Title: Copepod species abundance from CalCOFI zooplankton samples as an environmental index used in Harvest Control Rules for sardines in the California Current

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BACKGROUND. Until recently, the fraction of the sardine stock that could be harvested from the California Current was set by stock-recruit and temperature-recruit relationships. However, temperature data used in these analyses (sea surface temperature at Scripps Pier, CA) have been shown to no longer be a reliable predictor of sardine recruitment success (McClatchie et al. 2010) and as a result, the Coastal Pelagic Species Management Team (CPSMT) recommends exploring other environmental variables. Six "high priority research and data needs" for Pacific sardine have been identified in the most recent CPS Stock Assessment and Fishery Evaluation document (SAFE 2011, p. 69), one of which is "exploring environmental covariates to inform the assessment model and to address recent research that brings into question the temperature-recruitment relationship". In addition, the SAFE 2011 document identified the need for new information on climate change, and that efforts to explore relationships between ocean condition and climate oscillations (PDO, ENSO and NPGO) should be added to the body of information on potential environmental impacts on CPS Essential Fish Habitat.

The CalCOFI program was initiated in 1949 to determine why the sardine stock had collapsed and to determine (if possible) the degree to which the collapse was related to changes in the oceanography of the California Current. After more than 60 years, the only environmental co-variates that have shown promise in explaining recruitment variability are various measures of sea surface temperature. Given that sardines eat copepods, it is highly likely that there is a good correlation between inter-annual variations in sardine recruitment and abundance of their prey, copepods. CalCOFI samples are typically measured for volume of zooplankton, but it has been found that the **species composition** plays a critically important role.

Using a time-series of copepods from the northern portion of the California Current (off central Oregon), we have done a preliminary analysis between species composition and sardine recruitment (Figure 1). The strongest correlations are with the Newport Line "Copepod Community Index" (CCI) and the biomass of southern copepod species, those species that are transported north during winter and years with anomalously warm ocean conditions. Because copepods collected from the northern California Current provide a relatively strong index of sardine recruitment in the central and southern California Current, we suggest that there is a high probability that a copepod species data set collected from the southern California Current will have even greater value. When combined with hydgrographic [e.g. SST] and climatic [e.g. PDO, NPGO, etc.] metrics, this could prove to be an effective ecosystem approach to improving stock assessments.

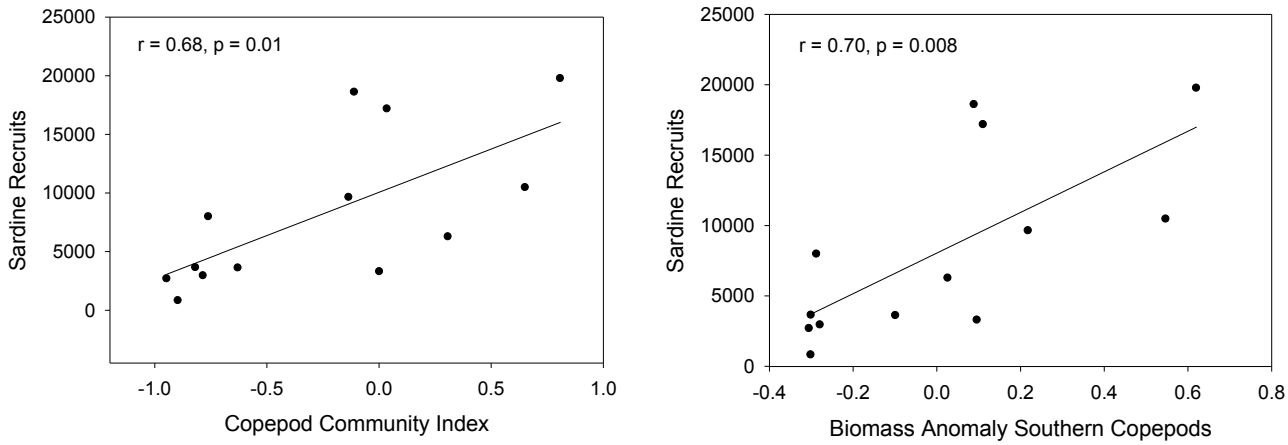

Figure 1. Correlation of sardine recruits (R_Age 0) with copepods. The left panel shows correlation with the copepod community index; the right panel shows correlation with the biomass anomaly of southern copepod species. The Copepod Community Index is the time series of the x-axis scores of an ordination of the copepod community off Newport, Oregon. Southern species are those species that are common off central and southern California and common off Oregon during the positive phase of the PDO and during El Niño events. The R_age 0 data are from Appendix D of the Draft "Report of the Pacific Sardine Harvest Parameter Workshop" held on 5-8 February 2013 in La Jolla.

APPROACH

We propose to:

- Enumerate zooplankton samples collected annually by the CalCOFI program from 1987 - present to provide data on abundance and biomass of copepod **species** for the stock assessment of sardines. This will yield a 27-year time series of copepod species that will allow study of relationships between sardines, copepods, the PDO, NPGO and the MEI
- Test for "environment-sardine" recruitment relationships by using data from the time series of abundance of copepod species, the PDO, NPGO and MEI, from 1987 to present.

This proposed effort will involve enumeration of ~ 300 CalCOFI CalVET zooplankton samples (20 cm diameter Bongo nets of 150 µm mesh) that are collected on the quarterly CalCOFI cruises (since 1987) at mid- and outer-shelf stations on Line 76.7 and Line 80 (north of and adjacent to Point Conception, respectively). This region is within the coastal upwelling zone and the two stations selected for study are in similar water depth as two stations along the Newport Line for which we have a copepod time series. Furthermore, the stations are north of a major faunal boundary (Pt. Conception) and away from the southern California Bight where circulation is complex. Enumeration of samples will follow the same protocols that have been used for 18 years at our lab in Newport, Oregon. Use of copepod data from existing samples is cost-effective

since the samples already exist and therefore represent "data-in-the jar". Moreover, such data could contribute to a more holistic ecosystem approach to management of sardines, and if successful, would be among the first examples where data on a component of the food chain upon which fish feed (copepods) is used in the stock assessment. It is well known that small pelagic fish show highly variable population dynamics due in large part to climate variability, yet few stocks are managed with consideration of the environment. Sardines are a classic example of the use of environmental data in the assessment in that the sardine stock has been managed by tracking SST. Our proposed research will take this one step further by considering the basin-scale forcing of the local physical environment (PDO, NPGO and MEI) **and a key component of the ecosystem, copepods, upon which sardines feed**.

Some previous work has been done on enumerating species in CalCOFI samples (Rebstock 2001, 2002). Our proposed work differs from these studies in that we will be looking at samples from smaller-meshed nets to capture a greater range of species and stages, will be looking at samples throughout the year, and will be using samples from north of Point conception where the hydrography is less confounded by a persistent eddy within the California Current Bight (Sverdrup and Fleming, 1941). We also will test for correlations between interannual variations in copepod species composition and the basin-scale drivers of variability: the PDO, NPGO and MEI. We expect the NPGO and MEI to have the highest correlations because it has been suggested by Chaak and DiLorenzo (2009) that the shelf and slope waters of the California Current south of ~ 38°N are more heavily influenced by the NPGO whereas waters north are best correlated with the PDO, a fact which we have already demonstrated (e.g., Keister et al. 2011). In the coastal northern California Current, during cool phase of the PDO, coastal waters from the Gulf of Alaska account for a greater proportion of water transported into the northern California Current (NCC) whereas during warm phase, southerly flow is weak and a greater proportion of the water feeding the NCC is from offshore. This transport-driven alternation of cold water vs. warm water copepod species has important consequences for food chain structure. Off Oregon, during cool phase, large, lipid-rich copepods are transported to the shelf waters of the NCC (Bi et al. 2011) whereas during warm phase, a greater proportion of water originates from offshore and/or south of Oregon and small lipid-poor copepods are transported to the coast. Thus the basin-scale variations in winds that drive the PDO along with the NPGO, both of which drive differences in transport, result in local food chains with vastly different lipid, and thus bio-energetic, content.

BENEFITS

1) **Develop a multi-tiered ecosystem-based assessment of sardine recruitment.**

These findings, mentioned above, that differences in transport account for differences in copepod community structure, thus bioenergetics of the food chain capture the remarks of Dick Parrish (Feb 2013 Coastal Pelagic Species meeting; La Jolla, CA), who noted that "net onshore flow of nutrient-poor offshore waters (associated with downwelling events or El Niño) resulted in poorer [sardine] recruitment than when water comes from a northern source". We suggest that we will

find two copepod community types off southern California: a temperate community of cool water species (some of which will have sub-arctic affinities) and a tropical community. This expectation matches relationships between inter-annual variations in the volume of zooplankton collected in CalCOFI samples and transport in the California Current, first proposed by Reid (1962), and shown later by Chelton and Davis (1982), Chelton et al. (1982), and Roesler and Chelton (1987) and elaborated upon by Roemmich and McGowan (1995) and McGowan et al. (1998). There is a key difference between these findings (which relied upon the volume of zooplankton collected) and our proposed work where we will focus on species composition and community structure instead of just bulk measures of "zooplankton biomass".

2) **Contribute to the broader California Current Integrated Ecosystem Assessment (CCIEA).** Two of the most highly-ranked of 40 indicators in the CCIEA are zooplankton-related community indicators from the Newport Line: the Northern Copepod Biomass anomaly and the Copepod Community Index. Therefore we expect that a time series of zooplankton species from the CalCOFI samples will prove to be equally valuable. Zooplankton time series provide some of the best opportunities to understand marine ecosystem responses to climate change because zooplankton are the foundation of the ocean food web, linking oceanographic conditions and primary production to upper trophic levels and fueling the delivery of ocean ecosystem services. Once sample analysis is completed, we would then have two long time series in the California Current: off Point Conception at 35°N (nearly 30 years) and off Newport at 45°N (20 years).

3) **Incorporate indices of climate variability**
A wide array of indices of climate-scale variability have been developed in the last 15 years. Many of these indices (e.g. PDO, NPGO, ENSO) have had strong correlations with physical and biological processes in the California Current. This is largely in part due to the fact that there are long-term data sets available on time (multi-decadal) and space scales relevant to investigating climate-scale influences on ecosystems.

4) **Utilize and further develop a long-term data set**
The CalCOFI data set is a unique resource that has not been fully developed. Long-term data sets are rare, due to the high cost of collecting and analyzing data over many years. A great deal of information remains "in the jar" of the CalCOFI zooplankton samples and it will take coordinated efforts, such as the one proposed here, to ultimately extract the wealth of data.

DELIVERABLES. We propose to enumerate a total of 242 CalVET samples collected by the CalCOFI program since 1987 along Line 76.7 at station 49 (water depth = 69 m, total of 77 samples); and Line 76.7 and Line 80, at station 51 (water depth 240 m, total of 165 samples). Note that from 1987-1992, these stations were only sampled in spring and occasionally in winter; but from 1993-until present, each station has been sampled 4 times per year. These two stations

were chosen for analysis because they represent shelf and slope waters and have similar water depths to the two stations along the Newport Line where we enumerate all samples from NH 05, (water depth = 62 m) and NH 25 (water depth 300 m). This will help provide consistency for incorporating the data into the Integrated Ecosystem Assessment (CCIEA). Further, we propose to enumerate at least 85 CalVET samples collected since 1997 during the spring SWFSC sardine surveys from the same sampling depths as given above (~ 70 m and 250-300m), 5 samples per cruise. From these samples, we will develop a copepod community index that we expect will index sardine recruitment and can be incorporated in to the Harvest Control Rules (HCR). Members of our team (Emmett and Hill) are part of the Coastal Pelagic Species Management Team (CPSMT) and will be able to directly convey our findings to the group responsible for developing the HCR, and will be able to directly receive and respond to suggestions on how best to incorporate environmental variables into the stock assessment and HCR.

All data will be archived in several places including (1) our data base in Newport, (2) the COPEPOD database maintained by Todd O'Brien at NOAA-Fisheries Science and Technology Office in Silver Spring and (3) in the CalCOFI zooplankton data base.

Summary. The CalCOFI program was initiated in 1949 to determine why the sardine stock had collapsed and to determine (if possible) the degree to which the collapse was related to changes in the oceanography of the California Current. Indeed, the very term "fisheries oceanography" evolved from the early days of the CalCOFI program. After more than 60 years, the only environmental co-variates that have shown promise in explaining recruitment variability are various measures of sea surface temperature. Given that sardines eat copepods, we find it surprising that no one has systematically enumerated the copepods (especially the smaller copepods which sardine eat, such as those caught in the small-mesh CalVET samples) to produce a time series of abundance of copepod species that would then in turn be used to look for correlation between inter-annual variations in sardine recruitment and abundance of their prey, copepods. Given that copepods from the Newport Line are highly correlated with sardine recruitment in southern California, we fully expect that a copepod time series generated from the CalCOFI samples will prove even more valuable. Moreover, if this proposed research is funded, a wider range of data, such as the CalCOFI ichthyoplankton data or pelagic fish caught in the sardine trawl surveys, could be compared to the copepod time series with regard to basin-scale climate forcing. Both data sets could be used to better understand interactions among species at many trophic levels providing a broader view of the California Current ecosystem.

Statement of Previous Results. One of the main goals of the FATE program is to produce leading indicators of physical, biological, or ecosystem characteristics which can be used to inform fisheries management and stock assessment activities, with a particular emphasis on the linkage between climate and ecosystem response. Two of the operational products listed on the FATE website are a result of data analysis supported by past FATE awards to Peterson: (a) ecological indicators associated with salmon forecasting < http://www.nwfsc.noaa.gov > (click on 'salmon forecasts') and at (b) dates of spring and fall transition of coastal upwelling, seen at <http://www.cbr.washington.edu/status/trans>. Also, as noted above, two of the most highly-ranked of 40 indicators in the CCIEA are zooplankton-related community indicators from the Newport Line, the Northern Copepod Biomass anomaly and the Copepod Community Index. The "Drivers" section of the California Current IEA is parsed into three parts: southern, central and northern California Current. The northern California Current section is prepared by the Peterson lab, with some support from FATE.

Previous FATE awards to McClatchie and Hill involved testing the hypothesis that additional predictors can improve predictions of sardine recruitment based only on spawning stock biomass and temperature (SSB+T), which is the current environmental index used in stock assessment. Using theoretical justifications for factors affecting sardine recruitment success, we selected predictor variables known to affect recruitment through population size, growth and starvation, advective loss and physiological tolerance. SSB+T performed better than prediction based on SSB and the Multivariate ENSO index alone. The SSB+T model could be improved by adding predictors based on measured geostrophic current velocities and model-derived vertical Ekman transports.

Examples of publications relevant to Peterson's involvement with the FATE program include:
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