson and Schwing, 2003), and years identified as normal (2004) and abnormal (2005) for California sea lion foraging based on tracking data (Weise et al., 2006). The impact of environmental conditions and prey availability on sea lion foraging patterns was identified using an empirical orthogonal function (EOF) decomposition of simulated annual mean sea lion distribution, sea surface temperature (SST), and sardine and anchovy population abundances.

The first EOF mode for sea lion distribution primarily identifies a north-south shift in foraging patterns, although it also suggests that when sea lions aggregate nearshore in the southern part of the domain (i.e., between 34 and 36 °N), they tend to favor more offshore locations in the northern part of the domain (i.e., between 36 and 38 °N) (Fig. 1, left panel). The foraging patterns associated with mode 1 correspond to variability in sardine abundance off central California, with sea lion individuals typically shifting to the north (south) during periods of high (low) sardine abundance (Fig. 1, center and right panels). The second EOF mode isolates foraging variability that is either coastal along most of central California (i.e., between 35 and 38 °N) or offshore and near the southern and northern ends of the simulated range (Fig. 2, left panel). The time amplitude of mode 2 indicates that model individuals favored more offshore, southern and northern locations during the 1990s, then switched to

more coastal foraging over a narrow latitudinal range starting in 2001 (Fig. 2, center panel). During the second half of the record, 2005 also stands out as a strongly anomalous year during which foraging patterns switched from predominantly nearshore to offshore. The foraging pattern identified by mode 2 correspond to SST variability associated with coastal upwelling off central California (Fig. 2, right panel), with sea lion individuals foraging preferentially nearshore during years of strong upwelling and venturing further offshore during periods of anomalously warm coastal SSTs (e.g., 1993 and 2005).

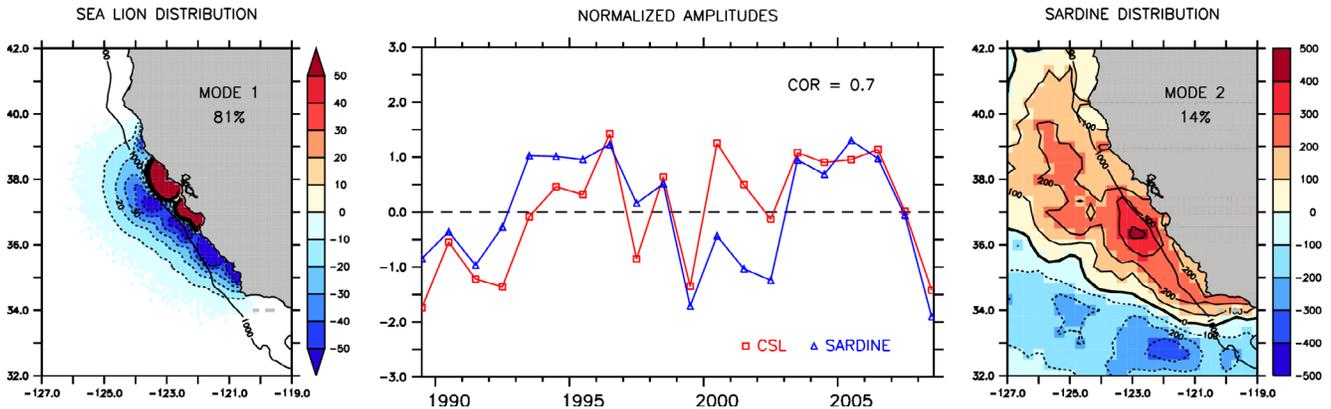


Figure 1. Foraging patterns: alongshore variability. First EOF mode for sea lion distribution and second EOF mode for sardine abundance. Left and right: spatial patterns and percent variance explained. Center: normalized amplitudes (red squares = sea lion; blue triangles = sardine).

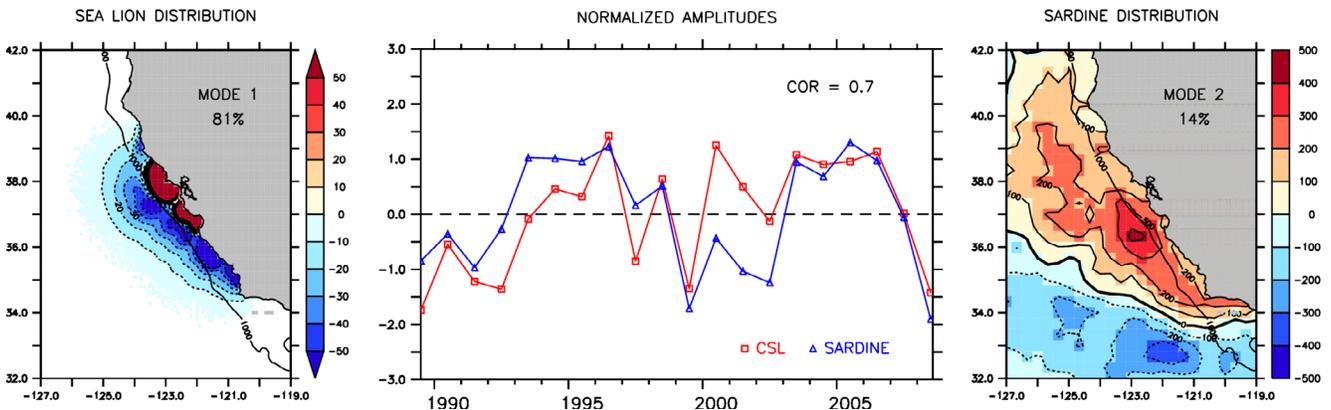


Figure 2. Foraging patterns: cross-shore variability. Second EOF mode for sea lion distribution and second EOF mode for sea surface temperature. Left and right: spatial patterns and percent variance explained. Center: normalized amplitudes (red squares = sea lion; blue triangles = temperature).

A direct comparison between model output and sea lion tracking data collected in 2004, 2005 and 2006 further illustrates the significant offshore shift in foraging locations, with 2004 displaying mainly nearshore foraging along the entire central California coast (Fig. 3, left panel), 2005 showing substantial offshore foraging at most latitudes (Fig. 3, center panel), and 2006 displaying an intermediate pattern where sea lions foraged nearshore in the southern half of the domain (Pt. Conception to Monterey Bay) but ventured further offshore in the northern half (Monterey Bay to Cape Mendocino) (Fig. 3, right panel).

We also evaluated foraging success by considering interannual variations in simulated fat depot (i.e., a proxy for optimal growth conditions). By comparing interannual changes in fat depot against EOF modes for environmental variability (i.e., SST) and prey availability (i.e., sardine and anchovy abundances), we found that fat depot correlates most strongly with the second EOF mode for sardine abundance (i.e., the EOF mode associated with inshore vs. offshore foraging) (Fig. 4, top panel). While sardine account for a smaller fraction of the sea lion diet in the model (on average 4.6 kg day^{-1} compared to 8.4 kg day^{-1} for anchovy), interannual changes in prey availability are substantially larger for sardine, with a standard deviation of 15% of the mean compared to 5% for anchovy (Fig. 4, bottom panel). This effect is further compounded by the fact that sardine have a higher energy density (7.3 kJ g^{-1}) than anchovy (6.6 kJ g^{-1}), market squid (4.4 kJ g^{-1}) and mackerel (6.4 kJ g^{-1}), meaning that replacing sardine by other prey sources would negatively impact sea lion growth and fat deposition. Hence, years for which sardine availability is substantially reduced in the simulation (i.e., 1991 and 1999) exhibit a sharp decline in the ability for sea lions to accumulate fat.

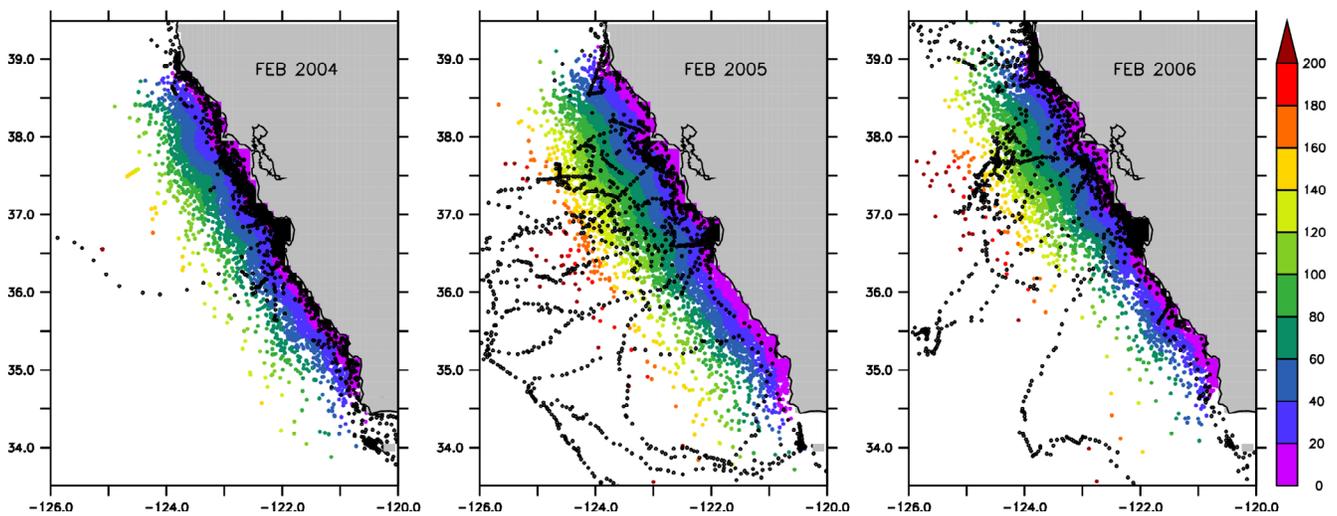


Figure 3. Foraging patterns: model-data comparison. Simulated (colored circles) and observed (black circles) foraging locations for male sea lion individuals off central California in 2004, 2005 and 2006. Simulated locations are for February and color scale represents offshore distance (km). Observed locations are based on tracking data collected during winter (Nov-Mar) of 2003-2004, 2004-2005 and 2005-2006.

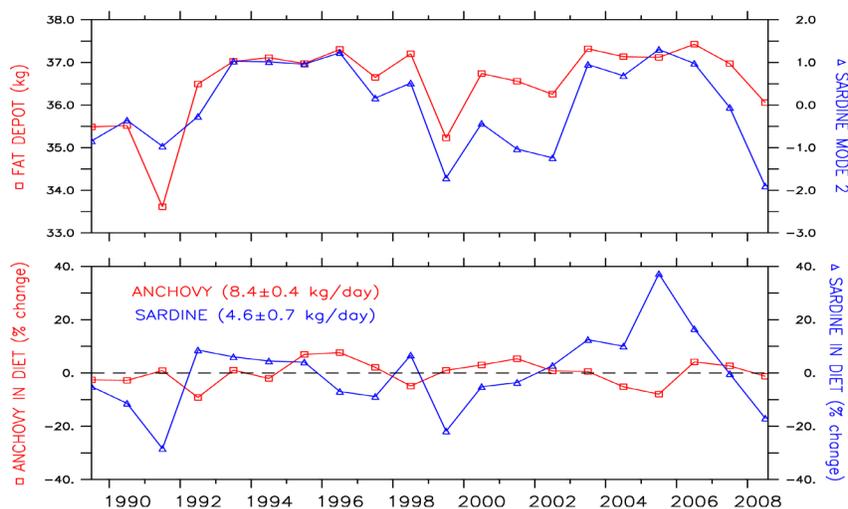


Figure 4. Foraging success and diet composition. Top: sea lion fat depot (left y-axis and red squares) and EOF mode 2 amplitude for sardine abundance (right y-axis and blue triangles). Bottom: relative change of anchovy (left y-axis and red squares) and sardine (right y-axis and blue triangles) contributions to sea lion diet with respect to 20-year mean.

IMPACT/APPLICATIONS

While focusing on the development of an individual-based model for California sea lions and its incorporation into a fully-coupled ecosystem model, the proposed research will pave the way for building a more comprehensive end-to-end modelling framework that can account for multiple species across several trophic levels. This information will eventually lead to characterizing biological “hotspots” (i.e., the aggregation of multiple marine organisms over multiple trophic levels) in the CCLME, or other regions where similar fully-coupled ecosystem models may be implemented (e.g., Southern Ocean). A main advantage in using model output to diagnose the occurrence and persistence of biological hotspots is the access to all physical and biological variables (e.g., water column temperature, primary production, growth rates, behavioral cues) over the range of spatial and temporal scales needed to determine which particular environmental conditions and which particular foraging strategies were conducive to aggregation over multiple trophic levels. In the future, our ecosystem model could be used to predict how climate variability may impact suitable habitat distributions in the CCLME or other regions of the world oceans.

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PUBLICATIONS

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