# A WARM DECADE IN THE SOUTHERN CALIFORNIA BIGHT

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## ABSTRACT

The year 1992 in the Southern California Bight is embedded in a 17-year warm anomaly which is the longest in the 1922–94 period. The length of the warm anomaly may make it more useful for studying the effects of global change on fish with generation times of 5 years than the usual ENSO event lasting 1–3 years. The trend since 1985 of zooplankton volume and anchovy spawning biomass has been downward, and that of sardine has been upward. Although the trends in the growth rates of fish populations can be observed, the causes result from the combined effects of the environment in the absence of a significant fishery. Directed, long-term, process-oriented research on the anchovy and the more subtropical sardine is needed to "explain" differences in population growth rates: incidental data from static monitoring and fish stock assessment are necessary but will not likely be sufficient to construct combined effects of temperature and zooplankton on population growth rates of sardine and anchovy.

## INTRODUCTION

The Southern California Bight (SCB) is a partially isolated habitat within the California Current region. Topographically, the outer margin of the SCB is a ridge which extends southerly from Point Conception to Cortez Bank offshore of the Mexican border. Hydrographically, the California Current jet veers to the Mexican coastline west and south of the SCB. The interior of the SCB contains a semipermanent cyclonic gyre which flows among several islands and shoals and over several deeper, isolated basins. It is an important spawning habitat for both the central stock of the northern anchovy and the northern stock of the Pacific sardine (Ahlstrom 1967).

Temperature change can be expected to cause many biological changes (Fields et al. 1993) and to implicate other kinds of important change. For example, in 1992, during a warm spell, the Pacific sardine appeared in abundance for the first time in four decades off Vancouver Island, British Columbia (Hargreaves et al. 1994). Biologically, the SCB is a spawning and retention area for young fish, including sardines (MacCall 1990). During some El Niño/Southern Oscillation (ENSO) events, dominant plankton in the SCB react differently relative to the rest of the adjacent coastal waters (Colebrook 1977; Smith 1985; Jackson 1986).

Considerable monitoring activity at the urbanized coast of the SCB extends more than a century into the past (Hubbs and Roden 1964; Eppley et al. 1978; Smith and Eppley 1982; Dailey et al. 1993). Scripps Institution of Oceanography Pier (SIO Pier) temperature and salinity measurements have been conducted daily since 1916. Temperatures at the SIO Pier have been analyzed at hourly, weekly, and seasonal scales (List and Koh 1976; Piñeda 1991, 1994). Temperature changes at the SIO Pier are representative of coastwide temperatures at time scales longer than weeks. Interannual temperature anomalies at the SIO Pier represent anomalies over adjacent ocean areas in the northeast Pacific Ocean (Mooers et al. 1986; Latif and Barnett 1994). Biological oceanography surveys to find the cause of the collapse of the Pacific sardine in the California Current region began in the 1940s (Bernal 1981).

The purpose of this report is to describe the SCB in the last decade (1985–94) with comparison to the long-term record of the SIO Pier and to the 45-year record of CalCOFI measurements in the SCB.

## SOURCES OF DATA

The sources of data are the SIO Pier measurements initiated in 1916 and the measurements of surface temperature and salinity and epipelagic zooplankton volume from the CalCOFI surveys that have been conducted in the SCB, among other areas, since 1951.

The monthly temperature anomalies for the recent period are referred to a 50-year series (1940–93) of monthly means of daily temperature measurements from the SIO Pier. The longer-term fluctuations are shown in a 24-month running mean.

The anomalies of CalCOFI survey station temperatures and salinities are assembled from incomplete time series because of the vagaries of ship scheduling, timing, policy, and availability of ship time. As opposed to the SIO Pier, where 30 measurements are taken per month

with no direct spatial averaging, no CalCOFI station was sampled more than once a month, and the anomalies are assembled as a spatial average over a 16,000 sq. n. mi. region—Morro Bay (CalCOFI line 76.7) to San Diego (CalCOFI line 93.3) and offshore 120 n. mi. (CalCOFI station 70)—in which the SIO Pier is at the southeastern periphery. There have been no studies of how missing years, months, and stations affect the utility of these anomalies.

The biomass assessments of sardine and anchovy used for fisheries management are available only from 1985 to 1994 (Barnes et al. 1992; Jacobson et al. 1994; revisions and updates—L. D. Jacobson, SWFSC, pers. comm. July 6, 1994, and January 3, 1995). The more recent estimates are subject to annual revision based on new data from surveys and from the fisheries.

## BIGHT WARMING

The SIO Pier recent period represents 17 years of positive anomaly which began in 1977 and reached a local minimum in 1987. From this assembly, it appears that the recent period is the longest warm anomaly in the 1922–94 period and exceeds the duration of the 15-year cold anomaly of 1942–57 (figure 1). Although the subject warm spell is marginally warmer than the 1957–59 and the 1982–83 warm periods, there was more contrast in the 1957–59 period, which emerged from the surrounding cold spell.

Annual averages from the CalCOFI surveys (figure 2) exhibit a 2-degree range. All annual averages since 1983 have been well above 15 degrees and approach the maximum 17 degrees in 1992 for the surveyed interval 1951–94. The mean temperature for the SCB CalCOFI surveys is 15.2 degrees, and the standard deviation is 2.2 degrees. Some differences with the SIO Pier anomalies can be noted in figure 3. Some of the difference can be explained by the years in which cruises were missing or quarterly rather than monthly from 1961 to the end of the record. Missing data are plotted as "zero" anomalies. The major features of the SIO Pier anomaly are reproduced in the CalCOFI surface-temperature data.

The plankton displacement volume determined by CalCOFI surveys has been noted to be inversely related to temperature (Reid et al. 1958; Reid 1962). The general effect can be seen in figure 4. Particularly notable are the low values in 1958–59 and the declining trend from 1972 through 1994, with the values of 1991–94 comparable to the low values of 1958–59. When the mean value of 221 ml per 1000 $m^3$ and standard deviation of 400 ml per 1000 $m^3$ are plotted as anomalies (figure 5) the inverse relationship to temperature is clear.

The long-term record of salinity anomalies from SIO Pier (figure 6) illustrates the unusual nature of the recent years. The low salinity of 1992 is materially lower
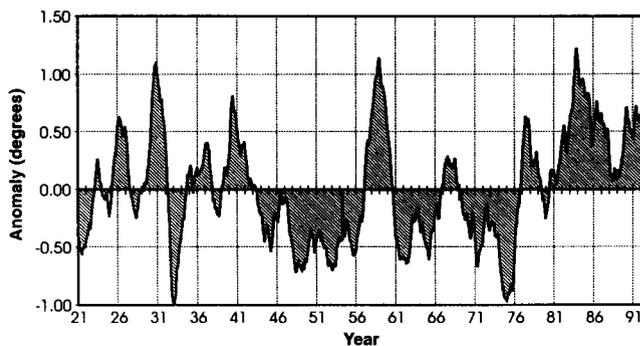


Figure 1. SIO Pier temperature anomaly, smoothed with a 24-month running average.
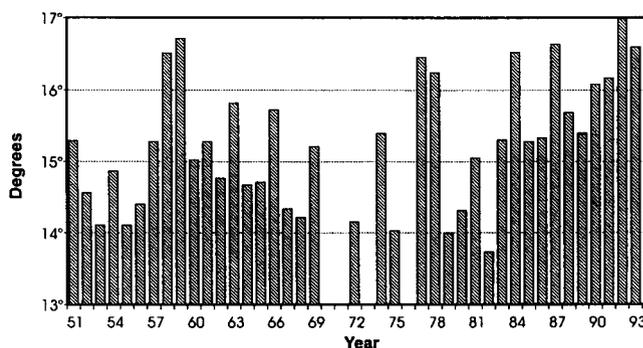


Figure 2. CalCOFI survey 10-meter temperatures.
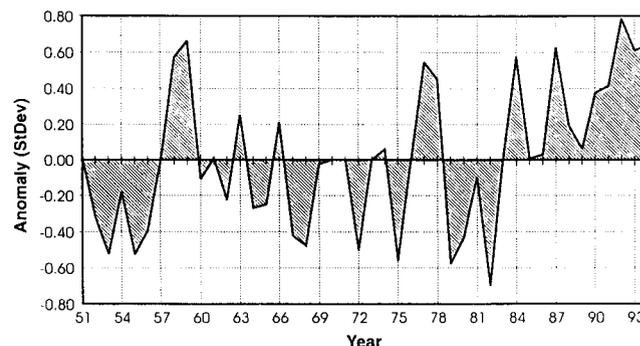


Figure 3. CalCOFI survey 10-meter anomalies: mean 15.2°C., standard deviation 2.2°C. Missing years shown as 0 anomaly.
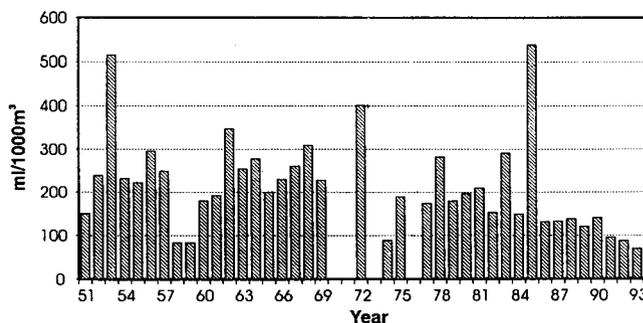


Figure 4. CalCOFI survey plankton volume in ml per 1000 cubic meters.
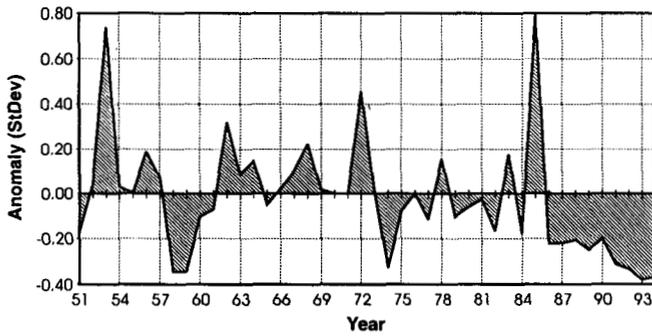
Figure 5. CalCOFI survey plankton volume anomalies: mean 221 ml, standard deviation, 400 ml. Missing years shown as 0 anomaly.
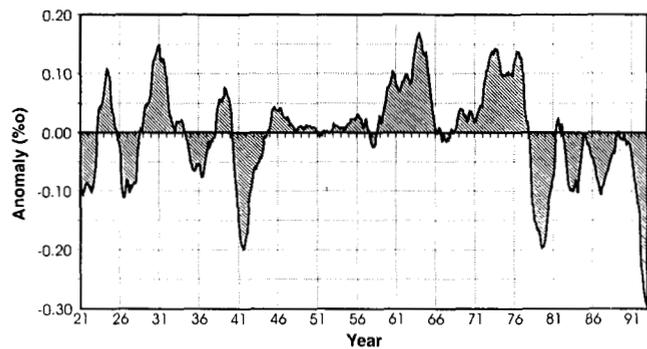


Figure 6. SIO Pier salinity anomaly, smoothed with a 24-month running average.
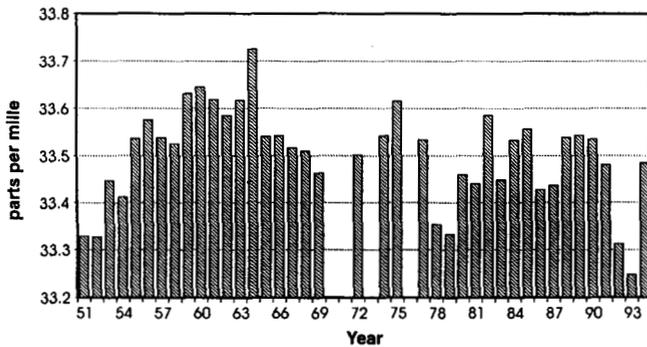


Figure 7. CalCOFI survey 10-meter salinities.
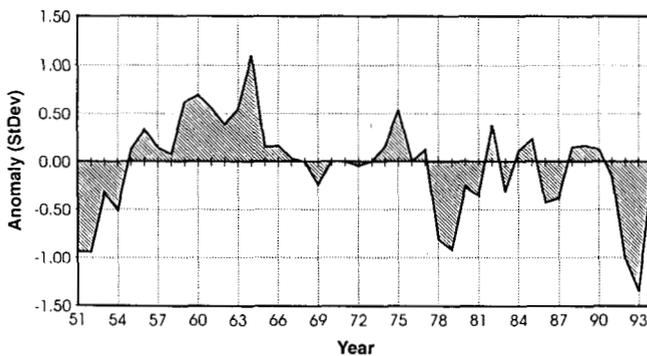


Figure 8. CalCOFI survey 10-meter salinity anomalies: mean 33.51 parts per thousand, standard deviation 0.19 parts per thousand. Missing years shown as 0 anomaly.

## Anchovy and Sardine Spawning Biomass
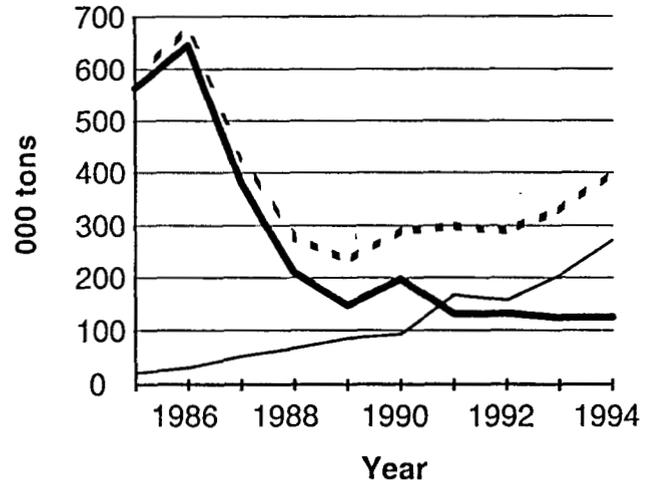


Figure 9. Trends in spawning biomass in thousands of metric tons of anchovy (*heavy solid line*), sardine (*light solid line*), and the two species combined (*dashed line*).

in this assembly than in any previously measured period. This trend is reversed only in 1994 from the CalCOFI survey record (figure 7) and anomalies (figure 8). The mean salinity for the SCB since 1951 is 33.51 ppt; the standard deviation is 0.19.

Between 1985 and 1991, northern anchovy spawning biomass decreased from 600,000 metric tons to about 125,000 metric tons, where it has remained through 1994 (figure 9). During the period of decline the rate was 0.8 (Lambda), which is well within population growth and decline rates originating in early life history, but not juvenile and adult parameters (Butler et al. 1993). Although measured with less precision, the standing crop of anchovy larvae diminished at a similar rate (figure 10). The fishing mortality during this interval ranged from 0 to .2 and averaged .1 (Jacobson et al. 1994).

The rate of population change in Pacific sardine has continued steadily from 1985 to 1994 from less than 20,000 metric tons to slightly less than 300,000 metric tons (figure 9). The standing crop of sardine larvae, although measured with very low precision, increased at a similar rate (figure 10). The population growth rate was 1.3, which is close to the theoretical maximum rate of change (Murphy 1967) of 1.5 (Lambda). This rate of change is well within the range examined by Butler et al. (1993) for early life-history population parameters.

The joint minimum of spawning biomass of anchovy and sardine populations was reached in 1989, after which the joint biomass increased at about 6 percent per year (Lambda = 1.06; figure 9). It is not certain that the individual estimates of spawning biomass are precise enough

## Sardine Larvae
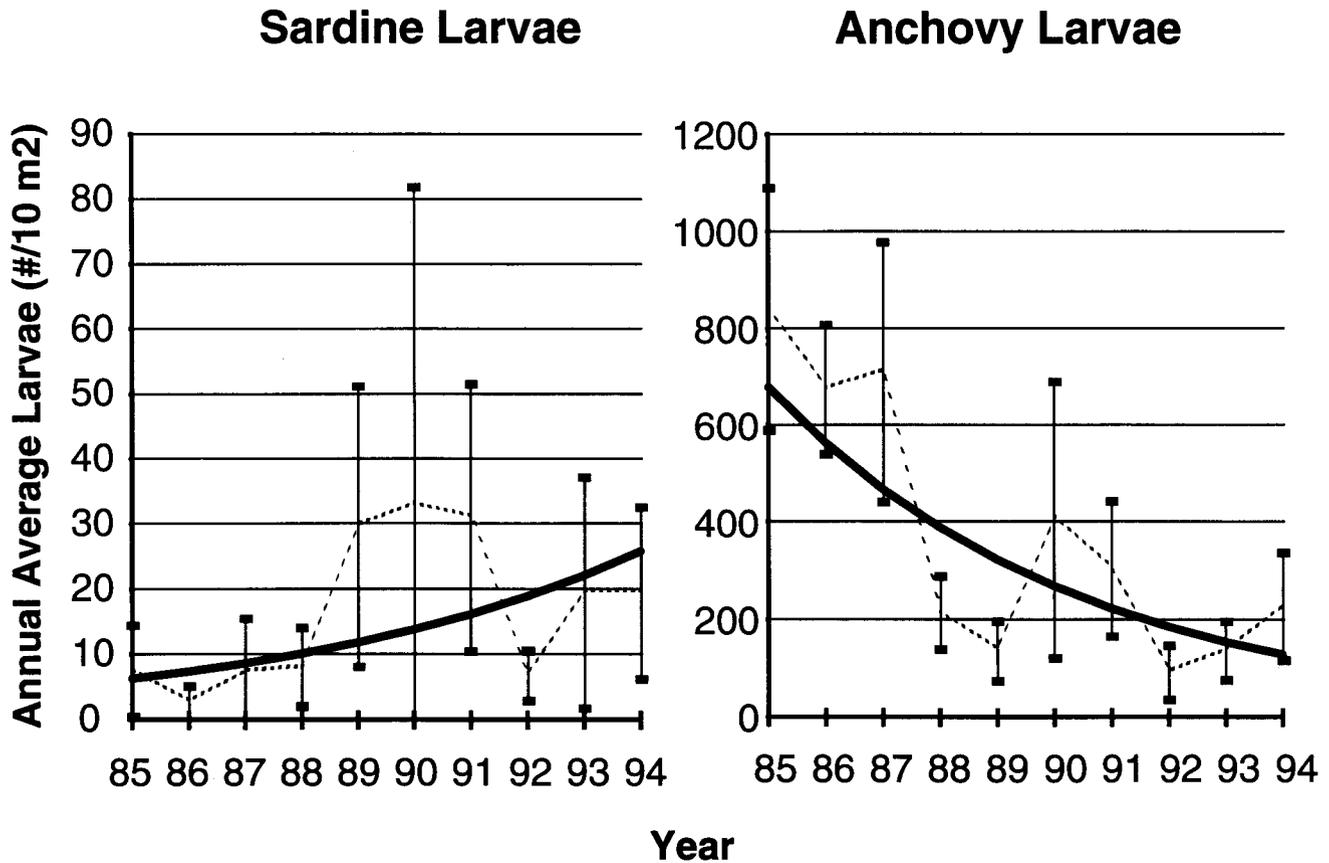
## Anchovy Larvae



Figure 10. Trends in standing crop of sardine and anchovy larvae. The *dashed line* connects the means of successive years, and the *error bars* are plus or minus two standard errors. The *trend lines* are fitted to exponential models. The rate of increase of sardine larvae is 17 percent per year (Lambda = 1.17), while the adult spawning biomass increases at 31 percent per year over this period. The trend in anchovy larvae and spawning biomass is the same, decreasing at 17 percent per year.

to document an increase in the joint biomass density of these two planktivores inhabiting the SCB.

Annual change of surface temperature and zooplankton volume at the same sites evaluated for sardine and anchovy larvae are shown in figures 11 and 12. The temperature curve shows a linear and gradual increase in temperature, usually within the two standard error bands. The 1987 and 1992 values are more than 0.6 degree above the trend, and only 1989 is materially lower than the trend. The zooplankton shows a precipitous drop in 1985 followed by a gradual decline. Reid (1962) also noted the inverse trend in zooplankton and temperature.

## DISCUSSION

If we assume that the warming of 1992 is one reason why the more subtropical fish—sardine—gained biomass in the last ten years and why the temperate fish—anchovy—lost biomass over the same period (figure 9), it is interesting to speculate on the many mechanisms that would involve temperature change. It is outside the scope of this report to completely ana-

lyze how temperature affects sardine and anchovy, but describing some direct and indirect effects may be sufficient. Current information would not support arguments for either competition or habitat replacement. In the competition scenario, limited food production at primary and secondary stages will support a trophically limited biomass of sardine, anchovy, and all the other herbivores and carnivores of planktonic forms. Under the habitat replacement argument, the anchovy and sardine occupy distinctive habitats which coexist variously in time and space within the SCB and adjacent areas.

It seems clear that sardine and anchovy populations are changing within the SCB and adjacent habitats. Although the SCB is open habitat, it is interesting to describe some direct and indirect mechanisms other than migration that could contribute to population change. Under direct effects I include incubation, maturation, gut evacuation, and viscosity (in increasing order of speculation). Under indirect effects I include primary production, expatriation, and exotic predators (all equally speculative).

## Small Plankton Volume



## Surface Temperature
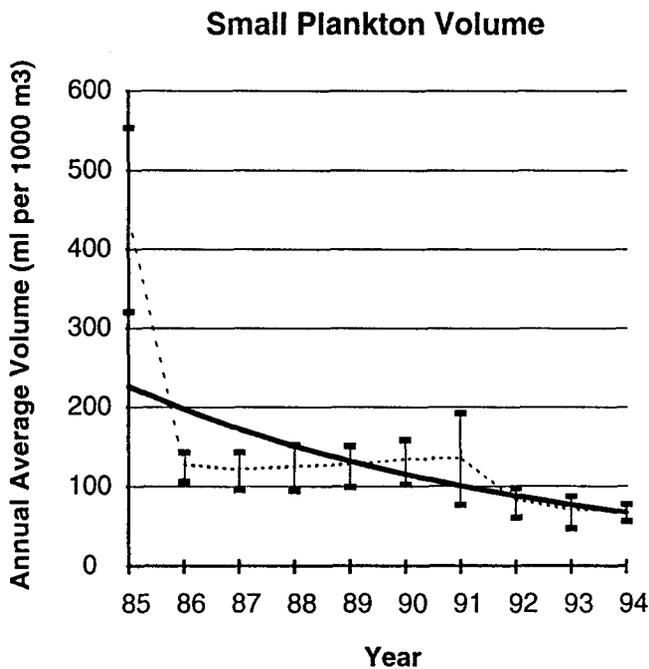


Figure 11.  A linear trend in average annual surface temperature taken on the same CalCOFI cruises as the zooplankton and fish larvae are collected. The mean rate of temperature rise is about 0.17 degrees per year. The *error bars* represent plus or minus 2 standard errors of the mean.
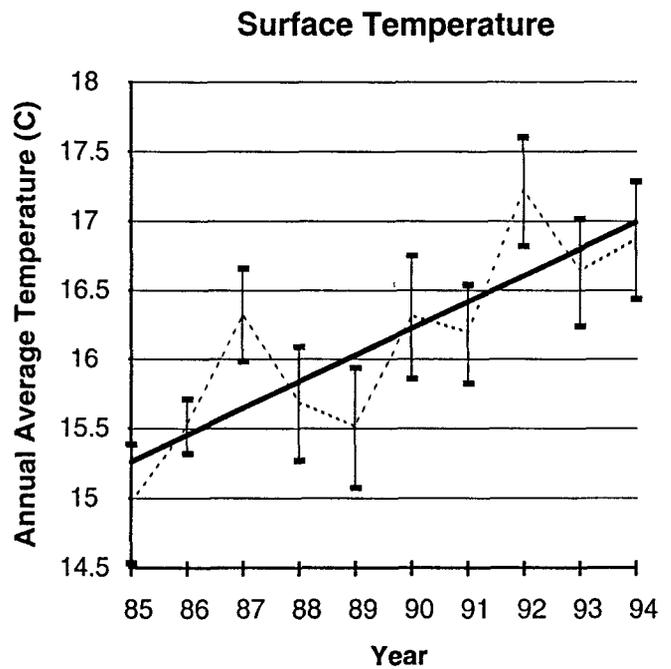
Figure 12.  A decadal trend in zooplankton displacement volume. The smooth rate of exponential decline is about 13 percent per year (Lambda = 0.87).

## Direct Effects

*Incubation.*   The duration of the embryonic period of sardine and anchovy is directly and probably exclusively controlled by temperature (Zweifel and Lasker 1976). If all other parameters of the life cycle remain the same, a sardine population at equilibrium at a temperature of 15.5°C will increase at a rate of 10 percent per year at 16.4°C owing to the effects of more rapid hatching and proceeding to first feeding, which marks the end of the embryonic period (Butler et al. 1993). The positive effect in this case is shortening the time of high mortality as embryos and proceeding to the larval stages and beyond, where mortality is less. Similarly, anchovy at equilibrium at a temperature of 14.5°C will increase at a rate of 10 percent per year at 15.0°C owing to the effects of more rapid hatching and proceeding to first feeding (the end of the embryonic period). The equilibrium temperature for anchovy would cause, all other things being equal, a 10 percent annual decline in sardine numbers. These effects are at temperatures well above the sardine and anchovy embryo lethal limits of 13 and 12 degrees C, respectively.

*Maturation.*   Methot (1989) used a temperature function to describe the maturation rate of young adult anchovy. Jacobson et al. (1994) have erected a simpler model which includes January–February SIO Pier temperatures as a proxy for the temperature at which juvenile anchovies develop. The fraction of 1-year-old anchovies

mature declines in temperatures below 14.5°. Jacobson and MacCall (in press) find that sustained ("mean five-season") temperatures above 16.5° are required to sustain significant catches from Pacific sardine stocks available to California.

*Gut evacuation.*   In the larval stage, the temperature effect on feeding and the rate of assimilation of food could be important. An individual larva must consume nearly its weight each day (Theilacker and Dorsey 1980). Because the larval anchovy is a visual feeder, feeding must be done in the daylight hours. For most anchovy larvae, spawned in winter, the feeding period may be materially less than 12 hours.

*Viscous resistance.*   Temperature affects viscosity and the energy that early larvae exert in locomotion and subcutaneous exchange of respiratory and excretory products with the medium. I would expect the subcutaneous exchange with the medium to decrease rapidly as larvae differentiate specialized organs, and I would expect the locomotory resistance to gain in relative importance. The Reynolds number for resistance to searching for food and particularly avoiding predation is in transition (Weihs, pers. comm. 1994) from viscosity dominated at 4 mm to inertia dominated at 40 mm. Since the direct temperature effect is primarily mediated through viscosity, the temperature effects will diminish with the larvae's somatic growth and differentiation of specialized respiratory and excretory systems.

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## Indirect Effects

*Primary production.* Since rapid growth is a requirement for high survival and population growth in anchovy and sardine, the temperature influence on population growth would be substantial for these coastal fishes. Transport and vertical distribution of nutrients are the principal effects (Ware and Thomson 1991).

*Expatriation.* The transport of coastal larvae out of the habitat where they can survive may constitute the major drawback to increased new production as favoring population growth of anchovy and sardine. Thus, either increased transport from the subarctic or increased Ekman transport offshore could move larvae from coastal habitats to areas of the ocean where oceanic water is mixing (Roy et al. 1992). In the present warm spell, warming might indicate shallow upwelling (Roemmich and McGowan 1995a, b), low vertical mixing, low California Current transport (Roemmich 1992), or low offshore Ekman transport, each favoring additional retention of planktonic stages and the resultant population growth of sardines and anchovy and other residents of the SCB.

*Exotic predators.* As warming proceeds, some large, mobile, tropical predators may move northward along the coast of California and increase the mortality of anchovy to a greater degree than the mortality of larger sardine. For example, the subtropical yellowtail, Pacific mackerel, and bonito, and the tropical tunas—skipjack and yellowfin—could represent significant additional sources of mortality for juvenile and adult sardines and anchovy.

## RECOMMENDATION

The warming of 1992 may itself be less important than the fact that it follows a sustained warm spell. Even more important to the productivity of the SCB, the warming was accompanied by low salinities, from which Roemmich and McGowan (1995a) infer a flow of nutrient-deficient water into the SCB. So in addition to recommending continued monitoring of the SIO Pier temperature, I suggest that the CalCOFI surveys continue to measure sections of temperature, salinity, nutrients, and zooplankton volume in order to interpret the more continuous records of temperature and salinity from the SIO Pier.

## SUMMARY

Because of the diverse mechanisms influencing the population growth of stocks of anchovy and sardines that spawn in the SCB, it does not seem likely that surveys for stock assessment and static monitoring of the environment will permit definitive explanations for population change: directed process studies may be necessary to identify the mechanisms which alone and in combination effect population change in SCB fishes.

Although many of the biological effects of the warm spell of 1992 in the Southern California Bight cannot yet be analyzed, there is a major distinction between this period and the earlier warm spells: the zooplankton volume is no lower than the 1958–59 annual average values (figure 5), but the 1992–93 low plankton and high temperature values result from a decadal sustained increase in temperature (figure 11) and a similarly long decrease in plankton (figure 12).

The relatively brief episodes of ENSO warming in earlier decades may have had less effect on the longer-lived organisms than the current sustained period.

## ACKNOWLEDGMENTS

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