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Paradigm or Paradox: Can we Attribute Species Changes to Global Climate Change in Light of Decreasing Water Temperatures in Central California?

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Project Title:

Paradigm or Paradox: Can we Attribute Species Changes to Global Climate Change in Light of Decreasing Water Temperatures in Central California?

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The distribution and relative abundance of marine species along the California coast is greatly affected by major climatic events, such as El Niño/La Niña events and the Pacific Decadal Oscillation (PDO; e.g., Lubchenco et al. 1993; Moser et al. 2000; Chavez et al. 2003). These climactic phenomena greatly influence oceanography in the California current and cause relatively rapid, step-like changes in species composition. In contrast, current estimates of rates of atmospheric warming are curvilinear in shape, thus raising the question, "Will species changes caused by global climate change be rapid or gradual in California?"

Climate experts have shown that the earth's atmosphere is warming and predict that global ocean temperatures will warm as air temperatures rise (Serreze 2010). In terrestrial environments, the atmospheric warming is expected to result in a 200 km pole-ward effective shift in habitats (Opdam and Wascher 2004). Some scientists have reported that this long-term shift is already occurring on land (Parmesan and Yohe 2003). There is also evidence for species distributions in the marine environment shifting either to greater latitudes or to deeper depths with warming water temperatures (e.g., Cowen 1985; Perry et al. 2005). In California, similar species shifts occur during El Niño periods, when warmer water masses surge pole-ward (Pearcy and Schoener 1987; Holbrook et al. 1997). Many warmer-water species that are advected northward can survive in more temperate waters, but not successfully reproduce. With permanent increased ocean water temperatures caused by climate change, southern species will likely be able to reproduce further north. Evidence for this occurs during warm oceanographic regimes (i.e., during phases of the warm PDO), when South American Sardine (*Sardinops sagax*) populations expand pole-ward and spawn in waters well north of Point Conception, California.

This predicted model of pole-ward shifts in habitats and species presents a paradox, however, in the waters off central California. Although global climate models predict warming waters, empirical evidence shows stable or decreasing water temperatures off central California (Breaker 2005). Many oceanographers believe the California Current entered into a cold phase, starting in 1999. Evidence of this can be seen in the Monterey Bay, where sea surface temperatures (SSTs) have decreased by up to 1°C over the past decade based on calculations and analyses that have yet to be published, and northern species not usually seen in central California have been observed from submersibles (Starr and Yoklavich 2008). In spite of decreasing water temperatures, however, there is evidence to suggest that southern species are more common off central California now than in the recent past.

The main goal of this study was to gather information about historical changes in water temperature and species composition, in order to identify variables that will enable us to predict changes in water temperatures and species abundances in California caused by global climate change. Our primary objectives were to (1) review the existing published and unpublished data sets to refine our

understanding of trends in sea surface temperature in central California; (2) review fish and climate data sets to determine if we could identify how species abundances changed relative to changes in water temperatures and basin-scale environmental indices; and (3) identify recent changes in species abundances in central California that are related to water temperatures.

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BACKGROUND

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Studies of Water Temperature

Numerous published studies have reported on the variability of long-term trends in water temperatures in Monterey Bay and the causes of this variability (i.e. Breaker and Lewis 1988; Breaker 1989; Breaker and Broenkow 1994; Breaker 2005; Breaker 2006). In the longest-term study, Breaker (2005) examined trends in temperature based on a 90-year record of daily sea surface temperature (SST) from Pacific Grove, California. Interestingly, the long-term linear trend in temperature was positive and statistically significant when the entire record was used, but not significant if only the period from 1930 to 2002 was evaluated. Further analysis revealed that there was a step-like increase in temperature in 1929 that separated much colder waters during the 1920s from warmer waters after that time. The increase of +0.9°C to +1.0°C occurred over a period as short as several days or less, and this "event" was not apparent at other locations along the California coast (i.e., Scripps Pier and the Gulf of the Farallons temperature stations). This discrepancy in the temperature record has potentially large consequences. For example, Sagarin et al. (1999) reported a long-term increase in temperature in Monterey Bay, which they attributed to global warming. However, if the step-like increase in 1929 is inaccurate, then there has been no long-term change in water temperatures.

Despite the lack of evidence of long-term changes in water temperatures in Monterey Bay, we know that California has experienced periods of cold and warm ocean temperatures. Recent analyses of the temperature record from 2000 – 2009 show a noticeable decrease in temperature and an even stronger decrease since 2003 (~1.0°C). This decrease is consistent with air temperatures in Monterey that have decreased over the past 30 years, as fog and stratus clouds along the central California coast have increased. Also, El Niño events have caused waters to warm in California for short periods of time and as stated earlier, the Pacific Decadal Oscillation has resulted in warm and cold periods that last for decades. (Chavez et al. 2003; Breaker 2005).

Studies of Species Distribution

Numerous data sets exist with which to evaluate marine fish assemblages occurring in central California (Table 1). Surveys of larvae, newly settled young-of-the-year (YOY), and adults have

regularly occurred over the past 20 years, and a few data sets go back much further in time. Since 1949, CalCOFI has organized cruises to measure the physical, biological, and chemical properties of the California Current System from the California-Oregon border to the Baja peninsula. Although the extent of the total geographic coverage of the CalCOFI cruises has varied over the years, an extensive time series of hydrographic and biological data are available from fixed oceanographic stations. These data have been collected at least at tri-annual intervals, using standardized sampling and tow net techniques. Similarly, the National Marine Fisheries Service (NMFS) has been conducting larval fish surveys off central California (Ralston and Howard 1995; Field et al. 2007; Mills et al. 2007).

Information about juveniles and adult species were obtained from several comprehensive data sets held by the California Department of Fish and Game (CDFG), including landing data, recreational hook and line surveys, the on-board observers program, and creel surveys of spearfish tournaments. Data are available for all fishes that were identified, measured, and counted during these trips. In the on-board sampling program, Commercial Party Fishing Vessels (CPFV) vessels were chosen at random to carry fisheries observers on fishing trips departing from major California ports beginning in 1987. CDFG fisheries observers monitored only trips in which nearshore rocky reef species were targeted. During these trips observers recorded, identified, measured and counted any fishes caught; fishing depth and location were also recorded. That data set was extended into recent years by the Pacific States Marine Fisheries Commission (PSMFC) using similar sampling methods (Stephens et al. 2006). CDFG also has CPFV landing data that are available for many fish species caught in the CPFV fishery and landed at California ports from 1980-present. Additionally, CDFG personnel identified, measured, and counted all species caught at CenCal Spearfish Tournaments (from 1958 to the present).

Since 1977, NMFS has conducted triennial bottom trawl surveys have been used to obtain fishery-independent estimates of the distribution and abundance of commercially and recreationally exploited groundfish species in continental shelf waters off the U.S. West Coast. The NMFS surveys follow a stratified random sampling scheme to sample different areas and depth strata along the continental shelf and slope (Weinberg et al. 2002). However, these surveys cannot sample many nearshore areas due to high relief substrate and extensive kelp forests.

Since 1992, NMFS biologists have conducted submersible surveys, using standardized protocols, to evaluate species composition in central California (Yoklavich et al. 2002, Yoklavich 2005, Starr and Yoklavich 2008). In another type of visual survey, the Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) has conducted SCUBA surveys from 1999 to the present. These SCUBA surveys were designed to identify and quantify species of fishes in nearshore rock reef areas in central California. Tenera, Inc., also conducts SCUBA surveys near the Diablo Canyon power plant. These surveys have

been conducted year-round since 1976. Data are available for all fishes identified and counted in these different surveys.

METHODS

Approach

We used multiple data sets and techniques to determine if we could identify how species assemblages changed relative to changes in water temperatures and basin-scale environmental indices. We first obtained smoothed temperature data and estimating trends of sea surface temperature (SST) in central California. For these analyses, we used data from Pacific Grove, the Farallon Islands, and offshore buoys in central California. Further, we used satellite imagery to map isotherms and measure temperature gradients in different seasons. Additionally, we obtained estimates of basin-scale environmental indices from data collected as part of the Central and Northern California Ocean Observing System (CeNCOOS) program. Next, we compared trends in water temperatures with trends in the relative abundance of fishes. We took three broad approaches in order to determine the relationship between environmental variation and changes in abundances of fishes in central California. We used (1) generalized linear model (GLM) analysis to calculate relative yearly abundance estimates for an assemblage of central California nearshore rocky reef fish species and identify trends in abundance; (2) Z-score comparison, linear, and logistic regression to compare temperature with fish abundance; 3) ANOVA to determine if there are observable relationships between seasonal or annual intrusions of warm water and fish abundance; and (4) Cross-correlation analysis to compare temperature and basin-scale environmental indices with fish abundance.

Study Area

The study area extended from Cape Mendocino (40° 26' N, 124° 25' W) southward to Point Conception (34° 27' N, 120° 28' W; Fig. 1). This same area, often designated as 'central California', is commonly used for management by the Pacific Fishery Management Council (PFMC). The species composition of nearshore rocky reef fishes is relatively consistent through this area. North of this latitude, the species composition changes more dramatically (Leet et al. 2001). Genetic work has also shown a distinct population break for some species at Cape Mendocino (Cope 2004). A southern borderline for central California oceanic conditions and biological community structure occurs at Point Conception (Ebeling et al. 1980; Foster and Schiel 1985).

Water Temperature

SST data from Pacific Grove are generally representative of waters along the central California coast. Although the temperatures per se may differ slightly from offshore waters, most of the variability is captured (Breaker 1989). The SST data from Pacific Grove from 1975 through 2010 were examined in greater detail than has been published to search for long-term trends. Similarly, SST data from the Farallon Islands were analyzed for the period 1975 through 2009. We fitted long-term linear and nonlinear trends to complete as well as selected portions of these time-series. Further, an analysis was conducted of the differences between the Pacific Grove and Farallon Island data sets to search for trends.

The PDO may have increased temperatures in Monterey Bay by as much as +0.5°C since the late 1970's (Breaker 2005); outside Monterey Bay the increase may have been even larger. Also, the 1976–77 regime shift, a quintessential event that strongly influenced the North Pacific, may have produced a sustained increase in temperature within the Monterey Bay and elsewhere along the central California coast, consistent with observations off southern California that revealed a sustained increase of almost 1°C (Breaker and Flora 2009). In addition to an analysis of the PDO, analyses were conducted to examine the impact El Niño warming episodes have had on the thermal structure of Monterey Bay. For the influence of the El Niño warming episodes and the PDO, a modal decomposition using Singular Spectrum Analysis (e.g., Golyandina et al. 2001) was conducted. The modes that contain the variability associated with El Niño and PDO episodes were selectively removed to isolate their influence. Long-term trends with and without these modes were fitted to the appropriate data and then compared. The influence of the 1976–77 regime shift was analyzed using the method of expanding means which looks at temperatures prior to, during, and following these events, out to periods of several years or longer (Breaker and Flora 2009).

Satellite SST

Since changes to the nearshore environment may be scale dependent, *in situ* and satellite SSTs may provide different data. Advanced Very High Resolution Radiometer (AVHRR) satellite SST data collected by National Oceanographic and Atmospheric Administration (NOAA) was examined as another source of temperature data. Pathfinder version 5.0 day and night science quality monthly images were used (Environmental Data Connector, Applied Science Associates, Inc.) and have a resolution of approximately 4.4 km. To examine seasonality, monthly images from February and August 1982 to 2009 were used. Data were loaded directly into ArcGIS 9.3 (ESRI, Redlands, CA) for spatial analyses. Spatial analyst tools smoothed images using nearest neighbor and contour surface were analyzed to create

isotherms. Isotherms of interest (February 11°C and 13°C, August 13°C and 15°C) were exported to create separate shape files.

Graticules were super imposed on the map every 0.25° of latitude. Using the measure tool, the distance was measured from shore to the respective isotherm every 0.25° from 35.5°N to 37.5°N latitude. Mean distances were calculated for each year to the 13° C isotherm in February and the 15° C isotherm in August. Additionally, the width of the temperature gradient (11-13° C February, 13-15° C August) was also measured for the same spatial scale. Years were then categorized in distances that were greater or less than 100 km and tested with an ANOVA with fish abundance data from Pacific Fisheries Information Network (PacFIN) on forty of the most commercially important species found in central California.

Fish Abundance Trend Analysis

Fish Species

Eighteen fish species that were regularly targeted by fisheries in the nearshore rocky reef habitats of central California were identified for use in trend abundance (Table 3; Cailliet et al. 2000; Starr et al. 2002; Allen et al. 2006). Although size at recruitment varies among rocky reef species, fish less than 15 cm (a generally accepted minimum size retained by any fishery) were not included in this study.

Abundance Survey selection

Determining which current or historic surveys to include in this analysis required employing several criteria. Survey data sets had to: (1) include abundance measurements in the form of count and effort for at least one of the study species; (2) collect at least two samples each year within the boundaries of central California; (3) conduct at least some sampling in nearshore rocky reef habitats; and (4) span at least one of the focus time-periods for this study (1988-2007 or 1999-2007) using the same methodology. In general, abundance data spanning less than a few years does not provide enough information to confidently depict a population trend for species living multiple years (E. Dick, pers. comm.). Most nearshore rocky reef species require at least a few years to recruit to the fishery (Allen et al. 2006).

Some surveys of abundance that collected data on nearshore rocky reef species in central California were not included in this study because: (1) data were not yet digitized; (2) permission for use could not be obtained; (3) effort data were not consistently collected; (4) they did not sample study species within the study area; or (5) they survey did not span one of the two time-periods used in the study. Six surveys fit the necessary criteria to be analyzed in this study and could be obtained, and one time-series (All Observers) was made by combining two sequential Observers surveys (Table 2).

Survey Data Organization

For each survey used in analyses, data were organized by excluding all species, samples and explanatory variables that did not fit the criteria. This process is referred to as subsetting the data, or determining what information is useful for the project (Stephens and MacCall 2004). Some survey samples within the data set were removed prior to analysis because data: (1) did not have survey effort information; (2) were collected outside the spatial boundaries of the study; (3) did not have data on one or more important explanatory variables; (4) were collected in a variable level with little or no replication (e.g. if only a few samples were taken in winter months for a survey, all samples were removed for that season); (5) used a methodology that differed from those prevailing in the majority of samplings; or (6) was the only sample for that respective year (only years with more than one sample were used to allow for precision analysis).

Catch and effort data were sorted separately from one another. For fishing surveys, every distinct site recorded was considered a sample. Some surveys recorded catch at several sites fished by a given boat in one day, in others only the port location was recorded and a single trip was a sample. Each transect was considered a sample for SCUBA surveys. For each sample, a positive (catch or observation) or zero count was included for a given species. Effort data often had to be re-formatted before analysis could proceed. All fishing time recorded in boat hours at a given site was converted to decimal hours and multiplied by the number of anglers actively fishing to calculate fish catch-per-angler-hour. An assumption of the model was that the amount of sampling effort alone did not change the probability of catch. In surveys where researchers did not record the number of anglers actively fishing at each site, it was assumed that all anglers fished the entire trip. The volume of water surveyed in each SCUBA transect was determined to calculate fish count density.

Categorical explanatory variables were selected for analysis based on information contained in each survey database. Only those variables likely to influence the abundance count of a given survey were considered. Categories were created for 'year' and 'season' based on sampling dates in all cases. Season was based on calendar dates: winter (December 22nd – March 20th), spring (March 21st – June 21st), summer (June 22nd – September 21st) or fall (September 22nd – December 21st). Surveys sampling locations were grouped into 'subregions' using latitudinal ranges appropriate to the particular survey area, addressing the issue of low replication at more specific sampling sites. Each additional variable collected by a survey (if applicable) was divided into two or more categories, defined with regard to the distribution of samples. In some cases, categories were already chosen by samplers, and these were preserved if replication was sufficient. In all cases, variables (aside from year, season and location) were only included if they were regularly recorded by a given survey. In some cases where a small percentage

of samples did not have information on a given explanatory variable, those samples were removed from analysis so that each sample had information on all categories.

The sections below describe the four surveys analyzed in this survey (and the one data set created by combining two surveys). Surveys were categorized as fishery-independent SCUBA surveys (2 surveys), fishery-dependent hook and line (3 surveys) and fishery-dependent spearfishing (1 survey). Each section summarizes information on: the groups responsible for collecting data, survey methodologies, survey time span and how data were organized.

PISCO Collaborative Central Coast Abundance Surveys (PISCO SCUBA)

The Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) utilizes SCUBA surveys to collect data on nearshore fishes following their protocols. Data used from the PISCO SCUBA survey for this study was collected by University of California personnel from Santa Cruz County to Pt. Conception (1999-2007). All fish observed were counted by PISCO, but only fish above 15 cm were considered for these analyses. The measure of effort for this survey was the 120 m^3 volume surveyed. Categorical explanatory variables for the PISCO SCUBA survey (if significant) were: 'Year', 'Season', 'Subregion', 'Level/Depth Zone', 'Visibility' and 'Transect Replicate.' Sampling seasons included summer and fall. Study sites were all rocky reef habitats and transects were located at random within these areas.

TENERA Inc. Diablo Canyon Nearshore Reef SCUBA Survey (TENERA SCUBA)

Tenera Environmental, Inc used SCUBA survey methods (CRANE 2004) to collect data in a small cove near Diablo Canyon, California (1976-2007). The sampling unit for this survey was the total fish counted by two divers surveying 200 m^3 transects simultaneously, starting at opposite ends. Explanatory variables for the TENERA SCUBA survey (if significant) were: 'Year', 'Season', and 'Transect Replicate'. A location variable was not deemed necessary for this survey, since transects were all within the same small cove.

CDFG Creel Survey of CenCal Spearfish Tournaments (CDFG CenCal)

California Department of Fish and Game (CDFG) surveyed fishes caught at recreational free diving spearfishing tournaments of the Central California Council of Diving Clubs (CenCal) organized several annual tournaments from Cape Mendocino to Pismo Beach. This was the only fishery-dependent spearfish survey included in this study. Years included in analyses were 1959-68, 1973, 1975-77, 1980-96, 1998-2006 (40 years total). Total effort for each meet was the sum of all individual divers time spent searching (aboard kayaks and underwater) and spearing fish. A sample for this survey was defined as a

single tournament. Tournaments had time limits and prizes were awarded to divers with the largest, most numerous and most diverse fish catches. Explanatory variables in the CDFG CenCal survey (if significant) were: 'Year', 'Season', 'Subregion' and 'Water Conditions.' Sampling seasons included spring, summer or fall.

PSMFC MRFS / CRFS Dockside Boat Survey (PSMFC Dockside)

In this fishery-dependent hook and line survey, the Pacific States Marine Fisheries Commission (PSMFC) interviewed recreational anglers at harbors throughout the study area 1980-1989; 1993-2007 (25 years total). Each interview of anglers returning from a day aboard a commercial passenger fishing vessel (CPFV) or private fishing boat was considered a sample. CPFV and private anglers used similar methods of anchoring or drifting and jigging baits/lures, although CPFVs often carry 10-50 times more angels than private vessels. Effort was the time of a fishing trip multiplied by the number of anglers onboard. Only fish kept by anglers and identified by PSMFC interviewers were used to calculate catch per hour for a sample. Samples were included in analyses if angler target species included any study species/group or if target was 'unidentified.' The Marine Recreational Fisheries Statistical Survey (MRFSS) covered the years 1980-89 and 1993-2003, whereas the California Recreational Fisheries Survey (CRFS) extended from 2004-2007 and sampled more regularly. All sites surveyed by the MRFSS program and only the lower traffic sites from the CRFS program were used because hours fished were only recorded at these sites. Explanatory variables for the PSMFC Dockside survey (if significant) were: 'Year', 'Season', 'Subregion', 'Distance From Shore' and 'Boat Type.'

CDFG CPFV On-Board Sampling Program (CDFG Observers)

The CDFG Observers survey was based on the CDFG observations onboard randomly selected CPFVs throughout the study area, 1988-1998. This fishery-dependent hook and line survey only monitored trips targeting rocky reef species (at all depths). Effort was the time anglers fished at a specific site (often several per trip). The total of fish kept or released at a site recorded by observers was the sample catch rate. Explanatory variables for the CDFG Observers survey (if significant) were: 'Year', 'Season', 'Subregion' and 'Depth Zone'.

PSMFC MRFSS/CRFS CPFV Observers Survey (PSMFC Observers)

The PSMFC Observers survey was based on the observations of PSMFC personnel onboard CPFVs across California. The Marine Recreational Fisheries Statistical Survey (MRFSS) covered the years 1999-2003, while the California Recreational Fisheries Survey (CRFS) extended from 2004-present. This fishery-dependent hook and line survey used similar methods as the CDFG Observers

survey, except in choosing samples to analyze. Unlike the CDFG Observers survey, all types of CPFV trips (not just rocky reef species trips) were observed by PSMFC. As the target species was not recorded by observers, any trip which used trolling to catch fish was removed, as well as any trip that did not catch at least one species of nearshore rocky reef species. Explanatory for this survey (if significant) were: 'Year', 'Season' and 'Subregion'.

CDFG/PSFMC CPFV Observers data set (All Observers)

The 'All Observers' survey was created by combining data from the CDFG and PSMFC CPFV surveys into a single data set (1988-2007). Similarities in all aspects of methods for the two surveys make it reasonable to analyze all 20 years of data together. Results did not replace either original (separated) Observers survey, but instead were compared with original surveys and other surveys that sampled the same time-span. The explanatory variables used for this GLM (if significant) were: 'Year', 'Season' and 'Subregion' (defined in CDFG Observers description).

Analysis Using Generalized Linear Models

The generalized linear model (GLM; Nelder and Wedderburn 1972) is a useful statistical tool for analyzing time-series fisheries data. The technique has been used by researchers to develop more accurate stock assessments (Ralston and Dick 2003, Cope and Punt 2005). The GLM is an outgrowth of the classical linear multiple regression model, allowing for non-normal data distributions to be analyzed (McCullagh and Nelder 1989). For a given GLM, inputs included: (1) a response or dependent variable (any measure of fish abundance in this case); (2) the appropriate sampling distribution; (3) a link function; and (4) one or more explanatory variables (Maunder and Punt 2004). GLMs were used to create time-series of relative yearly abundance from population abundance data collected for each study species by field surveys. A GLM that included sampling or environmental variables specific to each survey was fit to abundance data (i.e. fish count and effort). The yearly index values generated by a GLM depict the stock abundance trends as measured by a given survey after removing bias introduced by explanatory variables. Each index value represented the mean of modeled samples within a year.

The error distribution used in GLMs can be continuous (e.g. normal or Gaussian, log-normal, gamma) or discrete (e.g. Poisson, binomial or negative binomial; Dick 2004). A discrete distribution, the negative binomial (NB) was used for all GLMs. A primary reason for choosing the NB distribution is its usefulness for data sets containing few or many zero counts to be analyzed (Maunder and Punt 2004). Zero fish counts existed or were common for all of the abundance surveys used in this project (often 40% or more of samples). If not included in models, zero records may invalidate assumptions of the analysis as well as creating difficulties in computations (Lambert 1992; Maunder and Punt 2004). Using the normal or most other distributions requires ignoring zero records when analyzing abundance survey data

may, which can bias the resulting index in a positive direction (Maunder and Punt 2004). Therefore, zero records were included in calculating index values. However, some distributions that allow for zeros do not function correctly if the number of zeros is very low (e.g. binomial; E. Dick pers. comm.). The NB distribution is not negatively affected by data with many or few zeros.

Discrete distributions such as the NB and the Poisson are useful if the dependent variable is a count of fish caught or observed as opposed to a continuous measurement (e.g. fish weight; Maunder and Punt 2004). The NB and Poisson distributions are useful for modeling count data of relatively rare phenomena. A histogram of most count data 'tails off' steeply after peaking, demonstrating that higher counts in sampling are less common. A histogram of the NB distribution will tend to tail off even more rapidly than with the Poisson distribution (Hoffmann 2004). Because the majority of the data used for GLMs in this study were moderate to low counts of species, the NB was a reasonable choice of distributions. Data over dispersion may occur if intra-annual sample variance is greater than the mean, a common situation for the abundance data analyzed. This was another key reason for using the negative binomial distribution, as this distribution reflects the over dispersion not captured by the Poisson (which assumes variance equals the mean; Seavy et al. 2005). It is also useful to employ the Akaike Information Criterion (AIC) or other model selection criteria to compare the fit of models with different distributions to the same data. The AIC was used to compare models of the same data using the negative binomial and Poisson distributions, and the NB distribution proved to have lower AIC values. The NB distribution, for the purposes of this analysis, can be viewed as a Poisson distribution with a mean that follows the gamma distribution (Hilborn and Mangel 1997).

A link function can be used to relate the linear sum of explanatory variable effects (i.e. the linear predictor term) to the mean value of the response variable (Crawley 1993). The log link, commonly accepted for use with the NB distribution (McCullagh and Nelder 1989), was used in all GLMs. This link function restricts GLM index values to positive numbers, applicable for working with abundance survey data (Agresti 2002).

An abundance survey sample (i) can be modeled by a GLM with negative binomial distribution and log link as:

$$\log(\mu) = x_i \beta$$

where x = design matrix composed of all observations and explanatory variables, β = all coefficients (or levels) for each variable (e.g. spring, summer, fall for the season variable) and μ = the true mean response (Dick 2004). Fitted model values are found by: $\mu_i = \mu D_i$, where D is an error term drawn at random from the NB distribution (Dick 2004). To extract the 'year effect' from this model, the index of abundance for each year of a given study (μ_y) was calculated by the equation:

$$\mu_y = \exp(\beta + \beta_y)$$

where   is the model intercept and   y is the regression coefficient for the year variable both back-transformed to display original data scale measurements (Ralston and Dick 2003).

Sampling Precision

The intra-annual precision of fish count and effort samples was characterized in this study for each species in each survey using a coefficient of variation (CV), defined as CV = standard error/mean. CVs are dimensionless and scaled to the mean of a given distribution, as opposed to other measures of data variation (Hilborn and Mangel 1997). CVs may vary from zero (highest precision, no variability) upwards. Survey years with less than two associated survey samples were not included in analysis, since there could be no associated variability and a CV could not be calculated (Dick 2004). The logtransformed yearly index values resulting from each negative binomial GLM were backtransformed to the original data format to compute the yearly CV. This step exponentiates the GLM values, allowing the variability of the original data to be analyzed (E. Dick pers. comm.).

A jackknife procedure was used to calculate the CV for each year in a given data set, which has been used in existing stock assessments (e.g., Ralston and Dick 2003). The jackknife (Tukey 1958) is a specialized form of the bootstrap technique, which estimates standard errors for the GLM index values using the same number of iterations as data points (Efron and Tibshirani 1993). Both the jackknife and the bootstrap approximate the bias and standard error of a data set. Meyer et al. (1986) suggested the jackknife is more efficient, due to smaller number of computations necessary to achieve a similar result.

Yearly CVs below 0.30 were considered to represent highly precise intra-annual sampling, while CVs over 0.70 were considered high. Recent stock assessments have viewed data from years with CVs greater than 1.0 as too variable to include in an index (Ralston and Dick 2003; Cope and Punt 2005). In this scenario, the value of the standard error is larger than the mean, and therefore confidence in the index value is low. Years with CVs greater than 1.0 were not removed from analysis or results displays, but should be considered less reliable abundance estimates. Conclusions made about fish species trends using low precision surveys (or years within surveys) should take this important caveat into account.

Explanatory Variable Selection

To design a GLM model that best fits a given abundance survey data set, variable selection analysis was completed for each species. This process compared models of the same data set using different combinations of explanatory variables (e.g. years, season, location, etc.). Including factors that demonstrate large fish count variation among levels will reduce model variance, evidenced by lower deviance values and AIC scores. However, when non-significant explanatory variables are incorporated in the model, variance may increase due to unnecessary complexity, creating a less precise index

(Maunder and Punt 2004). Analysis of Variance (ANOVA), AIC or Bayesian Information Criteria (BIC) can all be used to evaluate these competing models. The AIC is useful for variable selection in data sets with at least 40 data points (Burnham and Anderson 2002). The BIC may provide results with less bias for large sample sizes (n > 1000; Burnham and Anderson 2002). To create a model with only those variables that explain a significant amount of fluctuation in data, a 'penalty' term is employed for both AIC and BIC (Hilborn and Mangel 1997). The BIC is calculated similarly to the AIC, but includes a penalty term that increases with sample size, while the penalty term for AIC remains constant. Use of the BIC can reduce the chance of selecting unneeded explanatory variables for GLMs in surveys with large sample sizes.

GLMs for each species in a given survey were simplified by including only explanatory variables that significantly affected the dependent variable. A few different methods for selecting variables to include in GLMs were compared in this study; however, ANOVAs were used to make the final choice of explanatory variables. This model selection method was used based primarily on clarity and efficiency in displaying results. Every variable that was significant using an F-test ($p < 0.05$) was included in the final GLM. The only exception the variable 'Year' was included in all GLMs, because the purpose of using GLMs in this study was to detect a trend in abundance data over a time-series. AIC was also used to indicate which explanatory variables (1st order) and interaction terms (2nd order) were significant in a given model, but results were not reported, as they compared well with ANOVAs. BIC was employed in addition to ANOVAs for testing interactions when sample sizes were greater than 1000, and results are given for comparison.

All GLM analyses were run in the downloadable statistical program, R (http://www.r-project.org/), using a unique R-script that was created and tailored to suit each survey's dependent and explanatory variables in calculating the yearly index values and CVs based on original survey data for each species. ANOVAs were computed in R to evaluate the significance of explanatory variables and interaction terms. An R function, called 'STEP', was used to calculate AIC or BIC values for the GLMs. Each GLM was run in R and output was organized into yearly abundance index values and coefficients (variable levels).

Linear Regressions

To quantitatively assess whether trends were significant, linear regressions were run using yearly abundance index values (from GLMs). A linear regression was completed for each species with year as independent and annual mean abundance index as dependent variable. One regression was done for the full temporal extent of each survey, while others regressions were completed for 1988-2007 and 1999-2007. Slope regression coefficients (β) indicated the direction of linear trends. In tables, any $\beta \geq 0.0001$

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was considered positive,   ≤ -0.0001 were negative and values in between were considered zero. However, only   's with p-values that differed significantly from zero (< 0.05) were considered significant trends.

To indicate whether surveys produced similar trends over the same time-period, significant linear regressions were compared for each species. When two significant trends existed for the same species, t-tests were used to determine if the slopes differed. Survey trends were compared for the two time-periods: 1999-07 and 1988-07. T-tests were calculated using linear regression, with the GLM yearly index value as the dependent variable and using the interaction term of survey year and survey number (three independent variables) to determine significantly different trends (< 0.05).

Focus Species

GLM abundance trends were plotted for four species only. These 'focus species' were chosen based on: (1) having sufficient data for most surveys to be analyzed; (2) showing strong correlations with temperature in cross-correlation analysis. The species are: Lingcod (*Ophiodon elongatus*)*,* Blue Rockfish (*Sebastes mystinus*)*,* Vermilion Rockfish (*Sebastes miniatus*), and Copper Rockfish (*Sebastes caurinus*). These four species represent two of the three main groups comprising the study assemblage (i.e. nearshore rockfishes and solitary predators). Seaperch species (family Embiotocidae) were not included as focus species because they were not counted regularly enough to be analyzed in most surveys. However, the three rockfish (Genus *Sebastes*) species chosen do have somewhat different life history patterns (feeding and distribution etc.) relative to one another (Cailliet et al. 2000; Allen et al. 2006).

 Plots were created from yearly indices of abundance values generated through GLMs in R for focus species to evaluate trends qualitatively. To plot several survey results on the same scale, yearly index values were standardized before plotting. Standardization was achieved by dividing the mean of all yearly index values for a given species in a given survey into each yearly index value. The resulting yearly values, standardized to the mean, could then be plotted and compared to other surveys of the same species. Unlike other standardization methods (e.g. Z-scores) this method of standardization preserves variability among yearly index values by not setting the standard deviation for yearly values. Because GLMs produce a relative abundance index, the actual value of a given point on the plot was less important than its position in relation to points for other years (higher, lower or similar). Trend lines were also plotted separately for linear regressions of abundance data for focus species in the two time-periods.

Yearly index values from the All Observers survey were used to examine trends for the four focus species in 1988-2007, while the PSMFC Observers survey data were used to plot trends for 1999-2007. This survey was chosen for comparing trends in focus species due to the generally high precision in sampling for focus species, data collection during every year of the two time-periods used here, excellent

coverage of the sampling area for the study (geographically and by depth) and reliable estimates of sampling effort. Blue Rockfish was investigated in more detail than other focus species. Adults of this species tend to prey on lower tropic levels than the other three focus species, making Blue Rockfish more likely to be affected by changing temperatures in a shorter amount of time.

Fish Abundance and Temperature Analyses

Three methods were used for analyzing fish abundance and temperature data from eight fish data sets containing a combined total of 94 species and 32 groups of species or age classes. The relative yearly abundance estimates calculated using the GLM analysis described previously were used in some of these analyses as indicated by corresponding survey names. Other fish data sources used included two sources of fisheries landings as well as stock biomass estimates from existing NMFS stock assessments. Temperature data sets used for these analyses included Pacific Grove (PG) and Farallon Islands (FI) shoreline sensors and satellite SST (Table 1).

The first method involved comparing z-scores. Abundance values were used based on GLM analysis as well as other data sets for which abundance values were first normalized relative to the mean abundance for each time series. Abundance for each year was assigned a symbol to indicate whether it was within one standard deviation of the mean, one standard deviation above, or one standard deviation below the mean. Warm (1977-1993) and cool (1998-2006) ocean temperature years were analyzed separately to show trends in fish abundance in light of temperature regimes.

Linear regression analyses were conducted to determine relationships of fish abundance with SST. Commercial landings data from the CALCOM database were plotted as a response variable to SST to determine potential linear relationships. Species used in this analysis were selected based on NOAA's designation of landings to be "very reliable" (Pearson et al. 2008). Plotted data were then fitted with a linear equation and analyzed for goodness of fit. Abundance data were offset from PG SST data to analyze significance of 0, 3, 4, 5, 6, and 7 year lags.

Abundance data for some species was not robust enough to explore with linear regression due to sporadic presence in central California fish data sets. These species could hypothetically be more likely to have their presence predicted by SST. For these species, a binomial logistic regression was conducted using three abundance surveys (Observers, CDFG H&L and CenCal). Abundance data were compared with SST data from FI, PG, and mean distance of isotherms obtained from satellite SST.

Cross-correlation analysis

Cross-correlation analysis was used to determine relationships between fish abundance and physical ocean conditions and how much lag time occurred following a change in physical conditions that

a change in fish abundance was noticeable. Data were analyzed using Palentological Statistics (PAST; Hammer et al. 2001). Three different time series were evaluated, 1977-93 (warm ocean years), 1998-2007 (cool ocean years), and from the start of a fisheries data set to 1975 when fishing effort greatly increased. When the time-series were split into warm and cool time periods, temperature data from FI and PG were used in cross-correlations. Yearly averaged data from Farallon Islands (FI) and Pacific Grove SST (PG) were compared separately for 11 species with relative yearly abundance estimates from each of the following fish abundance data sets: CenCal, Observers, PISCO, Stock Assessments, Tenera. When the time-series were not split into the two time-periods, two physical variables [PG and dissolved oxygen (DO)] and two environmental indices [El Niño Modoki (EMI), North Pacific Gyre Oscillation (NPGO)] were used to compare with fish abundance in cross-correlations. FI was not used for this second analysis because it was highly correlated with PG and thus deemed unnecessary. Fish abundance data sets used in this second analysis included: CenCal, stock assessments, and Observers. These three abundance datasets were selected because they had sufficient data to perform the analysis. Cross-correlation analysis used a particular physical variable as the independent variable and fish abundance from a given data set as the dependent variable. Lags in cross-correlations were only considered to be appropriate for 0-8 years based on life histories of California nearshore marine fishes. The lag with the greatest correlation value as well as the signal (positive or negative) of the relationship was recorded along with the significance (p-value). These were then compared with one another to determine if correlation signs of an individual species matched between or among fish abundance data sets (hereafter referred to as trend agreement). Species included in this analysis were not all compared with all environmental variables due to differences in time spans of data sets.

   Due to the relatively small numbers of data points (one per year) and the short length of the two time periods being considered (1977-93 and 1998-2007), the validity of p-values used to assess significance of cross-correlations is highly uncertain. As an alternate approach to using p-values or trend agreement among abundance surveys, cross-correlation plots for fish abundance and temperature were compared visually using two different shoreline temperature time-series as a way to validate results. Fish abundance data sets (CenCal, Observers, PISCO, Stock Assessments and Tenera) were compared separately with each of two temperature data sets (FI and PG). Negative or positive peaks at identical lag times in correlation plots using PG and FI were identified for a given species and abundance data set. A 'peak' year in the plot was distinguished by its value relative to the rest of the plotted years, and a minimum value of 0.2 away from zero (negative or positive; Fig. 2). This analysis was used for six of the most commonly caught nearshore rocky reef fish species (Lingcod, Blue Rockfish, Black Rockfish [*Sebastes melanops*], Vermilion Rockfish, Kelp Rockfish [*S. atrovirens*] and Cabezon [*Scorpaenichthys marmoratus*]). Lag times of zero or greater than eight years were not considered in this analysis. If more

than three peaks matched for PG and FI temperature lags for a given fish abundance and temperature data set combination, the data set was removed from the table due to excessive data variability (there were two cases of this). When two or more peaks agreed in the cross-correlation plots, at different lag times, fish abundance data sets were used to validate results in either time-period.

<div align="center">

RESULTS

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Water Temperature

Long-term data sets indicate that waters along the California coast are getting colder (Fig. 3). In this report, we briefly examine three questions related to this change. First, how evident is this cooling along the central California coast and in Monterey Bay? Second, when did the change to cooler conditions occur locally? And third, why is it happening? Increased upwelling between April and September has occurred primarily along the central California coast between 32°N and 40°N (Mendelssohn and Schwing, 2002). The climate of the North Pacific experienced a major transition in late 1998 that resulted in a cooling of the coastal waters in the California Current by several degrees, and that this change was concurrent with a sign reversal in the phase of the PDO (Peterson and Schwing 2003). This event may not have been related to the PDO, however, since the patterns of sea level pressure and SST anomalies showed little resemblance to those normally associated with the PDO (Bond et al. 2003). Consistent with a sustained change in the climate system of the North Pacific, however, stronger upwelling-favorable winds, increased coastal upwelling and cooler SSTs along the California coast were observed from 1982 to 2008 (Garcia-Reyes and Largier 2010).

Linear regressions of daily SST have shown that temperature at Pacific Grove in Monterey Bay has decreased by approximately -0.7° C over the past decade and by almost -0.5° C over the past five years. These changes are significant when we compare them to the mean annual cycle which has a range of only 3° C (Breaker 2005). To further elucidate this cooling trend, we examined temperature data from Pacific Grove and the Farallon Islands off San Francisco from 1975 to 2010 to provide a broader framework within which to interpret this trend. This period includes the major 1976-77 regime shift that signaled a change from cooler to warmer conditions, and four major El Nino episodes occurring in 1976-77, 1982-83, 1992-93 and 1997-98, and one moderate episode in 1986-87. According to McGowan et al. (1998), the frequency of warm events has increased since 1777, which, together with the regime change in 1976-77, initially led to a period of rapidly increasing temperatures. SST data from NDBC buoy 46012 was also examined and found to be highly correlated with the data from the Farallons (r = 0.9) and Pacific Grove (r = 0.85), but contained major gaps and so has not been included. Running linear trends in SST at

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Pacific Grove and Farallon Islands show several oscillations that differ greatly in magnitude despite their close proximity (Fig. 4 and 5).

Smoothed versions of monthly-averaged SSTs from 1975 through 2010 at Pacific Grove and from 1975 through 2009 at the Farallon Islands show similar patterns (Fig. 6). The blue curves show greater smoothing and suppress the influence of the El Niño warming episodes that have occurred during the period of observation. The red curves display less smoothing and so the influence of El Niño warming has not been completely removed. Following the blue curves, temperatures gradually increase from the mid-1970's up to the mid-1990's and then gradually decrease up to the present time, generally consistent with the climatic change in late 1998. The red curves show greater cooling starting in 2003 at Pacific Grove and in 2005 at the Farallons. The observed rates of cooling range from about $-0.02°C$/year since the mid-1990's, to about $-0.06°C$/year since the early-to-mid 2000's. Similarly, results of analyses near the Monterey Bay Aquarium revealed a significant long-term decrease in temperature at a depth of 17m since 1996 (Booth et al. 2010). By comparison, Garcia-Reyes and Largier (2010) observed cooling rates of $-0.04° C$/year to $-0.06° C$/year for the same the region between 1982 and 2008, but with no indication as to when significant cooling within this period began.

To gain more insight into the nature of the cooling process, we stratified the data by month in order to see if any seasonal patterns exist. Linear trends at each location were calculated over the length of the record for each month. The slopes were found to be negative between October and April, and positive between May and August. Positive slopes during the upwelling season were surprising and so we took a closer look to see what might explain this unexpected result. Although the scatter in the monthly data is high, repeating patterns did emerge. In most cases, SSTs increased rapidly from 1975 to the early 1980's, followed by a slight decrease in temperature between the mid-1980s and the mid-1990's. Between October and April, temperatures generally decreased starting in the mid-to-late 1990's, and between 2000 and 2005, temperatures decreased more rapidly up through 2009. Between May and August, however, we found that temperatures often increased, starting as early as the late 1990's. The smoothed lines (depicting data from February and July at Pacific Grove) that are shown in Fig. 7 are generally representative of the patterns we have just described for both locations. Based on the slopes of the linear trends, cooling clearly outweighs warming because cooling occurs for seven months of the year and warming for only four. If we combine these results for all 12 months we reproduce the pattern of cooling shown in Figure 6.

Returning to the three questions that were initially posed, we now we address the third question - why are temperatures along the central California coast and in Monterey Bay cooling? According to the Bakun (1990) hypothesis, global warming should cause continental low pressure systems adjacent to regions of coastal upwelling to become more intense, increasing the onshore-offshore pressure gradient

and thus the alongshore winds that produce coastal upwelling. To our knowledge, however, this hypothesis has neither been verified nor universally embraced (P. Mote, pers. comm.). That ocean temperatures could be increasing during the height of the upwelling season was unexpected, based on the results of previous studies. Thus, our results, although limited to two locations, do not appear to be consistent with those obtained by Garcia-Reyes and Largier (2010). We note that the cooling they observed is based on data acquired from NDBC buoys that are located approximately 20km from the coast. Strictly speaking, these buoys lie slightly beyond the expected region of active coastal upwelling based on dynamical considerations.

Also, the model results of Capet et al. (2004), show that the drop-off of the alongshore winds due to frictional effects next to the coast favor Ekman pumping (i.e., shear-driven upwelling) rather than coastal upwelling per se. Thus, processes other than coastal upwelling may be important. To specifically address warming during the summer, we refer to the model results of Di Lorenzo et al. (2005), who found that large-scale changes in surface heat fluxes over the eastern North Pacific can outweigh the effects of upwelling along the coast in causing changes in temperature possibly explaining observed ocean warming in summer. These results could signal the growing importance of global warming whose influence would be expected to be greatest during the summer. If global warming does play a role, we need to address the question of how this influence is partitioned between local and remote (i.e., advective) forcing.

The PDO appears to be an important factor that is contributing to lower temperatures off central California. Within two degrees of the coast and north of 31°N, the PDO signal is a dominant source of variability (Lluch-Cota et al. 2001). Thus, it is not surprising that the PDO index, for the yearly-averaged data, is highly correlated with temperatures at the Farallons and Pacific Grove (Fig.8). Lagging did not produce higher correlations using the monthly values. Correlation coefficients of 0.81 and 0.71 were obtained for the Farallons and Pacific Grove, respectively. Cross-correlations between the Farallons, Pacific Grove, and the PDO were also calculated using a 12-month moving window and showed that the strength of the relationships vary significantly over the 35-year period from 1975 to 2009. To summarize, the climate shift that occurred in the late 1990's resulted in a change from warmer to cooler conditions, and the yearly-averaged PDO index has been negative for the past four years (2007-2010). These results are consistent with the overall cooling we have observed, but not necessarily with indications of summer warming over the past decade. Finally, it is noteworthy that there have been fewer and weaker El Nino warming events since 1998.

At this point, we consider why greater cooling has taken place between October and April. Over the past five decades, winter storms in the North Pacific have increased both in frequency and intensity, according to Graham and Diaz (2001). At mid-latitudes, relatively large latent and sensible heat fluxes occur in the cold sectors of winter storms that are major contributors to the cooling process (Cayan 1992).

The surface winds associated with these storms also increase mixing in the surface layer bringing cooler waters to the surface.

Satellite SST

Year-to-year mean distance of isotherms from shore in central California varied greatly from 1982 to 2009 (Fig. 9). Mean distance from shore of the 15° C varied from close to shore to 100 – 200 km offshore during this time period. August 15° C isotherms were on the coast in 1984, 1991, and 1992. Maximal distance offshore occurred in 1999 at 482 km from shore. Great variability was also observed in the location of the February 13° C isotherm, from 0 km to 712 km. Over a small time span of two years, the location of 15° C isotherm varied greatly as observed between August 1984 and 1986 (Fig. 10). Similar large fluctuations occurred with August temperatures for 1989-1990, and 1998-1999. These large fluctuations may influence abundance of near shore fishes that are not abundant in central California on an annual basis.

ANOVA results of isotherm mean distances with fish abundance data produced few significant results (Table 4), all of which were with the location of isotherms during August. Significant results occurred for salmon species (Chinook [*Oncorhynchus tshawtscha*] and Coho [*O. kisutch*]) and sharks (Common Thresher [*Alopias vulpinus*] and Shortfin Mako [*Isurus oxyrinchus*]), however there were additional species of pelagic sharks that were analyzed but did not provide significant results. Cooler SSTs along the coast during February may be indicative of higher productivity, but have little to no influence on the landings of nearshore or pelagic species during the year. Parsing data into seasonal catches may provide additional clarity to detect significant relationships.

GLM Analysis

Stock Abundance Trends

Some species exhibited significantly increasing or decreasing abundance trends, as determined by linear regressions of GLM yearly index results (Table 5). Although most species had positive or negative slopes (not zero) based on our definitions, most trends were not significant. No species had significant trends for all surveys sampling them. Kelp and Blue Rockfish had regression slopes ('s) trending upward in all surveys (except the TENERA SCUBA data set), but not all were significant. All significant survey trends were upward or flat for Gopher (*S. carnatus*), Olive (*S. serranoides*), Vermilion, Brown Rockfish (*S. auriculatus*), Striped Seaperch (*E. lateralis*), and Lingcod. The other species were a mix of down, up and flat trends (some significantly, some not).

When all abundance survey years were considered, few patterns in the significance of linear abundance trends were clear within survey categories (Table 5). Only the PISCO SCUBA survey had a

large percentage of significant trends (42%) for the SCUBA survey category. For the fishery-dependent hook and line category, only the 'All Observers' time-series had a large percentage of significant trends (57%). The other category (fishery-dependent spearfishing) had relatively low proportions of significant trends. In general, surveys with time-spans longer than twenty years had relatively few significant linear trends.

Directions of significant linear trends were not consistent among species within survey categories (Table 5). All categories had some species with upward and some with downward trends. However, trends were mostly upward for the fisheries-dependent hook and line survey category and were all upward for the CDFG and PSFMC Observers surveys. It is important to note that the surveys often cover different time periods, thus making the trends applicable only over certain years.

When linear regression results were examined for particular time periods, the number of surveys being considered was reduced and patterns became clearer. In 1988-2007, the significant linear trends for the TENERA SCUBA (1 species) and CDFG CenCal (5 species) surveys were all downward (Table 6). In contrast, significant trends for the PSMFC Dockside (3 species) and All Observers (8 species) surveys were upward in most cases. For 1999-2007, all significant trends were upward for the PSMFC Observer survey and the majority of trends were upward for all fishery-dependent hook and line surveys (Table 7). In contrast, the only significant trend for the CDFG CenCal survey was declining, and the majority of significant SCUBA survey linear trends were downward for this time period. During each different time period, all survey slopes (significant and non-significant) were rarely all negative or positive for individual species.

When different survey abundance trends were compared for a given species in a particular time-period,   's were mostly significantly different (Table 8). Only three unique survey combinations were actually compared because of the low number of significant linear regressions. The five t-tests indicated all trends were significantly different for the five species tested. Three survey trends for Blue Rockfish in 1999-07 were similar (upward) when compared by analysis of covariance (ANCOVA).

Sampling Precision

In general, mean CVs were below 1.0 for each species in abundance surveys where the jackknife analysis could be completed (Table 9). This was considered the maximum threshold for useful data. However, abundance survey samples for many species were relatively precise in some surveys (mean CV < 0.30), but highly variable in others (mean CV > 0.70). Only Yellowtail Rockfish (*Sebastes flavidus*) had mean CVs below 0.30 for all surveys; this species also had the lowest mean CV (across surveys). However, Yellowtail*,* Brown*,* Blue Rockfish, and Lingcod all had mean CVs below 0.30. Kelp and Grass

Rockfish (*S. rastrelliger*) had the highest CVs on average (> 0.70). All other species had a mix of high, low and mid-range (0.30-0.70) CVs for different surveys.

Mean CVs varied considerably for some surveys (all species) and for some individual species (among surveys). The CDFG CenCal survey had the highest mean CV (0.82) and the lowest number of samples per year. The PSMFC Dockside survey had the lowest mean CV (0.21) and highest number of samples per year. Some survey categories had higher precision than others for certain species. SCUBA surveys had low mean CVs (< 0.30) for most species with the notable exceptions of Vermilion Rockfish, Gopher Rockfish, and Lingcod. Striped Seaperch, Pile Seaperch (*Rhacochilus vacca*), Kelp Rockfish, and Black-and-Yellow Rockfish (*S. chrysomelas*) all had clearly lower mean CVs in SCUBA surveys compared to other categories. Fishery-dependent hook and line surveys also sampled most species with high precision. This category had lower mean CVs than other survey categories for Vermilion, Gopher, Canary (*S. pinniger*), China (*S. nebulosus*), Blue Rockfish and Lingcod. However, Kelp Rockfish had extremely low precision (mean CV > 1.0) for the CDFG and PSMFC Observer surveys. The fishery-dependent spearfishing category did not have lower CVs than other surveys for any species but did provide the only GLM abundance index results for Grass Rockfish. Vermilion and Copper Rockfish both had especially low precision in this survey (mean CVs > 1.0).

Focus Species

During 1988-2007, abundance trends in the All Observers survey were positive for focus species, except Copper Rockfish (Fig. 17 and 18). However, the only significant regression slopes were found in Blue Rockfish and Lingcod (both positive). In 1999-2007, trends for the PSFMC Observers survey were positive for all focus species, but slopes were significant only for Blue and Copper Rockfish (Fig. 19 and Fig. 20).

Yearly abundance index values for Blue Rockfish often varied among surveys, although major highs and lows were often similar among surveys (Fig. 11). The trend slopes for the TENERA SCUBA, PISCO SCUBA and CDFG CenCal surveys differed noticeably from other surveys trends across years (Fig. 12). Index values of the All Observers survey (combining the CDFG and PSMFC Observers surveys) matched well with those for both original Observer surveys, indicating that combining the two observer data sets in tables and figures is reasonable. Most surveys' slopes were positive when considering all survey years in linear regressions (Fig. 12). Slopes were significant for the PISCO SCUBA, TENERA SCUBA, CDFG Observers, PSMFC Observers and All Observers surveys. Significant slopes were positive (increasing) among all surveys, except the TENERA SCUBA survey. R-squared values were above 0.45 for all surveys with significant 's (except TENERA SCUBA). Directions of regression slopes for 1988-2007 were mixed (two negative, two positive), but significant

only for the TENERA SCUBA (negative) and All Observers (positive) surveys (Fig. 13 and 14). In 1999-2007, slopes were again mixed for this species, but positive for all surveys with significant slopes (the PSMFC Dockside, PSMFC Observers and PISCO SCUBA surveys) (Fig. 15 and 16).

The TENERA SCUBA and All Observer surveys data were compared for 1988-2007 with a t-test that showed these trends were statistically different (Table 8). The TENERA SCUBA decreased, while the All Observers survey increased for this time-period. An ANCOVA comparing significant linear regressions for three surveys in 1999-2007, demonstrated that abundance trends were increasing similarly.

Intra-annual precision in sampling for Blue Rockfish was one of the highest among species used in this analysis on average (across all surveys) (Table 9). The CDFG CenCal survey had the highest yearly CVs and PSMFC Dockside had the lowest for this species. Only the CDFG CenCal survey had annual CVs above 0.70, and several years were above 1.0. The PSMFC Dockside, PSMFC Observers, CDFG Observers, All Observers and PISCO SCUBA surveys had CVs below 0.30 in all years.

Fish Abundance and Temperature Analyses

Fish abundance data were plotted to detect trends in abundance in light of central California ocean temperature regimes: warm (1977-1993) and cool (1998-2009). These data provided no apparent patterns or trends regardless of data set or species. For some data sets, such as TENERA SCUBA, different age classes were also analyzed such as juvenile and YOY fishes (Fig. 21). Several species or groups analyzed (e.g. Black-and-Yellow/Gopher YOY, Jacksmelt [*Atherinopsis californiensis*], Olive/Black-and-Yellow Rockfish, and Kelp Rockfish) displayed no change for 1977-1993. Year to year variation in species abundance would be expected to be greater than data indicate, especially for juvenile and YOY rockfishes that are highly variable based on environmental conditions.

Eight species were analyzed using linear regression analyses. In all comparisons with Pacific Grove SST, only three regressions were significant (Table 10). California Halibut (*Paralichthys californicus*) and Petrale Sole (*Eopsetta jordani*) were the only species that had significant results (p $\leq$0.05), however, the highest R^2 value of all species analyzed was 0.17 (California Halibut, lag 5 years, p=0.01). English Sole (*Parophyrs vetulus*), another flatfish species, provided neither significant results nor high R^2 values. The species analyzed make up a variety of different groups of fish species along the central coast including some commercially and recreationally important species. Limited amount of species with "very reliable" abundance data caused the scope of this analysis to be narrow.

Logistic regression analyses provided no clear trends in presence or absence of species in central California (Table 11). California Sheephead (*Semicossyphus pulcher*) was analyzed using four abundance data sets with six SST data sets. With all of these analyses, the majority of results (19 of 24)

produced high p-values (p >0.5). Similar patterns were observed with Pacific Tomcod (*Microgadus proximus*), which compared two abundance data sets with six SST data sets.

Cross-correlation analysis

Cross-correlation analyses of physical variables and abundance provided conflicting results. Due to overlap in species among the data sources, results from different fish data surveys were compared to one another to detect potential patterns with SST data. Cross-correlation results for FI and PG show several significant results at various lag times, the most significant occurring at zero years (Fig. 22). However, there were several species that did not have similar cross-correlation results (signal direction and lag times) for the two sources of SST using the same abundance data set (Table 12). Additionally, these trends (positive or negative) did not necessarily hold true when comparing warm and cool years, such as Black Rockfish using CenCal data. In this case, results suggest Black Rockfish abundance is always increasing regardless of the SST trend. Nevertheless, significant results were revealed for most species compared with SST at PG and FI for both cool and warm time periods (Table 13). Interestingly, while 40 percent of species showed similar trends in cross-correlation signals in warm years for both PG and FI, only nine and 18 percent had similar trends in cool years for PG and FI respectively. Lag times of significant cross-correlations seldom matched for a given species among the various abundance data sets.

Cross-correlations of fish abundances and environmental variables when the time-series were not split into warm and cool year periods resulted in significant p-values for less than 50% of the 35 species analyzed (Table 14). The percentage of species with data showing similar trends was not much different than those observed in previous analyses (Table 10). Comparing fish abundances with basin-scale environmental indices such as PG, EMI, and NPGO yielded similar numbers of species with significant cross-correlations, which was nearly double that observed with DO. EMI was the only variable with greater than 50% agreement in trend among data sets for a single species and the lowest was PG with 16.7% of species showing similar results. Black Rockfish data from the CenCal survey showed three significant cross-correlations with SST from PG, two with NPGO, and one with DO (Table 15). These significant correlations are relatively similar in the number of years by which abundance change lags environmental changes (with the exception of a 7 year lag). However, there was no consensus as to the signal of the cross-correlation. Comparing these results to Black Rockfish data from the stock assessment did not yield a stronger conclusion as to the nature of the relationship between abundance and ocean temperature or environmental indices.

Comparisons of the peaks and troughs of cross-correlation plots displayed similar pattern in some cases, such as when Vermilion Rockfish was analyzed using CenCal data compared with EMI and NPGO (Fig. 23). Additionally, both cross-correlations show significant relationships at a 2-3 year lag. Cross-

correlations with PG and DO have inverse relationships but they vary in magnitude and timing of lag. These results indicate that analyzing a single environmental variable with abundance data from a single source may not provide an accurate representation of relationships.

For the six species tested by comparing cross-correlations plots between PG and FI temperature time-series for a given species and fish abundance data set, there was generally at least one case where distinct peaks occurred at the same lag time and with the same direction (positive or negative; Table 16). Often there were two peaks or more that agreed (at different lag times), and sometimes in contradictory directions (negative and positive) for a given fish abundance data set. When different fish abundance data sets were used to validate potential correlations, there were at most two similar lags found per species. In most cases these were similar within the 1998-2007 time-period, but a few overlapped in both time-periods. If correlations at a one-year lag time were not considered (a very short amount of time for a significant population change to occur in these species), there was only one lag time, which agreed among two or more fish abundance data sets for each species. All validated correlations were negative (except for one year lags in Black Rockfish), with lag times of 1-4 years (except one possible 7 year lag for Lingcod) depending on the species. The fish abundance surveys 'Observers' and 'PISCO' agreed most often for the 1998-2007 time-period. These two surveys also had the lowest average coefficient of variation of the different data sets. In 1977-1993, fewer fish abundance data sets had similar cross-correlation plot peaks, and these peaks seldom agreed. Results from the plot comparison analysis are quite different from results of other

SUMMARY

The main goal of this study was to determine if we could relate historical changes in water temperature to changes in abundances of fish species, in order to predict changes in water temperatures and species abundances in California caused by global climate change. Our primary objectives were to (1) review the existing published and unpublished data sets to refine our understanding of trends in sea surface temperature in central California; (2) review fish and climate data sets to determine if we could identify how species abundances changed relative to changes in water temperatures and basin-scale environmental indices; and (3) identify recent changes in species abundances in central California that are related to water temperatures.

Sea Surface Temperature

After a thorough analysis of long-term ocean temperature data sets from observations at Pacific Grove and the Farallon Islands, it is clear that surface temperatures are indeed cooling and the overall

cooling trend began in the mid-to-late 1990's at rates approaching 0.07° C/year. More intense cooling began in the early-to-mid 2000's at rates approaching 0.10° C/year, and continues up to the present time. Unexpected warming trends were found between May and August at both locations that are not necessarily consistent with increased coastal upwelling but instead may reflect the growing importance of global warming and its effect on surface heat fluxes over the eastern North Pacific. Significant cooling has occurred between October and April since the late 1990's, consistent with the overall cooling trend that has been observed. Increased winter storm activity may be primarily responsible for this cooling. Finally, the Pacific Decadal Oscillation appears to be an important factor in contributing to cooler temperatures along the central California coast. SSTs at the Farallon Islands and Pacific Grove are highly correlated with the PDO, consistent with its importance off central California. These results should not be considered in any sense conclusive but rather a starting point for further study to help improve our understanding of how and why the waters along the central California coast are cooling.

Temperature – Fish Abundance Relationships

Our study demonstrated that understanding water temperatures alone may not be sufficient to predict changes in abundance of marine fish species off central California. A much higher percentage of strong relationships between fish species abundance and temperature were found when time-series were split into warm and cool years compared to using the entire time-series in these analyses. Different fish data sets often provided conflicting results when used in cross-correlation analyses. Relationships between fish abundance and dissolved oxygen were weak overall. Basin-scale indices, combined with long-term fish abundance estimates, provided a greater number of clear relationships between fish and climatic indices. These results indicate that either: (1) not all existing fish data sets are sufficiently robust to accurately detect changes in abundance caused solely by changes in temperature, (2) there is sufficient variability in both temperature and fish data sets that a longer temporal data set is needed to detect trends, and/or (3) temperature alone is not a good indicator of trends in fish abundance.

The results of cross-correlation analyses support the hypothesis that not all existing fish data sets are sufficiently robust to accurately detect short-term changes in fish abundance caused solely by changes in temperature. Frequently, data sets derived from different sources provided conflicting information about abundance trends for the same species. Some of these conflicting results may be due to the short record of relatively accurate estimates of fish abundance. For almost all species, estimates of fish abundance prior to 1980 were based on landing records, which provide notoriously poor estimates of abundance. Market forces, reporting issues, fishery discards, variable fishing effort, advances in fishing technology and external drivers such as wars or the cost of fuel all greatly influence fishery landings. Also, many fishes caught were recorded as landings of market categories and not as individual species.

Our second hypothesis suggests that instead of inaccuracy in estimates of fish abundance, the problem is that high variability in both temperature and fish data sets precludes trend detection without long-term data sets. Abundances of some species track large climatic changes (e.g., McGowan et al. 1998; Chavez et al. 2003), suggesting our difficulties in correlating fish abundances with changes in SST may be related to the variability or "noise" in the data sets we were able to obtain. If this is the case, the problem primarily lies with the fish data sets because we used well-accepted analytical techniques to smooth the temperature data to enable trend detection.

The third hypothesis, that SST alone is not a good indicator of trends in fish abundance makes sense biologically. Fishes are able to relocate horizontally or vertically within the water column to respond to changing water temperatures. Also, many of the species in central California are longer-lived species (e.g., rockfishes) that have adapted to long-term changes in water temperatures. In the short-term, changes in temperature would have more impact on organisms that are more affected by the physical environment, such as phytoplankton and zooplankton, and their predators. Because plankton are prey for many central California fish species (especially in early life stages), variation in primary productivity might be better linked to changes in the abundance of fish species. Basin-scale indices incorporate a variety of variables, such as temperature, dissolved oxygen, ocean circulation and productivity, and thus may be better indicators of environmental conditions that influence fish abundance.

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