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OCEAN VARIABILITY AND ITS BIOLOGICAL EFFECTS – REGIONAL REVIEW – NORTHEAST PACIFIC

REUBEN LASKER
National Oceanic and Atmospheric Administration, National Marine Fisheries Service,
Southwest Fisheries Center, P.O. Box 271, La Jolla, California 92038, U.S.A.

A large number of environmental scientists and biological oceanographers in institutions bordering the northeast Pacific are studying the interaction between organisms at various trophic levels in the sea and changes in oceanographic conditions, including a major effort by the Coastal Upwelling Ecosystem Analysis (CUEA) program of the International Decade for Ocean Exploration (IDOE) and by a variety of other U.S. government supported projects to correlate ocean changes with biological variations. Among these is a NOAA-sponsored remote sensing study from aircraft and satellites using techniques that might be relevant to fishery oceanography. Upwelling events have occupied scientists up and down the margin of the northeast Pacific and correlations with larval fish survival, primary production, recruitment, growth and survival of crabs, and higher levels of the food web such as the distribution and abundance of migratory fishes have been examined. Historical analysis of variations in pelagic fish populations as far back as 150 years has been a recent area of investigation at Scripps Institution of Oceanography and correlations with past and present ocean conditions are being attempted. A recent study has shown that tree-ring growth and albacore migration can be tied together. In 1958, an unusual warming took place in the waters off California and recent studies have provided several interpretations of the cause of this phenomenon, the biological and oceanographic consequences of which have been recently documented. These and other aspects of research in the northeast Pacific on ocean variability and its biological effects are reviewed.

INTRODUCTION

In this paper, I have reviewed and selected for comment some of the newer approaches being taken to explain biological events in the northeast Pacific. Much of the information presented here is still in preparation and was obtained from the scientists themselves.

Currently, activity in the study of ocean variability is at a very high level in the northeast Pacific. Large programs such as NORPAX[1], OCSEAP[2], CUEA[3] and CalCOFI[4], sponsored respectively by the U.S. National Science Foundation (NSF), the U.S. Department of Interior's Bureau of Land Management, the International Decade of Ocean Exploration of NSF, and a California Department of Fish and Game – National Marine Fisheries Service (NOAA)[5] – Scripps Institution of Oceanography consortium, are currently in progress. Long-term monitoring of sea-surface temperatures by the National Marine Fisheries Service provides information used by oceanographers for studies of ocean variability and meteorologists for long-range weather predictions (Dickson and Namias, 1976). A NORPAX ship-of-opportunity program of vertical temperature profiles (expendable bathythermograph casts) and surface salinities exists from the U.S. west coast to Hawaii and has enabled Saur (1976) to monitor the seasonal and non-seasonal changes in surface temperature and salinity patterns, the sub-surface temperature structure, the heat content of the upper layers of the ocean, the boundaries between water masses and, by inference, the circulation of major currents in the northeast Pacific Ocean (Fig. 146).

[1] NORPAX – North Pacific Experiment.
[2] OCSEAP – Outer Continental Shelf Environmental Assessment Program.
[3] CUEA – Coastal Upwelling Ecosystem Analysis.
[4] CalCOFI – California Cooperative Oceanic Fisheries Investigation.
[5] NOAA – National Oceanic and Atmospheric Administration.

OCEAN CLIMATE AND WEATHER

Cause and effect relationships are constantly being sought to explain and predict anomalous oceanic conditions and their consequent biological effects. For example, one interpretation of the intensive warming of the California Current from 1957 to 1959 is given in a recent paper by Jones (1975) who describes ad-

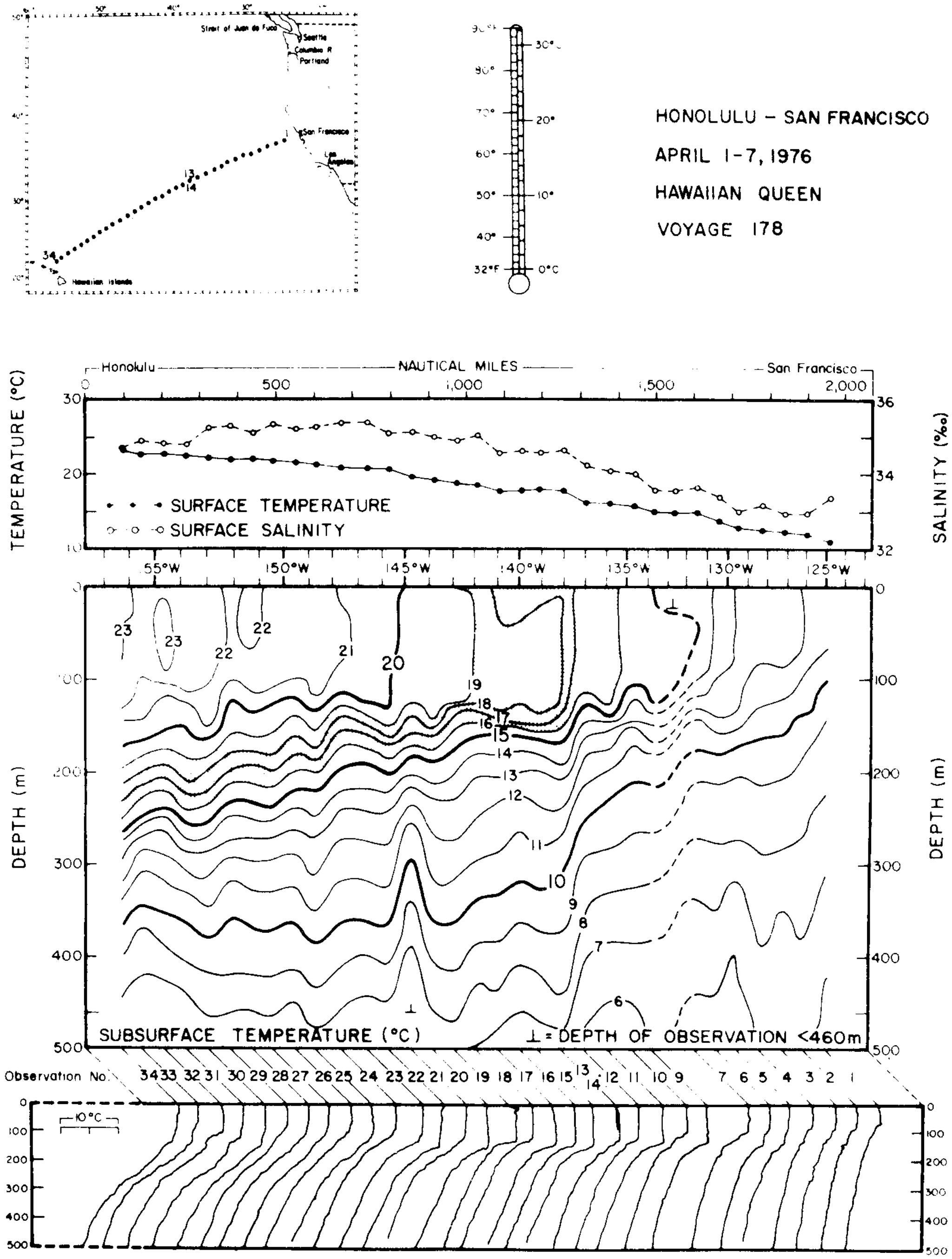

Figure 146. Example of ship-of-opportunity temperature profiles and surface salinity across the northeast Pacific and California Current (from Saur, 1976).

vection of warm water across the Pacific and links this to yearly changes in winter westerly winds over the north Pacific and to yearly changes in the Kuroshio Current. The ultimate cause of ocean and atmospheric changes, i.e., the qualitative and quantitative linkage between the ocean and the atmosphere is an intense area of study, particularly by Namias and his co-workers at the Scripps Institution of Oceanography. About the northeast Pacific Ocean, Namias (pers. comm.) writes that:

"During the last decade, empirical studies have shed a great deal of light upon the interrelationships between the northeast Pacific and the overlying atmosphere. In general, the sea and the air tend to act as a coupled system. In fact, linear regression equations have been derived which can specify the sea-surface temperature (SST) from the contemporaneous sea level pressure or 700 mb height or vice versa. Four term equations can explain roughly 80% of the variance. Although specifications derived in this manner are far from perfect, the essence of the large scale patterns is usually represented.

Auto-correlation studies have shown that SST anomaly (departure from a long-period mean) fields retain their characteristics over periods of several months to a year, while the atmospheric pattern correlations die away quite rapidly. The ocean acts as a conservative element due to its large heat storage capacity and relatively sluggish movement. There is a definite tendency toward recurrence or reemergence of cold season SST anomaly patterns during the following cold season. This recurrence is ascribed to storage of anomalously cold or warm water that is shielded by a shallow layer in summer but is stirred up to the surface by the increased wind stress during cold months. There is some evidence that SST anomalies are indicative of oceanic thermal anomalies extending to the main thermocline and even at times one or two hundred meters below this."

UPWELLING

Wide fluctuations in catch occur in almost all of the world's large commercial and sports fisheries and over a spectrum of time periods, from days to centuries. They are attributed to variations in fishing intensity and to changes in the natural environment. Also, environmental changes may vary widely in geographical extent from highly localized events to those of ocean-wide scale. The effects of these factors on the abundance and availability of commercial fish populations must be understood to achieve efficient harvesting and effective management.

Ultimately, biotic processes in the ocean will only be understood and predicted if we can predict with precision and timeliness what is going to happen to the ocean environment. In response to this need, oceanographers in the northeast Pacific have recognized the desirability of synoptic and timely oceanographic indices that could be used to correlate with biological events. Thus, Bakun of the Pacific Environmental Group of the National Marine Fisheries Service, Monterey, California, now provides, in addition to the work of Saur, monthly, weekly and daily coastal upwelling indices based on computations of Ekman transport divergence adjacent to the coastal boundary at 3° intervals along the west coast of North America. Monthly upwelling indices (Bakun, 1973) have been correlated with Dungeness crab fisheries off the west coast of the U.S. by Peterson (1973) and by Botsford and Wickham (1975). They found that increased upwelling favoured fishing success; lag times of $^1/_2$ year to $1^1/_2$ years indicated the effect to be on juvenile rather than on larval stages. Peterson explains the lag time as "probably a direct result of slow energy transfer through the pelagic environment to the benthos."

Parrish (1976) used this monthly upwelling index and a newer one, based on offshore surface layer divergence derived by Bakun and Nelson (in press), to analyse the Pacific mackerel fishery by regression analysis. Increased coastal upwelling in the vicinity of the spawning grounds just before or during the spawning season was found to favour recruitment, while increased convergence offshore appeared to be an inhibiting factor. Inclusion of these environmental factors in spawner-recruit functions resulted in models that describe nearly 80% of the variation in recruitment over the period 1946 to 1968 (Fig. 147).

Peterson and Miller (1975), studied year-to-year variations in the zooplankton of the Oregon upwelling zone within 10 km off the shore during 1969, 1970 and 1971. Peak abundances of zooplankton appeared during June and July of 1969 and 1970 when upwelling was strong in the inshore zone. 1971 was a relative weak upwelling year, and this correlated with low zooplankton abundance inshore. Neritic species were obviously abundant in 1969 and 1970 while some did not even appear 1971. Generally, offshore species were also numerically abundant in 1971, the poor upwelling year.

The CUEA program's objective has been to apply an interdisciplinary approach to biological productivity and its dependence upon coastal circulation in an upwelling regime. The research focuses around the development of realistic ecosystems models using the latest results from concurrent physical and biological field experiments conducted as part of the study. One of the most important objectives is the prediction of

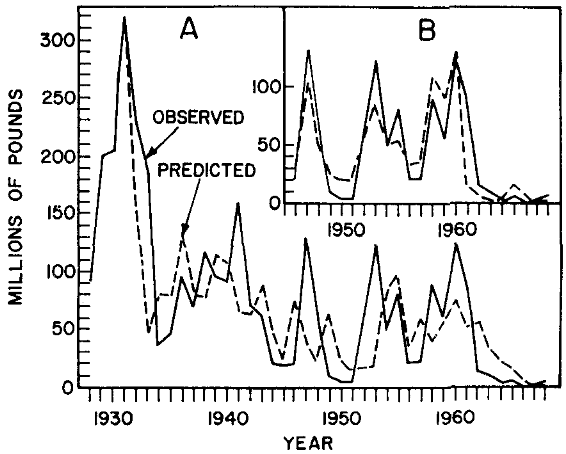

Figure 147. Observed and predicted recruitment of Pacific mackerel; A, Ricker sea level model; B, Ricker transport model (from Parrish, 1976).

fishing success from environmental changes being monitored.

Research of Inter-American Tropical Tuna Commission scientists in the CUEA program has been centered around the evaluation of remotely sensed observations (from aircraft and satellites) in ways that will be beneficial to fishery oceanography. Their recent work has suggested the possibility of using satellite temperature data from the scanning radiometer aboard NOAA satellites to obtain the optimum SST corresponding to tuna fish catch for different marine environments (Stevenson and Miller, 1974).

Infra-red satellite radiometry of SST has revealed that eddies and meanders of 100–300 km diameter in the California Current are coherent and persistent for days and sometimes weeks. Oceanic thermal fronts can be clearly seen when horizontal gradients exceed 0·5 to 1·0°C per kilometre (Bernstein et al, 1977) (Fig. 148). Plans for 1976 include the use and comparison of digital data from a geo-stationary satellite with data from a very high resolution radiometer at a time when tuna may be migrating through a region often expected to include a significant thermal front. Albacore, for example, seem to congregate at thermal fronts.

MIGRATION OF ALBACORE AND TRANSITION ZONE OCEANOGRAPHY

Real-time readout of SST and determination of frontal systems by satellite is closely related to work being done by Laurs and Lynn (1977) on seasonal migration of the albacore *Thunnus alalunga*. In 1972, 1973 and 1974, broad scale surveys were carried out in the northeast Pacific with intensive oceanographic sampling and a substantial fishing effort. Their results demonstrated that the shoreward migration of albacore is associated with the transition zone between the cool, low salinity Pacific sub-arctic water to the north and the warm, highly saline eastern north Pacific central water to the south. Transition waters are found in a zonal band across the north Pacific bounded by sharp horizontal gradients in temperature and salinity. Laurs and Lynn (1977) show convincingly that when the transition zone is distinct, it concentrates migrating albacore, and that they stay in the zone for a few weeks and catch rates are predictably high (Fig. 149). When, as in 1974, the transition zone is broad and indistinct, the albacore occur over a much broader area during their migration and move rapidly inshore, staying no more than several days in the weak transition zone (Fig. 150). Laurs and Lynn (1977) postulate that the important factors responsible for the albacore's response are ambient temperature preferences, food availability, and thermal gradients as these affect body thermoregulation by the albacore. They believe these are integrated and superimposed on the innate drive of the fish to migrate across the north Pacific Ocean.

Saur (1976), in his analysis of the April 1976 transition zone development, predicted that it would be weak in the summer months. Laurs (pers. comm.) says that this was indeed the case and the albacore were, as predicted, spread over a large area of the ocean in June and travelled through the zone rapidly.

ANCHOVY RECRUITMENT

Strong coastal upwelling may be detrimental to recruitment for some fish species. Lasker (1978) gives evidence based on field and laboratory experiments with first-feeding northern anchovy (*Engraulis mordax*) larvae that the break-up of dense patches of properly-sized food particles and the substitution of small diatoms for easily seen and ingested dinoflagellates was inimical to anchovy larval survival in California waters. Because of the clear-cut and rapid phytoplankton succession and the onset of upwelling in 1975 during the northern anchovy's spawning season (Figs 151 and 152), Lasker predicted that the 1975 northern anchovy year class would be a relatively poor one. At the time of writing (August 1976) all indications are that the 1975 year class will be a bad one compared with those preceding it. The timing of the onset, the duration and the areal extent of upwelling along the California and Baja California coast, therefore, may be important predictors for recruitment of clupeids.

Figure 148. Infra-red photograph of the west coast of North America, 11 September 1974, showing large-scale meanders of the California Current and coastal upwelling. Dark ocean areas are warm, light are cold. Feathery light areas to the left of the photograph are clouds. (Photo courtesy of Merritt Stevenson, Inter-American Tropical Tuna Commission, La Jolla, California, and the National Environmental Satellite Service Field Station, Redwood City, California.)

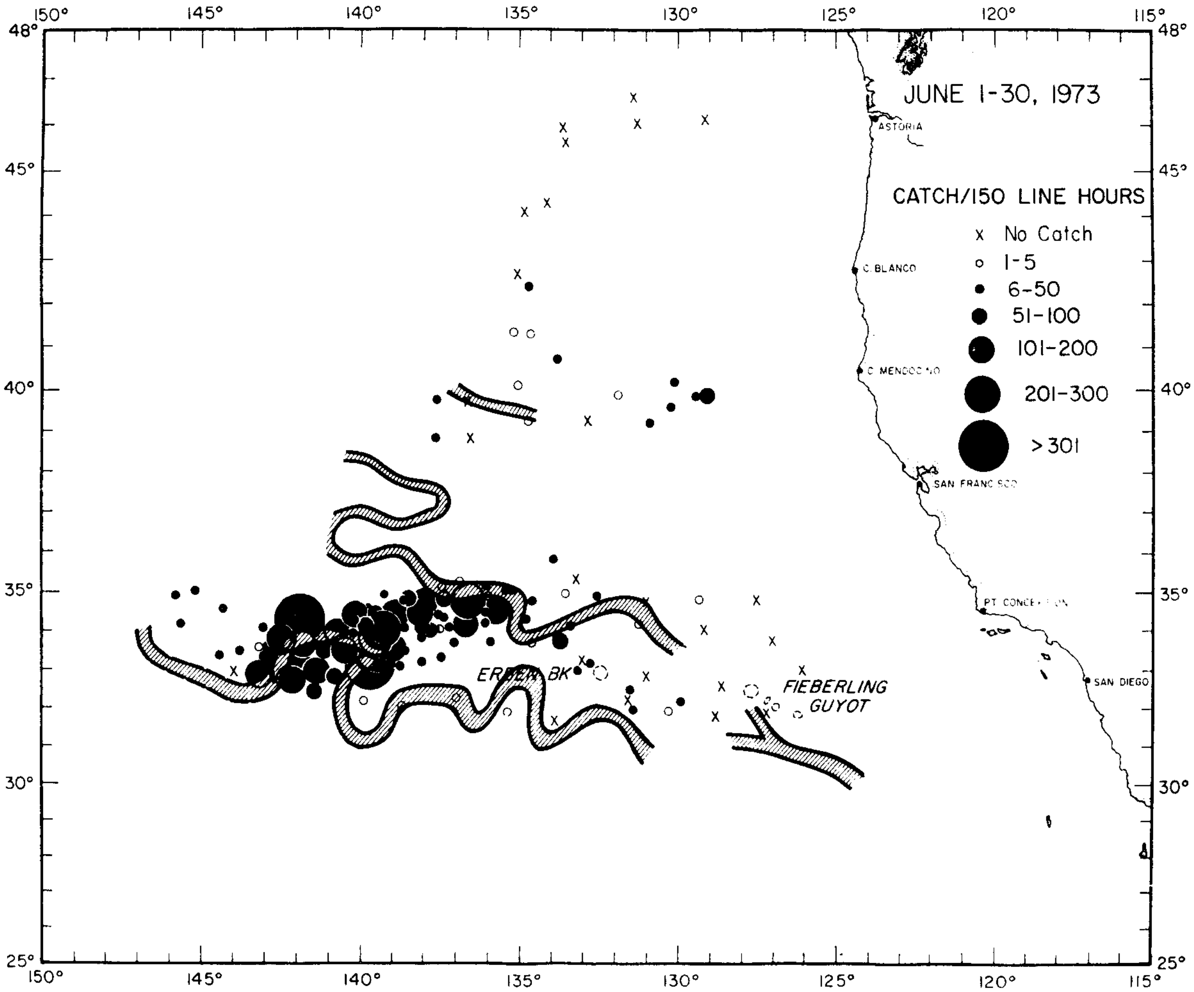

Figure 149. Albacore catch per 150 line-hours by American Fishermen's Research Foundation's charter vessels and locations of fronts delineating Transition Zone waters during 1–30 June 1973 (from Laurs and Lynn, 1977).

Other oceanographic factors may have to be known for accurate anchovy year class prediction. For example, in 1975, prior to upwelling, conditions in the Southern California Bight favoured the growth and multiplication of the armoured dinoflagellate *Gonyaulax polyedra* which is used as food by anchovy larvae. Laboratory experiments (Scura and Jerde, 1977) showed that this dinoflagellate is a poor food for anchovy larvae. Thus, the additional factor of the dominance of nutritionally poor larval anchovy food may be important in predicting larval anchovy survival. Understanding the relationship between oceanographic variability and phytoplankton species succession, therefore, becomes an important area of study. Eppley and Harrison (1975) summarized work on causative mechanisms for red tides. From available evidence they show that dinoflagellate blooms are associated with steep, shallow thermoclines. When nutrients are low in the shallow mixed layer (< 10 m), but high underneath the thermocline, the vertical migratory range of the dinoflagellates enables these to obtain the nutrients they need. Coupled with an unusual nitrogen metabolism (e.g., dark assimilation of nitrates; Harrison, 1976) this provides dinoflagellates with an advantage over coastal diatoms when a shallow mixed layer exists.

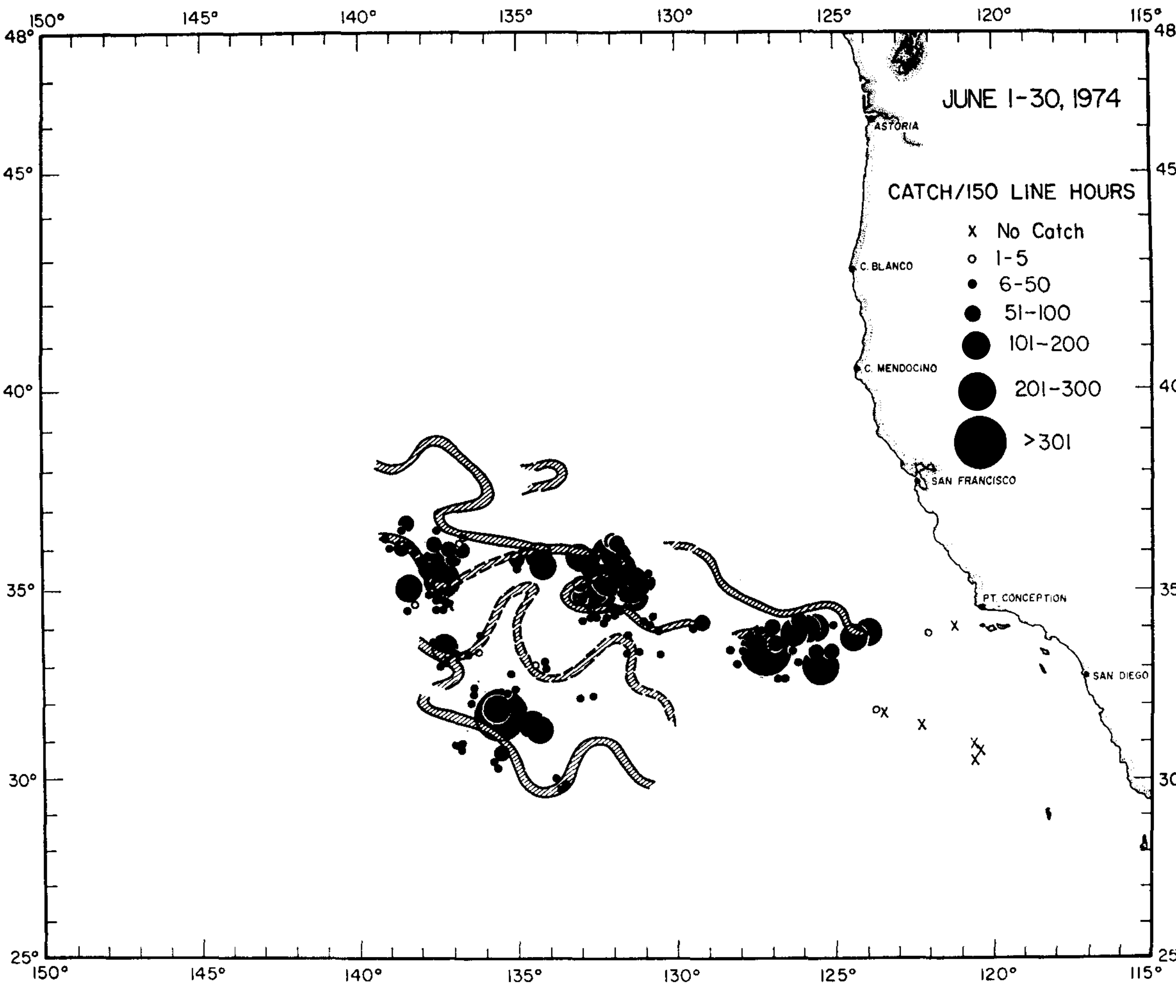

Figure 150. Albacore catch per 150 line-hours by American Fishermen's Research Foundation's charter vessels and locations of fronts delineating Transition Zone waters during 1–30 June 1974 (from Laurs and Lynn, 1977).

FISHERIES ANALYSIS

Environment Canada scientists have looked at British Columbia fisheries with the objective of developing predictive indices for sizes of stocks and movement of fish to aid in managing the fisheries. Because there is not very much known about the interaction of trophic levels in this region, Wickett of the Pacific Biological Station, Nanaimo, B.C., has applied multiple regression statistics to assess the fraction of variance of annual catches of various species of fish or in annual changes of migration routes due to various indices of ocean variability for which long-term data sets exist. For example, he found a predictive relationship between the percentage of Fraser River sockeye salmon that return to their river by the passages between Vancouver Island and the mainland if he considered annual variations in the amount of Fraser River water discharged into the ocean and the wind stress forcing the freshwater against the coast and the north end of Vancouver Island; 71% of the variability in the percentage of returning salmon could be accounted for by using these two indices (Wickett, 1975). Similarly, rainfall at spawning, hours of bright sunlight, and the time when fry are moving offshore were all correlated with the even-year stock size of pink salmon along the central British Columbia

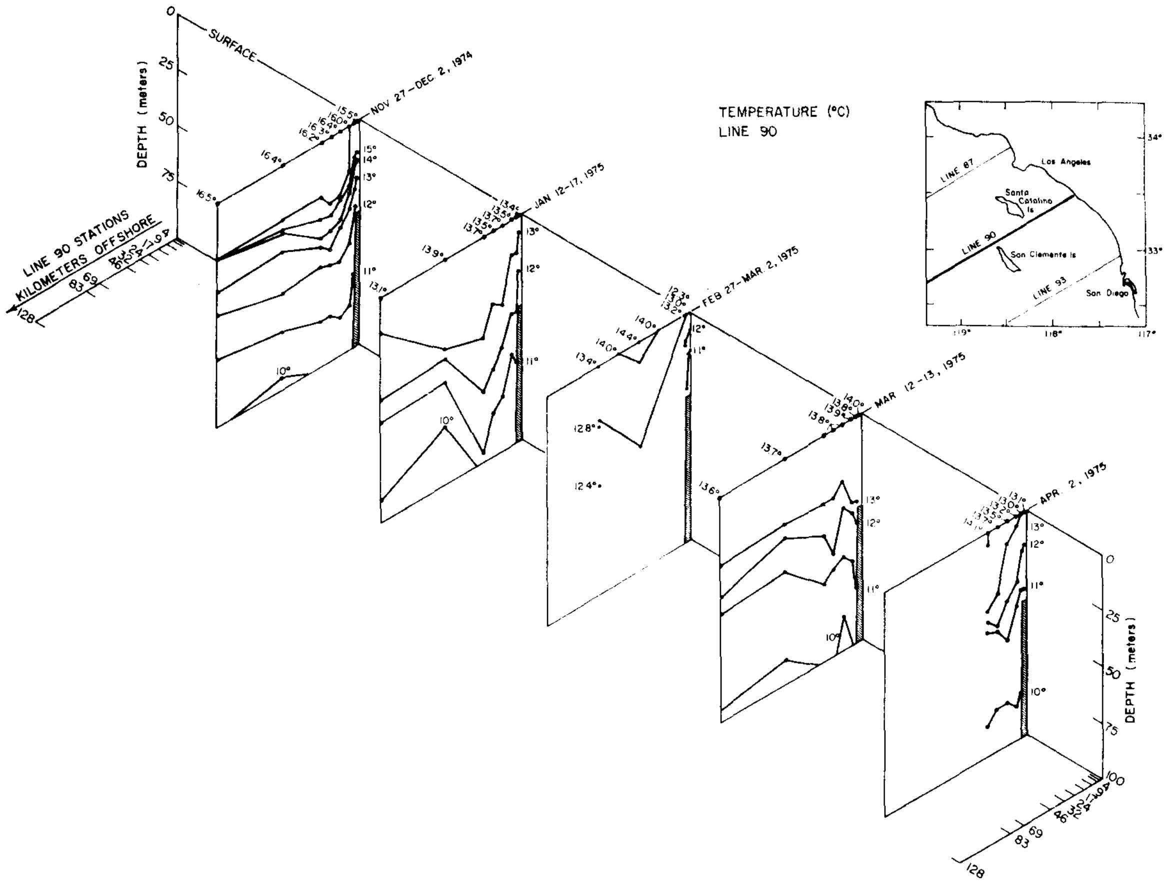

Figure 151. Temperature profiles during five cruises from November 1974 to April 1975. Line 90 extends from Dana Point to offshore between Santa Catalina and San Clemente Islands (from Lasker, 1978).

coast, and 89% of the variance in stock size from 1930 to 1974 could be accounted for in this way (Wickett, pers. comm.) (Fig. 153).

An identification of the basic principles that determine periodic phenomena in the sea has been attempted by Favorite and Ingraham (1976) who have found that during periods of sunspot maxima (approximately every 11 years), there is a shift in the mean winter position of the center of the Aleutian low pressure system from the Gulf of Alaska to the western Aleutian Islands. This results in a reduction of the mean cyclonic, windstress transport in the Gulf of Alaska by about 20%. While the authors have not yet been able to correlate this shift with any biological events, they believe there is evidence to suggest that the 11-year sunspot cycle is related to a 5- to 6-year sea-surface temperature maxima-minima cycle in the northern north Pacific Ocean which is "largely in phase" with mean sea level maxima in the Gulf of Alaska. This latter phenomenon may, in turn, be correlated with dominant year classes of herring, e.g., in 1953 and 1958, years of temperature maxima in southeastern Alaska.

HISTORICAL OCEANOGRAPHY

Several unusual studies which might be termed "historical oceanography" have been done in the northeast Pacific over the last few years. The first of these by Soutar and Isaacs (1974) provided biomass estimates of pelagic fish over the past 180 years, as indicated by fish scale deposition in anaerobic basins off California and Baja California because anoxia prevents decomposition of the organic scales. Using

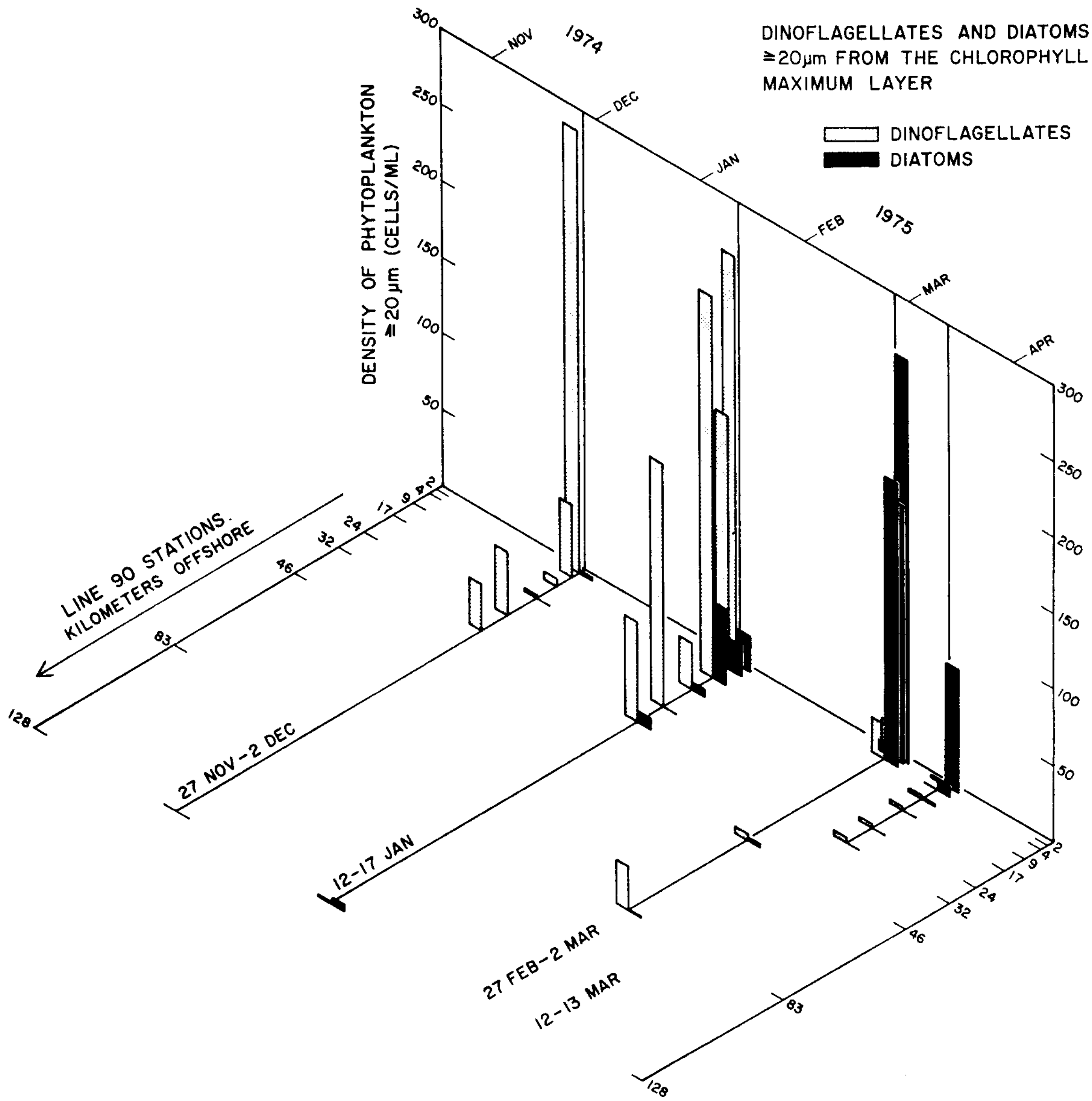

Figure 152. A comparison of diatom and dinoflagellate abundance along CalCOFI line 90 (see Fig. 151) over the anchovy spawning season (from Lasker, 1978).

over 80 meteorological recording stations in southern California, these authors have now developed seasonal rainfall indices for Santa Barbara, Los Angeles, San Bernardino and San Diego, for the years 1865 to 1970. The four indices were found to be closely related and reflected the regional storm systems generated in the north Pacific that are the source of nearly all the rainfall run-offs in coastal southern California. A temperature index has also been constructed, although from fewer stations; the high degree of correlation in temperature from these reflects the regional extent of temperature anomalies (Namias and Born, 1970)

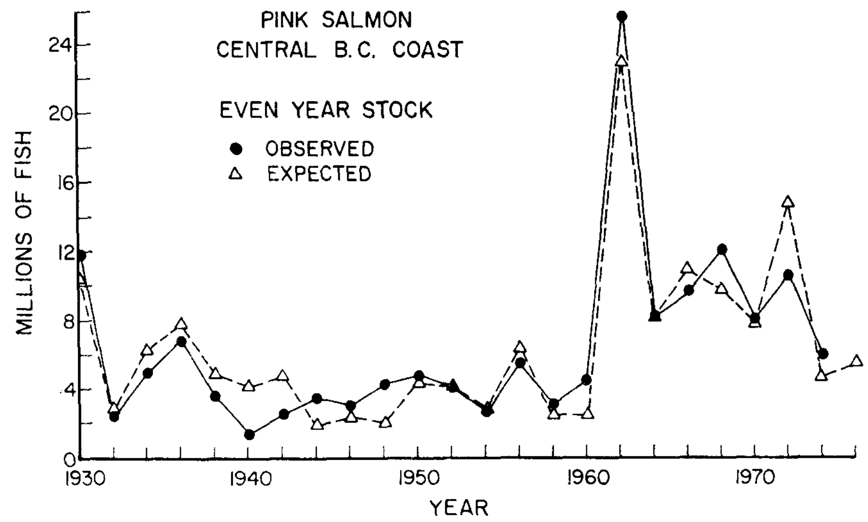

Figure 153. Predicted and observed pink salmon even-year stock from central British Columbia (Wickett, pers. comm.).

and permitted Soutar and Isaacs to construct a central California seasonal temperature index. They have found that a correlation matrix set-up for temperature, rainfall, tree growth and the thickness of sediments in anaerobic basins adjoining California demonstrates the dominant effect of rainfall on both tree growth and on sedimentation and that undisturbed deep oceanic sediments may be used, therefore, to interpret the paleoclimate.

Similarly, Poelchau (1974) developed a temperature-of-the-ocean index in the northeast Pacific by using silicoflagellates as bioclimatic indicators. Soutar is currently examining over 100 forms of radiolarians and silicoflagellates to assess regional patterns of climatic variability around Southern and Baja California.

Because albacore migration is related to the thermal structure of the eastern north Pacific Ocean and the catch estimated from landings off the U.S. west coast

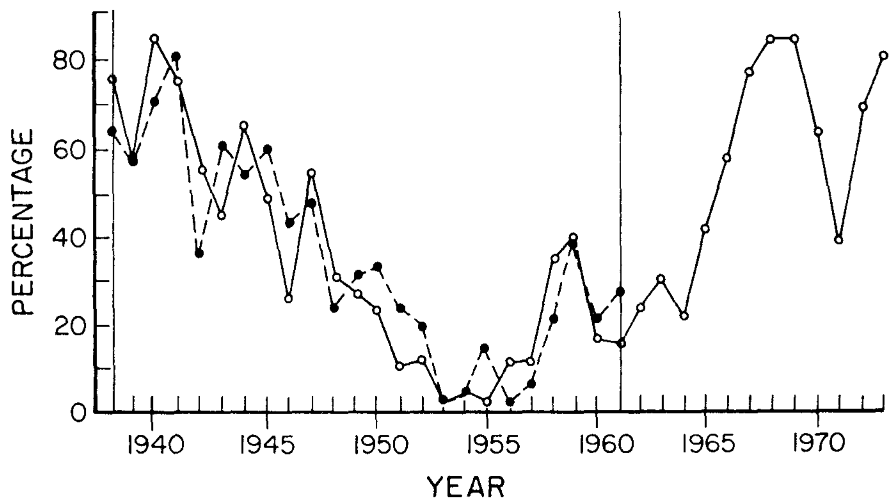

Figure 154. Percentage of the total north American west coast albacore catch taken north of San Francisco, estimated from landings data (——) and percentage catch taken north of San Francisco derived from the calibration equation applied to tree-growth data over the dependent data periods (-----) (from Clark et al, 1975).

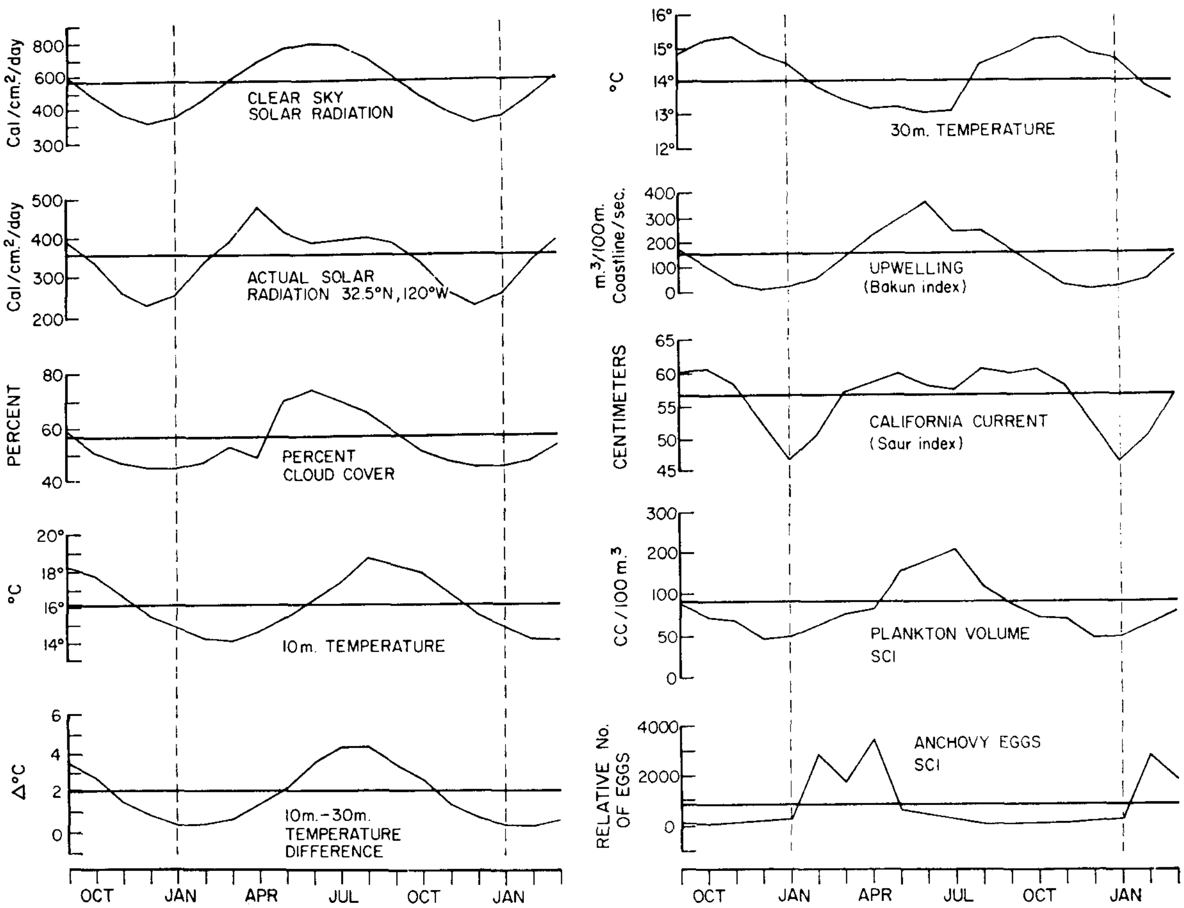

Figure 155. Seasonal cycles of physical and biological parameters in the Southern California Bight (from Lasker and Smith, in press). SCI = Southern California Inshore region.

is related to the extent of the northward migration along the west coast, Clark et al (1975) believed that the growth of conifers in western North America and the catch of albacore would both be influenced by the same air-sea interaction processes. They found a correlation between patterns of tree ring growth and albacore catch and used this to reconstruct the variability in north-south distribution of migrating albacore for the past 250 years (Fig. 154).

TIME SERIES

Time series of oceanic and biological parameters have had their protagonists and antagonists, but without these series, the magnitude and extent of important single events and deviations from the "average" conditions would go undiscovered. The only ocean temperature and salinity time series available over long periods of time in the California region have been from shore stations, notably from the Scripps Institution of Oceanography's pier in La Jolla and a number of similar stations north of San Diego. CalCOFI oceanographic and biological multi-ship surveys began as early as 1940, but complete data sets are available only so far for the years 1951 through 1969.

Some short-term and long-term data for the California inshore region alone, which includes the Southern California Bight, have been summarized by Lasker and Smith (in press) (Fig. 155). These show the mean timing of atmospheric, oceanic and biological events. Anchovy spawning generally begins when the California Current has slackened, and upwelling is at its

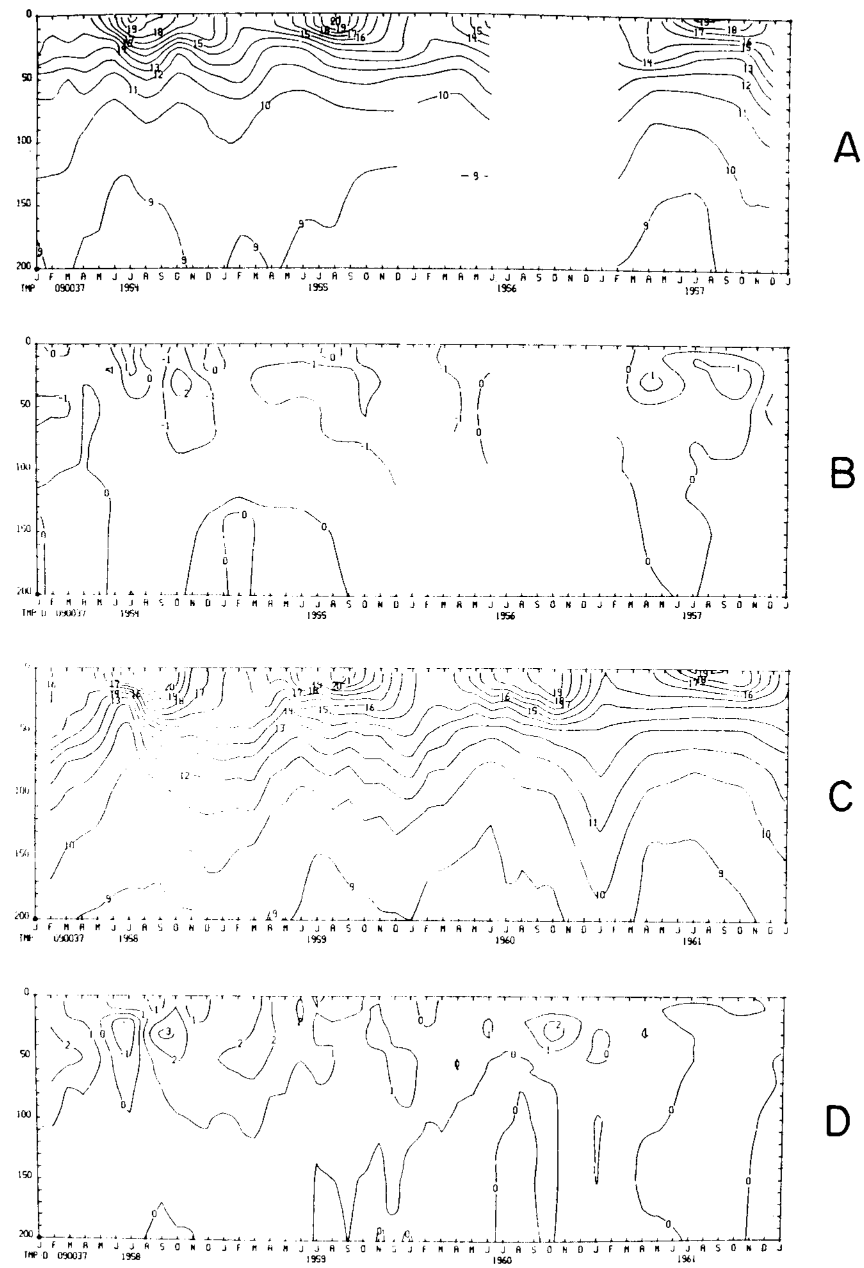

Figure 156. Time series (1954 through 1961) of temperature with depth (A and C) and temperature anomalies (B and D) at 33°11′N 118°22·5′W in the Southern California Bight. (CalCOFI data compiled by L. E. Eber).

lowest ebb. Until now, however, this mass of temporal data, which encompasses horizontal and vertical physical and chemical changes in the California Current, has been inaccessible because it was not in a useable and retrievable form. Efforts to rectify this situation are now being made at the Southwest Fisheries Center in La Jolla. Figure 156 is an example of temperature with depth for a single station 36 miles off Pt. Dume, California. This clearly shows the anomalies for the 1957–1959 warm-water years. Oceanographic data from the entire CalCOFI area are now available for analysis by fishery biologists to see if correlations can be made between physical parameters and fluctuations in biotic populations (Eber, 1977). Biological information to correlate with oceanic changes is also being made available in easily usable forms, e.g., tables and graphs. For example, Smith (pers. comm.) has just completed a 1951–1969 time series of larval anchovy abundance showing how mortality differs from year to year between larval size classes.

From a 14-year time series (1949–1962) produced for the north Pacific by Eber et al (1968), Eber (1971) traced temperature anomaly fields in the north Pacific and identified the existence of a standing wave in the current structure which could affect the partitioning of the West Wind Drift Current as it approaches the north American coast and splits into northward and southward flowing branches. A southward excursion of the current is reflected in a strong negative anomaly offshore; a swing back northward appears as a positive anomaly in the Gulf of Alaska. This would have the effect of reducing the normal flow of cold water into the California Current allowing it to become warmer.

Zooplankton volumes from CalCOFI surveys were related by Wickett (1967) to mean meridional Ekman transport for January to August, 1000 miles upstream of the CalCOFI survey area for the years 1952 through 1959. Greater outflow of high nutrient sub-arctic water into the California Current resulted in higher zooplankton volumes. Less than normal flow of the California Current in 1957–1958 seems consistent with this. Colebrook (1976) applied principal component analysis to zooplankton distributions for 17 major taxonomic categories from CalCOFI collections for the period 1955 to 1959. He showed that a large proportion of the variability in biomass of zooplankton could be associated with hydrographic events. The upstream-downstream distribution and abundance of zooplankton biomass was determined to be the first principal component by Colebrook while onshore-offshore distribution and abundance was found to be the second principal component. There seems little doubt that the reduction in zooplankton biomass connected with the first principal component in 1958–1959 was in some way related to the anomalous change in temperature which began off southern California in 1957, its northward spread along the western north American coast in 1958 and persistence into 1959, and the associated reduction in flow southward out of the sub-arctic circulation of the north Pacific. The second component, Colebrook believes, was strongly influenced by fluctuations in coastal upwelling.

Using factor analysis to examine its multivariate structure, Hemingway (in prep.) has described the California Current from 21 physical, chemical and biological variables taken in 1969 from 216 stations. Three physical regimes were described numerically, i.e. mixing, upwelling and thermal stratification. He found that nutrients and high chlorophyll due to phytoplankton production was associated with mixing and upwelling regimes whereas first-feeding anchovy larvae were associated with upwelled and thermally stratified water, but not with mixing regimes.

CONCLUSION

This brief review of selected activities in the northeast Pacific Ocean illustrates a steady and encouraging progress in understanding how biological changes are affected by the ocean environment. There is a strong momentum for research on ocean variability in this geographic area and a continuing awareness of its importance.

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