1. Title: **Transport indices of ecosystem structure and productivity in the California Current**

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4. Project Duration: 1 year

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6. Year 1 Request: $81,989

7. Year 2 Request: $0

8. Other investigators: see above

9. Institutional breakdown of Year 1 budget:NOAA SWFSC $44,904, of which $41,704 to UCSC, and NOAA NWFSC $37,085, of which $36,485 to OSU-CIMRS

10. Institutional breakdown of Year 2 budget: $0

BACKGROUND. The California Current Integrated Ecosystem Assessment (CCIEA) includes numerous indicators for the ecosystem state of the northern California Current (NCC). Among the most informative are indicators based on copepod community structure measured along the Newport Hydrographic Line (NHL)that correlate withrecruitment of salmon (Peterson and Schwing 2003, Burke et al. 2013, Peterson et al. 2013, Peterson et al. 2014), sablefish (Schirippa and Colbert 2006, Peterson et al. 2014), and sardine (Peterson et al. 2014), and have strong potential to support stock assessmentsand forecasts of commercial fish stocks several years into the future (Mackas et al. 2007). Data collected along the Trinidad Head Line (THL) off northern California using identical protocols show similar promise, while providing the opportunity for powerful comparative analysis of ecosystem indices across the NCC.

The power of copepod-based indicators derives from (1) consistent affinities of different copepod species for cold water versus warm water and for nearshore versus oceanic distributions (Peterson and Keister 2003, Hooff and Peterson 2006), reinforced by (2) qualitative differences in energy content among these groups. Specifically, several cold-water species (e.g., *Calanusmarshallae* and *Pseudocalanus mimus*) are rich in wax esters and fatty acids, tend to dominate coastal zooplankton communities during the summer upwelling season (typically May through September), and are especially productive when cool conditions prevail throughout the California Current System (CCS).In contrast, lipid-poor, warm-water taxa are more common during winter or when El Niño events or persistently warm conditions (as indicated by positive Pacific Decadal Oscillation values) disrupt community transitions related to the onset of seasonal upwelling and equatorward flow (Fisher et al. 2015).

Analysis of zooplankton data collected along the NHL has revealed patterns in how the planktonic ecosystem of the NCC responds to forcing over time.This time series spans several ‘natural experiments’structured by environmental and climate variability,which has allowed detection of climate-ecosystem correlations at inter-annual to decadal scales, and the formulation of mechanistic hypotheses that link ecosystem responses to physical forcing (Peterson and Schwing 2003,Hooff and Peterson 2006,Keister et al. 2011, Bi et al. 2011, Schroeder et al. 2013). Comparative analysis of observations from NHL and THL confirm these patterns, but also highlight important alongshore variability in community structure, which has implications for food chain bioenergetics, and how these communities respond to climate events.

Transport holds a central place in these hypotheses, stemming from the apparent role of basin-scale dynamics in controlling the source waters—hence the copepod communities—that feed into the NCC. For example, persistently negative values of the Pacific Decadal Oscillation (PDO) correspond to stronger influx of watersoriginating in the Gulf of Alaska and off coastal British Columbia flowing south along the coast, whereas persistently positive values of the PDO indicate a greater proportion of water arriving from the sub-tropical portion of the Transition Zone that lies offshore of the NCC (Keister et al. 2011). Indeed, at annual to decadal time scales, copepod biomass closely tracks the PDO andthe Ocean Niño Index (ONI;Figure 1), each of which captures a major mode of variability in large-scale wind forcing that drives the dynamics

of the North Pacific (Peterson et al. 2002, Peterson and Schwing 2003,Hooff and Peterson 2006,Keister et al. 2011, Bi et al. 2011, Francis et al. 2012, Fisher et al. 2015). Visual comparisons of these time series are quite striking, and statistical correlations are significant at the < 0.05 level, yet such correlations explain only about 23-28% of the variability in copepod community structure.

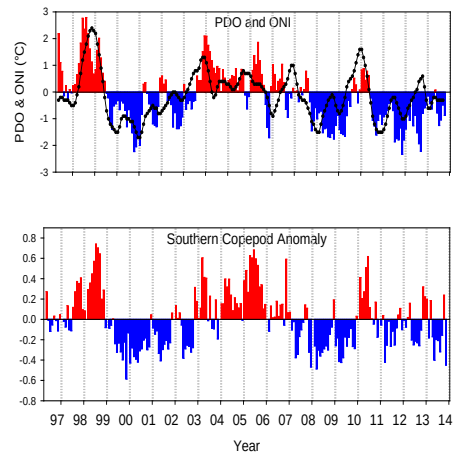

Figure 1. Comparison of PDO and ONI (upper panel) and monthly biomass anomalies of southern (warm water) copepods at NH05 (lower panel).

Local transport also affects cross-shelf (Bi et al. 2012), and alongshore (Petersonand Keister 2002) structure and connectivity in copepod communities and how they change over time; these findings find further support in ongoing comparative analysis of copepod data from NHL and THL (see below). Therefore, information on transport at smaller scales is needed both to address outstanding questions of how well zooplankton-based indicators for the NHL represent the broader NCC, and to enhance our understanding and predictability of latitudinal variability in recruitment to salmon and other fishery stocks.

In sum, basin-scale indices such as the PDO are too coarse to serve as robust predictors of transport directly affecting coastal waters where most fishery resources are found, and where data that underpin highly informative, zooplankton-based ecosystem indicators are collected. By linking variability in copepod community structure to coastal transport at a smaller scale, we propose to develop purely physical indices that are grounded in ecosystem responses, and can be used to hindcast periods prior to zooplankton sampling, and thus have strong potential for having greater explanatory power for understanding variability in recruitment to fish stocks.

APPROACH. We propose a study to (a) develop local-scale indices of transport derived from ocean circulation models for the California Current that integrate evolving ocean responses to basin-scale and local-scale forcing, (b) quantify local- and regional-scale response of alongshore- and cross-shelf transport of shelf waters to basin-scale variability associated with the PDO, El Niño, and the North Pacific Gyre Oscillation, (c) evaluate the utility of local-scale transport indices as predictors of copepod community structure, (d) compare the timing (and lag) of copepod indicator species at two locations (NHL and THL) to infer whether alongshore transport and/or local production are driving those variations, and (e) explore the utility of a model-based hindcast of copepod community structure to 1980, 16 years prior to the onset of continuous observations along NHL.

Copepod Data. Copepods are sampled along both NHL and THL using identical protocols and gear (vertical ring net tows from 100 m or within 5 m of the sea floor), coupled with concurrent hydrographic measurements. Samples have been sorted almost exclusively by a single person (Peterson) minimizing the potential for analyst bias within the data set. Major aspects of copepod

species composition are readily discerned using non-metric multidimensional scaling (NMDS). Our analysis will focus on data for midshelf stations (NH05 and TH02), but be extendable to similar time series for offshore stationsthat are presently available for NHL andare being developed with FATE funding for THL.

ROMS Model Products. Over the last decade, the UCSC ocean modeling group (Edwards and Moore) have developed several ocean model products for the CCS, by implementing the Regional Ocean Modeling System (ROMS; Shchepetkin et al.2005) within a domain extending from south of the US/Mexico border to just south of the Strait of Juan de Fuca, and offshore to 134°W (Veneziani et al.2009a). This model has supported several studies of physical dynamics, larval transport, and biogeochemistry in the CCS (e.g., Veneziani et al. 2009b, Drake et al. 2009, Drake et al. 2011, Petersen et al. 2010, Goebel et al. 2010, Jacox et al. 2014). Further details can be found in Moore et al. (2013) and at http://oceanmodeling.ucsc.edu.

For this project, we propose to develop transport metrics primarily from twomodel reanalyses of the CCS, RA1 (1980-2012) and RA2 (1999-2013). Both resolve ocean dynamics on an identical grid with 1/10 degree horizontal spacing, and use 4-dimensional variationaldata assimilation as implemented in ROMS (e.g., Broquet et al. 2009a, 2009b, 2010, Moore et al. 2011a, 2011b, 2011c), and differ only in the data products[1] from which surface forcing (e.g., winds, heat fluxes, etc.) is obtained. Both models assimilate sea surface height, sea surface temperature, and *in situ* temperature and salinity when available throughout the period of assimilation.

Because data assimilation rigorously constrains models by adjusting control variables (e.g., model initial conditions) to minimize (in a least-squares sense) discrepancies between model output and observations, ocean state estimates from such models should more reliably represent observed conditions than unconstrained nonlinear models. Both reanalyses to be used in this work have shown strong correspondence with field observations along the central CA coast,and have suppoted elucidation of factors affecting distributions of krill and juvenile rockfish (Schroeder et al. 2014). Preliminary comparisons to hydrographic conditions in the NCC are also favorable (data not shown). Because copepod community structure is closely related to hydrographic conditions, we will corroborate modeled ocean state through comparisons to hydrographic data collected along our cross-shelf transects with a focus on observations at stations where copepodsare sampled.

We will extract metrics of NCC physical properties from the reanalyses for statistical comparison to the NHL and THL copepod data, including measures of temporal and spatial variability in upwelling (Figure 2; Jacox et al. 2014), cross-shelf and along-shore transport (including measures of integrated transport in various depth ranges and cross-shelf extents), and physical structure (e.g., mean depth or cross-shelf slope of particular isopycnals, upper ocean heat content, and other hydrographic parameters). In addition, we will extend results from a

[1]RA1 is forced with fields from the ECMWF ERA-40 reanalysis (1980-1986), or with the Cross-Calibrated Multi-Platform (CCMP) wind product in conjunction with ERA-40 fields (1987-2001) or the ERA-Interim reanalysis product (2002-2012).RA2 is forced by the high resolution COAMPS model (Hodur et al 2002).

preliminary analysis that links copepod community variability to transport extracted from data-assimilating ROMS models (e.g., Figure 3) to develop indices of recent source waters arriving in the vicinity of copepod sampling stations for comparison to copepod community structure (Keister et al. 2011).

Statistical relationships between the copepod data and these metrics will be evaluated by analysis of the full overlapping time series(1996-2013 years for NHL, 2008-2013 for THL). Assessment of model fit and significance will account for potential spurious correlations between autocorrelated time series (following, e.g., Keister et al. 2011). Model skill will be evaluated by excluding subsets of data from model fits and comparing predictions based on reduced data sets to excluded data.

The work proposed here will substantially extend and refine these preliminary results, and in particular will elucidate connections between large-scale forcing and local transport over annual to decadal time scales.Moreover, by comparing the timing (and lag) of copepod indicator species and community characteristics at the two locations (NHL and THL) we will also be able to infer whether alongshore transport or production more strongly contribute to variations in community structure.

BENEFITS. This research addresses several FATE research themes, including developing oceanographic indicators and investigating specific mechanisms driving interactions between fisheries and climate (Topic 1); improving and augmenting indicators that are currently or being used in Ecosystem Status Reports and Integrated Ecosystem Assessments (Topic 3); evaluating the

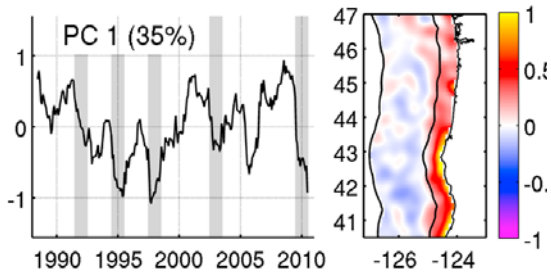

Figure 2: First Principal Component (left panel) and corresponding EOF (right panel) of vertical transport anomaly at 40m off Oregon derived from RA1 (1980-2012).From Jacox et al. (2014). This PC captures temporal variability; other PCs capture spatial pattern.

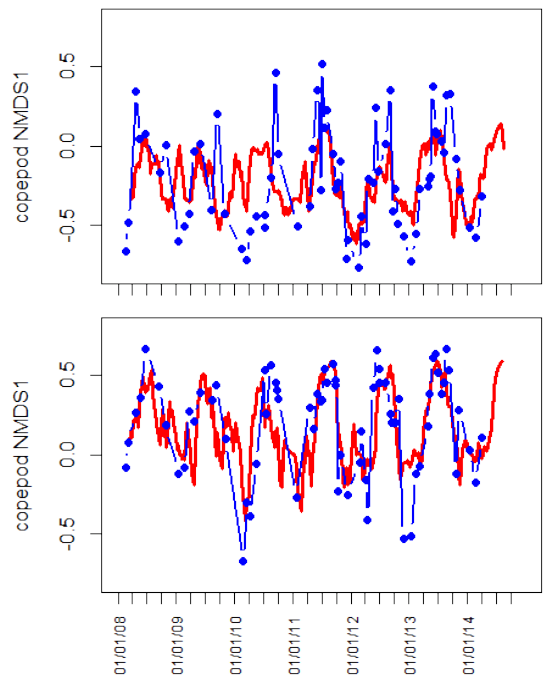

Figure 3. Results from a preliminary comparison of NMDS axis 1 (an index of copepod community structure; blue) to predictions from an empirical model linking community structure to a transport index (based on the direction(s) from which source waters arrive) derived from ROMS (red) for TH02 (upper panel, R=0.46) and NH05 (lower panel; R=0.69). The ROMS data used for this analysis is drawn from two different products: an historical reanalysis (up to 2010) and results extracted from a near-real-time product (from 2011 on).

feasibility of forecasting oceanographic processes and their ecosystem impacts over short (1-10 years) and long (20+ years) time-scales (Topic 5); and identifying how environmental indicators can supplement or be considered alongside stock assessment output (Topic 6).

It is widely recognized that"an incomplete understanding of the impact of climate and other physical parameters on populations can lead to ... unintended impacts to fishery stocks"[2].*By integrating local transport into our understanding of how physical forcing drives change in copepod community structure and ecosystem state, we expect to substantially increase our ability to explain and forecast variability in ecosystem state and the productivity (recruitment) of fishery stocks both in the NCC and, ultimately, throughout the CCS, over time and space.*Success in this work will allow us to (1) extend insights (and indices) from the NHL time series (and, with greater uncertainty, from the THL time series) deeper into the past, enriching existing environment-salmon correlations as well as supportingbroader application tostock assessments for sablefish, whiting, sardines, rockfishes, and other long-lived species (as called for in the CCIEA Draft Three-Year Work Plan), and (2) develop candidate indices for other regions of the NCC that reflect alongshore variability in ecosystem responses to basin-scaleforcing and have potential to elucidate variability in recruitment to salmon and other fishery stocks along the coast.

The strength of physical indices emerging from this work will be explicitly grounded in the clear links between zooplankton and higher trophic levels in the NCC, and will provide a basis for extending zooplankton-based recruitment indices deeper into the past, thereby increasing their potential utility in stock assessments. Moreover, these indices will help to elucidate the ecosystem basis for physical-recruitment correlations (e.g., Ralston et al. 2013) and lay critical ground work for examining drivers of spatially variable recruitment (e.g., Field and Ralston 2005). Immediate application of these indices to forecast models will support existing short-term forecasts for salmon and the broader ecosystem (e.g., www.nwfsc.noaa.gov and FATE J-SCOPE efforts) by strengthening the link between physical forecasts and ecosystem response. Moreover, insights from this work will enhance our ability to explore ecosystem responses under different scenarios of ongoing climate change. Finally, this work will complement ongoing and future efforts (e.g., Leising et al. "Model-based physical and biological spring transition indices for the California Current System" proposed to FATE) to link modeled zooplankton production to observed community structure as the basis for more sophisticated ecosystem indicators.

DELIVERABLES. Based on this work, we will deliver:

- new indicator(s) of alongshore transport derived from historical and ongoing ROMS ocean state productsposted to our "Salmon Forecasting" web-page and added to the California Current IEA "Drivers" section
- one or more peer-reviewed publications
- several talks on this work at FATE PI and other scientific meetings

[2]NOAA Fisheries website "Fish Stock Assessment 101 Series: Part 1—Data Required for Assessing U.S. Fish Stocks"

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