FATE (FY2010) proposal. Development of a new environmental index for sardine assessment incorporating invertebrate predators and prey.

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Total request: $84,000 in each of two years

Background: The sedimentary record shows that Pacific sardine (*Sardinops sagax*) populations have fluctuated greatly in biomass long before the advent of commercial fishing (Baumgartner et al., 1992). Sardine stocks are prone to collapse, contraction in range, and re-expansion, as well as to shifts in dominance in the small pelagic fish community (Schwartzlose et al., 1999). To an unknown degree, the changes in sardine abundance are driven by changes in their environment. There is considerable uncertainty as to the relative contributions of density-dependent factors such as competition, predation and food supply, and density-independent factors such as temperature, the distribution of water masses, and climatic processes operating at different scales (e.g. ENSO cycles and "regime shifts")(Lluch-Belda et al., 1989). It is also unclear which stage of life is most affected by environmental variability. Spawning habitat is strongly impacted by environmental variability, but recruitment success is thought to be determined by natural mortality at the late larval or juvenile stage (Watanabe et al., 1995; Takahashi and Checkley, 2008). Migratory movement of the adults large enough to travel long distances is also affected by environmental variability, and recent speculation suggests there may be transfer of migratory behavior from older to younger cohorts.

Despite uncertainties about the mechanisms by which the environment affects populations, the possible range of effects makes it desirable to incorporate an index of environmental variability into the Pacific sardine stock assessment.

There are very few fisheries stock assessments or harvest policies that incorporate any measure of environmental variability. The Pacific sardine harvest policy is unusual in using temperature as one parameter in the formula for a decision rule-based harvest guideline (Hill et al., 2008; Pacific Fishery Management Council, 1998). The following formula has been used to determine an appropriate (sustainable) F_{msy} exploitation fraction:

FRACT ION = 5%, 0.248649805(T^2) − 8.190043975(T) + 67.4558326, 15%

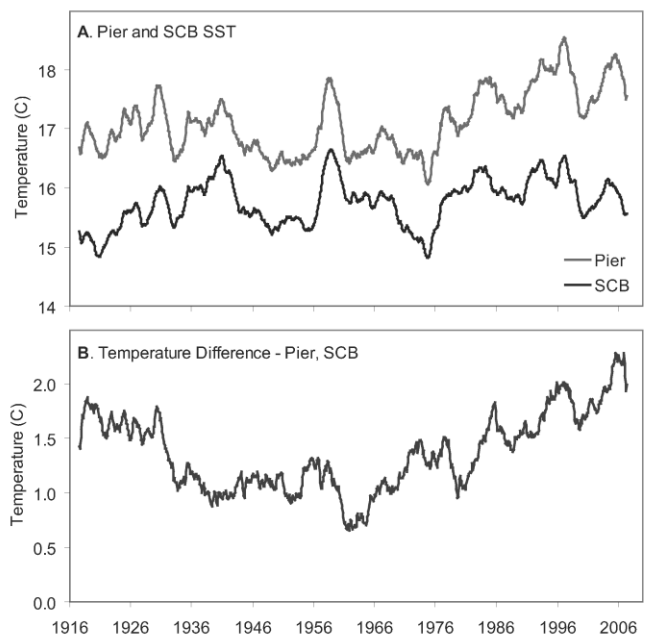

Fig. 1: (A) Comparison of the three-year average of monthly time series of SIO pier surface temperature with the 10 m depth reconstructed offshore temperatures. (B) Difference between the two time series calculated as Pier temperature - SCB temperature.

for T < 16.8, 16.8 to 17.3, > 17.3^{o}C

where T (^{o}C) is the running average sea-surface temperature at Scripps Institution of Oceanography Pier (SIO pier), La Jolla, California during the three preceding seasons (July-June). Presently F_{msy} is constrained and ranges between 5% and 15%. The T values observed from 1981 through 2008 have consistently been larger than 17.3^{o}C. Consequently the F_{msy} exploitation fraction has consistently been 15%; and this remains the case under current oceanic conditions. Essentially this means that the environmental index has no effect on the harvest guideline under current conditions, but if T values drop this could lead to a decision to reduce the exploitation fraction.

Recent work (McClatchie et al. submitted) showed that the SIO pier temperatures are no longer showing the same trend as the offshore Southern California Bight temperatures where sardine spawn (Figure 1). This indicates that if temperature is to be used as an environmental index in the stock assessment, it would be more appropriate to use the offshore temperatures.

Equally important, the relationship between temperature and sardine reproductive success no longer appears to hold in the light of recent data (Figure 2). This result is perhaps to be expected (Myers, 1998). That being the case, the basis for the current decision rule in the CPS-FMP based on the environmental temperature criterion is no longer justifiable. We need a new model, based on other environmental parameters. A cautionary note might be that any new model should be frequently reassessed to determine if the underlying relationships can withstand adding new data.

Approach: The goal of this proposal is to fund development of a new environmental index for the sardine assessment.

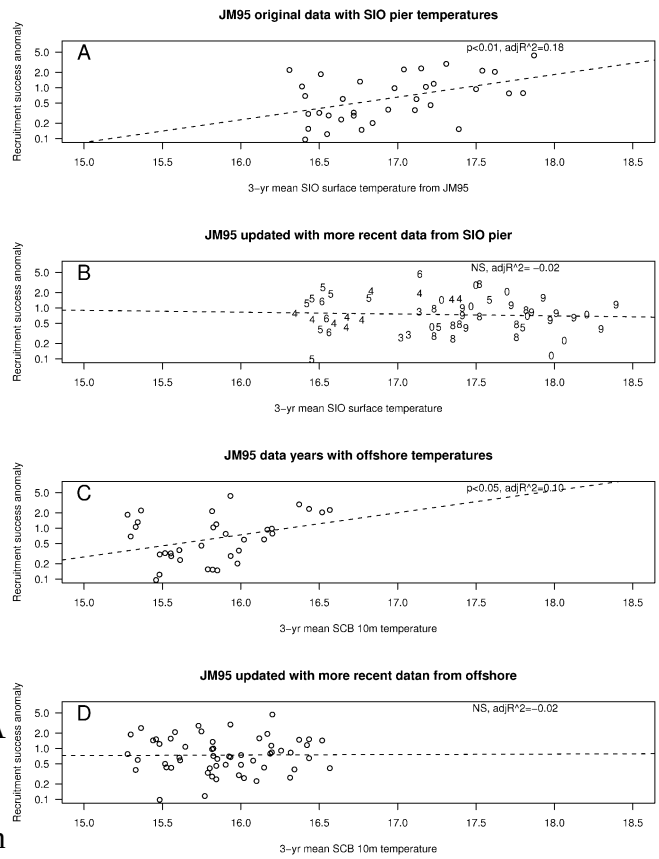

Fig. 2: (A) Anomaly of reproductive success in relation to the 3-year mean SIO pier surface temperature using data from Jacobson and MacCall (1995) Table 1 (Erratum). Dashedline is the log-linear fit. (B) Same as (A), butincluding recent years (1991-2007) for both recruitment success and SIO pier temperatures.Numbers labeling points represent decades (3=1930s, 0=2000s). (C) Same as (A) but usingoffshore Southern California Bight (SCB) rather than SIO pier temperatures. (D) Same as (B) but using offshore SCB temperatures.

Recent work indicates that sardine larval distributions and abundance are more related to environmental variables (temperature, salinity, mixed layer depth, and zooplankton displacement volume) than are the densities of sardine eggs (McClatchie et al., in review). None of the correlations between sardine **eggs** and environmental variables were significant after correcting for autocorrelation. For sardine **larvae**, a positive correlation between larval densities and mixed layer depth was still highly significant ($p < 0.001$) after correcting for autocorrelation. This relationship was independent of the relationship with other environmental variables (see Figure 3).

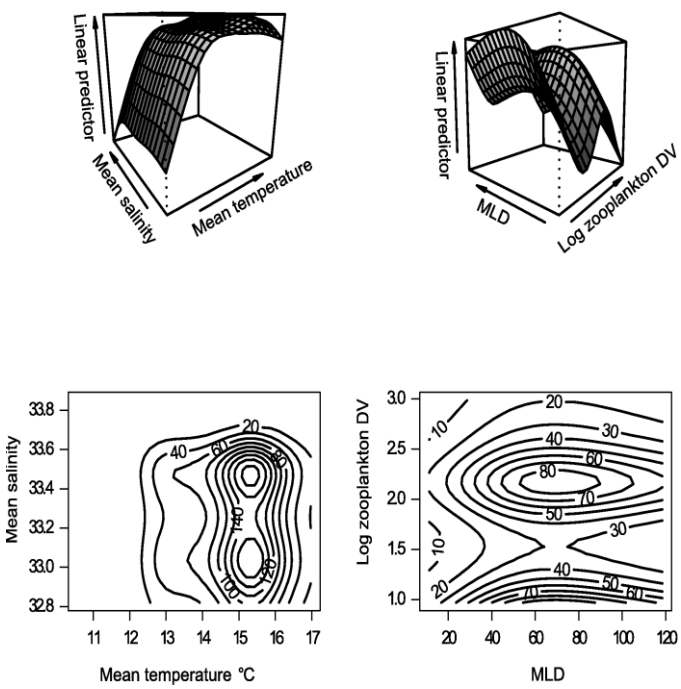

Fig. 3: Visualization of response surfaces of Pacific sardine larval densities (larvae 10m−2) from a GAM. (A) Smoothed surface in terms of mean temperature (oC) and mean salinity (psu) in the upper 50 m of the water column. (B) Contour plot of the temperature and salinity surface. (C) Response surface in terms of mixed layer depth (m) and zooplankton displacement volume (ml 1000m−3). (D) Contour plot of the mixed layer depth and zooplankton displacement volume surface.

The strong spatial correlation between larval densities and mixed layer depth is consistent with results showing that wind stress is correlated with modeled recruitment indices (Rykaczewski and Checkley Jr., 2008), since increasing wind stress generally deepens the mixed layer. Rykaczewski and Checkley Jr. (2008) also inferred that prey particle size structure affects recruitment success, indicating the need to know about the abundance and size of sardine larval prey. Earlier studies showed that temperature and zooplankton concentration can be used to determine the limits of sardine spawning habitat (Lynn, 2003). Furthermore, unpublished work (Checkley, Scripps Institution of Oceanography) suggests that there is an inverse relationship between biomass of adult euphausiids and sardine eggs, possibly due to predation. Agostini et al. (2007) suggested that refuge from zooplankton predation on sardine larvae may play a key role in encouraging outbreaks of successful sardine recruitment in warm years.

All of this evidence is consistent with **an hypothesis that the depth of the mixed layer imparts an effect on sardine larval densities and spatial distributions by affecting the abundance, size structure and type of both ichthyoplankton invertebrate predators and sardine larvae prey.** Based on this hypothesis we plan to develop a new environmental index incorporating the densities of sardine larvae, depth of the mixed layer, size distribution and abundance of prey, and the abundance of functional groups of invertebrate ichthyoplankton predators.

There have been many studies addressing the effect of environmental factors like temperature,

salinity, chlorophyll, mesoscale features and flow on
sardine spawning habitat, biomass, growth, survival and recruitment variability (e.g. Logerwell & Smith 2001, Reiss et. al. 2008, Takahashi & Checkley 2008, MacCall 2009, and references therein) but there are few studies on the impacts of biological factors. This is largely because the time-series of zooplankton biological data have been limited to zooplankton displacement volume where the effects of prey availability and the abundance of ichthyoplankton invertebrate predators are confounded. Where zooplankton samples have been counted to species, it has generally been necessary to pool samples for practical purposes (to reduce effort) which results in loss of spatial information for the smaller species (<25 mm total length)(Lavaniegos and Ohman 2007). In the proposed work we plan to separate the prey from the predator variables and to retain the spatial information by applying the Zooscan to measure size spectra and by classifying zooplankton into functional groups, thereby reducing sorting time. Selected key samples will be sorted to more detailed taxonomic levels (Peterson group).

We will obtain new prey data from fine mesh (150 µm mesh) CalVET and PairoVET vertical net tows samples archived in the CalCOFI collections at SIO. We will use these fine-mesh net samples because they collect zooplankton in the size range eaten by larval sardine, whereas the coarser 550 µm silk mesh Ring net or 505 µm nitex mesh Bongo oblique net tows do not. The coarser mesh oblique tows will be used to obtain new data on predator functional groups because mobile predators like euphausiids readily avoid the smaller, slower nets, and even avoid the Bongo nets during daylight.

The sardine larval abundance data and the mixed layer depths (calculated following Kara et al. 2000) are already available in our databases. We will combine three approaches to obtain the predator and prey data from archived CalCOFI samples: (1) Visual counts of predators and prey by functional group (Figure 4), and by species in some cases, (2) automated counts by functional group using a ZooScan recently acquired by SWFSC, and (3) sizing of potential sardine larval prey items using the Zooscan.

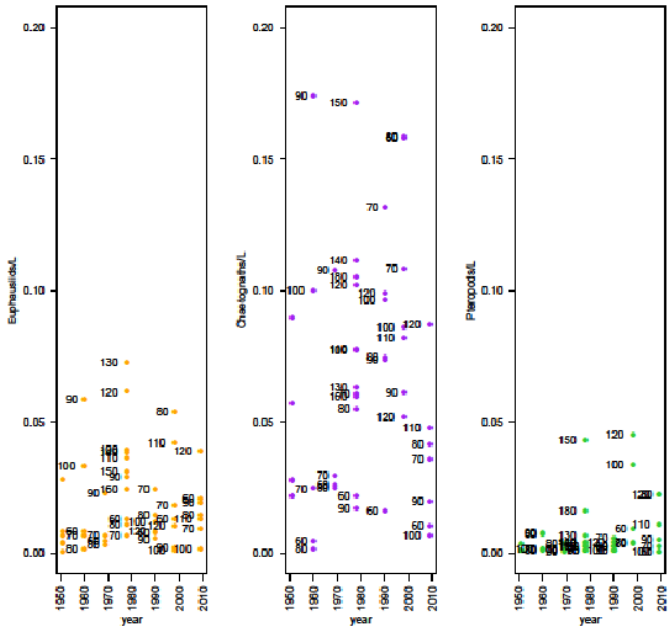

Fig. 4: Abundance of three functional groups of invertebrate ichthyoplankton predators at offshore stations (> station 60) along CalCOFI line 90 obtained at decadal intervals from night-time oblique Bongo tows. Samples were visually counted. Chaetognaths are the most abundant offshore where sardine spawn, and show evidence of declining abundance in recent decades, in contrast to euphausiids that seem to be increasing.

The background and approach for Peterson's efforts are based upon the long-term time series of zooplankton abundance and species composition from Newport OR. The project

which we propose will enhance the information on copepod species composition collected by the CalCOFI program. All that is available on copepod species composition is the work of Fleminger (1967) who produced charts showing spatial distributions of copepod species from samples collected in 1957 and 1958, and Rebstock (2001, 2002), who worked up samples collected by 505 µm nets only in **spring,** 1951-1999. She counted *Calanus pacificus* and other larger (and mostly) mesopelagic species. **There is no information at the species level of the smaller species which serve as food for larval and adult sardines** (e.g., *Paracalanus***,** *Ctenocalanus* and *Clausocalanus* and the nauplii of *Calanus pacificus***).**

Peterson's efforts will focus on copepod species and developmental stages from the CalVET and PairoVET samples. We focus on these because the small mesh (150 µm) collects the dominant epipelagic copepod species which are far more sensitive to environmental and climate signals than mesopelagic species. Samples from these nets are also ideal because they capture efficiently the eggs and nauplii of *Calanus pacificus* and most copepodite stages of the predominant *Paracalanus*, *Ctenocalanus* and *Clausocalanus* spp which are fed upon by larval fish and adult sardines. We propose two efforts: (1) enumerate a subset of samples that would contribute to calibration of the ZOOSCAN samples, and (2) enumerate all samples from the inner three stations along Line 80, in shelf and slope waters north of Point Conception. This line represents the coastal upwelling domain of the southern end of the California Current; and as such the time series will reveal interannual variations in copepod species composition and community structure driven by variations in both local upwelling as well as basin scale forcing associated with the North Pacific Gyre Oscillation (DiLorenzo et al. 2008, 2009). Species diversity is much lower in samples from the coastal upwelling domain than in samples collected in far offshore waters, thus making it easier to enumerate several hundred samples fairly quickly. From this time series we will generate indices similar to those already developed for Newport: copepod species richness (Hooff and Peterson 2006; Peterson 2009), copepod community structure (based on NMDS ordination analysis (e.g., Peterson and Keister 2003), and "northern" vs "southern" copepod species biomass anomalies (e.g., Mackas et al. 2006). Such a time series along with temperature and salinity data collected from the same stations will allow us to evaluate the relative role of the North Pacific Gyre Oscillation vs. the Pacific Decadal Oscillation and controlling interannual variations in copepod species composition and abundance. This work is exploratory, driven by the notion that a time series of copepod species abundance data from several shelf/slope stations can in fact index plankton dynamics in the broader southern California Current, and in turn might serve as an index for sardine recruitment success. We have shown that the Newport copepod index forecasts salmon extremely well (e.g., Peterson and Schwing 2003) and feel confident that we will find provocative and useful signals in the copepods from shelf/slope waters of the southern California Current.

Benefits: We will produce a new environmental index based on sardine larvae, mixed layer depth, and measures of invertebrate predators and larval prey and new copepod indices similar to those produced for Newport Oregon that we anticipate will help to predict recruitment variability of sardines. If this work is successful, we will propose additional work in the future that will allow us to expand more fully into the spatial domain and to produce indices directed at characterization of interannual variation in sardine spawning habitat in relation to both physical variables (SST, mixed layer depth) and biological variables (distributions of predators and prey).

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