DETERMINATION OF SURFACE DRIFT PATTERNS AFFECTING FISH STOCKS IN THE CALIFORNIA CURRENT UPWELLING REGION

by

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Abstract

Surface marine observations are used to infer the large-scale seasonal patterns of ocean surface drift near the coast in the California Current. Striking conformities are noted between these patterns and regional faunal groupings. In the Pacific Northwest coastal fish species having pelagic larvae tend to spawn during the winter season when surface wind drift is generally directed toward the coast, rather than during the more productive upwelling season. In the region of vigorous upwelling off Northern California, which is characterized by strong offshore surface transport through most of the year, there is a paucity of locally spawning species. Rather, the fish stocks which harvest the massive productivity of that region are mainly migrating species which spawn under the more favorable drift conditions of the Southern California Bight. Closed gyral circulations in the Southern California Bight and off southern Baja California appear to foster favorable spawning conditions, leading to distinct faunal assemblages.

The apparent dependence of spawning strategies upon surface drift conditions suggests the hypothesis that anomalies in surface drift patterns could be a cause of the observed wide variations in spawning success of the major fishery species of the California Current region. Geostrophic currents tend to parallel coastal boundaries; thus a reasonable assumption is that major anomalies in the onshore-offshore component of surface transport are related to fluctuations in the surface wind drift. Indices of surface Ekman flux are derived from wind reports from ships at sea.

Other biologically important index series can be derived from related information. Offshore-directed surface Ekman flux can be linked to locally wind-induced coastal upwelling. Ekman flux divergence offshore of the coastal boundary zone may control concentration or dispersion of fish larvae, food organisms, and predator organisms. Wind mixing energy added to the water column can destroy vertical stratification of food particles, thought to be important to survival of first feeding fish larvae. Such index series have been applied to studies of the variations of such stocks as Pacific mackerel, Dungeness crab, English and Dover soles, northern anchovy, rockfish and Atlantic menhaden.

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Introduction

The California Current is a highly productive upwelling system, containing important fishery resources. The coastal fisheries have historically been subject to extreme fluctuations which have resulted in economic hardships. The Pacific sardine fishery expanded rapidly in the early 1930's to become the region's most important fishery, with 774,000 MT landed in the 1936-37 season. Thereafter the stocks declined to the point that the fishery had virtually disappeared by the late 1960's. Similarly, Pacific mackerel landings reached a peak of 66,500 MT in 1935-36, only to decline to a level near 1,100 MT by 1969. Estimates of northern anchovy spawning biomass off Southern California indicate an explosive increase from 267,000 MT in 1951 to 5,635,000 MT in 1965 and a recent decline to 1,180,000 MT in 1978. The lack of obvious relationships between stock size and recruitment in these and other pelagic species indicates an important effect of environmental conditions on the viability of the stocks. Truly effective management of the fishery resources of the region will require a capability to predict and allow for the effects of environmental variability. Recently, some promising hypotheses have been formulated, and environmental index time series suitable for testing the hypotheses are being developed.

Surface Ekman transport

Winter and summer distributions of surface Ekman transport, computed from the wind stress summaries of Nelson (1977), are presented in Figures 1 and 2. In these presentations summaries of stress computations from each available surface wind observation in the surface marine observation file (TDF-11) were made for each one-degree areal quadrangle. Each vector symbol represents a discrete sample which is completely independent of every other sample. No spatial smoothing has been applied.

During the winter (Figure 1) Cape Mendocino marks a division between generally onshore-directed Ekman transport to the north and offshore-directed transport to the south. Strongest offshore transport occurs off central Baja California. During the summer (Figure 2) Ekman transport tends to be directed offshore throughout the region, most strongly from Cape Blanco to Point Conception. The Southern California Bight, south of Point Conception appears as a local minimum in offshore transport.

Since offshore Ekman flux is the primary driving force for locally wind induced coastal upwelling (Figure 3), the area south of Cape Mendocino is characterized by coastal upwelling throughout the year. To the north, there is a seasonal alternation, with coastal upwelling predominating in summer and downwelling predominating during winter.

In these presentations (Figures 1 and 2) spatial detail has been achieved by compositing all available data in a given season from a large number of years, basically on the grounds that seasonal variability in temperate latitudes is generally large compared to interyear variability. Such spatial resolution is never available in a synoptic sampling (Figure 4). For most practical applications a time series of variations in transport is required. However in forming time series from sparse observations which are sporadically distributed in time and space, the variability introduced by random errors in measurement or by changes in spatial distribution of reports may be as large as the variability in the processes themselves. Some method of objective analysis which filters out the small scale variability is required to produce homogeneous time series. Well developed objective analysis techniques are routinely employed by meteorological agencies.

One approach to producing time series indicators of Ekman transport is Bakun's (1975) upwelling indices. These are computed from synoptic surface atmospheric pressure analyses generated at the U.S. Navy's Fleet Numerical Weather Central. Wind reports are included in these analyses as equivalent pressure gradients according to the "Fields by information blending" methodology (Holl and Mendenhall, 1972). A geostrophic approximation and a simplified treatment of the planetary boundary layer are used to estimate the sea surface stress and resulting Ekman transport (Bakun, 1973). The component of Ekman transport perpendicular to the coast is resolved, positive values indicating offshore transport and negative values indicating onshore transport. A one-year sample of daily means of the 6-hourly synoptic computations (Figure 5) illustrates the characteristic seasonal and shorter scale variability.

Off the coasts of the states of Washington and Oregon (48N and 45N latitudes) the seasonal pattern is dominated by short intense bursts of onshore Ekman flux caused by winter storms. The summer season exhibits much lower energy pulsations, chiefly in the offshore direction. Off the state of California (39N, 36N) the summer is characterized by intense bursts of upwelling-producing offshore transport; the winter season is a more equal mix of onshore and offshore transport events. Off the state of Baja California in Mexico (30N, 27N) a lower level but steadier succession of offshore transport pulses continues throughout the year; the maximum intensity of upwelling producing offshore Ekman flux tends to occur in the early spring rather than in the late spring and early summer as is the case further north. At all the locations a large amount of the variance occurs in the "atmospheric event" frequency range, encompassing periods from greater than a day to several weeks.

Reproductive Strategies of Fishes

On the large time and space scales involved in the larval drift of a fish stock, the surface flow field can be adequately viewed as being a linear combination of the geostrophic flow field and the surface drift caused by the stress of the wind on the sea surface. A satisfactory approximation to the surface wind drift is provided by the Ekman transport. The conceptual picture, then, is of a thin surface layer of Ekman drift which varies in phase with atmospheric weather patterns, superimposed on a deeper, more slowly varying geostrophic flow field (Parrish, Nelson and Bakun, manuscript). Geostrophic flow in the California Current tends to parallel the coast; in the Southern California Bight south of Pt. Conception a cyclonic gyral circulation exists most of the year (Reid, Roden and Wyllie, 1958). A similar cyclonic circulation tends to occur off southern Baja California, south of Punta Eugenia (Bakun and Nelson, in press).

The flow patterns that can be inferred from the combined Ekman and geostrophic fields suggest that, for purposes of larval transport, the California Current system can be divided into four regions:

(1) The Pacific Northwest region (north of Cape Blanco),
(2) The region of maximum upwelling (Cape Blanco to Pt. Conception),
(3) The Southern California Gyre (Pt. Conception to central Baja California),
(4) The southern Baja California region.

The correspondence of the reproductive strategies of California Current fishes to this regional subdivision is striking.

(1) In the Pacific Northwest region, the surface Ekman drift is predominently offshore during the summer upwelling season, and strongly onshore during the winter. Nearly all the dominant commercial Pacific Northwest fishes have a late winter spawning period. This is not the expected spawning period for a temperate fish fauna as it comes well before the maximum plankton blooms. In contrast most of the north Atlantic cold temperate fish fauna has short spawning periods coincident with the spring plankton blooms (Cushing, 1975). Evidently, in the Pacific Northwest the necessity for avoidance of loss of epipelagic eggs and larvae from the favorable near-coastal zone outweighs the necessity for high food availability. Another common adaptation for reducing larval loss in Pacific Northwest fishes is the avoidance of epipelagic eggs. A common example is the spawning of demersal eggs in protected inshore waters (e.g. herring, lingcod, cottids, and most of the other intertidal and littoral fishes of this region). Other strategies include livebearing (rockfishes and embioticids), anadromous spawning (salmonids and osmerids), deep water spawning (pleuronectids and sablefish), and extensive migrations to areas of more favorable larval transport (hake, sardine, albacore).

(2) In the region of maximum upwelling, between Cape Blanco and Point Conception, Ekman transport is generally offshore, intensely so during the spring and summer. The adaptations to avoid larval loss found in the temperate component of the fauna are similar to those described for the Pacific Northwest. There is probably a continuous colonization of the upwelling region by larvae which are advected into the region from the Pacific northwest region. The subtropical component of the fish fauna in this region is principally composed of adults which use this region as a feeding ground, but do not spawn there (i.e. hake, sardine, bonito, white seabass, Pacific mackerel, and albacore). Very few coastal fishes have their center of abundance in the upwelling maxima region; bocaccio, *Sebastes paucispinis*, and chilepepper, *Sebastes goodei*, (both live bearers) appear to be the best examples. Apparently, coastal species with pelagic eggs and larvae have great difficulty in maintaining large resident populations in this region of strongest offshore transport and upwelling. Rather, the commercially important harvesters of the massive

organic production of this area are migrating species which spawn under the more favorable transport conditions of the Southern California Gyre.

(3) In the Southern California Gyre, south of Point Conception there is a local minimum of offshore Ekman transport near the coast at all seasons of the year. The geostrophic component of flow forms a closed gyre. The dominant pelagic fishes of the California Current System (i.e. those which have supported large fisheries) all spawn in this region. The adult sardine, hake, jack mackerel and Pacific mackerel migrate to the northward areas for feeding. The central stock of the northern anchovy, probably because of limited swimming ability due to their small size, remains principally within the Southern California Gyre.

(4) In the southern Baja California region a number of pelagic fishes have subpopulations which are distinct from those in the Southern California Bight. These include sardine (Clark 1947), Pacific mackerel (Roedel 1952) and northern anchovy (Vrooman and Smith 1971). In addition, a large tropical component appears in the fauna of this region due to northward warm water advection along the coast and proximity to the warm Gulf of California.

This general pattern of correspondence between reproduction strategies and ocean flow characteristic suggests that the necessity for minimization of offshore loss of reproductive products by seaward transport processes must have exerted a particularly strong control on the development of spawning characteristics. This in turn implies an important effect of transport conditions upon reproductive success, leading directly to the hypothesis that deviations from "normal" transport conditions, to which reproductive strategies are adapted, may be a cause of the very large recruitment variations observed in the coastal fisheries of the California Current.

A major problem in defining the environmental-biological relationships which are required to construct useful predictive models for fishery management is that there are generally available only very small time series samples with which to work. Fishery data characteristically yield one data point per year and the period over which the time series can be considered homogeneous does not normally exceed ten to twenty years. To sort out a multitude of possible environmental effects from a series with ten to twenty data points is a statistically impossible task. It is necessary therefore to either find the means to reduce the multitude of environmental factors to one, or at most several, indices of integrated environmental state, or to hope that one or perhaps two environmental factors will have such a dominant effect as to be discernible through the "noise level" generated by the other environmental effects not accounted for. The considerations presented above suggest that surface drift during the early egg and larval period may be such a dominant environmental factor for some of the major coastal fishery species of the California Current.

Wind stress curl

At a coastal boundary, the divergence in the surface Ekman transport is controlled by the offshore component, as indicated in Figure 3. In the open ocean, away from the vicinity of the boundary, Ekman divergence is controlled by the wind stress curl (Fofonoff, 1963). Positive wind stress curl induces Ekman divergence; negative curl induces convergence. Thus there are four possible combinations of convergence or divergence within a narrow coastal boundary zone and offshore of that zone (Figure 6). Certainly there could be a significant biological difference between the two coastal upwelling situations (types C and D in Figure 6). In the former (type C) there would be continued divergence and lower intensity upwelling offshore of the coastal upwelling zone. In the latter (type D), convergence and downwelling prevail offshore; formation of convergent surface fronts where organisms would tend to be concentrated would be favored. These could be areas either of good feeding success or of high vulnerability to predation.

There are no routine measurements of wind stress curl. However, since forming the curl of a vector field is a linear operation, the curl of a mean field should resemble the mean of the corresponding curl field. The curl fields (Figures 7 and 8) corresponding to the winter and summer stress fields (Figures 1 and 2) were computed by forming finite difference derivatives among neighboring one-degree squares (Nelson, 1977). Much of the smaller scale detail, particularly in the northern portion of the winter distribution (Figure 7) can be attributed to sampling errors which are amplified when derivatives are taken. However the coherent larger scale features are certainly significant, appearing consistently in Nelson's (1977) long term monthly fields.

Negative wind stress curl, or surface convergence, predominates in the offshore region throughout the year. From this offshore region, a lobe of negative wind stress curl extends shoreward to the central Baja California Coast between Punta Baja and Punta Eugenia. This feature appears consistently during all seasons of the year. In this same area of coast there is a consistent local maximum in the offshore Ekman Transport (Bakun and Nelson, in press). Thus the area from Punta Baja to Punta Eugenia represents a type "D" situation (Figure 6) with vigorous coastal upwelling coupled with convergence and downwelling offshore of the coastal upwelling zone.

To the north and south of this lobe of negative curl are regions of positive wind stress curl, or surface divergence, which extend from 100 to 300 km offshore. Particularly strong positive curl characterizes the Southern California Bight. This strong positive curl area expands northward, following the northward seasonal progression of coastal upwelling, to occupy virtually the entire coast during summer (type C, Figure 6).

During the spring upwelling maximum off Baja California, sea surface flow is parallel to the coast and strongly equatorward in response to the pressure gradients established by the upwelling of denser waters near shore. When the upwelling relaxes in the fall, the surface circulation tends to separate into semi-independent cyclonic gyres (Figure 9) in the regions of positive wind stress curl. From Punta Baja to Punta Eugenia, where the curl is negative, flow remains equatorward along the coast (Bakun and Nelson, in press). Possible explanations for this correspondence of flow and wind curl patterns include (a) the existence of some approximate "Sverdrup balance" near the coast (Nelson, 1977), and (b) the effect of surface Ekman pumping whereby the pressure gradients set up between areas of surface convergence and divergence would induce geostrophic currents parallel to stress curl contours. This is a matter of ongoing research at out laboratory. In either case fluctuations in wind stress curl pattern would be related to variations in current pattern.

The lobe of negative curl which appears to separate the gyres of Figure 9, is located also at the separation between the Southern California Gyre and Southern Baja California faunal regions, discussed in the previous section. An example of the faunal separation is the existence of separate subpopulations of northern anchovy (Figure 10). It is possible that fluctuations in the strength of the negative curl lobe could influence exchanges between the central and southern anchovy populations.

There is a lack of sufficient data density (Figure 3) to resolve features of the size of the negative curl lobe in any synoptic sampling in order to form time series to test and utilize this possibility. Presently we are forced to rely on an untested assumption that the small scale features would fluctuate in the same general sense as the much larger scale which can be resolved by the available data (Bakun and Nelson, in press). Satellite systems, with wind stress sensors yielding the 50-km resolution designed for SEASAT-A would seem to allow us, for the first time, to view wind stress patterns on the same scale that they may actually affect fishery stocks.

Applications

Computed upwelling indices (Bakun 1973) which estimate the fluctuations in offshore Ekman transport, and offshore divergence indices (Bakun and Nelson, in press) which reflect variations in the large scale wind stress curl pattern, are beginning to be utilized in studies of California Current fishery stocks. A statistical model which explained less than twenty percent of the variance in Pacific mackerel recruitment was improved to explain seventy-eight percent of the variance (Figure 11) by the addition of two environmental variables, the upwelling index and offshore divergence index series in the vicinity of the negative curl lobe off Baja California (Parrish and MacCall, in press). Apparent relationships with upwelling index series have also been demonstrated for anchovy (Anon., 1978), Dungeness Crab (Peterson, 1973, Botsford and Wickham, 1975), Coho salmon (Gonsolus, 1978), English and Dover sole (Hayman, 1978), and rockfish (Parrish, et al., manuscript). A similar computation of the onshore Ekman transport near Cape Hatteras, accounted for nearly sixty percent of the variance from a fitted stock-recruitment curve for the Atlantic menhaden fishery (Nelson, Ingham and Schaaf, 1977).

Concluding remarks

In defining the effect of the environment on fishery stocks we must deal with a space-time continuum of processes; the necessary coverage is generally not available from research vessel operations. Recently, progress has been made using routinely-collected maritime data. Composite long term seasonal summaries of surface wind and ship drift observations have revealed features not resolvable in available synoptic samplings. Comparisons of these features to known biological features have motivated testable hypotheses. Consistent time series on the lower resolution scale that is available synoptically have been generated from analyzed meteorological fields. These have been used to test hypotheses and establish fishery-environmental relationships suitable for management purposes.

Important new findings on the sensitivity of pelagic fish stocks to the breaking up of fine-scale food strata by wind mixing during early larval feeding (Lasker, 1978) have not been discussed here. However, their application in fishery management will similarly require consistent time series indicators of the effect of wind acting on the sea surface.

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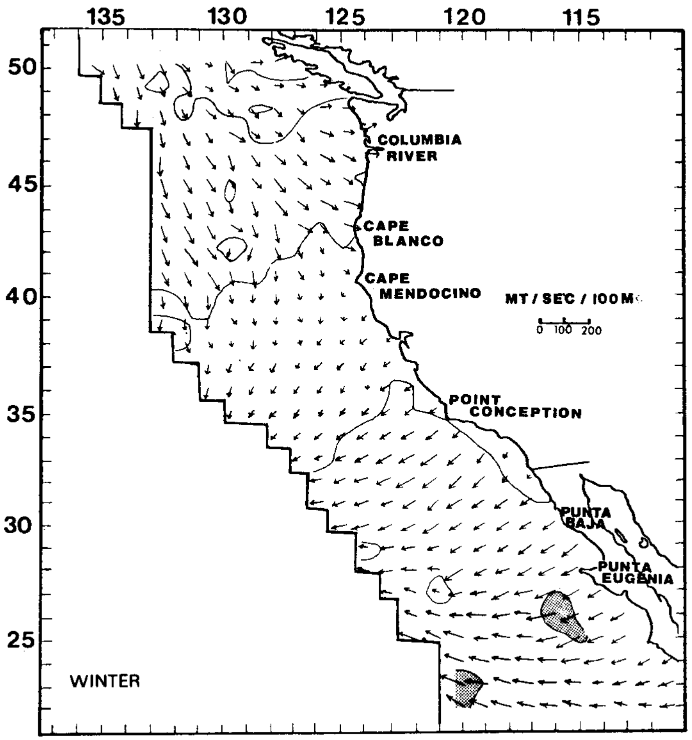

FIGURE 1. SURFACE EKMAN TRANSPORT DURING WINTER (DECEMBER THROUGH FEBRUARY LONG TERM 1° MEANS). CONTOUR INTERVAL IS 50 METRIC TONS PER SECOND ACROSS EACH 100 M WIDTH. AREAS OF TRANSPORT GREATER THAN 100 MT/SEC/100 M ARE SHADED. STRESS ESTIMATES WERE COMPUTED FROM EACH AVAILABLE SURFACE WIND OBSERVATION AS THE PRODUCT OF THE SQUARE OF THE WIND SPEED, THE DENSITY OF AIR (CONSIDERED A CONSTAND EQUAL TO 0.00122 GM/CM^3), AND A CONSTAND DRAG COEFFICIENT (0.0013) AND VECTORIALLY AVERAGED BY ONE-DEGREE "SQUARE" AREA. THE EKMAN TRANSPORT, DIRECTED NINETY DEGREES TO THE RIGHT OF THE MEAN STRESS, WAS CALCULATED BY DIVIDING BY THE LOCAL CORIOLIS PARAMETER.

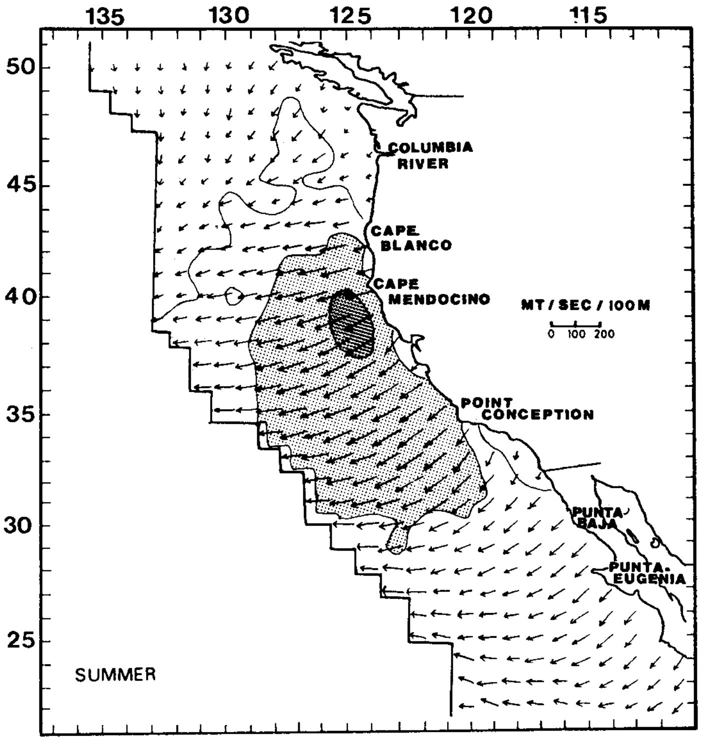

FIGURE 2. SURFACE EKMAN TRANSPORT DURING SUMMER (JUNE THROUGH AUGUST LONG TERM 1° MEANS).

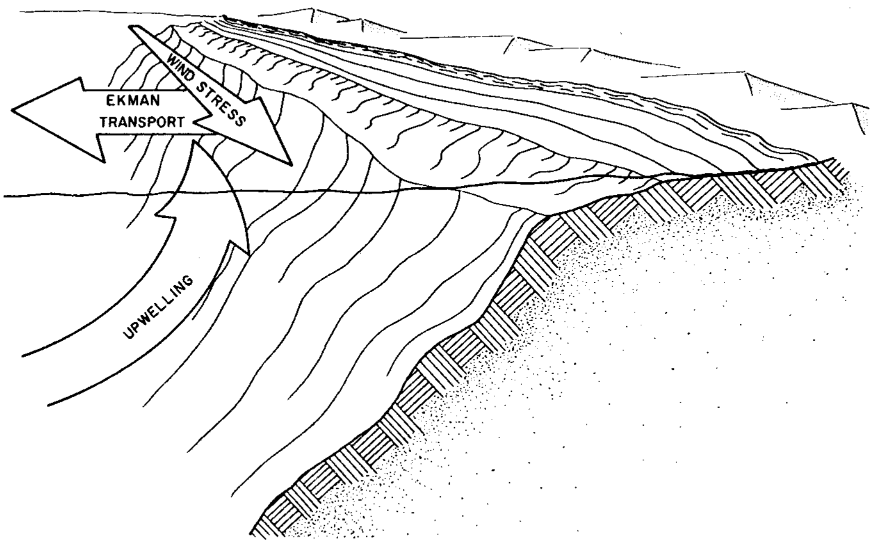

FIGURE 3. A CONCEPTUAL DIAGRAM FOR LOCALLY WIND INDUCED COASTAL UPWELLING. A COMPONENT OF WIND STRESS PARALLEL TO THE COAST AND DIRECTED EQUATORWARD INDUCES OFFSHORE TRANSPORT IN THE SURFACE EKMAN LAYER OF THE OCEAN. TO THE EXTENT THAT THIS OFFSHORE FLUX IS NOT BALANCED BY INFLUX OF HORIZONTAL SURFACE FLOW, THE BALANCE IS MAINTAINED BY UPWELLING OF DEEPER WATERS.

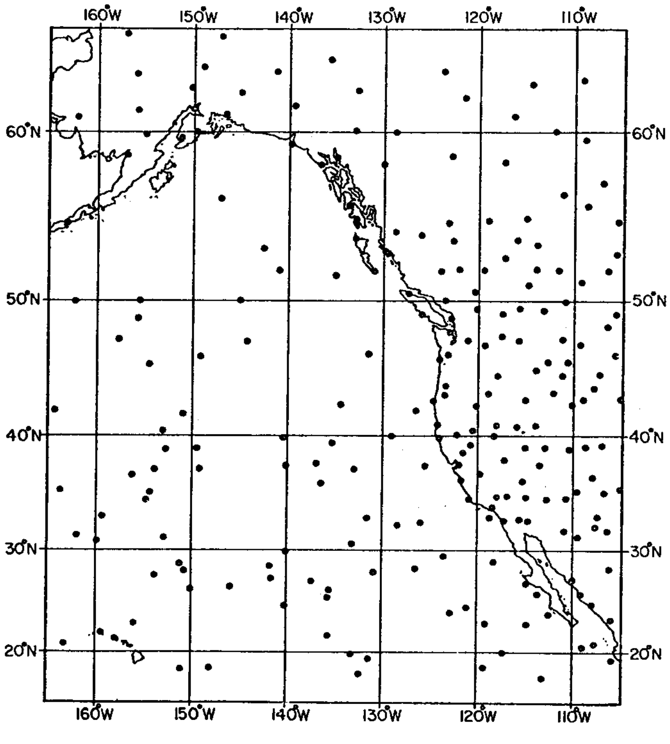

FIGURE 4. A TYPICAL DISTRIBUTION OF REPORTS AVAILABLE FOR A SYNOPTIC SURFACE ATMOSPHERIC WIND-PRESSURE ANALYSIS. THIS PARTICULAR DISTRIBUTION IS FOR 1800 GMT ON 5 JANUARY 1974.

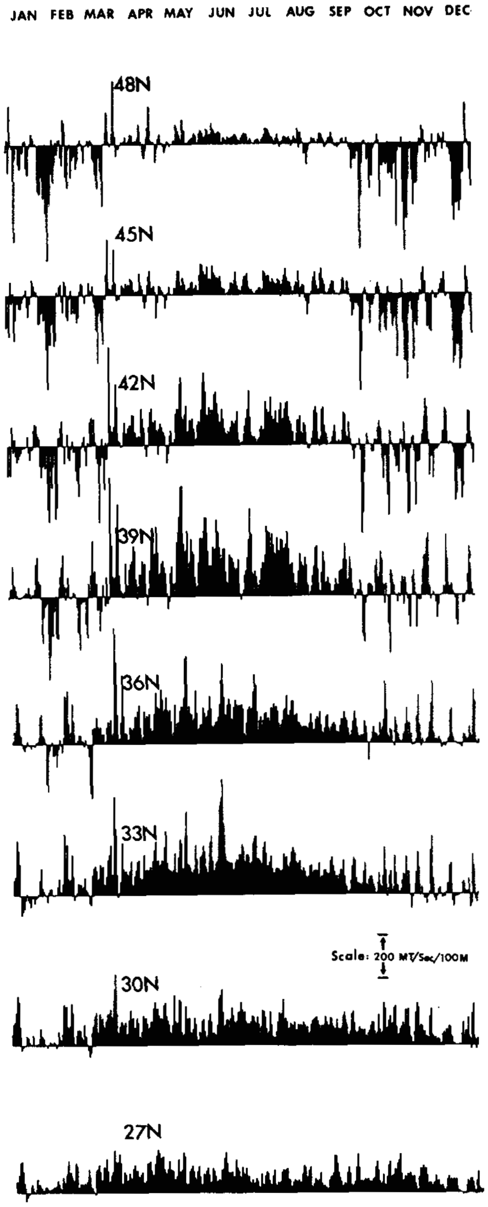

FIGURE 5. DAILY UPWELLING INDICES FOR 1975 AT 3-DEGREE INTERVALS FROM THE WASHINGTON COAST TO CENTRAL BAJA CALIFORNIA. THE MAGNITUDE OF THE ALONGSHORE WIND STRESS IS INDICATED BY THE LENGTH OF THE BARS; THE SCALE IS SHOWN ON THE FIGURE. UNITS ARE METRIC TONS PER SECOND PER 100 M LENGTH OF COAST. BARS EXTENDING UPWARD INDICATE SOUTHWARD STRESS EVENTS, WHICH CAUSE OFFSHORE EKMAN FLUX AND PRODUCE UPWELLING; THOSE EXTENDING DOWNWARD INDICATE SOUTHWARD STRESS EVENTS, WHICH PRODUCE ONSHORE EKMAN TRANSPORT AND RESULTANT COASTAL DOWNWELLING.

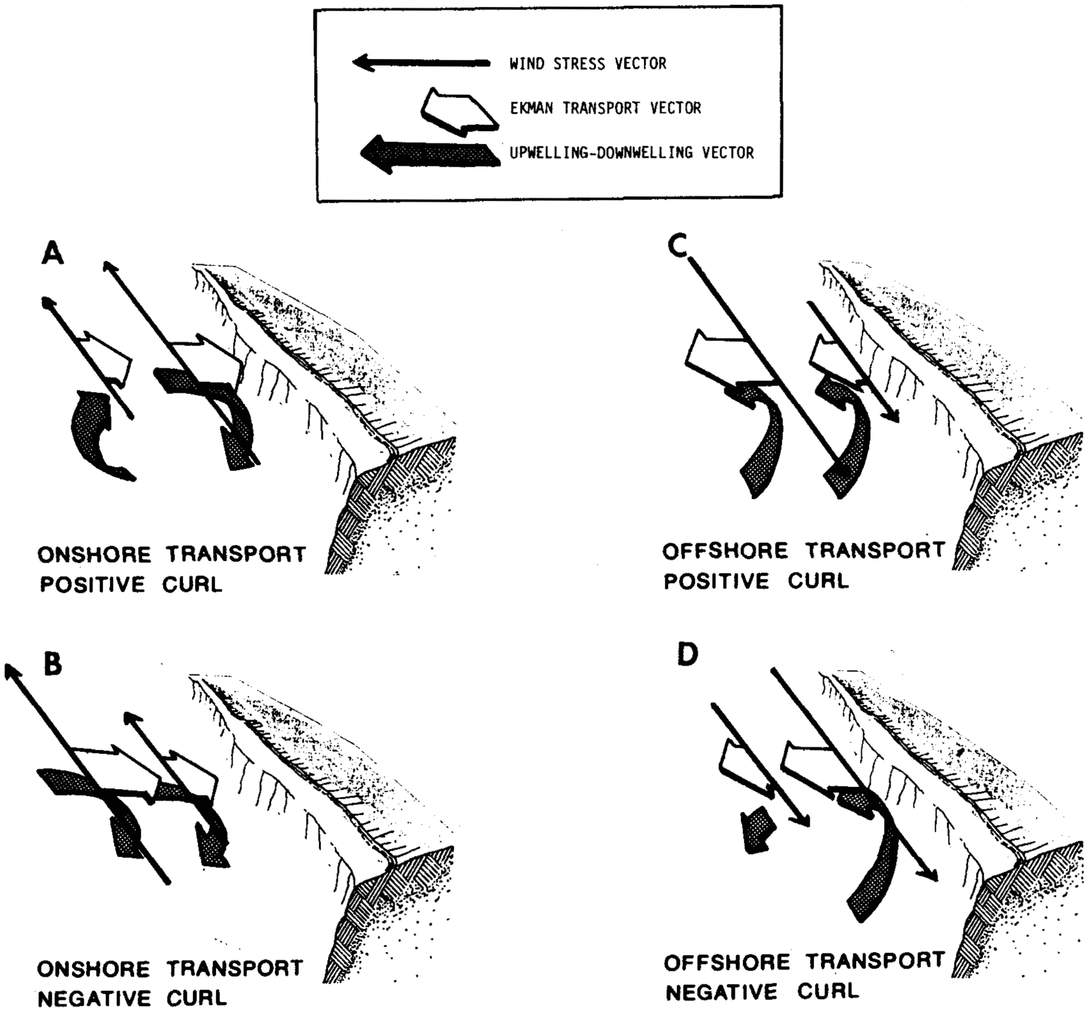

FIGURE 6. CLASSIFICATION OF WIND STRESS EVENTS ACCORDING TO COMBINATION OF COASTAL AND OFFSHORE CONVERGENCE OR DIVERGENCE. A. ONSHORE EKMAN TRANSPORT AND POSITIVE WIND STRESS CURL; CONVERGENCE AND DOWNWELLING AT THE COAST, DIVERGENCE AND UPWELLING OFFSHORE. B. ONSHORE EKMAN TRANSPORT AND NEGATIVE WIND STRESS CURL; CONVERGENCE AND DOWNWELLING AT THE COAST, CONTINUED CONVERGENCE OFFSHORE. C. OFFSHORE EKMAN TRANSPORT AND POSITIVE WIND STRESS CURL; DIVERGENCE AND UPWELLING AT THE COAST, CONTINUED DIVERGENCE OFFSHORE. D. OFFSHORE EKMAN TRANSPORT AND NEGATIVE WIND STRESS CURL; DIVERGENCE AND UPWELLING AT THE COAST, CONVERGENCE OFFSHORE.

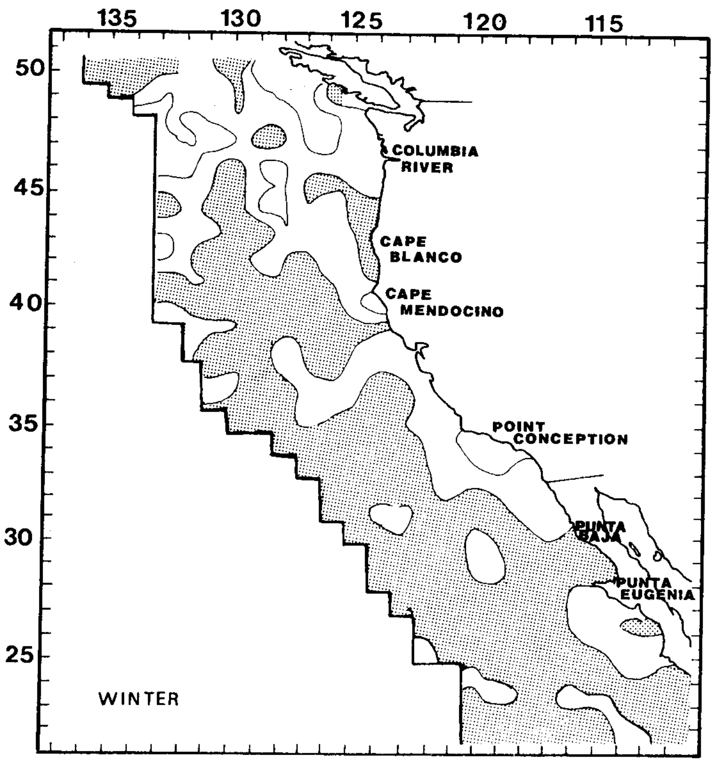

FIGURE 7. WIND STRESS CURL DISTRIBUTION DURING WINTER (DECEMBER THROUGH FEBRUARY LONG TERM MEANS). CONTOUR INTERVAL IS 0.25 DYNES CM^{-2} PER 100 KM. NEGATIVE CURL VALUES ARE SHADED; I.E. SHADED AREAS INDICATE SURFACE EKMAN CONVERGENCE, UNSHADED AREAS INDICATE EKMAN DIVERGENCE.

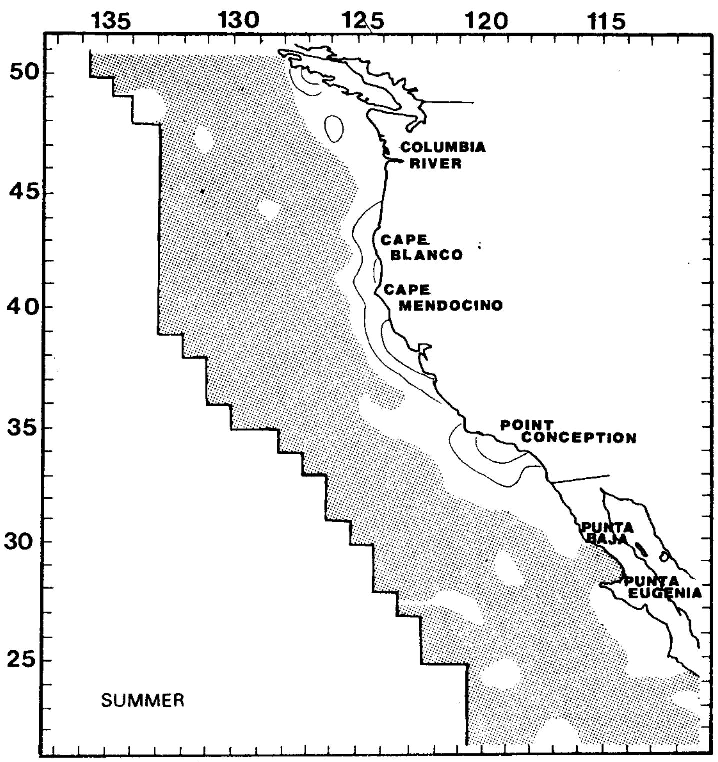

FIGURE 8. WIND STRESS DISTRIBUTION DURING SUMMER (JUNE THROUGH AUGUST LONG TERM MEANS). CONVERGENT AREAS ARE SHADED; DIVERGENT AREAS ARE UNSHADED.

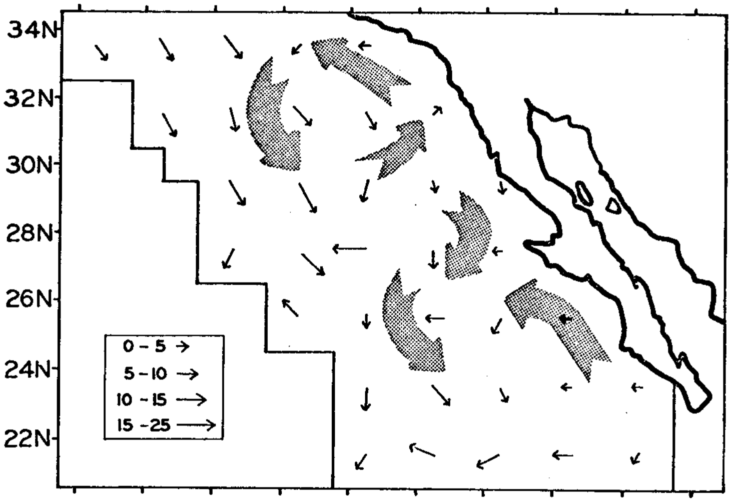

FIGURE 9. SHIP DRIFT DURING OCTOBER, NOVEMBER, AND DECEMBER. OBSERVATIONS WERE SUMMARIZED BY 2° "SQUARE" AREAS FROM THE NAVOCEANO SHIP DRIFT FILE. THE SMALL ARROWS, INDICATING MEAN DRIFT, ARE SCALED ACCORDING TO THE KEY AT THE LOWER LEFT. LARGE ARROWS SUGGEST THE INFERRED CIRCULATION PATTERN. SHIP DRIFT OBSERVATIONS ARE DERIVED FROM DIFFERENCES IN DEAD-RECKONING AND VERIFIED POSITIONS ASSEMBLED FROM SHIP'S LOGBOOKS.

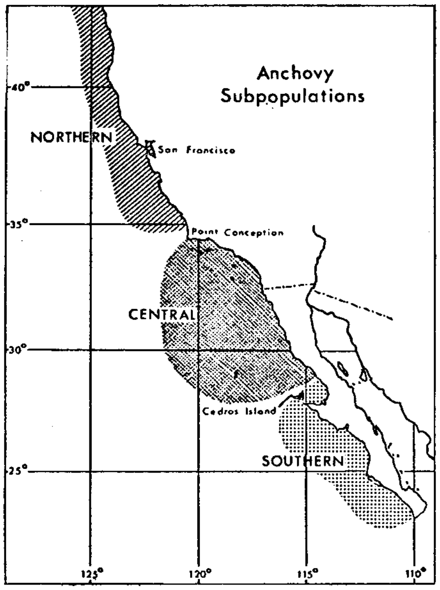

FIGURE 10. THE WINTER DISTRIBUTIONS OF ANCHOVIE SUBPOPULATIONS IN THE CALIFORNIA CURRENT (AFTER VROOMAN AND SMITH, 1971).

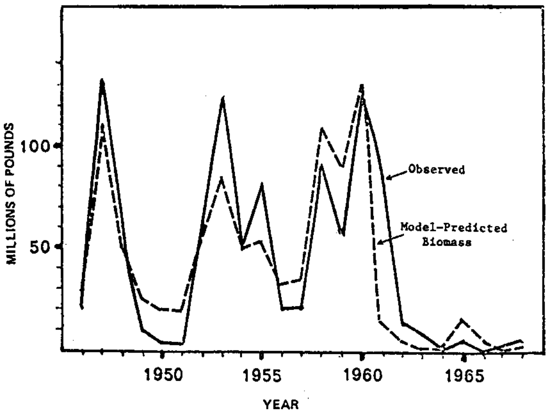

FIGURE 11. YEAR-CLASS SIZE IN THE CALIFORNIA STOCK OF PACIFIC MACKEREL.