Title: Indicators of phenology in the northern California Current

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Project Summary. We propose to develop indicators related to phenology (the timing of seasonal activities) in the northern California Current (NCC), using our 20+ year Newport Hydrographic Line time series of biweekly measurements of temperature, salinity, nutrients, chlorophyll, and abundance and species composition of plankton (phyto-, zoo-, ichthyo-) and krill. We will also analyze data on vector winds from NOAA data buoys, currents from Oregon State University moorings located off Newport, sea level from the tide gauge at Newport, and data on sablefish recruitment and hake landings. The project will focus on (1) processes associated with the timing (phenology) of the onset of biological production in winter, (2) comparison of the physical and biological dates of spring and fall transition, (3) investigation of possible shifts in the seasonal peaks in the abundance of the dominant copepod species in summer, and (4) study of statistical relationships between (a) sablefish recruitment and phenology indicators associated with winter production and the biological spring transition, and (b) variations in the timing of arrival of northward migrating whiting off Oregon relative to phenology indicators.

This proposal addresses a core research area of the NWFSC Annual Guidance Memo (p. 6): "Build on [the] Integrated Ecosystem Assessment and refine the set of tools in the IEA toolbox to effectively implement the Council's Fishery Ecosystem Plan", and answers a need identified in the NOAA-Fisheries Climate Science Strategy "to develop indicators that provide early warning of impending shifts in phenology and distributions…".

Background. The classical view of productivity in the California Current holds that production in the California Current depends largely upon the length and strength of the coastal upwelling season (e.g., Bakun et al. 2015). However, this paradigm has been challenged recently in two respects: first, production events in late winter and early spring are critical for successful recruitment of winter-spawning invertebrate and finfishes including many that are fished commercially (Dungeness crabs (Shanks 2013), pink shrimp (Hannah 1993, 2011), rockfish (Black et al. 2010; Black et al., 2014), and sablefish (Schirripa and Colbert 2006; Holt and Mantua 2009). In addition seabirds such as the common murre (Zador et al. 2009; Schroeder et al. 2009), Cassin's auklets (Sydeman et al. 2006; Schroeder et al. 2009) and Rhinoceros auklets (Borstad et al. 2011; Bertram et al;. 2009) have life history strategies that include reproduction during the winter and early spring because downwelling and poleward transport enhances larval retention (Shanks and Eckert 2005, Yamada et al. 2015). Thus any process that disrupts the timing of winter/spring reproduction events may affect subsequent recruitment of the winter-spawners.

Secondly, interannual variations in the species composition of zooplankton in the NCC in spring and summer sets the efficiency at which productivity is transferred to higher trophic levels (Keister et al. 2011; Bi et al. 2011; Francis et al. 2012) – transport processes associated with the Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO) govern the species composition of zooplankton that are delivered to the NCC. Maximum efficiency occurs when the PDO is in negative phase (NPGO positive) because at such times large-sized lipid-rich zooplankton are transported to the NCC from the coastal Gulf of Alaska (GOA), species which

are capable of feeding on the large diatoms that dominate upwelling systems; when the PDO is in positive phase (and NPGO negative phase), small lipid-poor subtropical species are transported to the NCC which cannot feed efficiently on large diatoms.

A better understanding of the magnitude and timing of winter production and of efficiency of energy transfer during spring and summer is needed because the NCC is a feeding ground for numerous **migrant** species which come to the NCC in spring to fatten-up. Species such as Pacific hake, sardines and anchovies migrate northward from the warm waters of the southern California Current; stocks of salmonids from the Columbia, Snake, Sacramento and coastal rivers migrate to the sea in spring. Other species travel thousands of miles from breeding grounds throughout the Pacific Basin to feed in shelf and slope waters off northern California, Oregon and Washington --sooty shearwaters from New Zealand, black-footed and Laysan albatross from Hawai'i, humpback whales from Peru and grey whales from Baja California. They come to the NCC expecting that a fatty food chain will be present.

In terrestrial systems, climate change is leading to striking changes in phenology including an earlier start to spring, earlier northward migrations, and earlier reproduction of local species (IPCC/AR5--Settele et al. 2014). However comparatively little work has been done on phenology in the marine environment (IPCC/AR5--Pörtner et al. 2014; Burrows et al. 2011; Ji et al. 2010; Batten and Mackas 2009; Sydeman et al. 2008), due largely to the fact that most biological oceanographic sampling programs are not designed to look at this phenomenon (e.g., annual trawl surveys of fishes and quarterly surveys by CalCOFI clearly cannot capture any aspect of phenology). Biological observation programs that can or do produce phenological data are very rare and for the California Current include the 20 year time series of plankton and krill observations along the Newport Line, 30 year time series of plankton and krill off Vancouver Island (Mackas et al. 2007) and long-term surveys of seabirds nesting at colonies on the Farallon Islands (for Cassin's Auklets),Yaquina Head (Newport) Oregon and Cape Flattery (for common murres), and Triangle Island BC (for Cassin's and Rhinoceros auklets).

Inspired by the work of Bob Francis and Steven Hare, we set out in 1996 to study the influence of the PDO on plankton abundance and species composition as well as phenology of key physical and biological events, knowing that a long time series of samples was needed. The idea was to collect in situ oceanographic data at the highest frequency and the lowest cost possible. Thus, we have now a unique 20+ year time series of fortnightly sampling along the Newport Hydrographic Line using CTDs and plankton nets, made possible by sampling from small boats (the 54' R/V Elakha). To date we have completed 541 surveys. In addition, we have also sampled offshore waters, quarterly in most years, from 1998-present using NOAA research vessels along multiple transect lines from Newport (44.6°N) south to Eureka CA (40°N), to at least 150 km from shore, during 84 cruises.

Approach and Deliverables. To understand better the causes of interannual variations in productivity in the NCC ecosystem, we propose (a) to generate products that index the phenology of winter production, (b) to estimate the date of onset of biologically-effective upwelling in spring and the end in fall, and (c) to work out relationships between the sign of the

PDO and NPGO and quality of upwelling as well as phenology associated with seasonal cycles in reproduction and biomass of copepods and krill, and recruitment and migration patterns of sablefish and Pacific whiting (hake). Below we list the phenological events that we will index, using both presence/absence (i.e., did the event occur?) and if so, what was the date when an event was initiated. Many of the methods follow those listed in Table 1 of Ji et al. (2010):

- Sablefish larvae and juveniles feed on copepods thus we want to determine when (in January) their prey species, *Neocalanus plumchrus*, *N. cristatus* and *Calanus marshallae,* awaken from diapause, and if the timing has become earlier. (see Liu et al. 2011; Liu et al. 2015 for studies of *Neocalanus plumchrus* and *N. cristatus*)
- Wind speed/direction and frequency of occurrence of clear skies in January and February. Calm winds and clear skies result in winter phytoplankton blooms (Parsons et al., 1966) off Oregon in some years. Timing, magnitude and duration of the bloom will be determined from SeaWiFS MODIS imagery and our *in situ* chlorophyll measurements.
- If there is a bloom in February, a burst in egg production by the *C. marshallae* and krill *Thysanoessa spinifera* occurs and cohorts of *C. marshallae* and *T. spinifera* are produced, resulting in enhanced biomass of these species by May which in turn feeds local and migrant upper trophic level species. If there is no bloom, biomass remains low until summer (e.g., Feinberg et al. 2010). Thus in some years, winter events 'precondition' the system for an enriched food chain by spring (as in Schroeder et al. 2009) whereas in other years, winter and spring production are uncoupled (as in Black et al. 2011).
- Date of biological spring and fall transitions will be indexed by the date when the copepod community has transitioned from a winter community (southern neritic and lipid-poor species transported north by the Davidson Current) to a summer community (northern lipid-rich species transported to the coastal NCC from the GOA, and vice versa. Dates will be determined from cluster analysis and from the x-axis scores from an ordination of the species abundance (Keister et al. 2011); both methods indicate when the copepod community has switched from a winter to summer community. Indicator Species Analysis will determine which species uniquely define the spring transition.
- Comparison of biological spring transition to physical transition. This is important because the onset of upwelling does not mean that significant secondary production has occurred. Northern copepods must be transported to the NCC from the coastal GOA, an event that may lag the onset of upwelling by many weeks. Date of the biological spring transition will be compared to several spring transition indices (Logerwell et al. 2003, Kosro et al. 2006; Holt and Mantua 2009 and Bograd et al. 2009) using the Bakun upwelling index, local winds and sea level. This work will demonstrate that the key aspect of potential changes in coastal upwelling in the future is not whether it is early/late, strong/weak, but rather, if/when the "right" copepods are delivered to the system.
- Test for shifts in the seasonal peaks in abundance/biomass of phytoplankton and the local copepod species, in spring and summer; phytoplankton phenology will be determined

from a combination of SeaWiFS and MODIS imagery and our *in situ* data; For copepods, calculate time of peaks in biomass peak for all copepod species (Batten and Mackas, 2009) and compare date of peaks to dates of physical and biological spring transitions; compare magnitude of peaks among years to strength of upwelling. Estimate median peak dates from cumulative abundance curves and sigmoid functions.

- Pacific Hake studies will include (a) timing of arrival of whiting determined from daily fishing records from the Port of Newport. (b) the rate of migration will be derived from daily landings records from ports off N. California, S. Oregon, N. Oregon and Washington); (c) the farthest distance north that hake have traveled will be estimated from the annual hake survey (since 1977) – see Ressler et al. (2007). We will test the hypothesis that hake migrate more slowly (quickly) when the PDO is in negative (positive) phase and euphausiid biomass is high (low). The latter will be tested using krill biomass data from our Newport time series. These timing indicators will serve as 'early warning indicators' that should be of value to those involved in negotiations concerning allocation of catches between US and Canadian fishermen.
- Sablefish recruitment (using recruitment data from the assessment models) compared to various winter phenology indices (timing of appearance and biomass of the *Calanus* and *Neocalanus* copepods upon young sablefish feed in winter/early spring; physical and biological spring transition dates). These indicators should be of value to stock assessment scientists when used as a supplement alongside assessment output.
- Recruitment of Dungeness crab larvae (retrospective analysis, using data generated on settlement of megalopae (see Shanks 2013) will be compared to timing of wintertime phenological events and date of biological spring transition.
- All of the work outlined above will be cast in the context of basin scale forcing associated with the PDO, ENSO and NPGO thus we need to test for relationships between these indices and the timing of the delivery of lipid-rich copepod species to the coastal NCC (Fisher et al. in press), phenology associated with seasonal cycles in reproduction and biomass of copepods (Peterson and Du, in press) and krill (Feinberg et al. 2010), and recruitment and migration patterns of sablefish and Pacific whiting.
- Continue to report to the Pacific States Marine Fisheries Commission, the Pacific Northwest Power and Conservation Council and NMFS West Coast Regional Office; initiate regular reporting to the Pacific Fisheries Management Council through the IEA.
- Addition of a "Phenology" button on our Center's website which will complement our "Salmon Forecasting" and "Newportal" buttons on our Centers webpage (www.nwfsc.noaal.gov).

Benefits and Expected Results. This work addresses directly 4 of the 6 Research Topics outlined in the FATE RFP: Topics 1 and 2- develop indices and statistical models of environmental and oceanographic indicators to investigate mechanisms driving interactions between fisheries and climate; Topic 3 – develop, improve and augment indicators that are currently used in Ecosystem Status Reports and Integrated Ecosystem Assessments (see Results

of past FATE research); Topic 4 – examine effects of climate variability on managed fisheries and ecosystems; Topic 6 – examine how our indices can be used alongside stock assessments (something that we already do in our salmon forecasting). Considering indicators **alongside** a stock assessment is a realistic expectation given the difficulty of **directly** incorporating indicators into stock assessment models. Indeed, we have learned that statements such as this will be "a great year", "a good year" or "a poor year" are highly valued by the media, salmon managers and colleagues who are stock assessors.

This proposed work continues our pioneering work in the northern California Current on (a) our FATE-supported physical and biological indicators for tracking climate-related trends in lower trophic levels in the NCC, (b) application to salmon management through our FATE-supported forecasts of salmon returns to the Columbia River, and (c) will complement our ongoing reporting of ocean conditions to the Integrated Ecosystem Assessment (we write the NCC drivers section and contribute to the Ecological Integrity section where copepod indices are among the highest ranked ecological indicators).

Consideration of phenology is relatively new to marine ecology (Edwards and Richardson 2004; Visser and Both 2005; Poloczanska et al. 2013) and to the NCC (the only papers published to date seem to be on phenology of upwelling, *Neocalanus* and seabirds, as referenced above). The importance of the timing of delivery of lipid-rich copepods has also been highlighted clearly in studies in the North Atlantic (Beaugrand 2009; Kattner and Hagen 2009).

Our proposed work will heighten the awareness of scientists and managers of the need for such information as we all begin to weigh the consequences and mechanisms that link physical climate change with biological responses and subsequent impacts on commercially-important fish stocks. Of immediate interest is the impact of "the Blob" of 2013-2015 and El Nino of 2015-2016 on phenology associated with winter production, biological spring transition, summer production and the fall transition.

It is likely that an outcome of this work is that we will find only weak long term trends in the timing of phenological events because **variability in timing** among years (associated with sudden changes in the sign and magnitude of the PDO, NPGO and ENSO) will almost certainly overwhelm the long-term signals. On this point, it is becoming more and more apparent that in the NCC, increased variability in physical forcing and subsequent biological response **is** the dominant climate-change signal (e.g., Sydeman et al. 2013), **not** the long term trend!

Finally, our proposed work will demonstrate the importance of developing careful long-term records of phenological events, a new activity for the California Current that will hopefully inspire others to continue their incipient long-term time series of zooplankton (Eric Bjorkstedt's line at Trinidad CA begun in 2008, and Jaime Jahncke's sampling of zooplankton in the Farallon Islands begun in 2006. Armed with these kinds of data, we can eventually begin to look at latitudinal differences in phenology as well as alongshore gradients in hydrography and species composition and abundance of copepods and krill.

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Results of past FATE funding. We have developed and expanded our salmon forecasting efforts first funded by FATE several years ago. See our Center's Home Page for results of these efforts which are produced annually: <http://www.nwfsc.noaa.gov> and click on the "Salmon Forecasting" button. We have recently added to the Home Page a 'current ocean conditions' blog and can be viewed with the "Newportal" button. This site is still under-development.

Indicators that we have developed with FATE funding from the Newport Line data (and other long-term data sets such as the PDO) are a key part of the California Current Integrated Ecosystem Assessment. WTP (and Jay Peterson) are co-authors of the 'Drivers and Pressures' Chapter and produce all of the physical indices for the northern California Current section: http://www.noaa.gov/iea/Assets/iea/california/Report/pdf/Ocean%20and%20Climate%20CCIEA%202012.pdf. Copepod indicators are given in the Ecological Integrity Chapter <http://www.noaa.gov/iea/CCIEA-Report/key-ecosystem-components/index.html> where two indices (northern copepod biomass and copepod species richness) are among the top-ranked indicators. Our contributions to the IEA summary for 2015 can be viewed at http://www.noaa.gov/iea/regions/california-current-region/products/index.html.

We also contribute to the annual Ecosystem Status Report for the "Status of the Pacific Coast Coastal Pelagic Species Fishery" report published by the Pacific Fisheries Management Council (www.pcouncil.org, December 2014, see pages 52-57), and have been regular contributors to the annual State of the California Current Report published in the CalCOFI Reports series since 2004.

We regularly contribute our estimates of spring and fall transition dates to the University of Washington/Columbia Basin Research site: http://www.cbr.washington.edu/status/trans. This site shows estimates for the biological spring transition derived from a cluster analysis that constrains the data set to "two clusters", which are 'winter' and 'spring' rather than all possible clusters. We will further explore transition dates using x-axis scores from an ordination analysis because these scores seem to be more stable.

Finally, over the years we have published more than 100 peer reviewed publications on data from the Newport Line.