EL NIÑO NORTH

Niño Effects in the Eastern Subarctic Pacific Ocean

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Warren S. Wooster and
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Washington Sea Grant Program
University of Washington • Seattle

First published in 1985 by
Washington Sea Grant Program
University of Washington

Printed in the United States of America

Support for publication of these proceedings was provided in part by grant number NA84AA-D-00011, project A/PC-7, from the National Oceanic and Atmospheric Administration to the Washington Sea Grant Program.

KEY WORDS: 1. El Niño 2. North Pacific Ocean - El Niño effects
3. Environmental variability - El Niño effects

LIBRARY OF CONGRESS CATALOGING IN PUBLICATION DATA
Main entry under title:

El Niño North: Niño effects in the Eastern Subarctic
Pacific Ocean.

Bibliography: p.
1. El Niño Current--Environmental aspects--
North Pacific Ocean. I. Wooster, Warren S. (Warren
Scriver), 1921- . II. Fluharty, David L.,
1946- . III. Washington Sea Grant Program.
QH95.1.E4 1985 574.5'2636 85-15638
ISBN 0-934539-01-4

Washington Sea Grant Program
College of Ocean and Fishery Sciences
University of Washington 98195

WSG-WO 85-3
August 1985
$10.00

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Preface

The phenomenon of El Nino has become well known as a climatic anomaly affecting the entire tropical Pacific Ocean. In the last decade, a Nino paradigm has been developed that encompasses a plausible mechanism and promises to result in successful predictions. But as the record-breaking event of 1982-1983 has demonstrated, not all Ninos are the same, and reasons for the differences among them are not well understood.

In an earlier volume, Warren S. Wooster, ed., From Year to Year, Washington Sea Grant, 1983, the question of interannual variability of the environment and fisheries of the Gulf of Alaska and the eastern Bering Sea was examined. There is compelling evidence that for many species, a variable environment is associated with variable recruitment to fish and shellfish stocks, but the relationship is poorly understood. Just as the study of extreme years classes may illuminate the interaction, so may the analysis of extreme environmental fluctuations, of which El Nino is becoming one of the best known.

To explore these matters, a meeting on Nino effects in the eastern subarctic Pacific was held on 12 and 13 September 1984 at the Pacific Marine Environmental Laboratory, Seattle. The meeting was sponsored by IRIS (International Recruitment Investigations in the Subarctic) and was supported by the Northwest and Alaska Fisheries Center. Papers of the first day focused on the physical environment; the second day was devoted to examining the biological response. The program is given at the end of this volume.

The report on an earlier symposium on "The Changing Pacific Ocean in 1957 and 1958" (California Cooperative Oceanic Fisheries Investigations, Reports, 7, 1960) has become a classic and served to bring the Nino phenomenon to the attention of scientists from many disciplines. The record of the 1984 symposium may serve a similar purpose and thus with the help of Washington Sea Grant and the Northwest and Alaska Fisheries Center is published in this volume.

In some cases, abstracts of papers being published elsewhere are included. All papers were refereed. Unfortunately, it was not possible for all authors to provide acceptable manuscripts in time to meet the publication schedule. However, the papers included in the volume suffice to show how a Nino event such as that of 1982-1983 can perturb the ocean and its biota far from the equator and provide some insight into the research required if the environmental effects and their biological consequences are to be successfully predicted.

We thank colleagues who refereed the papers; K. Banse, D. Bevan, Glenn Cannon, B. W. Frost, D. Gunderson, Barbara Hickey, Reuben Lasker, John Liston, William G. Pearcy, Amy Schoener, James D. Schumacher, B. A. Taft, J. M. Wallace and Warren S. Wooster. We also appreciate the assistance of staff of Washington Sea Grant Communications in publishing this volume.

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THE PHYSICAL ENVIRONMENT

El Niño of 1982–83 in the Tropical Pacific

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Introduction

The oceanic manifestations of the 1982-83 Niño have been documented in three special issues of the Tropical Ocean-Atmosphere Newsletter (Numbers 16, 21, 28). In addition, presentations of tropical ocean and wind data are found in the El Niño Atlas 1982-83 (Leetmaa and Witte, 1985). This paper summarizes the extensive literature which was available at the time of the symposium.

Composite El Niño

The Niño event of 1982-83 differed in many respects from Niños of the period 1957-1977. Rasmusson and Carpenter (1982) have derived a composite Niño which spans the period 1950-1973. This composite representation has been averaged over the strongest six Niño events that occurred during this period. The basis of this compositing is the strong coherence that is seen in the pattern of SST and wind anomaly for each event. A three year time series of SST anomaly is plotted along a ship track (5°S-12°S) parallel to the coast for four major Niño events (1957, 1965, 1969, 1972) (Figure 1). The timing of the April (year 0) and January (year + 1) SST anomaly peaks is consistent among the events. The 1957-58 Niño differs from the others in that there were positive anomalies preceding the event and the SST's did not return to normal levels during year + 1. It has been noted that the composite Niño SST signal off South America can be considered as an amplification of the annual signal because the sharp rise at the beginning of the onset year coincides with the normal heating cycle (Rasmusson and Carpenter, 1982).

Studies of the composite Niño event have indicated a sequence of events that characterize the phenomena for the period 1957-1973 (Rasmusson and Carpenter, 1982); the evolution of the SST and wind anomaly fields for the composite Niño fields is shown in Figure 2. The Niño event is preceded by a rather long period of stronger than average easterlies in the western Pacific which

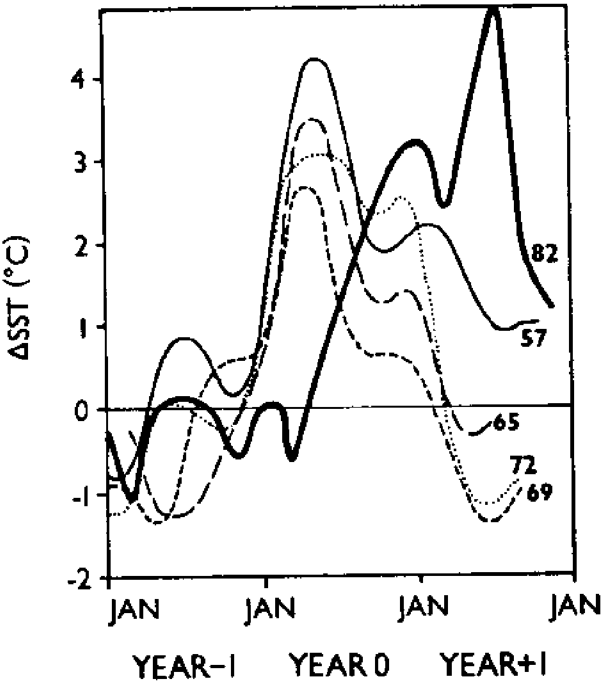

Figure 1. Time series of SST anomalies along a shiptrack (5°S-12°S) parallel to the coast which spans the period of four Niños (1957, 1965, 1969, 1972) and the average SST anomalies for a region bounded by 0°-10°S and 80°-90°W (1982). Year 0 refers to the onset year (maximum anomalies).

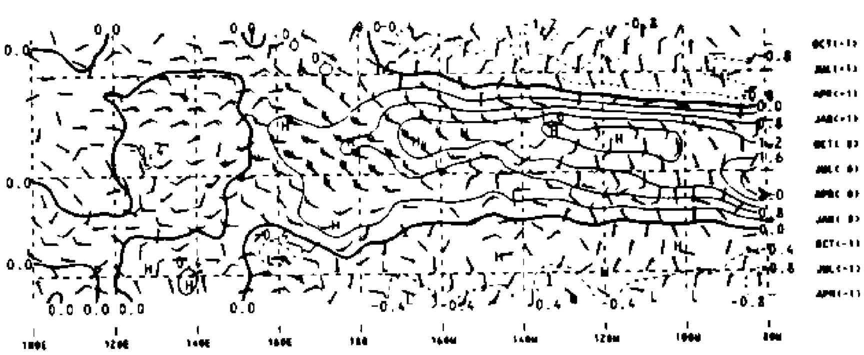

Figure 2. Time/longitude sections of composite wind and SST (°C) anomalies (5°N-5°S) along the equator (west of 95°W) and axis of maximum SST anomalies (95°W to Peru coast) during year -1 through year +1. For wind anomalies, a full barb is equivalent to 0.5 m s^{-1}. Reproduced from Rasmusson and Carpenter (1982).

depresses the thermocline and increases sea level in the western Pacific relative to the eastern Pacific. SST is slightly warmer (colder) than normal in the western (eastern) Pacific. In September of the year preceding the warming, the easterlies decrease west of the dateline. Warming of the surface layer off South America begins in December and increases to a maximum value in June or July (Figure 1); the warming is accompanied by an increase in sea level along the west coast of South America. Westerly wind anomalies appear in the central Pacific in the northern summer of year 0. The positive SST anomalies propagate westward along the equator from the eastern boundary so that by the end of the year 0 the maximum SST anomaly shifts to the central Pacific. The secondary peak in SST off South America (Figure 1) follows a sharp decrease in the northern spring of year +1 and a return to below normal SST. Warm SST persists in the central Pacific until the middle of year +1; by this time, the winds return to strong easterlies and the event has run its course.

1982–83 El Niño

The first evidence of the incipient event appeared in the late northern spring of 1982 when westerly wind and positive SST anomalies became noticeable (Figures 3, 4). The 1982-83 event was

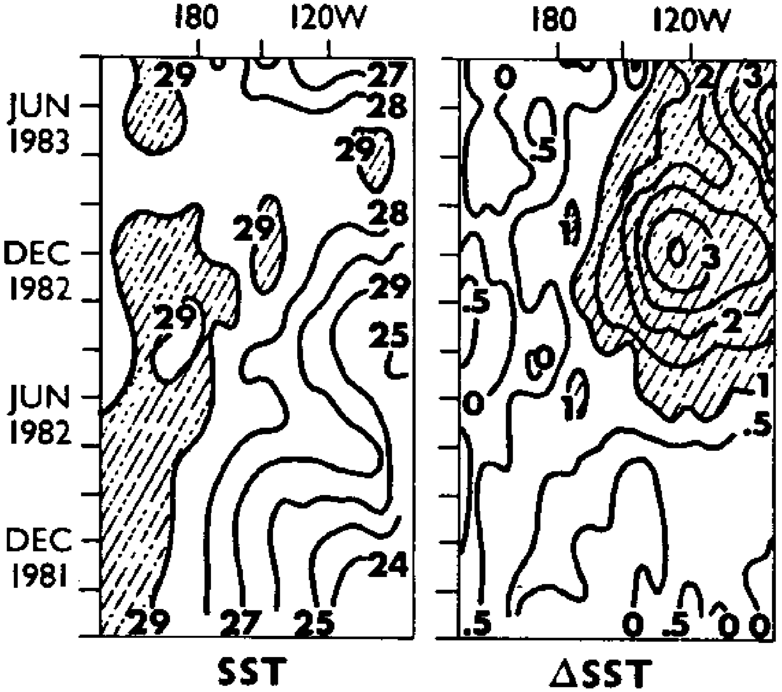

Figure 3. Time/longitude sections of SST(°C) and ΔSST(°C) anomaly (5°N-5°S) for 1981-1983. Shaded areas are SST > 29°C and ΔSST > 1.0°C. Reproduced from Arkin, et al., (1983).

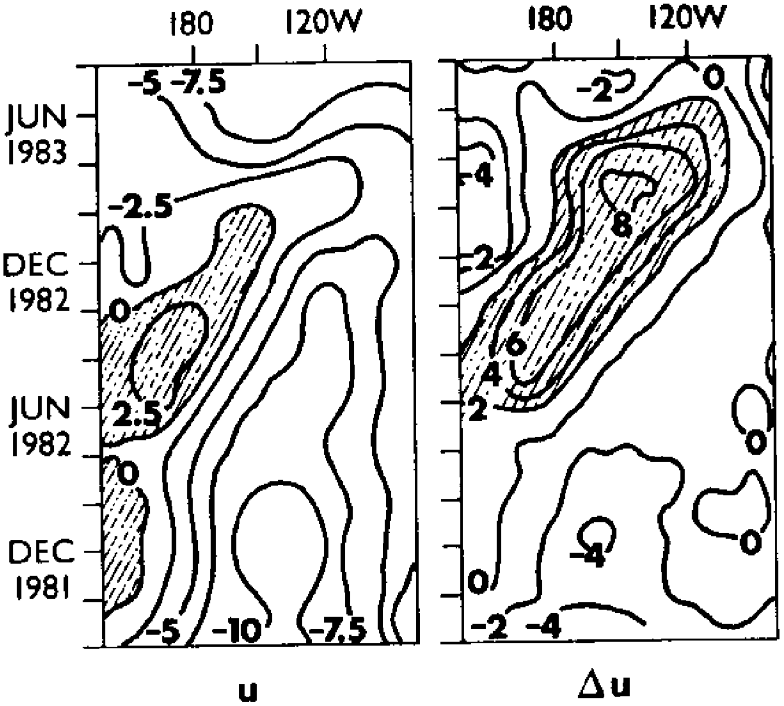

Figure 4. Time/longitude sections of zonal wind component (u) and its anomaly (Δu) ($m\ s^{-1}$) at 850 mb (5°N-5°S) for 1981-83. Shaded areas are u > 0 and Δu > 2.0 $m\ s^{-1}$. Reproduced from Arkin, *et al.* (1983).

not preceded by a period of strong easterlies and associated high (low) SST's in the western (eastern) Pacific so that both the timing of the initiation and the state of the system previous to the beginning of the event differed from Niño events of 1957-1973. SST in the eastern Pacific started to increase in northern summer and by December 1982 maximum anomalies (> 3.5°C) were observed at 120°W. The maximum SST anomaly (> 4.0°C) at the coast was observed in June 1983 (Figure 1). It may be seen that the anomaly was larger in 1982-83 than in the other major Niño events and the rise in temperature preceded the annual heating cycle by five to six months (the second rise in SST did coincide with the annual heating). Strong westerly wind anomalies persisted in the eastern Pacific (east to 140°W) until mid-1983. Comparisons of Figures 2, 3, and 4 show the following: (1) the 1982-83 event began in the late northern spring, not the late northern fall; (2) the SST signal was at least twice as large as the composite value; (3) the SST anomaly moved from west to east instead of east to west; and (4) the westerly wind anomalies penetrated much further east than in the composite Niño, and actually there were westerly winds at the equator in the eastern Pacific.

Associated with the changes in winds and SST's were large signals in sea level recorded at various islands located near the equator (Lukas, et al., 1984). In Figure 5 are shown island sea-level time series at Nauru (0°32'S, 166°54'W), Jarvis (0°23'S, 160°W), Christmas (1°59'N, 157°29'W) and Santa Cruz (0°27'S, 90°17'W). Large and sudden sea level changes are seen at Jarvis and Christmas; for example, Christmas sea level rose 25 cm between June and September of 1982. The Santa Cruz record shows a more gradual rise between September 1982 and early January 1983, with a broad secondary peak occurring in May 1983. In general these sea level changes are not related to local changes in winds but appear to be due to remotely forced equatorial wave motions (Cane, 1983). Sea level rose along the coast of South America several months after the rise at Santa Cruz, for example at Callao (12°S) the sea level began a 35 cm rise in October 1982 (Enfield, et al., 1983). These changes in sea level imply a large shift in mass between the western and eastern Pacific and a resulting change in the pressure field (Wyrtki, 1984). Time series of equatorial dynamic height of the sea surface based on ship of opportunity expendable bathythermograph (XBT) and sea-surface salinity data at three longitudes are plotted in Figure 6. During the pre-El Niño period (1980-81) the sea-surface dynamic height is about 60 dynamic cm higher in the western than in the eastern Pacific. Because of the

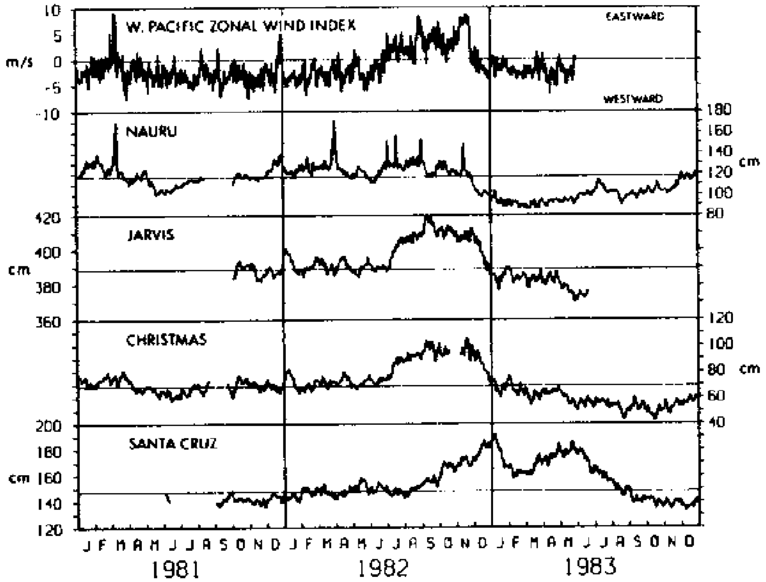

Figure 5. Time series of daily mean and zonal wind index for the equatorial Pacific near 170°E sea level from near-equatorial Pacific island stations. Thin horizontal lines indicate long-term mean sea level relative to an arbitrary reference. The locations of sea level stations is described in the text. Reproduced from Lukas, et al. (1984).

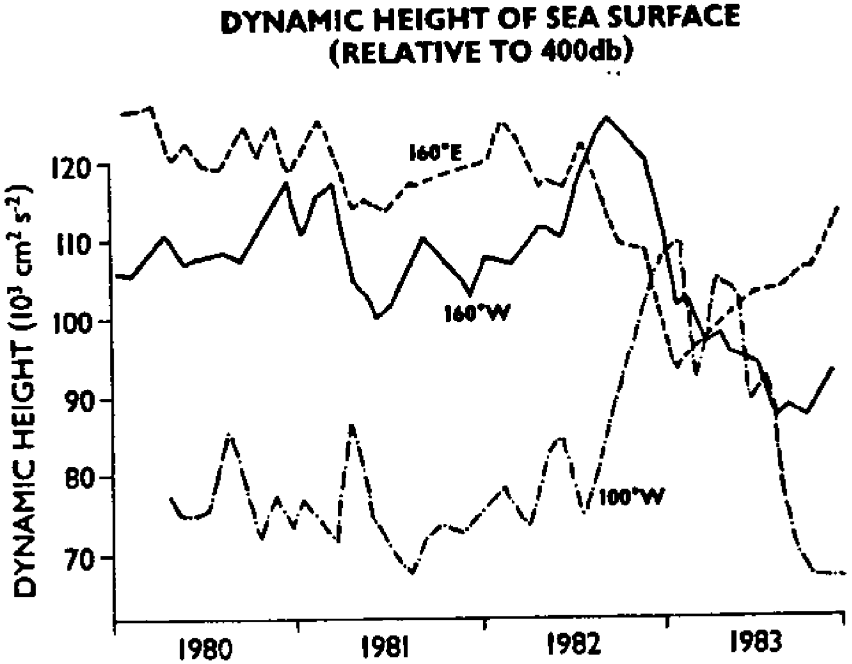

Figure 6. Dynamic height of the sea surface relative to 400 db at the equator (160°E, 150°W, 100°W) as calculated from XBT and surface salinity (data made available by W. Kessler, J.-R. Donguy and G. Meyers).

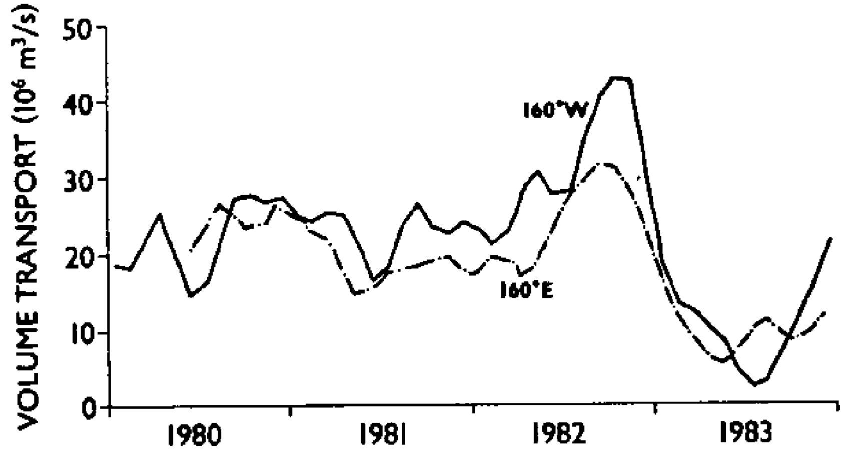

Figure 7. Zonal geostrophic volume transport of the North Equatorial Countercurrent at 160°W and 160°E (data made available by W. Kessler, J.-R. Donguy and G. Meyers).

east-west shifts in mass, the slope of the sea surface was reduced to zero in late 1982. Associated with the disappearance of the east-west pressure gradient, was a drastic change in the current structure resulting in the disappearance of the Equatorial Undercurrent in the central and eastern Pacific (Firing *et al.*, 1984; Halpern, 1983). Not only were there changes in the east-west sea-surface topography, but also the meridional sea-surface profile was modified dramatically which resulted in significant changes in the zonal off-equatorial currents. For example, the zonal geostrophic transport of the North Equatorial Countercurrent in both the western and central Pacific (computed from the XBT data set) increased by about 15 x 10^6 m^{3}s^{-1} in late 1982 and then decreased to very low values by mid 1983 (Figure 7). Significant changes in geostrophic flow in 1982-83 appear to have been limited to 10°N-20°S (the North Equatorial Current was not affected appreciably by the event).

Acknowledgments

This work was supported by the NOAA Equatorial Pacific Ocean Climate Studies (EPOCS) program. The author particularly thanks Jean-Rene Donguy, Gary Meyers and William Kessler for their willingness to share their calculations based on XBT data. Contribution No. 779 from NOAA/Pacific Marine Environmental Laboratory.

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Atmospheric Response to Equatorial Sea-Surface Temperature Anomalies

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University of Washington

Introduction

The Joint Institute for the Study of the Atmosphere and Ocean (JISAO), located in Seattle, involves scientists from the University's College of Ocean and Fisheries Sciences and the Department of Atmospheric Sciences and the NOAA Pacific Marine Environmental Laboratory. We have a post-doctoral and visitors program funded through the NOAA EPOCS program which is concerned with climatic variability on the interannual time scale and we have been encouraged by our Administrative Board to explore the possibility of studying year-to-year variability of fisheries recruitment. In both these topic areas, the El Niño phenomenon, the subject of this meeting, plays an important role.

The main purpose of this lecture is to give an overview of physical aspects of the El Niño and the related Southern Oscillation in the atmosphere. I will begin by showing some evidence concerning the global coherence of the phenomenon.

Empirical Evidence of Global Teleconnections

Fig. 1 shows a set of time-series of selected meteorological parameters; one data point per year. The top three curves are obviously very strongly related to one another: the correlation coefficients between them are all in excess of 0.8 and the correlations are especially high during the most recent part of the record, which corresponds to the most reliable observations. It is quite remarkable that the time series represent three different variables in three widely separated regions of the tropics (hence, the term "teleconnections"): the first one represents equatorial (6°N-6°S) sea-surface temperature (SST) for the region of the Pacific east of the dateline; the second represents rainfall at island stations in the equatorial central Pacific and the third represents sea-level pressure at Darwin, Australia, far to the west. All three time series represent annual averages (April through March). The years with above normal SST, rainfall and Darwin sea-level pressure tend to be associated with "El Niño" episodes along the South American coast. We have denoted the stronger episodes by vertical lines in the figure.

Curve (d) shows the sea-level pressure at Tahiti, which lies on the eastern end of the "see saw" for which Sir Gilbert Walker invented the name "Southern Oscillation" more than 50 years ago. The pronounced negative correlation between sea-level pressure at Darwin (c) and Tahiti (d) on the interannual time scale is evidence of the reality of this phenomenon.

Curves (e), (f) and (g) in Fig. 1 depict monsoonal rainfall in various parts of the subtropics. These curves are not as strongly related to (a), (b) and (c) as (a), (b) and (c) are related to one another (the correlation coefficients are on the order of 0.6). However, the relationships are still strong enough to be of some use in long range weather prediction. Note that "El Niño" years tend to be deficient in monsoonal rainfall in many parts of the tropics and subtropics. Other examples of drought regions (not shown here) include Indonesia, eastern Australia, and parts of French Polynesia and Brazil.

The curves labeled (h) and (i) represent samples of interannual climatic variability in temperate latitudes which appears to be related to El Niño events. The former, involving surface air temperature over southwestern Canada, was first noted by Walker and Bliss (1932) and the relationship has obviously held up well during subsequent years. The latter, which involves rainfall in the U.S. Gulf states, apparently escaped Walker's notice, but it appears to be equally strong. Other examples (not shown here) include sea-level pressure in the Aleutians and over the southeastern United States and temperature over northern Japan. There is also evidence of relationships involving temperate latitudes of South America. The relations between the Southern Oscillation (or El Niño events) and extratropical climatic anomalies appear to be restricted to the winter half of the year; I am not aware of any documented evidence of strong relationships during the summer season.

We have known about the existence of the kinds of relationships described in Fig. 1 for many decades already. The El Niño/Southern Oscillation phenomenon has generated a great deal of excitement during the past five years not because of the discovery of teleconnections, but because of the rapid development of our understanding of why they occur.

Equatorial Sea-Surface Temperature and Precipitation Patterns

A schematic view of the coupled atmosphere/ocean climate system which is relevant to "El Niño" events in the Pacific and presumably to phenomena in the other tropical oceans as well is shown in Fig. 2. In discussing this figure, I will quite arbitrarily begin by assuming that there exists a large-scale pattern of sea-surface temperature (SST) anomalies in some part of the tropical oceans. The atmosphere responds to the existence of such anomalies in a very complex manner: the redistribution of heat and moisture fluxes at the sea surface influences patterns of cloudiness, preci-

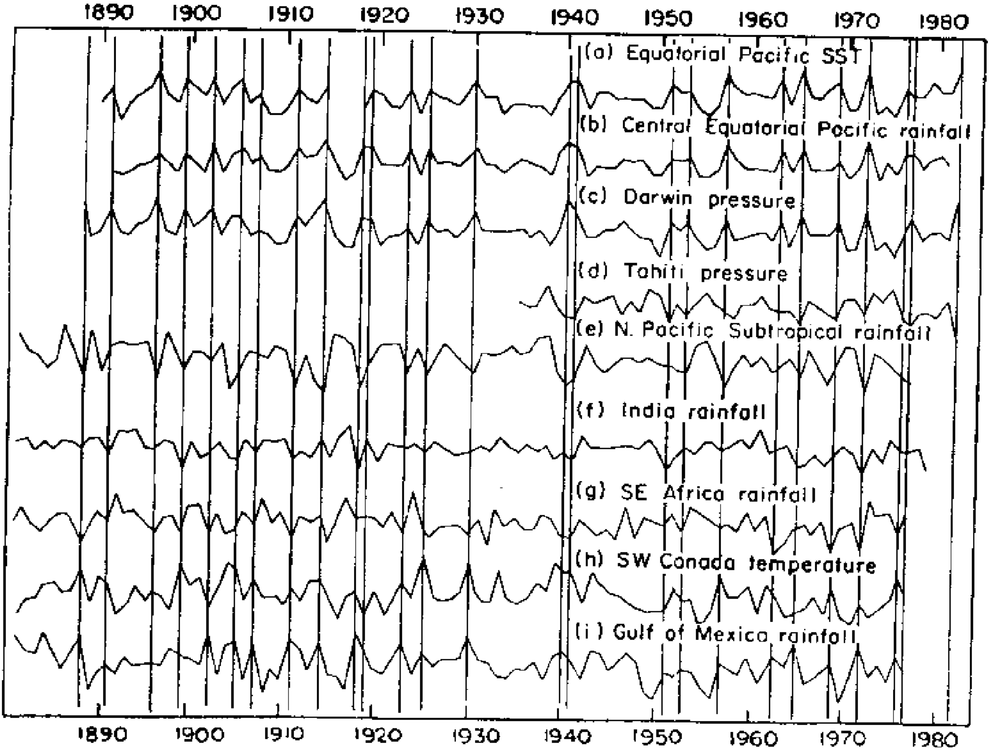

Fig. 1. Time series of selected variables whose interannual variability is related to the El Niño/Southern Oscillation phenomenon. Each data point represents an average over 1 year or a season, as indicated, where the years on the horizontal axis refer to the beginning of the averaging periods. (a) Equatorial eastern Pacific (South American coast to the date line) SST, April to March; (b) rainfall index for central equatorial Pacific island stations, April to March; (c) sea-level pressure at Darwin, Australia (12°S, 131°E), April to March; (d) sea-level pressure at Tahiti (17°S, 150°W), April to March; (e) rainfall index for the subtropical North Pacific, November to May; (f) rainfall index for India, June to September; (g) rainfall index for southeastern Africa, November to May; (h) temperature index for stations in southwestern Canada and the northwestern United States, November to April; and (i) rainfall index for stations in northern Mexico and the U.S. Gulf Coast, November to February. Vertical lines indicate El Niño/Southern Oscillation episodes as inferred from the top three series, after Rasmusson and Wallace (1983). Further details and quantitative values are available from E.M. Rasmusson.

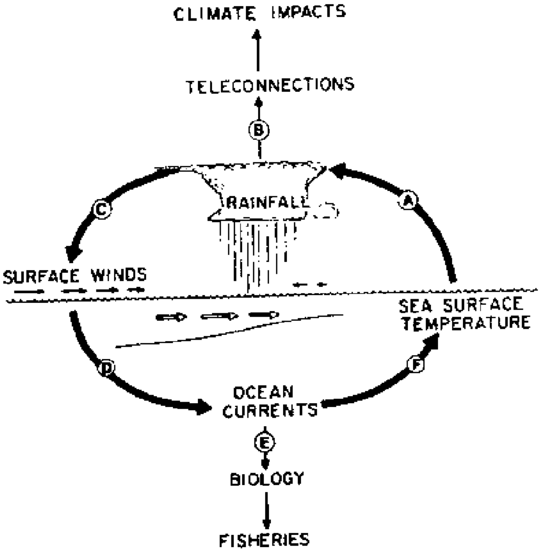

Fig. 2. Schematic illustration of the interactions between the tropical ocean circulations and the global atmosphere. See test for discussion.

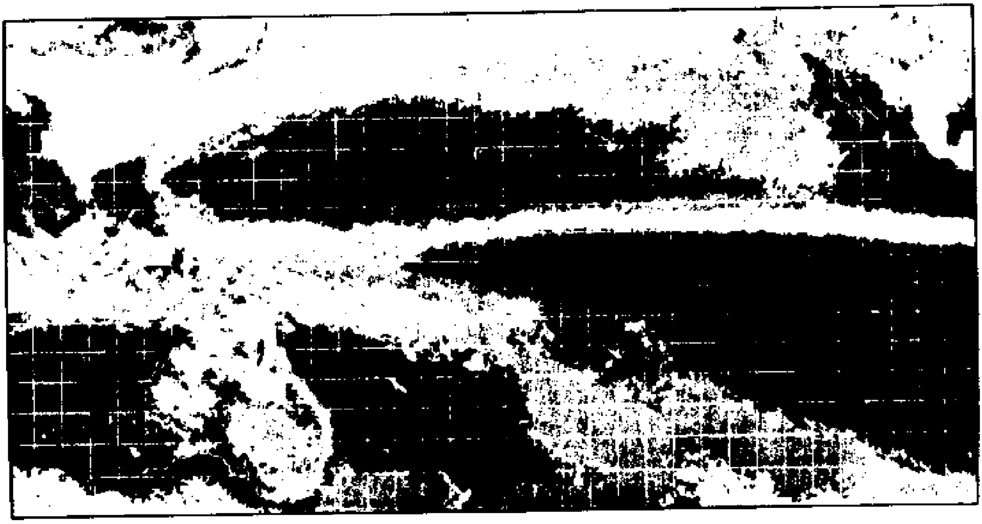

Fig. 3. Composite visible satellite imagery for Dec.-Feb. of four years, showing the Intertropical Convergence Zone, the South Pacific Convergence Zone, the Indonesian monsoon, and the equatorial dry zone. From Global Atlas of Relative Cloud Cover, 1967-1970, U.S. Dept. of Commerce/U.S. Air Force, Washington, D.C., 1971. Imagery available through the National Climate Center, Asheville, N.C. 28801.

pitation and latent heat release within the atmosphere, resulting in changes in large-scale air circulation patterns, including surface winds, which further modify the fluxes at the sea-surface, and so on. The net result of this complex chain of interactions is to effect a readjustment of the pattern of precipitation over the equatorial Pacific Ocean such that the heavy rainfall tends to follow the region of warmest SST.

In order to show how this relationship applies to the unperturbed climate system, we can compare Figs. 3 and 4b which show, respectively, the climatological mean distributions of cloudiness and SST during Northern Hemisphere winter. Note the 4-5°C SST gradient between Indonesia, where temperatures exceed 29°C and the eastern Pacific, where equatorial and coastal upwelling, advection of cold water from the south, and extensive low cloudiness (all direct or indirect consequences of the strong southeast trades, which extend across the equator to the Intertropical Convergence zone at 7°N in the eastern half of the Pacific) conspire to maintain SST's at a level considerably below the average in the equatorial belt. Extensive cloudiness, indicative of heavy convective precipitation, covers the equatorial belt over Indonesia and the extreme western Pacific, while the cooler eastern belt of the Pacific tends to be free of clouds. We can liken the equatorial ocean surface to the top of a stove, with a burner or heating element located over the warmest SST, near Indonesia, and the atmosphere to a shallow pan of water in which vigorous boiling (convection) is occurring over the burner and subsidence is located elsewhere.

The pattern of SST anomalies observed during El Niño episodes is such as to shift the region of warmest SST eastward from Indonesia toward the central Pacific Ocean and to weaken the overall east-west temperature gradient across the equatorial Pacific. The most recent El Niño was an extreme case: the pattern of SST anomalies during the 1982-83 winter, shown in Fig. 4c, was rather typical of El Niño events at that time of year, but the magnitude was two or three times as large as that observed in typical events. The anomalies were so large that the normal east-west SST gradient across the equatorial Pacific was completely eliminated. Fig. 4a shows that during this period, a pool of very warm surface water was observed near 150°W. During more typical events, the warmest SST is observed near the dateline and SST anomalies in the eastern Pacific are not large enough to counter the climatological mean SST gradient in that region.

In response to the altered SST gradient along the equator the belt of convective precipitation shifts eastward, leaving Indonesia in a drought situation and producing heavy rainfall at island stations in the central equatorial Pacific. For example, Canton Island, which has a desert climate during non-Niño years may experience rainfall amounts on the order of 300 mm per month for six or more consecutive months during El Niño episodes. During the recent 1982-83 event, the rainfall belt shifted even further eastward, as revealed by the distribution of outgoing longwave radiation (OLR) anomalies shown in Fig. 5. [Over most of the tropics negative OLR anomalies are indicative of an above normal frequency of deep con-

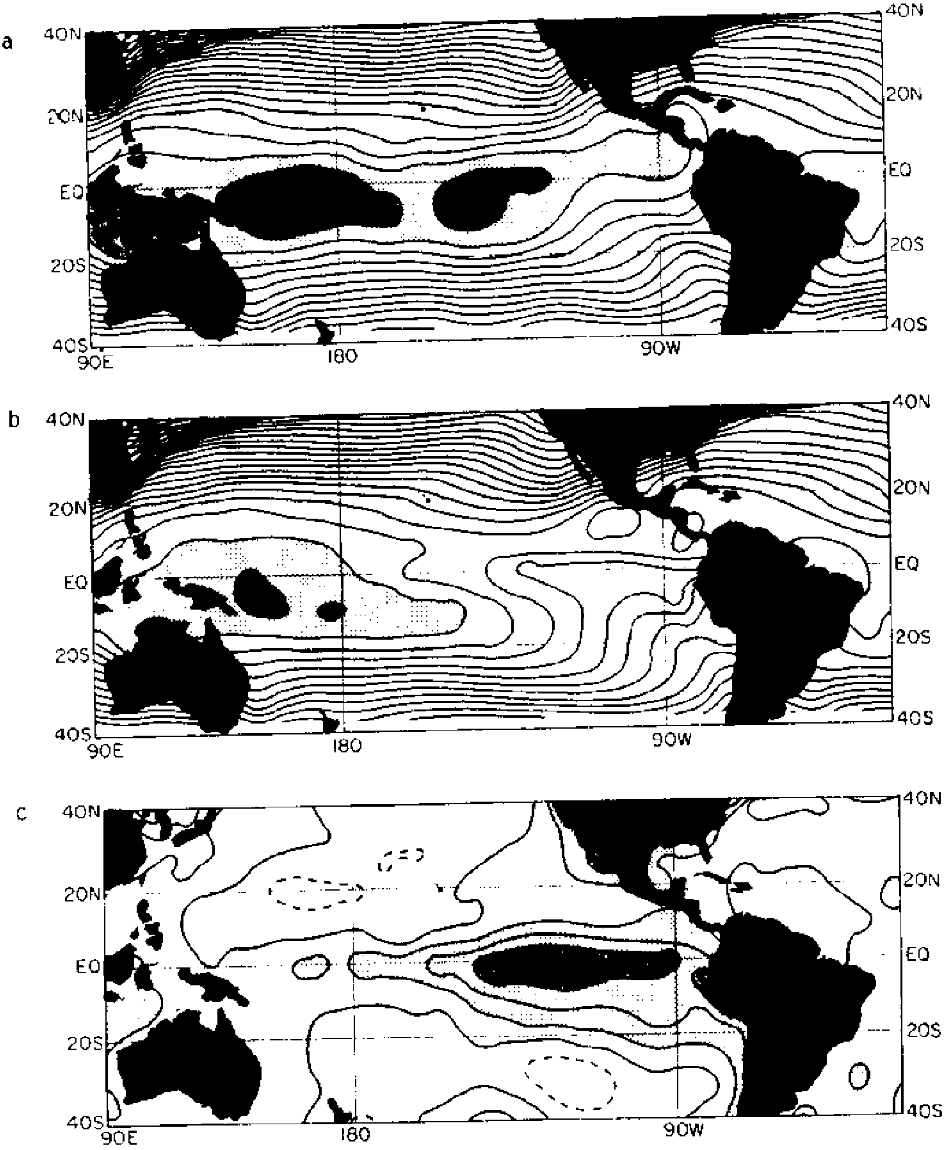

Fig. 4. Sea-surface temperature patterns (contour interval, 1 K). Top panel, December 1982 to February 1983. Middle panel, December-February climatology. The heaviest shading corresponds to SST's > 29°C. Lower panel, anomalies for December 1982 to February 1983. The heaviest shading denotes anomalies > 3 K.

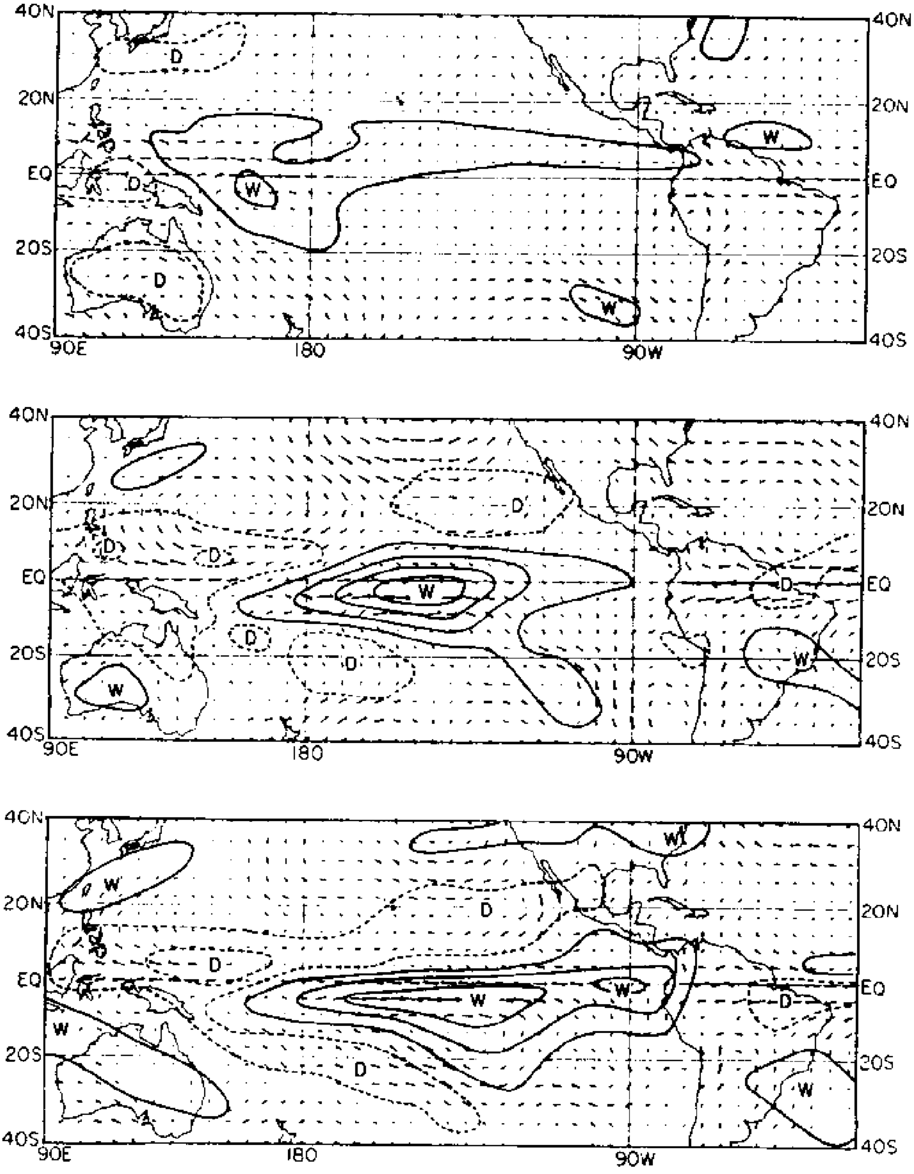

Fig. 5. Anomalies in satellite-sensed outgoing long-wave radiation (OLR) (contours) and wind at 850 mbar (arrows) for three seasons during the 1982-1983 episode. Top panel, June-August 1982; middle panel, December 1982-February 1983; lower panel, March-May 1983. Negative anomalies in OLR, indicated by the solid contours and labelled W for "wet," correspond to regions of enhanced precipitation, and vice versa (D, "dry"). Contour interval, 20 W/m^2 (where contours correspond to ± 10, ± 30, and so forth). The longest arrows correspond to wind anomalies on the order of 10 m/sec.

vective clouds with cold tops radiating to space, and vice versa.] As the event progressed, the belt of heavy precipitation shifted farther and farther eastward, following the warmest SST. The observed eastward shift of equatorial precipitation during El Nino events has been successfully simulated in a large number of recent general circulation model (GCM) experiments. It is represented schematically in Fig. 2 by the arrow labeled A.

There are some other important changes in the distribution of tropical precipitation during the El Nino events that are not so well understood. Even during rather modest Ninos, in which SST along the South American coast remains somewhat cooler than in the western Pacific, episodes of heavy rainfall have been observed along the coast of Ecuador and northern Peru. And in nearly all events the intertropical convergence zone (ITCZ), which corresponds to the prominent east-west band of heavy cloudiness in Fig. 3, shifts equatorward by a few degrees of latitude. The present generation of general circulation models used in sensitivity studies involving equatorial SST do not adequately resolve these more subtle, regional features and as yet we have no satisfactory theoretical explanation for them.

Atmospheric Teleconnections

Returning to Fig. 2, we see that the changes in equatorial rainfall produce teleconnections to higher latitudes and to other regions of the tropics by rearranging the distribution of planetary waves, as indicated by the arrow labeled B. A crude analogue of this process is described in Fig. 6, where we see a distribution of surface waves produced by an obstacle in a stream. If the obstacle is moved to another place, the downstream wavetrain will move with it, and the water levels at fixed points well downstream from the obstacle may rise or fall as a result. In Fig. 7 we see the distribution of Rossby-waves emanating from a tropical source or sink of vorticity in the presence of a uniform westerly flow on a rotating sphere. The vorticity source or sink shown in panel (a) represents the outflow from a localized region of heavy convective precipitation, and in this discussion I am treating it as a crude analogue to the obstacle in Fig. 6. The wavetrains in Fig. 7 are planetary in scale and they are oriented along "great circle routes" emanating from the localized region of forcing.

Fig. 7 is based on calculations involving a linearized barotropic model. The time sequence in the three panels (b) through (d) shows how the response develops after the perturbation is abruptly inserted into the flow. Within 2-1/2 days (panel (b)) there is a local response whose shape already resembles the equilibrium configuration which will not be fully realized until much later; at larger distances from the perturbation the flow is still virtually undisturbed. The stationary wavetrains downstream of the perturbation develop gradually, one center at a time, over a time interval of a week or two. Individual centers don't propagate, but wave energy clearly does disperse downstream from the source as the wavetrain develops. The rate of development of the downstream centers is related to the group velocity associated with Rossby-wave dispersion.

Linear, barotropic Rossby-wave dispersion is, by no means, the full explanation of atmospheric teleconnections. It has become increasingly apparent over the past few years that the teleconnection patterns observed in the atmosphere result from the interplay between a number of different dynamical mechanisms, some of which may be highly nonlinear. Further discussion of these matters would be inappropriate in this forum: it suffices to say that there exist plausible dynamical mechanisms which could account for the observed correlations between equatorial SST and rainfall anomalies and circulation patterns at higher latitudes and in other parts of the tropics.

On the basis of surface observations of past El Ninos such as these presented in Fig. 1, together with analyses of radiosonde observations and upper air charts it is possible to put together a global picture of circulation anomalies characteristic of El Nino episodes. Fig. 8 shows such a synthesis for the middle latitude winter season. The schematic cloud indicates the region of enhanced rainfall in the equatorial central Pacific and the arrows represent the sense of the atmospheric circulation anomalies at the jetstream level. Note the pair of anticyclonic circulation anomalies which straddles the region of enhanced rainfall, with centers in the subtropics, easterly wind anomalies over the equatorial belt and westerly anomalies near 30° latitude. This couplet appears with remarkable regularity in individual El Nino episodes: it is the most robust feature of the anomalous circulation pattern. Extending poleward and thence downstream from the anticyclonic gyre in the subtropical North Pacific is a planetary-scale wavetrain, with anomalous cyclonic circulation over the North Pacific and Gulf of Alaska, anticyclonic circulation over much of central and western Canada, and cyclonic circulation over the southeastern United States. The features over western Canada and the Gulf of Mexico are consistent with the climatic anomalies in those regions described in Fig. 1h,i. The presence of the upper level anticyclone and the southerly flow just to the west of it is conducive to above normal surface air temperatures in southwestern Canada and northwestern United States. The westerly wind anomalies over the Gulf are indicative of an abnormally strong subtropical jetstream which favors an active cyclone track across the southern U.S. The shape of the wavetrain is reminiscent of Fig. 7, though the correspondence is perhaps fortuitous in view of the complexity of the dynamical mechanisms responsible for the teleconnections.

The picture in Fig. 8 is supported by results from a growing number of general circulation model (GCM) sensitivity experiments at at least 8 different research institutions in five different countries. In these experiments a GCM is run for an extended period in which the SST pattern is prescribed in terms of the climatological mean conditions. Statistics on the time mean circulation pattern are compiled for this "control run" to construct a model climatology. Then the same model is rerun, starting from the same initial conditions, with the SST distribution prescribed in terms of the

Fig. 6. Schematic illustration of a wake caused by an obstacle in a uniform flow in a fluid with a free surface. Such wakes are apparent in patterns of low, stratiform clouds downstream of small islands.

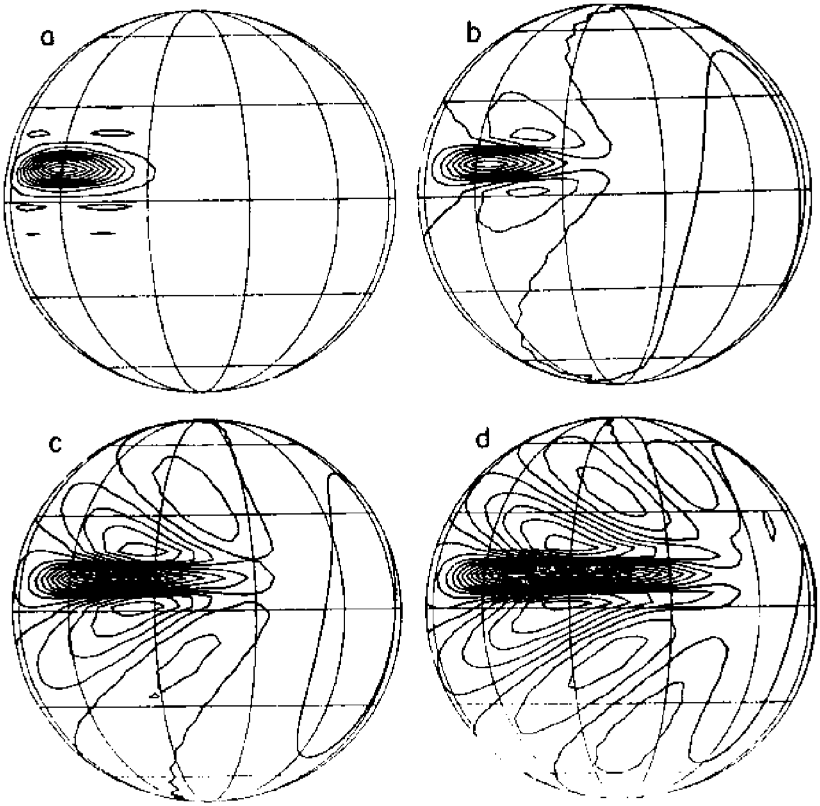

Fig. 7. Analytical solution for a linear barotropic model with a background flow consisting of pure superrotation with a westerly wind velocity of 15 m s^{-1} at the equator and a localized forcing located at 40°N. (a) The distribution of forcing, (b)-(d) solutions at 2½, 5 and 7½ days. Courtesy of Brian J. Hoskins, University of Reading.

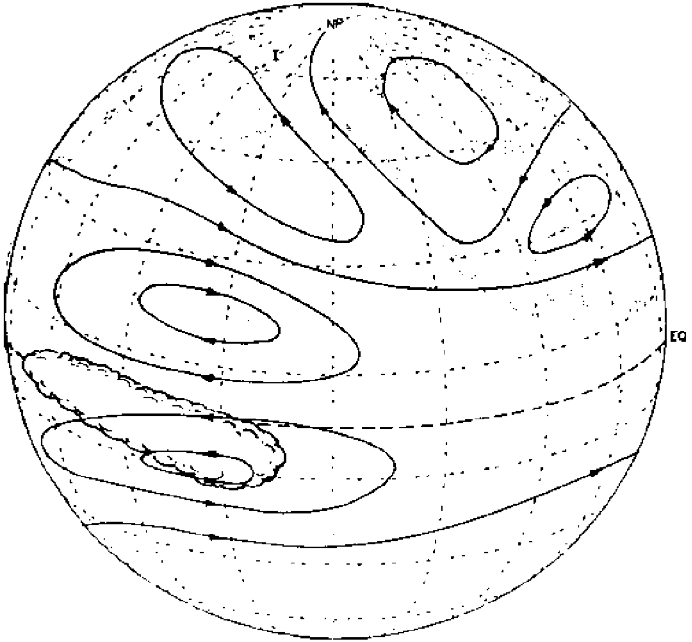

Fig. 8. Schematic illustration of rainfall anomalies and circulation anomalies at the jetstream level during Northern Hemisphere winter, based on a synthesis of data from many different El Niño episodes which occurred prior to 1980. The cloud indicates the region of enhanced rainfall in the equatorial Pacific. After Horel and Wallace (1981).

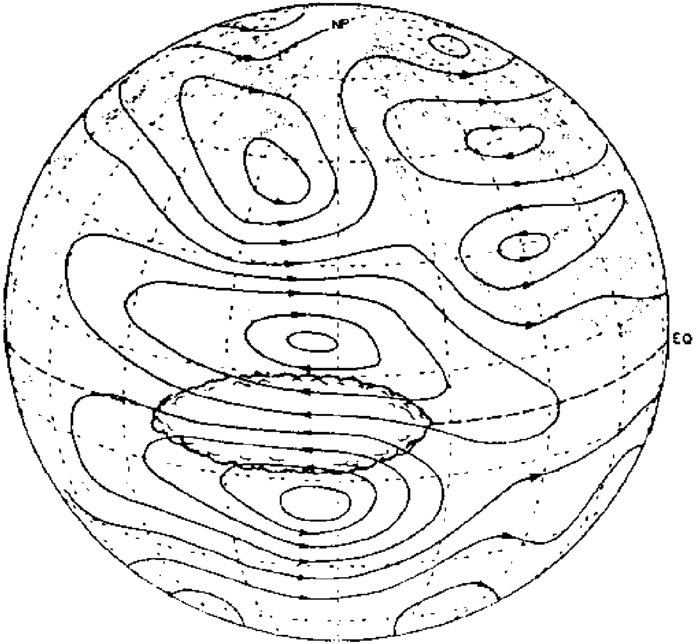

Fig. 9. As in Fig. 8, but for the 1982-83 episode. After Rasmusson and Wallace (1983).

same climatological mean conditions plus an anomaly field based upon conditions characteristic of El Niño episodes. Corresponding time mean statistics are compiled for this "anomaly run" and mean circulation anomalies due to El Niño are inferred by comparing climatologies for the control and anomaly runs. Virtually all these experiments have succeeded in simulating the anticyclonic dipoles straddling the region of enhanced precipitation and most of them show evidence of teleconnections to higher latitudes qualitatively similar to the observed. Results from GCM experiments increase our confidence in the reality of the observed teleconnection patterns.

Another independent verification of the picture in Fig. 8 is the pattern of circulation anomalies observed during the 1982-83 winter, when the most recent Niño was at its peak. The pattern is shown schematically in Fig. 9. It can be seen that the usual pair of anticyclonic circulation anomalies is present, but shifted slightly to the east of its position in Fig. 8, consistent with the unusually pronounced eastward shift of equatorial precipitation during the 1982-83 winter. The wavetrain over the Pacific/North American sector resembles the composite picture in Fig. 8, based on previous events. Consistent with this anomaly pattern, the 1982-83 winter was characterized by record low sea-level pressure in the North Pacific, warmth over western Canada and the northern United States from the Great Lakes westward, and very heavy precipitation over the Gulf States.

While the overall pattern in Fig. 9 is similar to that in Fig. 8, there are some regional-scale differences between the two patterns which had important implications for local climate anomalies. For example, the region of enhanced westerlies over the North Pacific along 30°N was located farther to the east during 1982-83 than in more typical events, bringing a series of damaging storms ashore onto the Southern California coast. The upper level anticyclone over Canada was farther to the southeast than usual, bringing mild winter temperatures to the Great Lakes and much of the northeastern United States whereas during the 1976-77 and 1977-78 Niño winters these regions suffered below normal temperatures. Even a partial understanding of these subtle distinctions between circulation patterns observed during individual El Niño episodes could contribute significantly to improving the skill of long-range weather forecasts.

The redistribution of equatorial precipitation during El Niño events impacts the planetary-scale circulation pattern not only at the jetstream level, but also at the earth's surface, as indicated in Fig. 2 by the arrow labeled C. Fig. 5 shows the 850 mb wind anomalies observed at three different stages during the 1982-83 Niño episode. (The 850 mb level is located about 1.5 km above sea-level and the wind anomalies there are at least qualitatively representative of the surface wind anomalies.) It can be seen that there is a consistent relationship between the OLR anomalies and the wind anomalies, with westerly wind anomalies in the equatorial belt near and just to the west of the region of enhanced rainfall and vice versa. A similar relationship has been observed in previous episodes [e.g., see Rasmusson and Carpenter (1982)], and it is consistent with the linear theory of equatorial waves [Matsuno (1966), Gill (1980)].

Atmospheric Forcing of the Ocean

The surface wind anomalies are the crucial link in the feedback from the atmosphere to the ocean, represented by the downward arrow labeled D in Fig. 2. Changes in zonal wind stress along the equator produce a strong response in the distribution of sea-level and surface and subsurface currents, and the ocean dynamics, in turn, has important implications upon biological productivity and fisheries and upon the distribution of sea-surface temperature, as indicated by the arrows labeled E and F in Fig. 2. Hence, we have come through a full circle in the sequence of atmosphere ocean interactions described in Fig. 2: the El Niño/Southern Oscillation phenomenon truly involves a two-way interaction between the two media. It is this close dynamical coupling that makes it such a challenging scientific problem.

I am sure that other speakers will elaborate further upon the oceanic aspects of this feedback loop. I will conclude by mentioning one other aspect of El Niño upon fisheries which is closely related to the main theme of this workshop. A pronounced El Niño signal has been found in sea-level, SST, currents, biological productivity, and fisheries recruitment not only in the equatorial belt, but also along the Pacific coast from Chile to at least as far north as California and perhaps farther. There are two possible mechanisms which may play a role in transmitting this signal from the equatorial belt to higher latitudes: (1) propagation of coastally trapped waves in the ocean, and (2) local forcing of coastal phenomena by anomalous surface winds associated with planetary-scale teleconnection patterns in the atmosphere. The latter mechanism should be largely restricted to the colder half of the year, when the atmospheric teleconnection patterns are relatively strong. Therefore, in order to explain apparent influences of El Niño upon fisheries in extratropical latitudes during summertime it is going to be necessary either to invoke the first mechanism, which can operate during any season, or to explain how the coastal ocean structure remembers the pattern imposed upon it by local winds during the previous cold season.

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Regional Atmospheric Forcing of Interannual Surface Temperature and Sea Level Variability in the Northeast Pacific

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Introduction

The variability of the sea surface temperature (SST) in the Eastern Subarctic Pacific Ocean has attracted a great deal of attention from oceanographers and meteorologists over the last three decades. This interest has been natural, since fluctuations in the SST in the waters off the west coast of North America may significantly influence the weather over the continent itself (e.g. Namias, 1976), and may also affect the migration patterns and oceanic survival of various fish species (e.g., Tully _et al_., 1960; Mysak _et al_., 1982). In the past few years there has also been much attention devoted to the interannual variations in sea level height (SLH) along the Pacific coast of North America (Enfield and Allen, 1980; Thomson and Tabata, 1981; Chelton and Davis, 1982).

There is a growing body of evidence connecting both the SST and SLH fluctuations in the Northeast Pacific with the familiar tropical Southern Oscillation (SO) phenomenon. It is now well established that a statistical analysis of data spanning many years will reveal a positive correlation between the SST in the tropical Eastern Pacific and that in the Northeast Pacific (e.g., Pan and Oort, 1983). It is also known that at least some of the major El Nino/Southern Oscillation (ENSO) events in the tropics were coincident with significant oceanic warmings and the occurrence of anomalously high SLH along the Pacific coast of North America. In particular, the mature phases of both the 1957-58 and 1982-83 ENSO events were accompanied by strong warmings in the Northeast Pacific (e.g., Tully _et al_., 1960; Tabata, 1983, 1984; Royer and Xiong, 1984).

Despite all of the research dealing with this subject, however, two important issues have still not been completely elucidated. Firstly, it is not clear how regular and predictable the relationship between ENSO events and the occurrence of anomalously high sea levels and SSTs in the Northeast Pacific really is.

In addition the actual mechanisms that may be responsible for producing a Northeast Pacific Ocean response to a tropical ENSO event are not completely understood. Enfield and Allen (1980) and Chelton and Davis (1982) have emphasized the possible role of coastally-trapped waves in propagating interannual signals generated in the tropics northward along the Pacific coast of North America. On the other hand tropical oceanic and atmospheric variations are known to be correlated with changes in the sea level atmospheric circulation in the Northeast Pacific region (e.g., Trenberth and Paolino, 1981; van Loon and Madden, 1981). Such variations in the extratropical atmospheric circulation could also significantly affect the oceanic conditions in the Gulf of Alaska (e.g., Haney et al., 1983).

The present brief paper reports on the results of an attempt to resolve these questions by means of a simple analysis of long time series of meteorological and oceanographic data. This investigation is described in more detail in Emery and Hamilton (1985; hereafter EH). As in EH, the present discussion will focus on results in the winter season (winter is the season with the largest interannual variability in both atmospheric and ocean surface conditions in the Northeast Pacific, e.g., Trenberth and Paolino, 1981; Namias, 1979).

Sea Surface Temperature Variations

Fig.1 shows the locations of the Amphitrite Point and Kains Island lighthouse stations for which long time series of SST data were available. The dashed curves in Fig.2 show the observed winter mean SST observed at the these two stations in a series of individual years (winter is defined as the period December through February; winter 1936 is December 1935-February 1936, etc.). Interannual variations of the order of 1-2°C are evident at both stations. Many of the peaks in these SST records coincide with the mature phases of ENSO events. Quinn et al. (1978) examined long historical records of tropical oceanographic and meteorological data and classified the intensity of various ENSO events as being weak, moderate or strong. In their view the onsets of strong ENSO events occurred in the years 1941, 1957 and 1972 (corresponding to mature phases in winter 1942, 1958 and 1973); moderate ENSO events began in 1939, 1953, 1965 and 1976 (i.e. mature phases in winter 1940, 1954, 1966 and 1977). Examination of Fig.2 reveals that the SSTs along the British Columbia coast were anomalously warm during the winters of 1940, 1941, 1954, 1958, 1966 and 1977, but were anomalously cold during winter 1973. Quinn et al. (1978) also identified 1943, 1951 and 1969 as onset years of weak ENSO events (mature phases in the winters of 1944, 1952 and 1970); only in the winter of 1970 is there a clear peak in the SST records shown in Fig.2. Thus it appears that, while there is a definite tendency for the occurrence of warm British Columbia coastal water to coincide with the mature phases of tropical ENSO events, this relationship does not hold for all ENSO episodes. It is also noteworthy that very warm winter SSTs are sometimes observed at the lighthouse stations

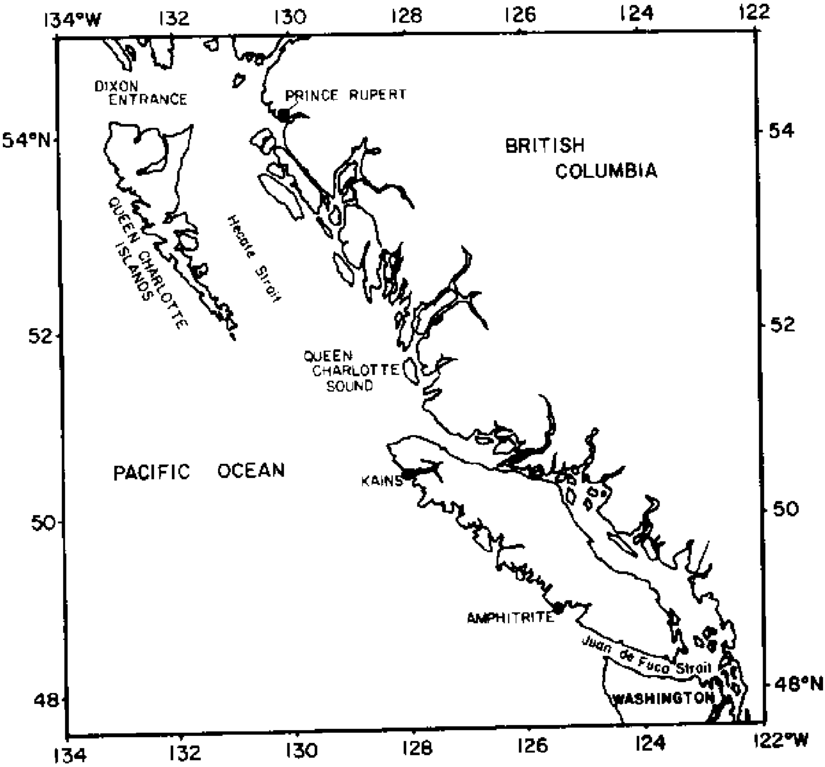

Figure 1. Map of the Canadian Pacific coast showing the locations of the stations from which oceanographic data were employed.

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at times unrelated to the occurrence of ENSO events (e.g., 1945, 1948, 1961, 1963, 1964).

In order to discover how these coastal SST variations might be related to the atmospheric wind forcing in the Northeast Pacific region, seasonal mean sea level atmospheric pressure (SLP) maps over the last half century were examined. These maps were produced from the daily digitized Northern Hemisphere SLP analyses assembled from various sources by the Data Support Section at NCAR (Jenne, 1975). The winter climatology computed from the data during the period 1947-82 is shown in Fig.3. The most prominent feature in the climatological SLP pattern is the Aleutian low which stretches from Kamchatka to the Alaskan Peninsula; the associated geostrophic surface winds are directed from the subtropical Pacific into the Gulf of Alaska. Examination of the SLP charts for the individual winters revealed that, when the atmospheric pressure pattern differs significantly from climatology, it tends to do so in one of two charcteristic ways. In some winters the Aleutian low has a similar shape and location

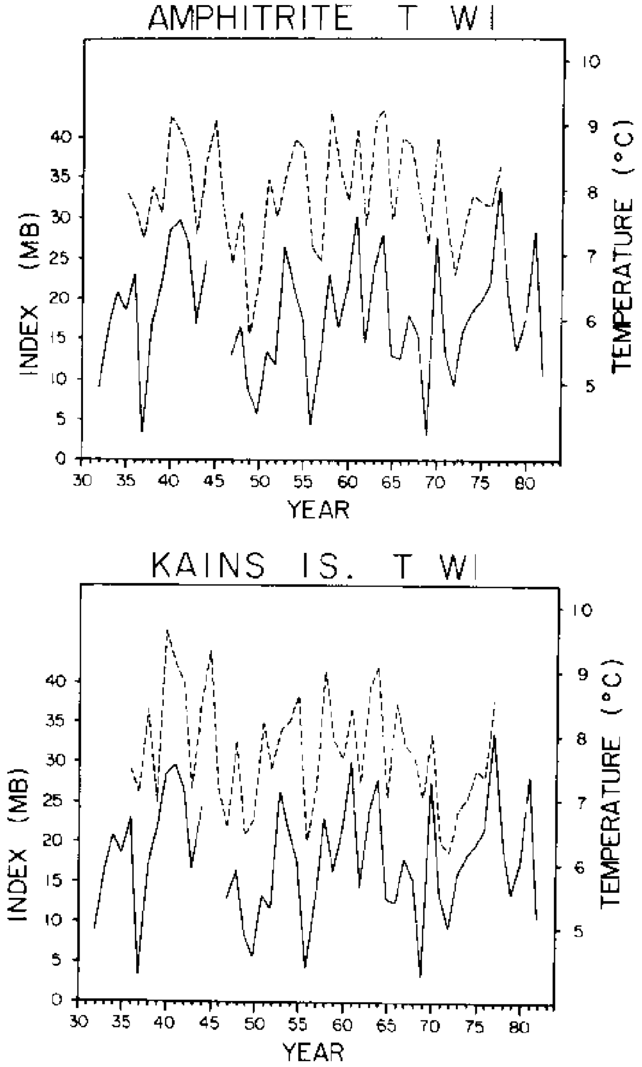

Figure 2. Time series of the Northeast Pacific winter pressure index (solid) and the observed winter mean sea surface temperature at Amphitrite Point (dashed upper) and Kains Island (dashed bottom).

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as in the climatology, but is more intense. In other winters the Aleutian low is significantly weaker than climatology; generally this is accompanied by a westward shift of the center of the low as well (more details concerning the characteristic variations of seasonal mean SLP can be found in EH).

Table 1. The correlation coefficients between seasonal mean coastal SSTs and the seasonal mean vaules of the Northeast Pacific atmospheric pressure index (NPI) as defined in the text. Values computed using data for the period 1947-1977.

Kains Island

	winter SST	spring SST	summer SST	autumn SST
winter NPI	.713	.594	.129	.047
spring NPI	--	-.250	-.208	-.334
summer NPI	--	--	.129	-.208
autumn NPI	--	--	--	.621

Amphitrite Point

	winter SST	spring SST	summer SST	autumn SST
winter NPI	.733	.487	.261	.145
spring NPI	--	-.074	-.112	-.338
summer NPI	--	--	.251	-.191
autumn NPI	--	--	--	.401

A simple index that reflects these characteristic fluctuations in the SLP was constructed by taking the difference in the seasonal mean pressure at 40°N, 120°W and that at 50°N, 170°W (grid points marked by dots in Fig.3). A large value of this index (designated the North Pacific Index or NPI) corresponds to an intense Aleutian low. The solid curves in Fig.2 show the NPI for each winter between 1932 and 1982. The similarity of the interannual fluctuations of the winter NPI and the winter SST at both Kains Island and Amphitrite Point is quite striking. Intense (weak) Aleutian lows are clearly associated with warm (cold) coastal SSTs. In EH North Pacific SST anomaly maps for individual winters were examined in conjunction with the corresponding SLP charts; EH concluded that the relation between the strength of the Aleutian low and the winter ocean surface temperature applies not only near the coast, but also as far west as 150°W.

Correlation coefficients between the seasonal NPI and lighthouse SST time series are presented in Table 1 (if each of the years can be regarded as providing an independent datum for each series, then correlations greater than .35 in this table are significant at the 95% confidence level). At both stations the winter NPI is well correlated not only with the winter SST, but also with the SST in the following spring (March-May). As noted in EH, these correlations are consistent with a view that interannual fluctuations of the SST in the eastern half of the Gulf of Alaska are largely produced by variations in the wind-induced surface layer horizontal advection. Thus in a winter with an anomalously intense Aluetian low, one can expect anomlously strong near-surface advection of warm water northeastward towards the British Columbia coast. This effect should be most important in winter, simply because the interannual fluctuations of SLP in the

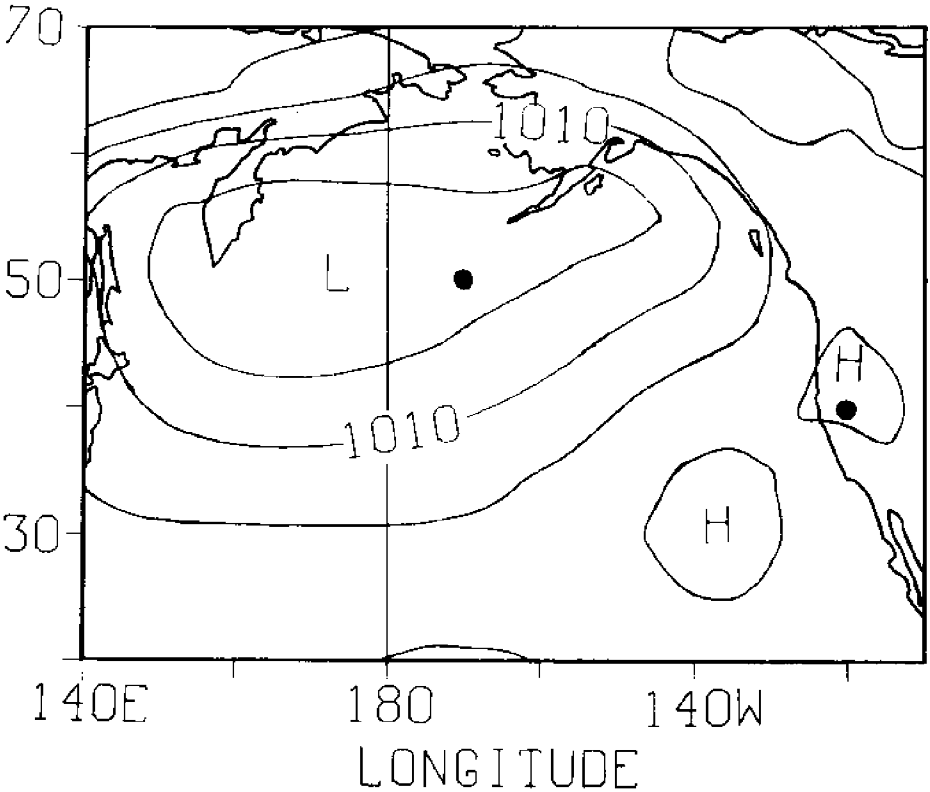

Figure 3. Mean sea level pressure during winter for the period 1947-82. The contour labels are in millibars and the contour interval is 5 millibars.

Northeast Pacific region are largest in winter (e.g., Trenberth and Paolino, 1981). The strong correlation of spring SST with winter NPI suggests that SST anomalies generated by the large anomalies occurring in the winter atmospheric circulation can persist for seasonal timescales. Correlations of the winter NPI with the SST in the following summer and autumn, while still positive, are quite small.

Examination of Fig.2 shows that the mature phases of ENSO events generally coincide with high values of the NPI (and thus with the occurrence of intense Aleutian lows). The statistical teleconnection between the Southern Oscillation index and the pressure in the Gulf of Alaska found by Trenberth and Paolino (1981) and van Loon and Madden (1981) presumably is largely a reflection of this general tendency. However, there are exceptions to this general rule, most notably in the winters of 1952 and 1973, when there were low values of the NPI and fairly weak atmospheric circulation in the Gulf of Alaska (see EH). It is noteworthy that the winters of 1952 and 1973 had anomalously cold SSTs along the British Columbia coast. These observations strongly suggest that the response of the Pacific coast SST to tropical ENSO events occurs largely via the atmospheric teleconnection that relates the strength of the Aleutian low to tropical atmospheric conditions. However, this atmospheric teleconnection appears not to function in a completely predictable manner; this explains why some ENSO events are not accompanied by warming of the British Columbia coastal waters. In addition, strong Aleutian lows certainly occur in winters unconnected with any tropical ENSO event; in such winters (e.g., 1961, see Fig.2) the surface waters in the eastern Gulf of Alaska are found to be anomalously warm.

Sea Level Height Variations

Winter mean SLH anomalies at various British Columbia coastal stations were also examined. In general there appeared to be good correlation between the SLH and the winter NPI, indicating that high coastal sea level is generally coincident with the appearance of an intense Aleutian low. This relationship is consistent with the most elementary conception of how the surface winds might affect the coastal SLH. In particular a strong Aleutian low will be accompanied by anomalously large northward surface wind stress throughout the Gulf of Alaska (or at least east of 150°W, see Fig.3). This should result in an anomalously large shoreward total mass transport, and presumably increased coastal sea levels.

As in the case of the coastal SST observations, the SLH data suggest that oceanic interannual variations along the west coast can be explained largely as a response to regional atmospheric forcing (at least in winter). The tendency for high British Columbia SLH to accompany the mature phases of ENSO events can then be explained as a consequence of the atmospheric teleconnection between the tropical Pacific and the Gulf of Alaska.

Conclusion

Striking empirical correlations were found between the strength of the Aleutian low and the British Columbia coastal winter SST and SLH. In particular, anomalously strong cyclonic atmospheric circulation in the Gulf of Alaska is invariably associated with warm coastal SST and high SLH. While it is true that warm SST and high sea levels are also generally associated with the mature phases of tropical ENSO events, this relationship is less regular and predictable than the connections with regional atmospheric forcing.

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El Niño Effects in the Kuroshio And Western North Pacific

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1. Introduction

The relationship between the El Nino events and the oceanic and atmospheric variations in the western North Pacific has been little studied. Only for the tropical region have variables such as sea level and wind stress been examined; it was shown, for example, that the sea level in the western tropical Pacific reaches very low values at the time of El Nino (Hickey, 1975; Wyrtki, 1977, 1979; Meyers, 1982). In the subtropical region, the flow pattern of the Kuroshio is highly variable (Fig. 1), these long-term variations appearing to be related to large-scale oceanic and atmospheric variations. However, no clear relation between Kuroshio variations and El Nino has yet been established. In this paper the observed variations of the Kuroshio path will be described in Sec. 3, and the oceanic and atmospheric variations in the western North Pacific, including the subarctic region, which seem to relate to El Nino events will be discussed in Sec. 4.

2. Data

Sea level, sea surface temperature (SST) and atmospheric temperature (AT) data were used. Daily mean sea levels at Kushimoto and Uragami (Fig. 2 shows locations) are published in <u>Tidal Observations</u> issued annually by the Japan Meteorological Agency (JMA). Monthly mean anomalies of SST in regions (2) and (A) (Fig. 3 shows locations) and of AT in the Hokkaido and Tohoku Districts, northern Japan (north of about 37^{o}N), were calculated by JMA. Also used were anomalies of SST in the eastern tropical region (H) from 1949 through 1982, analysed by Aoki and Yoshino (1984), and those from 1983 to 1984, calculated by JMA.

3. Long-term Variations of the Kuroshio Path

Flow of the Kuroshio south and east of Japan exhibits large changes over time (Fig. 1). East of Japan, the meandering flow of the Kuroshio Extension varies over the short term with the frequent formation of cold and warm eddies. South of Japan, from south of

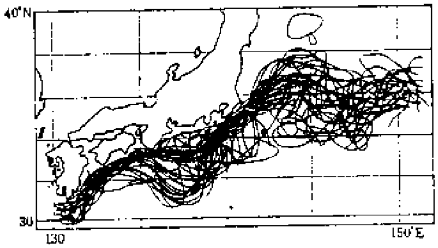

Fig. 1
Flow patterns of the Kuroshio from 1955 to 1964 (after Masuzawa, 1965).

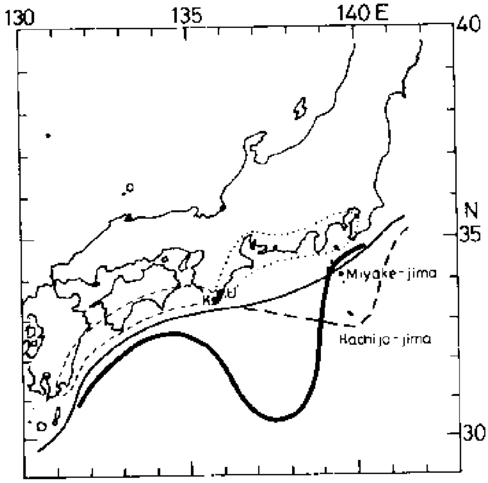

Fig. 2
Three typical paths of the Kuroshio: the large-meandering path (thick line), the nearshore small-meandering path (thin line) and the offshore small-meandering path (broken line). K and U indicate the sea level stations at Kushimoto and Uragami, respectively,

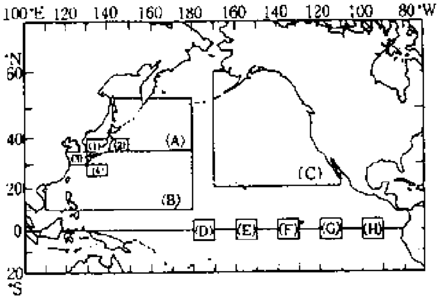

Fig. 3
Map of the regions where the SST data were averaged (after JMA, 1984).

Kyushu (about 131°E) to the Izu-Ogasawara Ridge (about 140°E), flow patterns are relatively regular and can be roughly classified into two stable types, the large meandering path (thick line in Fig. 2) and the small meandering path. The large meander persists for a few to 10 years and reappears after a similar long interval. This is the most conspicuous of the long-term oceanic variations near Japan. The small meandering path has two stable short-time types which persist for 1 to 7 months. One is the nearshore path along the south coast of Japan and passing Miyake-jima (thin line in Fig. 2); the offshore path passes south of Hachijo-jima (broken line in Fig. 2) (Kawabe, MS).

Periods of large meanders of the Kuroshio can be determined from coastal sea levels. Sea level variations at Kushimoto and Uragami reflect those of the regions to the west and east of these stations, as indicated in Fig. 2 by the areas surrounded by dashed and dotted lines (Tsumura, 1963; Kawabe, 1980a). These variations in the two areas are very different during small meanders and very similar during large. The sea level difference between Kushimoto and Uragami is a useful index of the large-meandering period of the Kuroshio (Moriyasu, 1958; Yagura and Goto, 1960; Tsumura, 1963; Okada, 1978; Kawabe, 1980a). From differences in daily mean sea level between Kushimoto and Uragami (in Fig. 4, the period of small differences and large meanders is underlined) and from Okada (1978) for earlier years, the following periods of large meanders have been identified:

Apr. 1906 - Sep. 1912 (6 years and 5 months)
Feb. 1917 - Mar. 1922 (5 years and 1 month)
Mar. 1934 - early 1944 (about 10 years)
Jul. 1953 - Dec. 1955 (2 years and 5 months)
May 1959 - May 1963 (4 years)
Aug. 1975 - Mar. 1980 (4 years and 7 months)
Oct. 1981 - Aug. 1984 (2 years and 11 months)

The large meander has been present for 35 years and 5 months in the period from 1895 to 1984, about 40% of the time.

Volume transport of the Kuroshio across lines south of Japan and in the East China Sea (Fig. 5) have been calculated by Nishizawa (1981) and Saiki (1984) (Figs. 6 and 7). They pointed out that during the large-meandering period the transport of the Kuroshio is small on the KG line along 137°E and large on the KB line in the East China Sea. This out-of-phase of transport variation can be also seen from the figures in Nitani (1972); its reason has been discussed (Konaga _et al_., 1980; Kawabe, 1980b) but is not yet understood clearly. The transport of the Kuroshio across the KG line decreases from 1969 to 1971 significantly. This may correspond to the brief large meander which was almost formed in 1969 but was not stable and so is not ordinarily classed as a large meander. The variation of Kuroshio transport has periods of 3-4 and 7-8 years in the region around the KF and KG lines (Minami _et al_., 1978) and of 5.5 and 8 years on the KB line (Saiki, 1982). The dotted line in Fig. 7 indicates the composite of the 5.5- and 8-year variations.

4. Oceanic and Atmospheric Variations in the Western North Pacific and Niño Events

Tropical region (south of about 15°N).

Vertical distributions of temperature and salinity along 137°E in January are shown in Fig. 8. At low latitudes the volume of warm

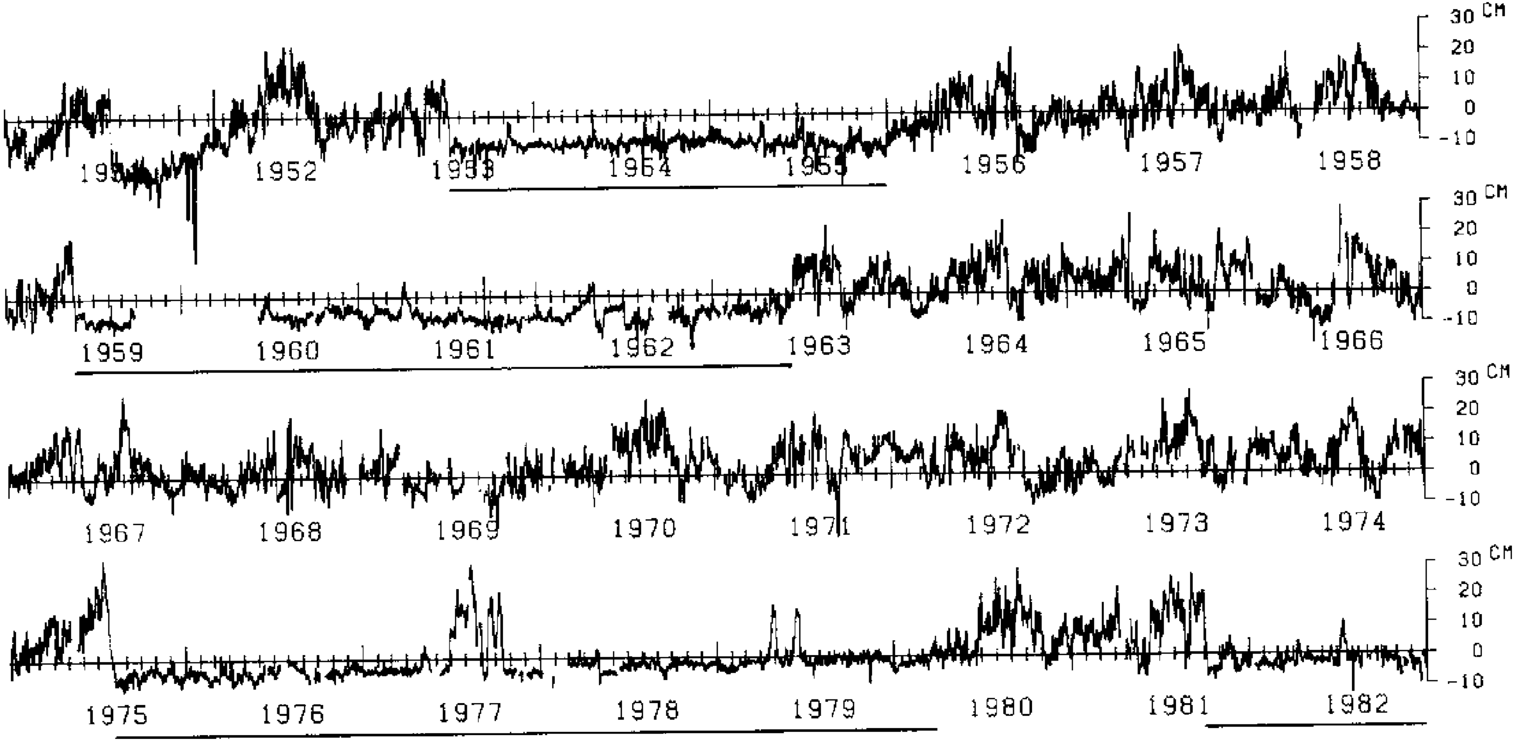

Fig. 4 Differences in daily mean sea level between Kushimoto and Uragami from 1951 through 1982 (Kushimoto minus Uragami). The mean value for the 32-year period is taken as the zero point of the ordinate. Underlining indicates the large-meandering periods of the Kuroshio.

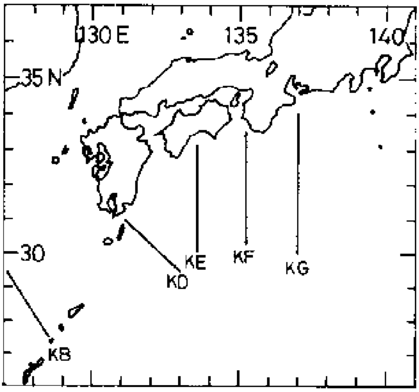

Fig. 5
Locations of the observation lines for the estimate of Kuroshio transport.

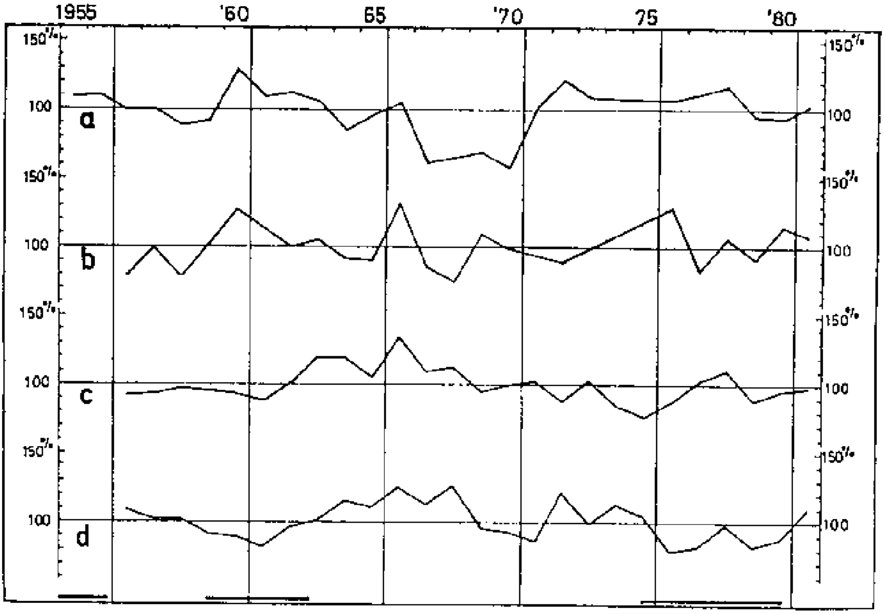

Fig. 6 Volume transport of the Kuroshio south of Japan calculated with reference to 1000 db and normalized by the mean value in each season (after Nishizawa, 1981); (a) KD line, (b) KE line, (c) KF line and (d) KG line. Solid bars in the lowest part indicate the large-meandering periods of the Kuroshio.

water above 28°C increased in 1970, 1971, 1972, 1974, 1976 and 1982, extending meridionally to about 13°N and vertically to near 100 m. Thus it appears that warm water accumulates in the surface layer prior to the El Nino events of 1972, 1976 and 1982, and that the volume of warm water then decreases during El Nino, although this is not so clear for the 1969 event. The large accumulation of warm

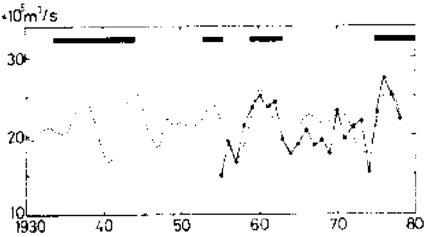

Fig. 7
Annual mean volume transport of the Kuroshio across the KB line in the East China Sea referred to 700 db (solid line), the composite of 5.5- and 8-year variations which are dominant in the transport variation shown by dotted line and the large-meandering periods of the Kuroshio (bars) (after Saiki, 1982).

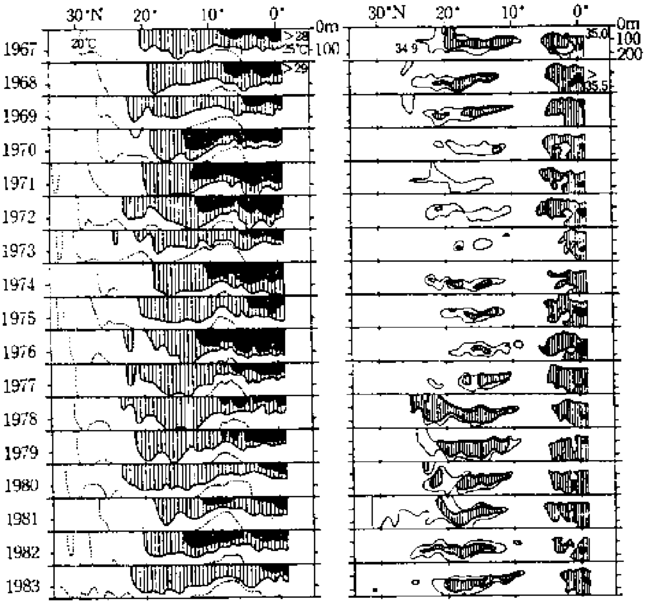

Fig. 8 Vertical distributions of temperature (29, 28, 25, 20°C) and salinity (35.5, 35.0, 34.9%) in the surface layer along 137°E in January, 1967 to 1983 (after JMA, 1984).

water corresponds to high sea level (Nagasaka, 1981). In the western equatorial region, water temperature at a depth of 50 to 100 m correlate more closely with Nino events than does the sea surface temperature (Japan Meteorological Agency, 1984).

The variation of salinity distribution is more evident in the region from 10° to 20° latitude than near the equator. The volume of saline water north of 10° is very small from 1970 to 1977, especially from 1970 to 1973, but there is no obvious relation between the salinity variation and El Nino.

Subarctic region (north of about 35°N).

Figure 9 shows monthly mean anomalies of sea surface temperature

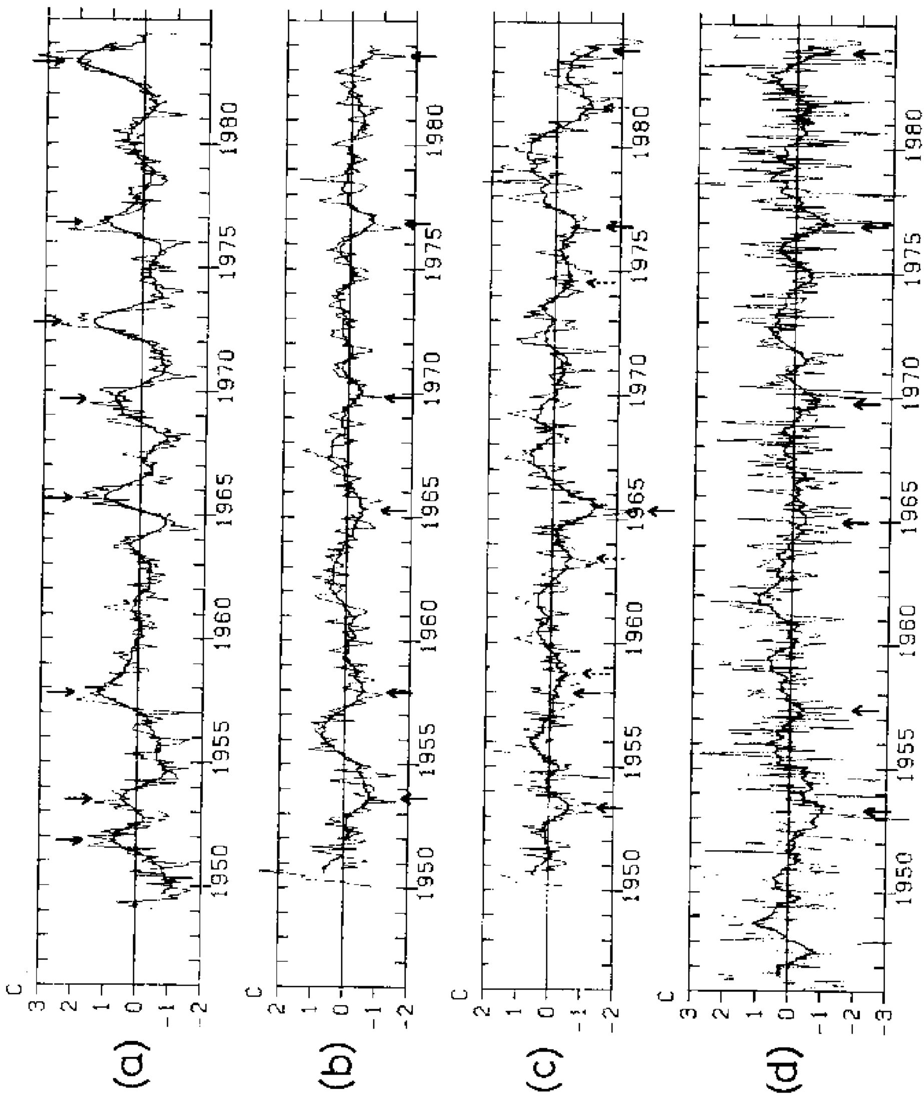

Fig. 9 Monthly mean anomalies of SST and AT from the seasonal variation. (a) SST in the eastern tropical region (H), (b) SST in the western subarctic region (A), (c) SST in the Oyashio region east of Japan (2), (d) AT in the Hokkaido and Tohoku Districts in northern Japan, north of about 37°N. Thick lines indicate 12-month running means. Downward arrows in (a) indicate the El Nino events, and upward solid arrows in (b), (c) and (d) indicate low temperature corresponding to the El Nino events. Upward dotted arrows in (c) indicate minima which do not correspond to El Nino and cannot be seen for SST in region (A).

(SST) from the seasonal variation in the region (H) (5^oS - 5^oN, 90^o - 100^oW), (A) (35^o - 53^oN, 130^o - 180^oE) and (2) (35^o - 40^oN, 140^o - 150^oE) and the anomalies of atmospheric temperature (AT) in the Hokkaido and Tohoku Districts, northern Japan (Fig. 3 shows locations). Eight SST maxima in region (H), indicated by arrows, correspond to the Nino events: 1951-1952, 1953, 1957-1958, 1965, 1969, 1972-1973, 1976-1977 and 1982-1983 (Fig. 9a). High SST in the region (H) also appears in 1980 which is as high as in 1953, but it is not regarded as a Nino event. The most remarkable feature is that SST in the regions (A) and (2) and AT in the northern part of Japan were low during Nino events. Low SST in region (A) occurred in 1953, 1957-1958, 1965, 1969-1970, 1976-1977, 1980-1981 and 1983 (Fig. 9b). The 6 minima, except for that in 1980-1981 were at the time of El Nino, and low SST in 1980-1981 may correspond to the high SST in the region (H) in 1980. However, SST was not low at the time of El Nino in 1951-1952 and 1972-1973. AT in the northern part of Japan was clearly low in 1947, 1952-1954, 1957, 1964-1965, 1969-1970, 1974, 1976-1977, 1981 and 1983 (Fig. 9d). Among these minima, except for that in 1947, low AT in 1974 and 1981 does not correspond to El Nino, but the other 6 minima occurred during Nino events and low SST in the region (A). Thus, low SST in the western subarctic region (A) and low AT in the northern part of Japan correlate clearly with most Nino events (1953, 1957-1958, 1965, 1969, 1976-1977 and 1982-1983 events), with the exception of the events in 1951-1952 and 1972-1973.

A similar relation can be seen for SST in the Oyashio region (2). SST in region (2) is low at the time of El Nino in 1953, 1965, 1976-1977 and 1983, though it is not always low at the time of El Nino (only slightly low in 1957-1958 and not low in 1951-1952, 1969 and 1972-1973) (Fig. 9c). Besides these minima, there are four significant minima in 1958, 1963, 1974 and 1981 that do not correspond to the El Nino events. Since these minima are not evident in region (A) SST, they are thought to be caused by spatially limited phenomena.

Variation of the southernmost extent of the Oyashio water is also informative (Fig. 10). The remarkable southward shift of the Oyashio water in 1958, 1963, 1973-74 and 1981 corresponds well to

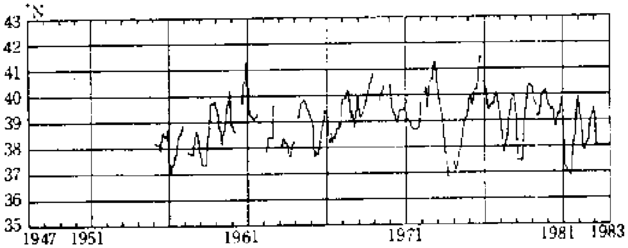

Fig. 10 5-month running means of the southernmost latitude reached by Oyashio water as indicated by 5°C isotherm at a depth of 100 m (after JMA, 1984).

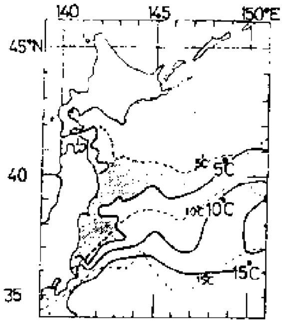

Fig. 11
Temperature distribution at a depth of 100 m in early May, 1984 (after Saiki, 1984a). Shaded area is the region below 5°C. Broken lines indicate the mean isotherms averaged from 1965 to 1983.

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the 4 SST minima found only in region (2) (the southward shift in 1956 and 1978 does not relate to low SST). The largest southward extension of the Oyashio water occurs from the end of 1983 to 1984 (Fig. 11; Saiki, 1984a) and corresponds to extremely low SST in region (2). Southward shift of the Oyashio water can be considered as one of the causes for low SST in region (2) not related to El Nino.

Power spectra of the time series in Fig. 9 are shown in Fig. 12. The dominant periods being significant at the 90% level are the 3.6-year period for SST in the region (H), the 6.1-year period for SST in the regions (A) and (2). Other apparent peaks are not statistically significant.

The 6.1 year SST variation in region A is highly coherent with variations of the same period of AT in the northern part of Japan (significant at the 99% level) and of SST in region (2) (significant at the 95% level), with little difference in phase. The 6.1 year SST variation in region H is not so highly coherent with those of the other time series, but is highly coherent at the 7.1 year period (close to the 80% significance level). The phase of the 7.1 year SST variation in region H lags SST in region A by 0.86 π, SST in region (2) by 1.16 π and AT in northern Japan by 0.92 π, thus is almost opposite in phase to the other three variations. This relates to the low SST and AT in the western subarctic region during El Nino as suggested in Fig. 9. Dominance of a 6 year period is also reported for variation of water temperature in the eastern channel of the Tsushima Strait (Miita and Tawara, 1984). Besides, SST in region H is highly coherent with SST in region A at the 2.1 and 3.9 periods with a phase lag of 0.95 π and 0.88 π and with SST in region (2) at the 1.9 and 3.9 year periods with a phase lag of 1.42 π and 0.57 π above the 90% level. Moreover, it is also coherent with AT in northern Japan at the 3.6 and 1.8 year periods with a phase lag of 0.41 π and 0.43 π above and close to the 80% significance level, respectively.

Subtropical region (15°N - 35°N)

Oceanic and atmospheric variations in the western subtropical region show no obvious relation with the El Nino events; for example, SST

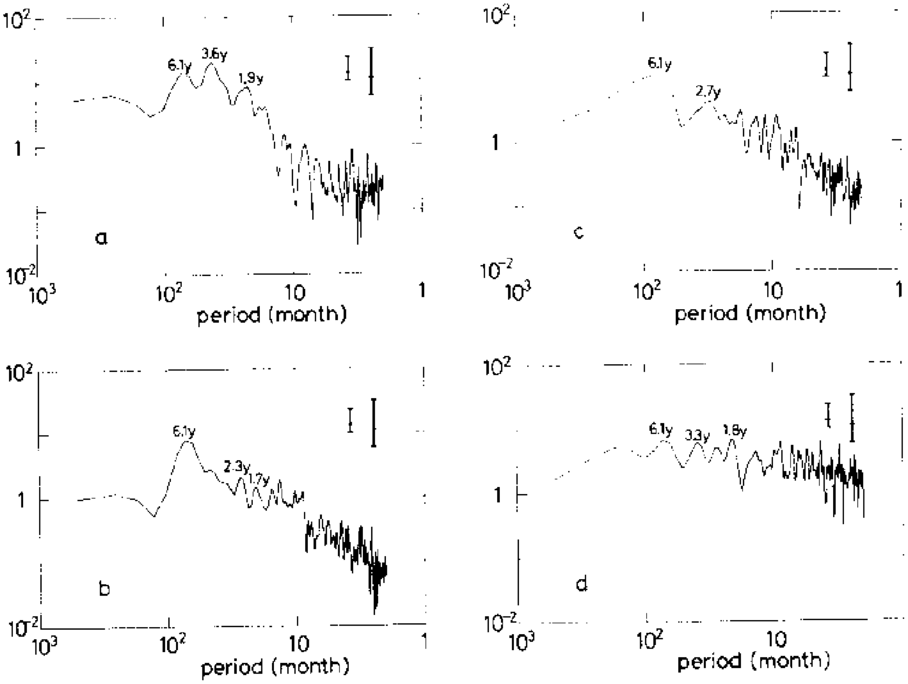

Fig. 12 Power spectra of the time series in Fig. 9 (°C^2 month). The data in the following periods were used; (a) Jan., 1949 - May 1984, (b) Jan. 1950 - Dec. 1983, (c) Jan. 1950 - May, 1984 and (d) Jan. 1946 - Jul. 1984. The vertical bars in the right upper portion indicate the 60% and 90% confidence intervals.

in the region (3), (4) and (B) (Fig. 3 shows locations), AT in the southern area of Japan and wind stress in small grids. However, one interesting relation is indicated by Saiki (1984b) who showed the variation of strength of the Ogasawara High (western part of the Pacific High), to correspond to the strength of the Trade Wind (Fig. 13). The Ogasawara High is weak before El Nino event and strengthens after its occurrence, while the large meander of the Kuroshio occurs within 1 or 2 years after the rapid increase of strength of the Ogasawara High in 1950-1951, 1957 and 1974, and disappears as this High weakens. The short-time meander in 1969, mentioned above, may also relate to the rapid increase in 1968.

The spectrum of occurrence of the large meander in the Kuroshio is shown in Fig. 14. The dominant period is about 20 years, and noticeable but statistically insignificant peaks can be seen at 3.4 and 8.5 years. The latter periods are similar to periods of the Kuroshio transport south of central Japan, indicated by Minami et al (1978), and the 8.5 year period is also almost the same as a dominant period in the Kuroshio transport in the East China Sea, indicated by Saiki (1982). Its coherence with SST in the region (H)

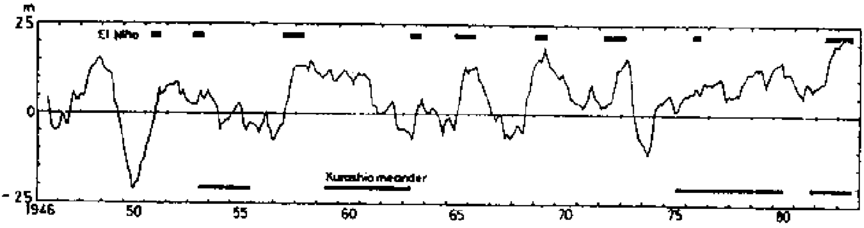

Fig. 13 12-month running means of 500 db height averaged in the region of 20° - 30°N, 130° - 170°E, an index of strength of the Ogasawara High (after Saiki, 1984b).

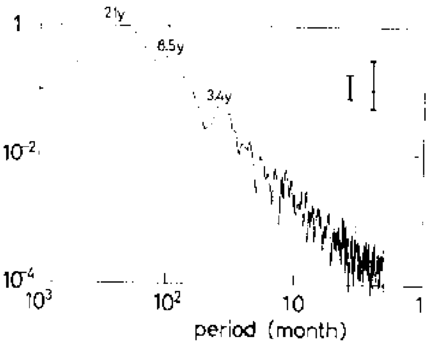

Fig. 14
Power spectrum of the occurrence of the large meander in the Kuroshio (Sept. 1897-Dec. 1982), normalized by the maximum power. The vertical bars in the right upper portion indicate the 60% and 90% confidence intervals.

is above the 90% significance level at the period of 3.3 - 3.6 years and above the 80% level at the 8.5 year period. This suggests the possibility of a connection between El Nino and the large meander of the Kuroshio with a period of about 3.5 years.

5. Discussion

Some relations between El Nino and water temperature in the surface layer of the western tropical region and SST and AT in the western subarctic region are presented in this paper. The relation is less obvious for oceanic variations in the western subtropical region. It is noteworthy that the relation with El Nino seems to be more pronounced in the subarctic region than in the subtropical region, despite the greater distance from the tropical El Nino region.

The 3.5 - 3.6 year variation is dominant for SST in the region (H), reflecting the occurrence of El Nino; there are small peaks of this period in AT in northern Japan and in the occurrence of the large meander in the Kuroshio, these being highly coherent. Okada (1981) pointed out that cool summers and bad crops occur in the Tohoku District in the years near the generation and disappearance of the large meander in the Kuroshio. The cool summers and bad crops must be connected closely to low AT in the Hokkaido and Tohoku Districts which occurs mostly at the time of El Nino. Thus there may be some connection between El Nino and the large meander of the Kuroshio.

There are other spectral peaks, such as those at 6.1 and 8.5 years that while not statistically significant relate to significant variations in relevant regions and variables. For example, the 6 year variation is dominant for SST in the western subarctic region and the 8 year variation is dominant in Kuroshio transport. It is important to examine the characteristics of these long term variations through further analysis of suitable long time series since these variations can be expected to have Pacific or world-wide dimensions and to play an important role in global teleconnections.

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The 1982–83 El Niño Event off Baja and Alta California And Its Ocean Climate Context

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Introduction

The 1982-83 El Nino brought extremely warm water to the coast of Alta and Baja California as part of one of the most intense ocean-atmosphere events of the century. This report describes this event in terms of surface and subsurface temperature, sea level, and large scale atmospheric pressure changes. The 1982-83 event is examined as part of the continuum of events occurring over the past 13 years (1971-83), a period containing two other tropical El Ninos (1972-73, 1976-78) and two California warming events seemingly unrelated to tropical warmings (1979-80, 1980-81). The 1976-77, 1977-78, 1979-80, 1980-81, and 1982-83 winters have been warmer than normal. Consequently, the period before 1976 was anomalously cool compared to the 13 year mean. These interannual variations are discussed in terms of physical characteristics of the California Current System and associated coastal upwelling, which are the predominant ocean features within 1000 km of the coast. The extreme nature of the 1982-83 event is examined by comparison with other winters of the series. Time-distance contour plots are used to graphically interpret interannual variations over the 13 year period and over the 2123 km distance from the southern tip of Baja California to the Alta California northern border.

The oceanographic term "El Nino", historically, has been applied to ocean surface warming events in the equatorial Pacific off the coasts of Peru and Ecuador. These events generally begin during the Christmas season. Hence, the Spanish words El Nino refer to the Christ Child. Since El Nino lasts through the northern winter, common terminology refers to two or more calendar years. More recently, El Nino became a generic term describing anomalous warm events in eastern boundary current regions of the world's ocean (Wooster 1960). Current understanding is that El Nino is part of a global ocean-atmosphere perturbation called "El Nino-Southern Oscillation" (ENSO) (Quinn 1974, Rasmusson and Wallace 1983). The Southern Oscillation is a quasi-periodic cycle (2-10 years) observed in the atmospheric pressure differences between Pacific and Indian Oceans and the Tahiti minus Darwin, Australia sea level pressure difference is a commonly used Southern Oscillation Index (SOI). Bjerknes (1969) found that El Nino events occur as the trade winds relax and the SOI drops sharply.

ENSO may include the tropical El Nino (TEN) and a California El Nino (CEN). Like the TEN, the CEN is characterized by warming in the coastal ocean's surface layers and both warm events may be synchronous. Other oceanic warming events also occur along the greater California coast (see below). These are mid-latitude warm (MLW) events. CEN events occur in concert with the TEN events: MLW events do not.

Major Geographic and Oceanic Features

The coast of Baja and Alta California extends 19.1 degrees of latitude from Cabo San Lucas at 22.9°N, to the northern California border at 42°N. East to west, the distance from Cabo San Lucas at 109.9°W to Cape Mendocino at 124.4°W is 14.5° (1363 km). In the following "California" refers to Alta California (USA).

The California Current transports cool, low salinity subarctic water southward along the greater California coast (Sverdrup, et al. 1942, Reid et al. 1958). Warmer, more saline, eastern North Pacific Central Water lies west of the California Current creating a positive temperature gradient from east to west as well as north to south. Consequently, warming along the coast can result from local heating and/or increased transport from the south and/or west.

Off central, southern and Baja California, a countercurrent flows northward inshore of the southward flowing California Current where it frequently becomes the dominant nearshore circulation feature (Wooster and Jones 1970, Wickham 1975). North of Pt. Conception, the surface countercurrent is generally most intense in late fall and winter (34.3°N). However, recent studies by Wickham and Tucker show countercurrent activity throughout the year during the warm 1978-80 period (Bird et al. 1984). South of Point Conception, the countercurrent is an important nearshore feature throughout the year, but it is not necessarily continuous with the surface Counter Current to the north (Reid 1960). The California Current System is characterized at depth by a weak poleward countercurrent having maximum speed and persistence over the continental slope. The California Current thickens seaward of 200 km resulting in a deeper countercurrent (Reid 1965, Hickey 1979).

The California Current System's western edge is a broad complex transition zone joining the subarctic transition on the north to the subtropical transition on the south as shown in Figure 1 (Saur 1980, Bernal and McGowan 1981).

Upwelling, caused by northerly winds and resulting offshore Ekman transport is a dominant oceanographic process in spring and summer along the entire California and Baja California coast (Sverdrup et al. 1942). Cooler, higher salinity subsurface waters are brought to the surface in a relatively narrow coastal band and then mixed and carried offshore by other advective processes (Smith 1968, Hickey 1979). The resulting density distribution enhances southward California Current flow. Upwelling occurs year-round off Baja California under the influence of the North Pacific High pressure system. Off central and northern California, however, the atmospheric high weakens and moves south in the winter as the Aleutian Low pressure system intensifies. The winds off central and northern California reverse as these pressure systems change. Downwelling occurs in winter under southerly winds asso-

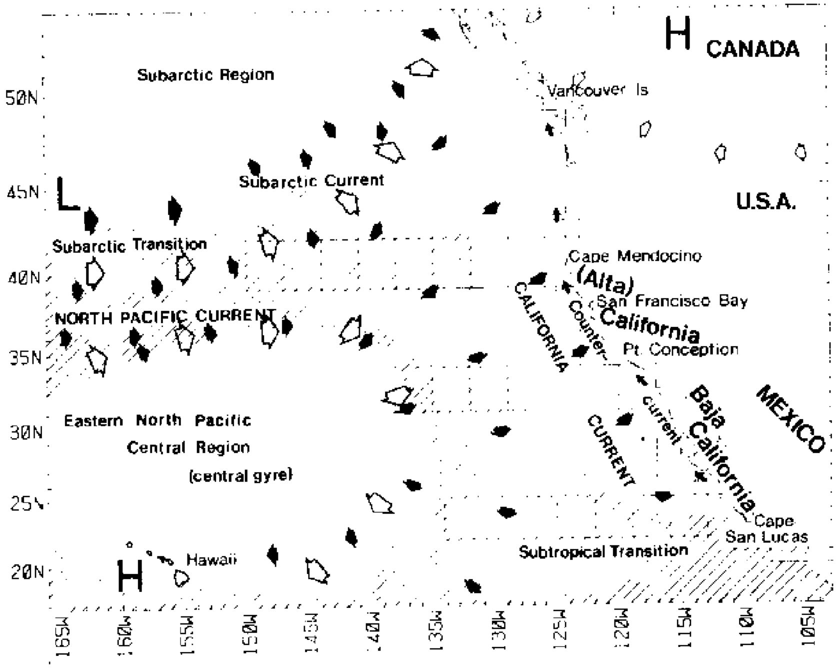

Figure 1. Schematic representation of northeastern Pacific Ocean climatology showing surface winds (open arrows), surface currents (solid arrows), and dominant atmospheric pressure systems: Aleutian Low, North Pacific High, and North American High. Letters "H" and "L" are near centers of action defined by Wallace and Gutzler (1981). Subarctic, California Current and Subtropical transition zones are indicated by hatching. Also shown are locations of $3^o x 3^o$ areas where surface and subsurface temperature are summarized.

ciated with intensified Aleutian Low, deepening the mixed layer and facilitating poleward flow along the coast.

Connections Between Tropical and California El Niños

El Nino years on the California coast coincide with El Nino years along the South American coast because of energy transfer from the tropics to mid-latitudes by both oceanic and atmospheric processes. Each process has received considerable attention in the literature (McCreary 1976, Picaut 1984, Rasmusson and Wallace 1983, Wallace and Gutzler 1981).

Tropical El Nino's are associated with slackening of trade winds blowing from east to west over the tropical Pacific. As the trade winds relax, the Southern Oscillation Index (SOI) falls, and even reverses, resulting in a downwelling disturbance which propagates eastward toward South America with characteristics of an equatorially trapped Kelvin wave (Halpern et al. 1983, Cane 1983). The energy transfer that occurs along the equator is the result of the radiation of many Kelvin waves that superimpose to form a beam of energy that propagates eastward and downward (Picaut 1984). When the eastern boundary is reached, poleward and downward-propagating, coastal Kelvin waves are formed. These Kelvin wave packets bring downwelling perturbations to the California coast. This wave energy with subsequent advective adjustment can produce a remotely forced CEN event. This is consistent with subsurface temperature observations from the California coast shown below.

The atmospheric connection to mid-latitudes involves a mechanism originally postulated over fifty years ago by Walker (Rasmusson and Wallace 1983). As the Kelvin wave propagates eastward along the equator, it is accompanied by anomalously high sea surface temperature (SST). Through evaporation and condensation processes, the warm water transfers increased energy to the atmosphere. This energy appears to set up a quasi-stationary tropospheric wave pattern as it propagates northward in great circle arcs (Wallace and Gutzler 1981, Horel and Wallace 1981). In this way, extensive tropical SST anomalies can be teleconnected to mid-latitudes through the atmosphere, altering wind forcing on the eastern subtropical Pacific, thousands of miles to the north (Bjerknes 1969, Quiroz 1983, Pan and Oort 1983). These teleconnections appear most significant in winter and their impact at mid-latitude depends upon ongoing subtropical processes (Wallace and Gutzler 1981, Rasmusson and Wallace 1983, Haney 1984).

The Pacific/North American (PNA) Index was developed to measure tropical to mid-latitude teleconnection (Wallace and Gutzler 1981). This index is derived from a linear combination of 500 millibar atmospheric height anomalies at "centers of action" along the great circle standing wave pattern from the tropics through the North-Pacific High, Aleutian Low, North American Continental High and Florida Low pressure systems. Each is intensified by the standing wave, so that higher highs and deeper lows will contribute positively to the index value. Three of these pressure systems are indicated schematically in Figure 1.

Horel and Wallace (1981) have presented important correlations between the PNA pattern and TEN activity. However, Douglas et al. (1982) point out that PNA type circulation can occur without TEN as it did in the winters of 1958-59, 1960-61, 1962-63, 1967-68, 1979-80 and 1980-81. Conversely, the intense TEN of 1972-73 occurred without a fully distinctive PNA pattern. It is probable that tropical forcing through the PNA pattern has maximum effect when in phase with pressure patterns brought about by complementary subtropical processes (Rasmusson and Wallace 1983). There also seems to be a time lag in the atmosphere's response to equatorial SST forcing (Pan and Oort 1983). The 1982-83 ENSO brought extreme El Nino conditions to the eastern tropical Pacific and the characteristic PNA pattern was formed over the North Pacific (Rasmusson and Wallace 1983, Halpern et al. 1983, Toole 1984).

Data Sources and Methods

El Nino is of large space and time scale and thus we based our analyses on historical data files of weather observations and ocean temperature profiles. The data were averaged by month for 3° longitude-latitude areas.

Surface and subsurface temperature and atmospheric pressure data were obtained from the archives of the U.S. Navy Fleet Numerical Oceanography Center in Monterey, California (FNOC). Sea surface temperatures (SST) were obtained from the file of surface marine weather observations received in real-time at FNOC. The wind speed and upwelling index data were derived from the 6-hourly northern hemisphere pressure analyses (Bakun 1973, 1975).

The SST data were averaged by month in 1° latitude-longitude areas and then further aggregated to provide means for the 3° latitude-longitude areas in transects along the coast and westward from the coast (Figure 1). The total number of observations in the study area for the 1971-83 period exceeded 300,000. Over half of the observations were taken within 100km of the coast. Monthly means for SST may represent several thousand values depending on location.

Subsurface temperature profiles were taken from the FNOC Master Oceanographic Observations Data Set, which is an archive of bottle casts, mechanical and expendable bathythermographs, and CTD casts. Although the number of subsurface observations is an order of magnitude less than that of surface observations, the improved accuracy of the individual observations yields a more accurate data set.

Sea level data for tide stations along the west coast of the United States were obtained from Mr. Ray Smith of the National Ocean Survey, Rockville, Maryland. Sea level data for two Canadian stations were obtained from Dr. S. Tabata, Institute of Ocean Science, Sidney, British Columbia and data from Baja California were obtained from Ing. Francisco Grivel Pina, Instituto de Geofisica, Mexico, D.F. Monthly means of sea level were computed from daily values.

Time-distance plots of the variables under study were produced to display large-scale fluctuations in time and space (e.g., Figure 2a). In each plot, time is on the horizontal axis with years and months indicated. The vertical axis is distance, either along the coast (as in Figure 2a) or offshore (as in Figure 4a). The monthly mean values are contoured allowing objective assessment of major patterns. Each contour line is interpreted as the excursion of an isopleth through time and space. Areas north of California and south of Baja California are often included in alongshore plots to allow greater spatial continuity of features. Anomalies of variables from the long-term mean were computed and plotted in time-distance form (as in Figure 2b) to show interannual changes.

Sea Surface Temperature

Figure 2a is a time-distance plot of sea surface temperature along the coast from south of the tip of Baja California to Vancouver Island. A pronounced annual cycle is shown by the large excursions of each contour line (isotherm). Farthest northward isotherm extension or maximum SST occurs in summer and fall. Minimum SSTs, as shown by farthest southward isotherm excursions, occur in winter or spring. Isotherms at higher latitude have larger annual excursions, eg. the 12°C isotherm crosses 12-18 degrees of latitude while the 20°C isotherm has about half this latitudinal excursion. The subtropical transition zone off southern Baja California is shown by the denser packing of isotherms south of 29°N. Interannual spatial variation in SST is weak south of 23°N.

The extreme nature of the 1982-83 CEN is reflected in the 16°C isotherm which extended as far north as San Francisco (37.8°N) in October 1983. This extension was unprecedented in the previous 11 years and represents an anomaly of 1.2-2.0°C or 2 to 2.2 times the between-year standard deviation (sdu) for that month and latitude. The minimum SST

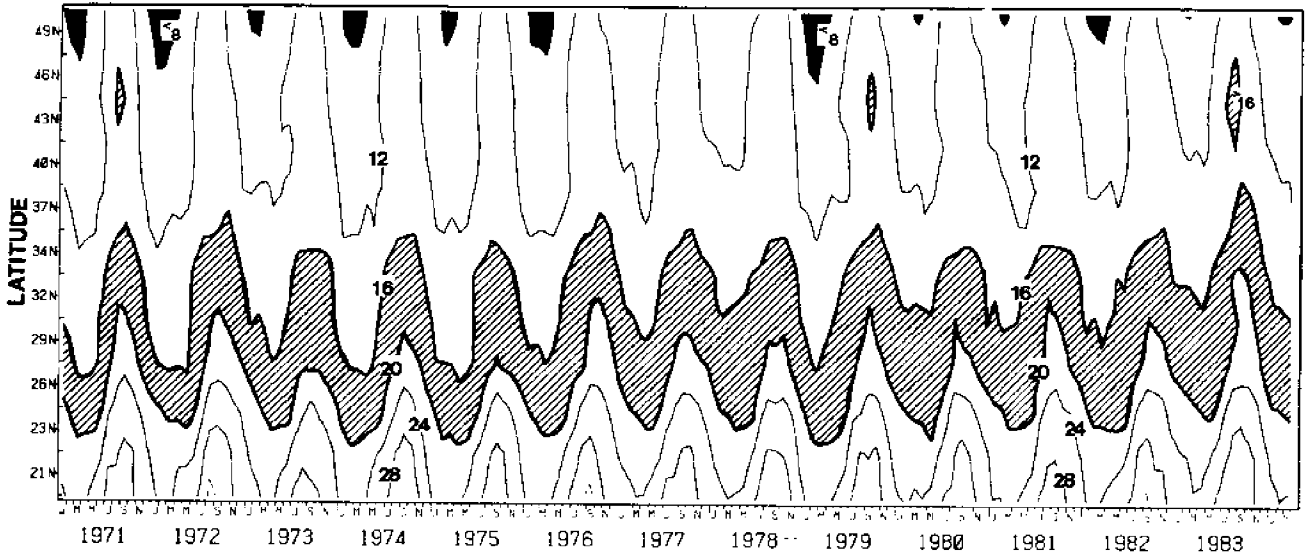

Figure 2a. Time-distance contour plot of monthly mean sea surface temperature (^oC) at 12 $3^o \times 3^o$ blocks of latitude and longitude on the alongshore transect from Baja California to Vancouver Island. Values are mean SST for $3^o \times 3^o$ blocks of sub-means for 1^o blocks. Contour interval is 4^oC.

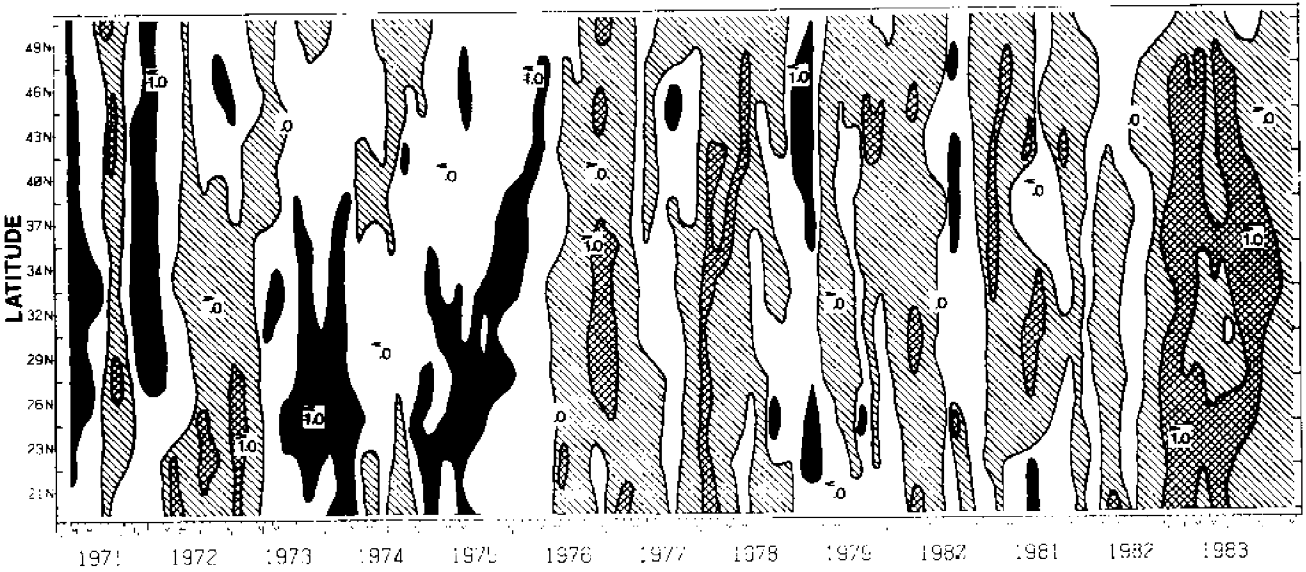

Figure 2b. Anomaly of monthly mean sea surface temperature on alongshore transect from Baja California to Vancouver Island. Hatched areas indicate anomaly between 0 and +1°C and cross-hatched areas greater than +1°C. Unshaded areas indicate anomaly between 0 and -1°C and areas shaded black anomaly less than -1°C. Block locations are the same as in Figure 2a.

during the previous spring was much warmer than usual. The maximum SST during fall 1982 was unusually high, equalled only by the fall seasons of 1979, 1976 and 1972, a MLW and two CEN years, respectively. Water of greater than 16°C was also present in an unusually large closed cell near 43°N. Warmer winters since 1976 are indicated by the reduction in areas less than 8°C near 49°N and by the greater distance between the 16°C and 20°C isotherms off Baja and southern California (23° -34°N). The maxima of the 20°C isotherm tend to follow those of the 16°C isotherm, but the 20°C minima are much more stable, causing the 16°-20°C band to widen in winter (Figure 2a).

The extreme nature of the 1982-83 event becomes more evident when the annual cycle is removed by taking anomalies from monthly mean values (Figure 2b). Areas representing anomaly greater than 1°C have wider meridional distribution and persist longer during the 1982-83 event than in any of the other warm events during 1971-83. The CEN winter of 1976-77 shows a comparable pattern. Figure 2b shows that during 1982-83, anomaly exceeding 1°C appears as two vertical bands connected at 24°N and 36°N by persistent periods lasting from November 1982 through November 1983. These vertical bands represent almost simultaneous occurrence of the anomaly over the range from 29°N to 49°N. Anomalies greater than 1°C occur first in the subtropical transition. The extreme anomaly (2.0°C or 2.0 sdu) south of 29°N represents a northward shift of the 20°C isotherm due to decreased or displaced input of cooler California Current water. Because of the steep SST gradient in the subtropical transition, a small geographical change in isotherm position will create relatively large anomalies. The area of anomaly persistence near 36°N on the central California coast probably reflects a relatively large decrease in seasonal upwelling and climatological tendency toward negative wind stress curl at these latitudes (Nelson 1977). Increased input of offshore water into the coastal region north of 46°N may have been responsible for persistence of the anomaly greater than 1°C in these areas.

CEN warming effects were partially negated in spring and summer 1983 by spring upwelling when anomalies remained positive but less than 1°C. Maximum SSTs normally occur in the inshore California Current System in the fall when both the California Current and the countercurrent are near minimum intensity and insolation has had maximum effect (Sverdrup et. al. 1942, Reid et al. 1958). The second period of extreme anomaly corresponds to this period of maximum seasonal SST. The tropical El Nino of this period also had two maxima in temperature (Smith 1984).

Generally warmer SSTs since mid-1976 are indicated by Figure 2b. Much of the period after 1976 had positive SST anomaly and much of the period before 1976 had negative SST anomaly. Extensive periods with positive anomaly during the 1979-80 and 1980-81 winters indicate MLW events, since there was no corresponding TEN activity.

The SST anomalies were summed for the entire coast for each 6 month period during 1971-84 to show large-scale features of the alongshore anomalies. Scaled values are plotted in Figure 3. A succession of warm events after the first half of 1976 produced a positive shift in SST involving the entire California Current System's inshore component. In the winter of 1976-77, there was a California El Nino accompanied by a tropical El Nino. In 1977-78, CEN and ENSO conditions reoccurred. Winter and spring of 1978-79

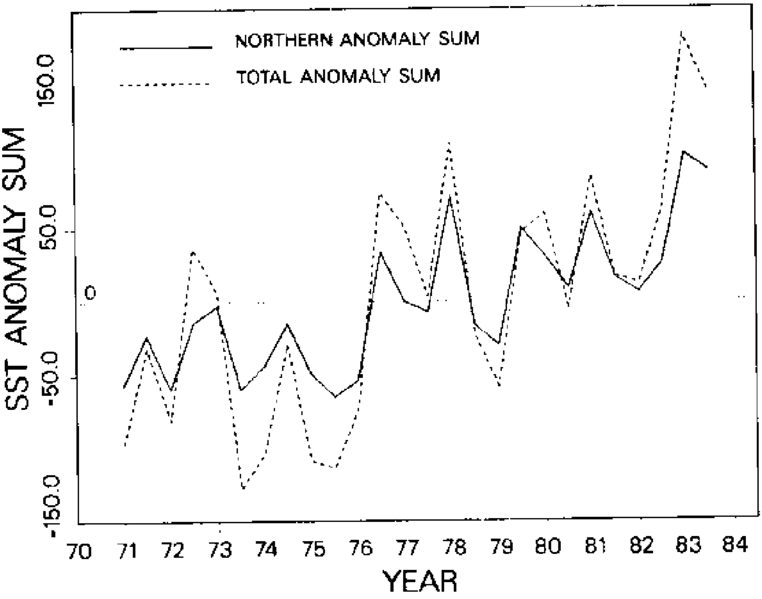

Figure 3. Six-month sums of SST anomaly on alongshore transect from Baja California to Vancouver Island. Abstract of data presented in Figure 2b. Northern Anomaly Sum is for northernmost 7 blocks of transect and Total Anomaly Sum is for all 12 blocks of transect.

were relatively cool, but temperatures remained above pre-1976 levels. In 1979-80, a MLW event occurred off California and Baja California. Similar though less extreme atmospheric and oceanic conditions occurred in 1980-81. The 1981-82 winter temperatures were near normal for the 13 year period. More recently, the extreme CEN and TEN 1982-83 season elevated coastal temperature to a 13 year high. In 1983-84 SSTs remained above normal through fall 1984. Note that during CEN years, the northern and southern portions of the transect both contribute to the total but during MLW years, the northern portion is dominant.

To examine the offshore extent of SST fluctuations, the data were abstracted to form three transects of nine 3° blocks extending from the coast 3000 km westward (Figure 1). A time-distance plot for the transect off Southern California (Figure 4a) shows warm fingers reaching in from offshore during summer and fall and cold fingers of California Current water extending offshore to near 126°W during the winter months.

Regions of cool water (less than 14°C) are prominent features from February through May in 1971, '72, '74, '75, '76, but appear in only one year after 1976 and this occurrence in 1979 is minor compared to the previous years. Cool water is brought into the coastal area from the north by the California Current. Upwelling is less important at the one month-3° scales. Lack of water less than 14°C since 1976 suggests a diminished California Current since 1976. During the third quarter of 1972, '76, '78, '79, '82 and '83 SSTs of greater than 18°C occurred over the entire zonal range (Figure 4a). In general these events precede MLW and CEN winters, and probably represent early surface countercurrent influence. Normally the areas within the 16°C isotherm are broken into inshore and offshore regions by the cool California Current maximum which occurs 200 - 400 km offshore. The absence of persistently strong California Current flow since 1976 has allowed the area greater than 16°C to become zonally continuous in summer and fall during five of the last eight years.

In 1980 and 1983 offshore water was cooler than in other years; SSTs greater than 22°C were absent at the western end of the Southern California transect (Figure 4a). Negative SST anomalies were widespread offshore in fall (Figure 4b). Both events followed winters of intense PNA-type atmospheric circulation. In both preceding winters, a deep Aleutian Low created high winds of long fetch blowing eastward across the Pacific. These intense and persistent winds may have redistributed the warm surface water of the central gyre and transition zone, decreasing horizontal density gradients in the upper layers and thereby decreasing the baroclinicity of the California Current Region. The warm water displaced onshore by southwesterly winds near the coast would tend to increase poleward countercurrent activity which would in turn bring more warm water into the coastal zone from the south. Comparison of Figures 4a and 4b shows that the absence of 22°C water offshore in 1980 and 1983 represents extreme negative anomaly (to -1.8°C, sdu to 2.4). Nearshore, positive SST anomaly is associated with each event. During 1983, the shoreward extension of the 20°C isotherm was the most extreme of the series, as shown by anomalies to 1.2°C (sdu to 2.5) in fall 1983 (Figure 4b).

The SST anomalies along the offshore transect tend to be of opposite sign in nearshore and offshore areas (Figure 4b). Note similarities among 1971, 1973, 1974 and 1975, which were cool years. Negative anomaly occurred in nearshore areas from 1971 through 1976, accompanied by positive anomaly offshore; producing horizontal density structure conducive to an enhanced California Current. In 1976 and the years following, negative anomaly commonly occurred offshore, accompanied by positive anomaly nearshore; opposing California Current baroclinicity.

Warm winters since 1971 were compared by summarizing the three offshore transects (Table 1). Offshore areas were divided into three 1000 km zones, with the nearshore zone containing most of the California Current System and the middle zone in the transition region (Figure 1). The outer zone of the northern transect extends into and sometimes through the northerly meander in the North Pacific and Subarctic Currents (Kirwan et al. 1978) where temperatures are more characteristic of the Subarctic Region. The transect off southern California reaches into the central gyre and the offshore zone of the Baja California transect remains in the subtropical transition.

In Table 1, the 1982-83 winter is shown to have the warmest SSTs of the series inshore and the coolest offshore. If the full length of each transect is considered, the 1982-83 CEN must be considered a cool SST event. In the inshore zone, the 1976-77 and 1983-84 winters were as warm as in 1982-83. Winter 1983-84 probably represents residual warming of the 1982-83 CEN. Note, the inshore zone remained warm in 1983-84, but offshore the cool anomaly of the previous year was lost in the southern and Baja California transects.

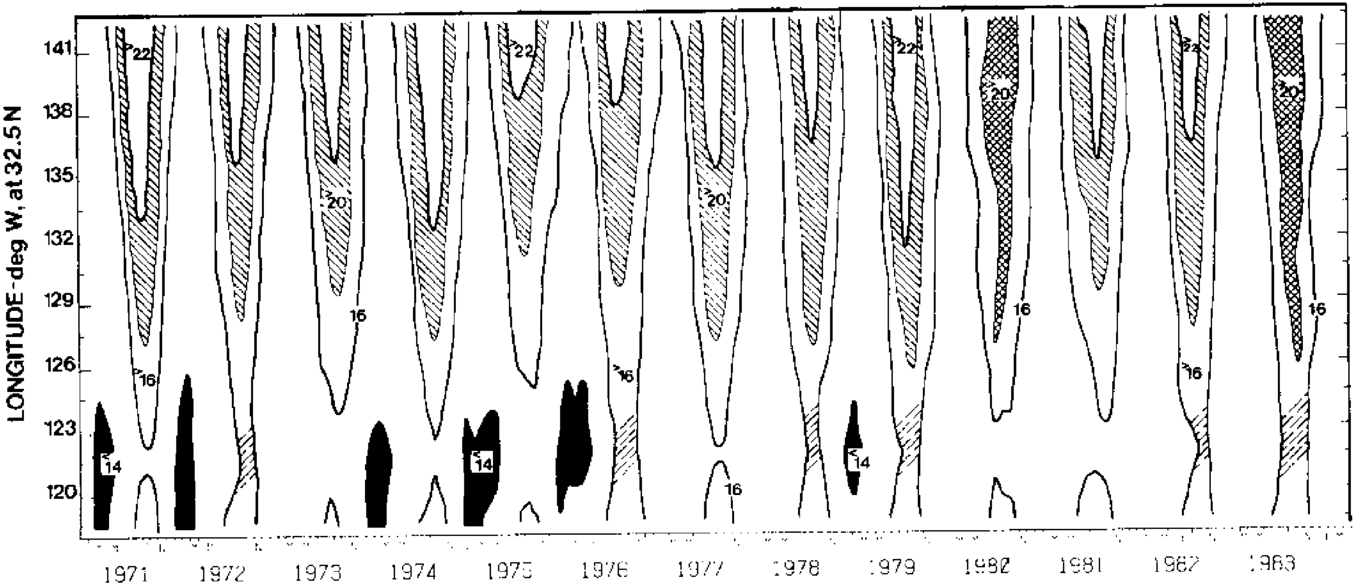

Figure 4a. See surface temperature of offshore transect west from southern California. The coast is at the bottom of the figure and the top of the figure is a point 2900 km offshore. The contour interval is 2°C except that the 18°C line is omitted. SSTs between 20°C and 22°C are hatched except for the two years 1980 and 1983 when SST greater than 22°C was not present offshore and the area greater than 20°C cross-hatched for emphasis (see text). Diagonal dashes near 122°W indicate years when SSTs greater than 16°C occurred continuously along the entire transect.

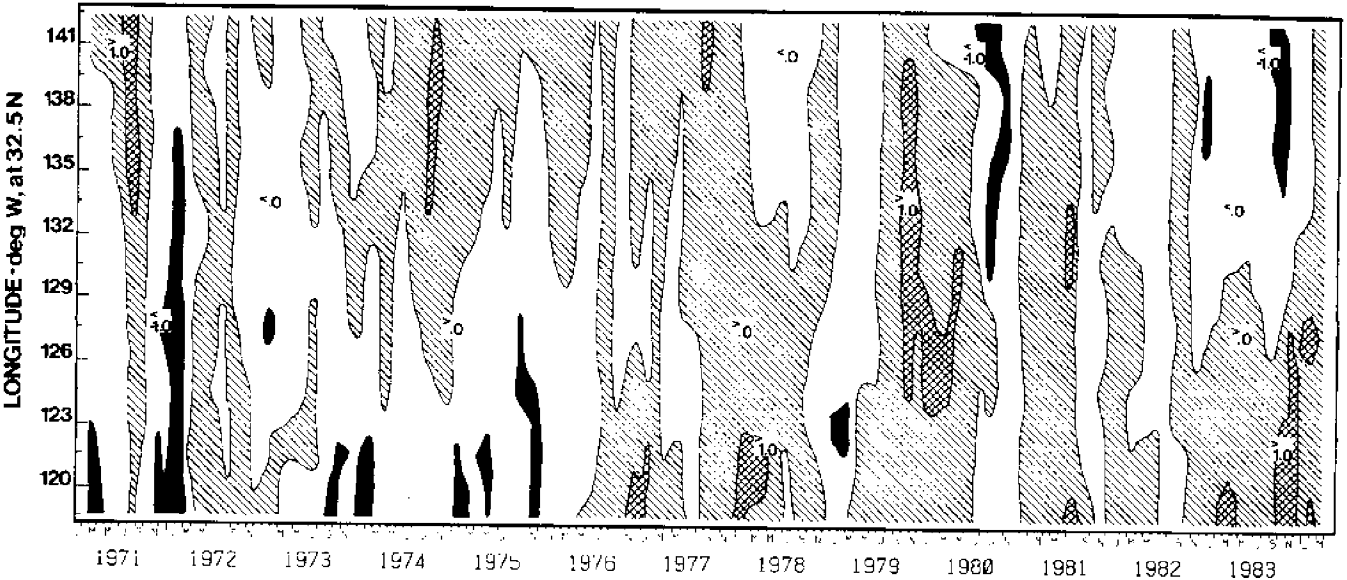

Figure 4b. Anomaly of sea surface temperature of offshore transect from southern California. Hatched areas indicate anomaly 0 to +1°C and cross-hatched areas anomaly greater than +1°C. Unshaded areas indicate anomaly between 0 and -1°C, and areas shaded black anomaly less than -1°C. Block locations are the same as Figure 4a.

Table 1. Summary table of SST anomaly during warm event winters (Nov.-Feb.) since 1971 along the three offshore transects; Northern California, Southern California, and Baja California. SST anomalies are summarized for 1000 km zones along each transect. The symbols represent SST anomaly in each zone along a transect; "W" represents areas having more than 50% positive SST anomaly and "C" represents areas having more than 50% negative anomaly. The numbers under each column are weighted average SST anomaly indices in each zone for each of the three transects; positive numbers representing positive anomalies and negative numbers representing negative anomalies. The anomaly indices are summed by winter in the sixth column and compared to event type (see text).

Winter	Transect		Zone		Event Type
(Nov-Mar)		Offshore 2000-3000	Middle 1000-2000	Inshore 0-1000 km	(Warm Index Total)
1972-73	North	W	W	C	CEN
	South	C (10)	C (-15)	W (-4)	(-9)
	Baja	W	C	W	
1976-77	North	W	W	W	CEN
	South	W (12)	C (15)	W (25)	(53)
	Baja	W	W	W	
1977-78	North	C	C	W	CEN
	South	W (1)	W (15)	W (19)	(35)
	Baja	W	W	W	
1979-80	North	C	W	W	MLW
	South	W (10)	W (20)	W (10)	(40)
	Baja	W	W	C	
1980-81	North	C	W	W	MLW
	South	W (-4)	W (19)	W (12)	(27)
	Baja	W	W	W	
1982-83	North	C	C	W	CEN
	South	C (-9)	C (-19)	W (27)	(-1)
	Baja	W	C	W	
1983-84	North	C	C	W	CEN
	South	W (2)	W (10)	W (26)	(38)
	Baja	W	W	W	

The 1976-77 CEN occurred at the end of a cool onshore - warm offshore period (McLain 1983). It appears that in this winter the central gyre remained warm from the previous period and that the inshore zone warmed under CEN influence. Overall, the SSTs of the 1976-77 CEN were the warmest of the series.

Since 1976-77, each warm winter has shown a tendency to negative SST anomaly offshore in the northern transect (Table 1). This could be the result of increased mixing by high winds in this area and/or a southward shift of the subarctic transition under the influence of basin-wide forcing due to persistent PNA circulation.

During the 1979-80 and 1980-81 MLW winters, warming occurred in the middle zone of all three offshore transects. Since this also occurred under

PNA pattern influence, the suggestion is that surface water is being transported from west to east under the influence of the intensified Aleutian Low. In the case of the MLW winters, warm surface water is moved from offshore into the middle zone. The Aleutian Low was even stronger in winter 1982-83 (Quiroz 1983). More water moved to the south and east in the offshore and middle zones bringing cooler water to the surface in the middle zone and extreme Ekman convergence at the coast. This is indicated by the 1982-83 pattern shown in Table 1. When extreme wind forcing relaxed in 1983-84, a more stable pattern returned offshore even though the inshore zone remained warm.

Subsurface Temperature

Mean monthly temperature time-distance plots at 100 and 200m depths for the same alongshore transect used for SST are shown in Figure 5. The seasonal cycle at 100m is influenced by vertical motion of the thermocline, especially off northern California where turbulent mixing causes mixed layer depths greater than 80m in winter (Husby and Nelson 1982). As with SST, subsurface isotherms make greater latitudinal excursion in the north (see Figure 2a). Isotherms are also more closely packed in the south, but the temperature gradient of the subtropical transition is not as large at 100m as it is at the surface.

In 1982-83, two northward excursions of the 10°C isotherm mark anomalous warming at 100m associated with the 1982-83 CEN (Figure 5). The first warming occurred in winter 1982-83 and after cooling in spring and summer, the second major warming occurred in late summer, fall and winter 1983. Resulting positive anomalies of up to 1.5°C (3.1 sdu) occurred between 46°N and 49°N in the first warming episode. The extreme excursions of the 10°C isotherm off central California in 1982-83 caused anomalies to 1.5°C (3.0 sdu) and 1.4°C (2.8 sdu) for the 1982-83 winter and 1983 fall respectively. Farther south between 29°N and 34°N, anomalies were 2.3 to 3.0°C (2.8 to 3.0 sdu) in winter 1983 and to 1.8°C (3.6 sdu) the following fall. These were the most extreme positive anomalies encountered in the study. The 8°C isotherm was depressed below the 100m level for the entire 1982-83 event (Figure 5). Relative extent of the two northward isotherm excursions varies with latitude and depth. The TEN associated first peak is more persistent with depth and distance south. This persistence is clearly suggestive of oceanic connection between tropical El Nino and California El Nino.

Extreme excursions of the 10°C isotherm at 100m are also seen during the 1972-73 CEN and the 1979-80 MLW winters. If northward excursion of this isotherm is considered alone, the 1979-80 winter is the most extreme, producing an anomaly of 1.6°C (2.7 sdu) at 43°N. The extremity of this winter was also evident at the surface (Figures 2a,b and 4a,b). These two events represent extremes of quite different forcing processes. The 1972-73 CEN was unaccompanied by a fully developed PNA pattern and the 1979-80 MLW event was unaccompanied by anomalous equatorial Kelvin wave activity (Douglas et al. 1982, Cane 1983).

The excursions of the 8°C isotherm during the 1972-73 CEN were as large at 200m as they were at 100m in the 10°C isotherm (Figure 5). The 1972-73 signal was also strong to the south in the subtropical transition, where

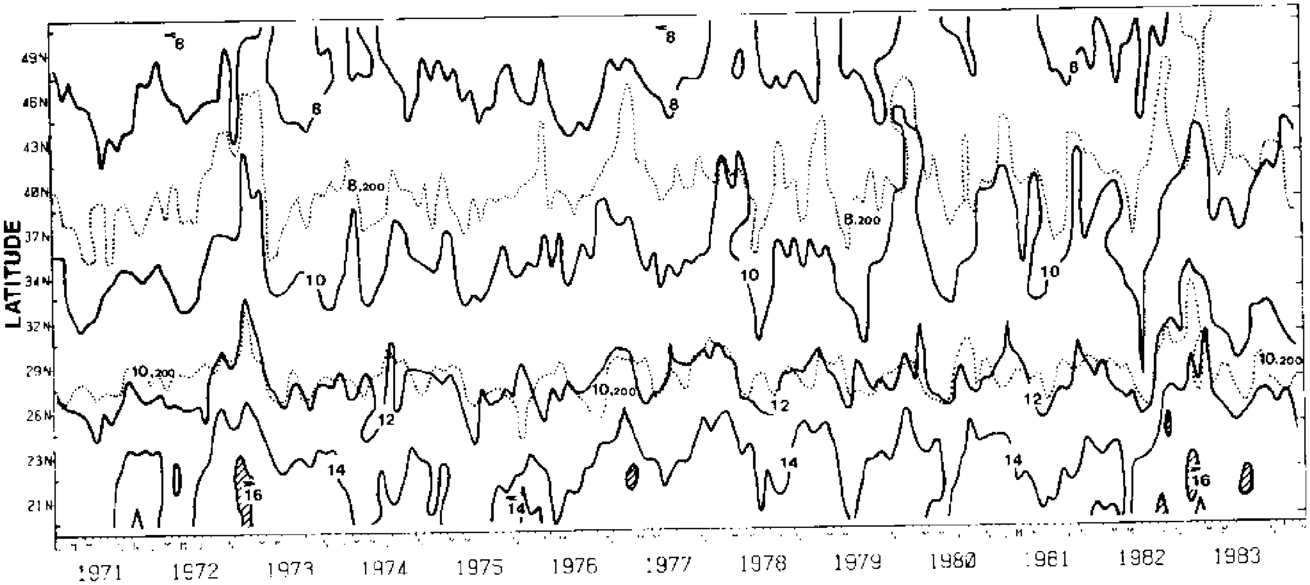

Figure 5. Monthly mean temperature at 100 m depth (solid lines) of alongshore transect from Baja California to Vancouver Island. Contour interval is 2°C. The 8° and 10°C isotherms at 200m (dotted lines) are also shown for comparison.

Table 2. Summary table of temperature at 100 m during warm event winters since 1971 along the three offshore transect. Symbols and numbers are the same as in Table 1.

Winter		Zone			Event Type
(Nov-Mar)	Transect	Offshore	Middle	Inshore	(Warm Index)
1972-73	North	W	W	W	CEN
	South	W (8)	C (0)	W (19)	(27)
	Baja	C	-	W	
1976-77	North	W	C	C	CEN
	South	W (16)	C (-16)	C (-7)	(-7)
	Baja	-	-	C	
1977-78	North	W	C	C	CEN
	South	C (-6)	C (-4)	C (-12)	(-22)
	Baja	-	-	C	
1979-80	North	W	W	W	MLW
	South	C (1)	C (2)	C (-14)	(-11)
	Baja	W	W	C	
1980-81	North	C	W	W	MLW
	South	C (-3)	W (17)	C (-9)	(5)
	Baja	W	-	C	
1982-83	North	C	C	W	CEN
	South	C (-2)	C (-4)	W (20)	(14)
	Baja	W	-	W	
1983-84	North	C	C	W	CEN
	South	C (-1)	W (-5)	W (16)	(10)
	Baja	W	-	-	

the extent of 16^{0}C water at 100m was as great in this period as at any other time in the series.

In contrast to the 1972-73 CEN, the 1979-80 MLW event's signal was halved at 200m and it appears not to have had pronounced influence in the south. This mid-latitude warming event is an example of locally forced coastal warming. Its signal is attenuated with depth and distance from areas of direct energy transfer.

The 100m and 200m alongshore temperature data for the 1972-73 CEN clearly suggest remote forcing from the south. The persistence of signal with depth without apparent attenuation indicates poleward and downward propagating coastal Kelvin waves (McCreary 1976). Although strong MLW events affect temperature at 200m, attenuation occurs with depth. Anomaly computations show the signal for the 1972-73, 1976-77 and 1982-83 CEN events to be stronger in terms of sdu below the thermocline than above. This trend is also shown in Figure 5 where the 1976-77 CEN appears stronger at 200m in the 8^{0}C isotherm than at 100m in the 10^{0}C isotherm. These are the years when a strong Kelvin wave signal would be expected (Cane 1983, Picaut 1984).

Table 2 summarizes the offshore 100m temperature anomaly in the same form as Table 1. The 1982-83 event produced a temperature anomaly pattern at 100m similar to that observed at the surface. The patterns at the surface and 100m were also similar during the following warm winter, 1983-84.

In contrast to the 1982-83 CEN, the inshore zone was cool at 100m during the 1976-77, 1977-78, 1979-80 and 1980-81 warming events. This may represent a large scale density adjustment with depth. Presumably similar adjustment occurred below 100m during the 1982-84 period.

Figure 5 shows conspicuous coastal warming at 100m during the 1976-77, 1977-78, 1979-80 and 1980-81 winters in the alongshore 3° blocks. However, the 3° latitude by 9° longitude areas summarized in Table 2 show that these winters have predominantly negative anomaly at 100m. Quite possibly, this points to the distinction between the coastal countercurrent, which appears instrumental in increased coastal warming in warm winters, and the diffuse offshore countercurrent or undercurrent. Kelvin wave influence would be expected to occur first in the region of the countercurrent. Offshore, it appears that the undercurrent becomes weaker as the California Current weakens (Table 1, Figure 4a) during warm events, leading to cool anomalies at depth in the inshore zone (Table 2).

The persistence of negative winter SST anomaly offshore on the northern transect as shown in Table 1 may represent a southward shift of the subarctic transition. It appears that a similar shift occurs in the 100m index four years later in winter 1980-81 and persists through winter 1983-84. This is shown by negative anomaly index in the offshore zones of the two northern transects. Examination of more detailed data shows that the cooling in this region began in 1977. This trend to cooler water in the offshore zone may represent a time-dependent deepening of the mean oceanic circulation brought by increased frequency of the PNA atmospheric pattern over the north Pacific. This climatic shift, which apparently favors warmer coastal water, undoubtedly contributed to the extremity and persistence of the 1982-83 CEN.

Sea Level

To examine the effects of the 1982-83 California El Nino on sea level, 6-month sums of sea level anomaly for Neah Bay, Washington and for Crescent City, San Francisco, Monterey, Los Angeles and San Diego, California were added together to give a value for the entire west coast of the United States. These scaled values are plotted with the corresponding scaled SST anomaly sum in Figure 6. The extremely high sea level anomaly values that occurred during the 1982-83 CEN event suggest an anomalously warm water column as the result of atmospheric and oceanic forcing of convergent ocean currents along the greater California coast.

The 1982-83 CEN resulted in the most extreme sea level anomaly in the 1971-83 record. If cool negative anomaly events are excluded, the 1972-73 CEN was next in extremity followed by the 1976-77 (CEN), 1977-78 (CEN) and 1979-80 (MLW) events. Greatest anomalies were in winter 1982-83 when anomalies greater than 20 cm occurred from San Francisco north to Sitka, Alaska. Anomalies of this magnitude and duration are unique in the National Ocean Survey's records for the west coast of the USA. A 90 year daily sea-level height maximum for San Francisco occurred on January 27, 1983. The 26 cm monthly anomalies for February and March 1983 at San Francisco were

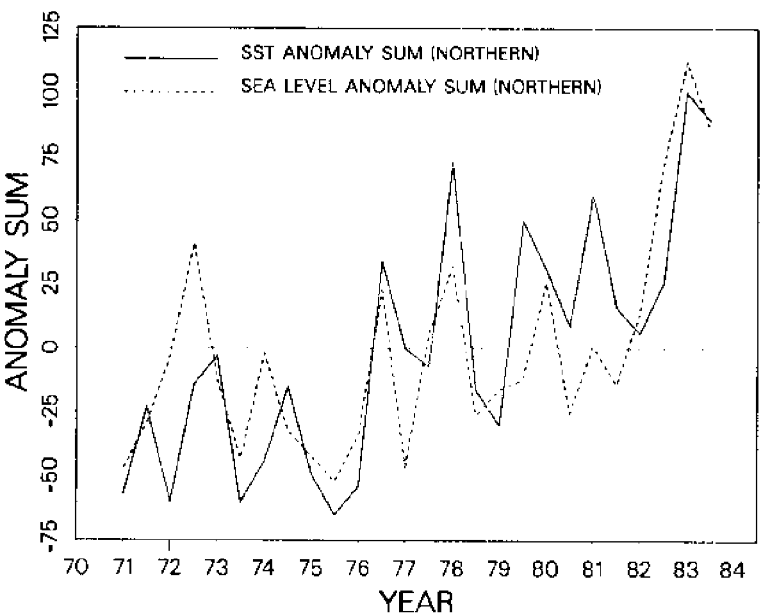

Figure 6. Six-month sums of anomaly of sea level at 6 tide stations along the northern portion of coast from San Diego, CA, to Neah Bay, WA. Six-month SST anomaly for the northern portion of coast are also included from Figure 1 for comparison.

without precedent in the 90 year record. High positive anomalies also made the 1983 yearly mean unique in the 90 year series. In southern California anomalies were less extreme with the largest monthly anomalies ranging from 10 to 15 cm.

Chelton and Davis (1982) related the first empirical orthogonal function of monthly sea level anomaly along the coast of North America to bifurcation of the North Pacific Current as it approaches the eastern boundary under the influence of basin-wide atmospheric forcing. When bifurcation favors northerly flow, there is sea level rise along the coast of Alta and Baja California. This represents the warm oceanic event response characterized by the years since 1976 (Figure 6). In the opposite extreme, the cool subarctic water flows south in an anomalously cool California Current and there are lower sea level heights.

This analysis agrees well with the implications of the above temperature data. Northerly winds in the western Pacific basin bring more cool subarctic water into the North Pacific Current allowing the subarctic transition to move south. This brings cool water to the offshore end of the northern transect (Tables 1, 2). The PNA-associated intensified Aleutian Low favors an increased northward flow of subarctic water. Consequently, the California Current System receives less cool water.

Wind Mixing and Upwelling Index

Wind stress on the sea surface mechanically mixes the ocean's surface layers and induces surface currents. The mixing effect of the wind is directionally independent and the rate at which turbulent kinetic energy becomes available to mix the upper ocean is proportional to the third power of the wind speed (Niiler and Kraus 1977).

An index of the turbulent wind events along the California coast was calculated from the 6-hourly northern hemisphere pressure/wind analyses of the Fleet Numerical Oceanography Center at six coastal locations from 24° to 39°N for the period 1974-84. The daily mean wind speed cubed was calculated from the mean of the four 6-hourly wind speed cubed values. To investigate the interannual variability in the atmospheric forcing, these daily time series of wind speed cubed were examined in terms of the number of daily means greater than a threshold value of 400 m^3/s^3 and the persistence of events above the threshold. It is emphasized that these wind speed values are representative of the large-scale wind forcing, characteristic of the approximate 3°x3° grid spacing of the northern hemisphere analysis.

Wind events for the central California coast (36°N) during the winter quarter (Dec. - Feb.) from 1974-75 to 1983-84 are described by the product of the number of daily means greater than the 400 m^3/s^3 threshold times the mean value of the wind speed cubed for these days (Table 3). This product is a relative index of the turbulent energy added to the water column during the various winters. The greatest turbulent mixing appears to have occurred in the CEN winters of 1977-78 and 1982-83. The third most turbulent winter was the mid-latitude warming event winter of 1979-80. These three winters occurred in winters when the PNA-type atmospheric circulation was strong (Wallace and Gutzler 1981, Quiroz 1983). This pattern was also observed at the other coastal locations, but with smaller magnitudes in the extreme events.

Equatorward winds blowing parallel to the California coast cause surface water to be moved offshore and subsurface water to rise in the upwelling process. Conversely, poleward winds cause surface water to be pushed toward shore, causing downwelling and northward flow. The upwelling index (Bakun 1973, 1975) provides a large-scale estimate of the onshore/offshore Ekman transport based on FNOC pressure/wind fields.

A time-distance plot of monthly mean upwelling index (Figure 7) shows that in the area south of 33°N, winds favoring coastal upwelling occur throughout most of the year. North of 33°N, winter winds favor onshore transport and resulting downwelling. These areas are seen in Figure 7 as cusps that extend southward to latitudes from 33° to 39°N. The hatched areas within the negative regions represent extreme downwelling of less than -200 cubic meters per second per 100m of coastline ($m^3/s/100m$). At 42°N the upwelling index exceeded this negative value for only two months in the entire 13 year record. These occurred during the anomalously warm 1982-83 winter. The shaded cells centered near 33°N represent periods of strong upwelling in spring and summer when the monthly values are greater than +200 ($m^3/s/100m$). Note the increase in upwelling at 21°N which occur in the spring and summer after 1976. These may be the result of a southward shift and/or intensification of the North Pacific High pressure center.

To examine the interannual variability in the upwelling index the consecutive positive values of the index greater than +200 at 33°N were summed for summer seasons during the 1951-84 period. The negative

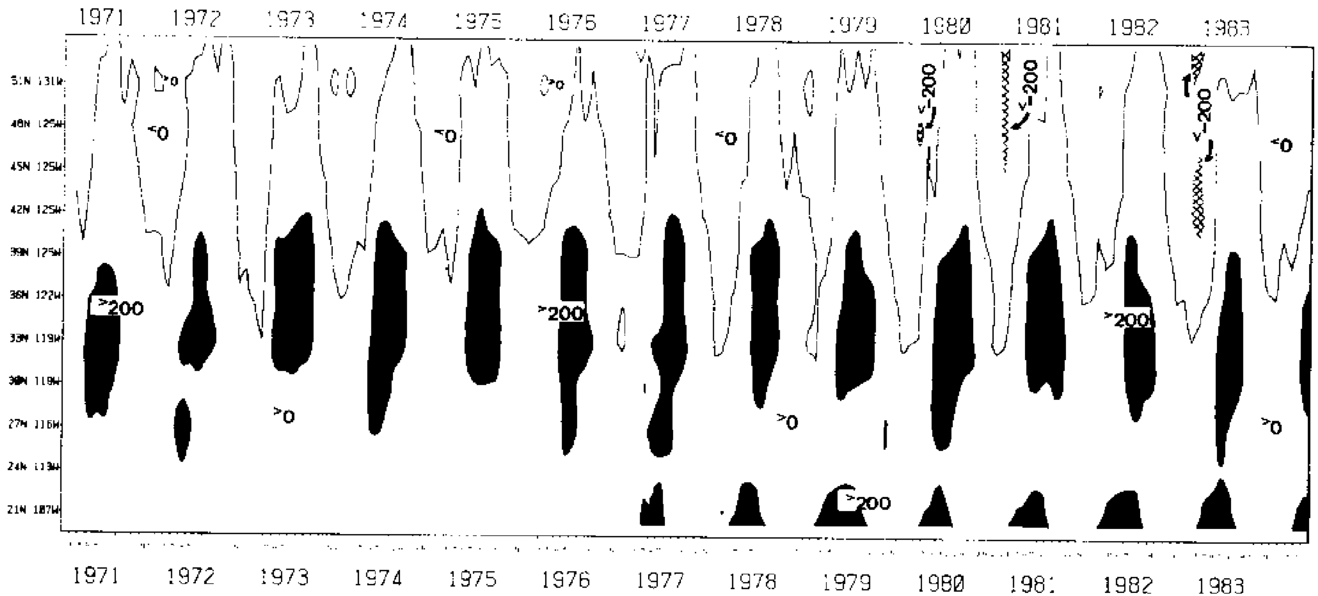

Figure 7. Upwelling Index computed by methods of Bakun (1973) for 12 locations along west coast from Baja California to Vancouver Island. Units are $m^3/s/100$ m of coastline. Solid lines represent zero upwelling index and enclose regions of negative upwelling or downwelling. Cross-hatched areas represent downwelling stronger than -200 upwelling index units. Areas shaded black represent cells of strong upwelling (greater than +200 units) along central and Baja California in spring and summer.

Table 3. Summary of severe winter (Dec.-Feb.) turbulent wind events off central California (36°N) during winters from 1974-75 to 1983-84. Computed from 6-hourly pressure fields from Fleet Numerical Oceanography Center. The first column gives the number of days when the daily mean wind speed cubed was greater than 400 m^3/s^3 and the second column gives the mean wind speed cubed value for those days. The third column gives the product of number of days times the mean wind speed cubed and indicates the amount of turbulent energy added to the water column. The last three columns summarize the turbulent energy transfer as events by giving the number of events of wind speed greater than 400 m^3/s^3, the mean duration of the events, and the standard deviation of the duration of the mean.

WIND SPEED CUBED > $400m^3/s^3$

SEASON	(1) NO. OF DAYS	(2) MEAN FOR DAYS>400	(3) (1)x(2)	(4) NO. OF EVENTS	(5) DURATION MEAN	(6) OF EVENT S.D.
1974-75	26	1096	28496	9	2.8	0.7
1975-76	9	760	6840	3	2.3	0.3
1976-77	4	516	2064	2	2.0	0.0
1977-78	27	1462	39474	5	4.6	8.8
1978-79	19	836	15884	6	2.2	0.2
1979-80	24	1388	33312	6	3.3	3.9
1980-81	11	1548	17028	4	2.3	0.3
1981-82	16	854	13664	5	2.4	0.8
1982-83	31	1261	39091	8	3.3	0.8
1983-84	12	1610	19320	3	2.3	0.3

upwelling index values at 42°N were also summed for each winter downwelling season (Table 4). The most extreme downwelling of the last 33 years occurred during the 1957-58 and 1982-83 fall and winter seasons which were two and three times the mean, respectively. During the winters of 1979-80 and 1980-81, the PNA-type circulation occurred over the North Pacific. They also had higher than average downwelling values at 42°N. The 1979-80 and 1980-81 winters were probably important in maintaining the anomalously warm SST regime since 1976.

Large negative values of the downwelling at 42°N are associated with the occurrence of PNA atmospheric circulation. Upwelling in the following spring and summer appear decoupled from winter downwelling. However, upwelling can also influence the overall impact of warm anomalies. Note that in the 1982-83 two seasonal influences related to upwelling lead to high California coastal SSTs. First, there appears to have been unprecedented downwelling which promoted northward coastal flow and warming during winter 1982-83. This was followed by indication of below average upwelling during the following spring and summer. This, in turn, was followed by the highest SSTs and highest SST anomalies (in sdu.) during fall 1983 (see Figures 2a,b).

Table 4. Summary of monthly upwelling index for winter and summer seasons from 1951-52 to 1983-84. The second column is the sum of negative monthly mean upwelling index values at 42°N during the winter downwelling season. Seasons with downwelling sums more negative than -300 units at 42°N are marked with double minus (--). The third column is a similar sum of positive upwelling index values during the following spring and summer at 33°N. These are the sum of consecutive monthly mean values greater than +200 units . Upwelling seasons with sums greater than +1500 units are marked with double plus (++). The fourth column indicates the occurrence of tropical El Nino (TEN) and Pacific/North American circulation (PNA).

MONTHLY MEAN UPWELLING INDEX ABSTRACT
1951-1984

SEASON	42N NEG.	33N POS.	EVENT
51-52	(194)	448	
52-53	(413)--	814	TEN
53-54	(215)	491	
54-55	(246)	1813++	
55-56	(230)	1656++	
56-57	(60)	1439	
57-58	(544)--	1535++	TEN, PNA
58-59	(139)	1955++	PNA
59-60	(101)	349	
60-61	(409)--	809	PNA
61-62	(64)	792	
62-63	(204)	1053	PNA
63-64	(168)	2261++	
64-65	(210)	1161	
65-66	(197)	1211	TEN
66-67	(165)	1319	
67-68	(189)	1511++	PNA
68-69	(269)	1584++	
69-70	(353)--	1404	TEN, PNA
70-71	(131)	1354	
71-72	(92)	1209	
72-73	(219)	1310	TEN
73-74	(198)	1383	
74-75	(121)	1217	
75-76	(54)	1055	
76-77	(128)	1266	TEN, PNA
77-78	(366)--	798	TEN, PNA
78-79	(99)	1446	
79-80	(369)--	1629++	PNA
80-81	(383)--	1546++	PNA
81-82	(215)	1157	
82-83	(765)--	984	TEN, PNA
83-84	(278)	1191	

DOWN 42:	MIN.	(60)
	MEAN	(251)
	MAX.	(765)
	--LT.	(300)
UP 33:	MIN.	349
	MEAN	1224
	MAX	2261
	++ MT	1500

Discussion and Conclusions

Our analyses suggest that the severity of the 1982-83 CEN was the result of several warming factors. Remote forcing occurred both through the atmosphere and through the ocean to cause warming in the California Current System which had already been warmed by remotely forced and local events of lesser, but similar nature.

Two maxima characterized 1982-83 warming that occurred within 300km of shore (Figures 2a,2b,4a,4b). The first maxima occurred nearly in phase with the tropical El Nino at all depth levels studied. At the surface the second peak which occurred in late summer and early fall 1983 was the most extreme. At the 100 and 200m depths, the first peak, which was most likely associated with coastal Kelvin wave activity, was the most extreme. The second maxima at 100m was reduced in expression south of 32°N and with depth (Figure 5).

Maximum temperature anomalies of 2°C, 3°C and 1.2°C occurred at the surface, 100m and 200m respectively. In terms of sdu, the highest value was 3.6 off Baja California with values to 3.0 throughout the alongshore transect at 100m. Anomalies with sdu values ranging to 2.0 and 2.5 at the surface and 200m, respectively, indicate a relatively unattenuated signal below the thermocline consistent with coastal Kelvin wave theory.

Comparison of the 1982-83 CEN with other warm events of the series has allowed considerable insight into the causes of its severity and persistence. The 1972-73 CEN occurred without the PNA atmospheric adjustment which occurred in 1976-77, 1977-78 and 1982-83. The 1972-73 CEN, which has a number of similarities to the 1982-83 event (Figure 5) provided an example of the oceanic tropical to mid-latitude connection. In contrast, the 1979-80 MLW event was accompanied by the distinctive PNA atmospheric pattern in a period without tropical El Nino activity. This coastal warming event also had several points of similarity to the 1982-83 CEN (Figures 4a,b). Overall, the 1977-78 CEN is similar to the 1982-83 event, though less extreme (Figure 4b, Table 3).

The 1982-83 event brought anomalous cooling in an area reaching from 1000-3000 km offshore. If the 3000 km area adjacent to the coast is considered, the 1982-83 CEN was a cool event rather than a warm one (Figure 4b, Table 1). This was the result of unprecedented development of the Aleutian low that occurred in winter 1982-83. As noted above, this low was probably the result of extra-tropical forces acting in concert with the tropical atmospheric connection. Cooling in the area 2000-3000 km offshore at 40.5N appears characteristic of years when anomalously warm water occurs at the coast (Tables 1, 2). However, no other offshore cooling event of the 13 year series was as extensive as the one that occurred during the 1982-83 CEN (Figure 4b, Table 1).

Coastal subsurface temperature patterns at 100m and 200m during the 1976-77, 1977-78 and 1982-83 CENs suggest downward and poleward propagating coastal Kelvin wave influences, since the signal at 200m appears stronger, in terms of sdu, than at the surface (Figure 5). The warming signal decreased with depth for the 1979-80 warm event, which appeared unrelated to tropical warming.

Coastal winds during 1982-83 winter were extreme (Figure 7, Tables 3,4). In terms of negative upwelling index, indicating a general tendency to Ekman convergence at the coast, the 1982-83 CEN winter was the most extreme of the 33 year series (Table 4). The 1957-58 CEN winter which also occurred with PNA atmospheric adjustment was second. Although the 1957-58 event is considered extreme, the accumulated seasonal downwelling index at 42°N was only 70% of that obtained for the 1982-83 winter. Extreme downwelling index or negative upwelling index is associated with the PNA atmospheric pattern, though not absolutely (Table 4).

Atmospheric and oceanic remote forcing appear to produce California El Ninos by enhancing normal processes that lead to warming, according to the following scenario. Coastal Kelvin wave activity depresses the thermocline along the coast. This in turn facilitates northward coastal countercurrent flow, which will bring anomalously warm water into the coastal zone, as indicated by Figures 2a, 2b, 3, 4a and 4b. Basin-wide forcing deflects subarctic water north away from the California Current. Consequently, more warm water reaches the California coast (Figure 6). Atmospheric patterns associated with mid-latitude adjustment to tropical influences may also cause local downwelling winds (Table 4) causing Ekman convergence at the coast, thereby inducing northward surface currents (Figure 6). These three warming processes contribute to positive temperature anomalies occurring at the coast during CEN years.

The data presented suggest that a climatic change occurred after the winter of 1976-77. The period before 1976 was characterized by positive SST anomaly offshore (Figure 4b), negative anomaly in the California Current System (Figure 3, 4a, b), negative sea level anomaly (Figure 6) and coastal winds favoring upwelling (Table 4). Four of the six winters since 1976 are classified as anomalously warm on the coast. These were accompanied by positive sea level anomaly and downwelling winds. The 1982-83 CEN occurred in an already warm period. This also contributed to its severity.

The 1972-73 CEN appears equal in positive anomaly to the 1982-83 CEN in subsurface temperature (Figure 5) and sea level (Figure 6). However, its expression, particularly at the surface (Figure 2b), was attenuated in the California Current System because it was opposed by locally forced processes rather than augmented by them.

Summary

1. Coastal ocean warming associated with the 1982-83 California El Nino was the most extreme of 1971-83 period. This warming appears to have been the result of at least two remote connections to the tropical El Nino, one through the ocean and the other through the atmosphere. Two major peaks of anomalous subsurface warming occurred. The earlier peak may primarily reflect oceanic propagation while the latter peak seems to be the result of the atmospheric tropical to mid-latitude connection.

2. Atmospheric patterns associated with the 1982-83 event brought extreme cooling in an area reaching from 1000 to 3000 km offshore. The 1982-83 period was a cool rather than a warm year if the entire 3000 km offshore area is considered. Offshore cooling is characteristic of

other coastal warming events (eg. 1979-80 and 1980-81) that can occur without tropical El Nino activity.

3. Persistence of warm anomaly below 100m during the 1982-83 event suggests the presence of oceanic propagation from the tropics consistent with coastal Kelvin wave activity. Similar strong persistence at depth occurred during the 1972-73 California El Nino, which was unaccompanied by atmospheric patterns associated with 1976-77, 1977-78 and 1982-83 California El Ninos. In contrast, the strong surface warming which occurred during 1979-80 unaccompanied by tropical El Nino activity, attenuated rapidly with depth.

4. In winter 1982-83 monthly anomalies based on 3° latitude-longitude areas exceeded 2.5°C at 100m with lesser magnitudes at surface and 200m.

5. Maximum alongshore SST warming occurred in fall 1983. During winter 1982-83 accumulated downwelling index at 42°N was three times the average value indicating a tendency to extreme Ekman convergence. This is the largest accumulated downwelling index recorded (33 year series). Non-directional wind mixing parameter for winter 1977-78 was as great as for 1982-83, but the downwelling index value was only half that recorded for 1982-83. The extreme accumulated downwelling value for 1982-83 represents local expression of the PNA pattern circulation.

6. Indirect evidence points to weakening of the cool California Current, onshore transport of offshore water, increased downwelling and counter current intensification as primary local mechanisms through which the oceanic and atmospheric remote forcing bring warming to the California coast. Atmospheric and oceanic forcing of warming processes occurred together during the 1982-83 California El Nino.

7. The second half of the 1971-83 study period is warm relative to the first half. The change occurred rather abruptly in winter 1976. Since five of the next seven winters were characterized by warm coastal waters and characteristic atmospheric circulation, residual warm effects have accumulated so that the 1982-83 California El Nino occurred in an already warm period with an atmospheric circulation already favorable to coastal warming. This warm setting also contributed to the extreme nature of the 1982-83 event.

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The Apparition of El Niño off Oregon In 1982-83

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The paper presented at the Meeting on El Niño Effects in the Eastern Subarctic Pacific in Seattle on 12 September 1984, has subsequently been expanded and accepted for publication in Journal of Geophysical Research, C(OCEANS), volume 90 as Paper 5C0086, entitled "The Signature of El Niño off Oregon, 1982-1983". The abstract of this paper was published in EOS, Transactions, American Geophysical Union, 66 (10) March 5, 1985 and is reproduced here:

> Current and CTD measurements were made over the Oregon shelf near 43°N between February 1981 and April 1984 as part of a large-scale west coast shelf experiment (SuperCODE). The data set includes a nearly continuous record of current velocity and temperature over the continental shelf off Coos Bay from May 1981 through January 1984, CTD sections off Coos Bay in January or February of each year from 1981 to 1984, and CTD sections off Newport (44.6°N) in April 1983, July 1983 and April 1984. The latter are compared with sections off Newport made during the previous two decades. Sea level from the Newport tide gage, daily sea surface temperature at Charleston (43.3°N), the alongshore component of the wind stress at 45°N and the large scale North Pacific atmospheric pressure pattern provide a climatological perspective. The initial manifestation of El Niño off Oregon was in October 1982: anomalously high sea level, high coastal sea surface temperature and increased poleward flow. These effects occurred within one month of the onset of El Niño off Peru and preceded any local (North Pacific) atmospheric effect by 2 to 3 months. The anomalous local meteorological conditions, which became manifest in December and January, greatly enhanced the initial effects and inserted their own signal. The first signals of El Niño probably arrived by an oceanic path, but there is no doubt they were subsequently reinforced by anomalous atmospheric conditions.

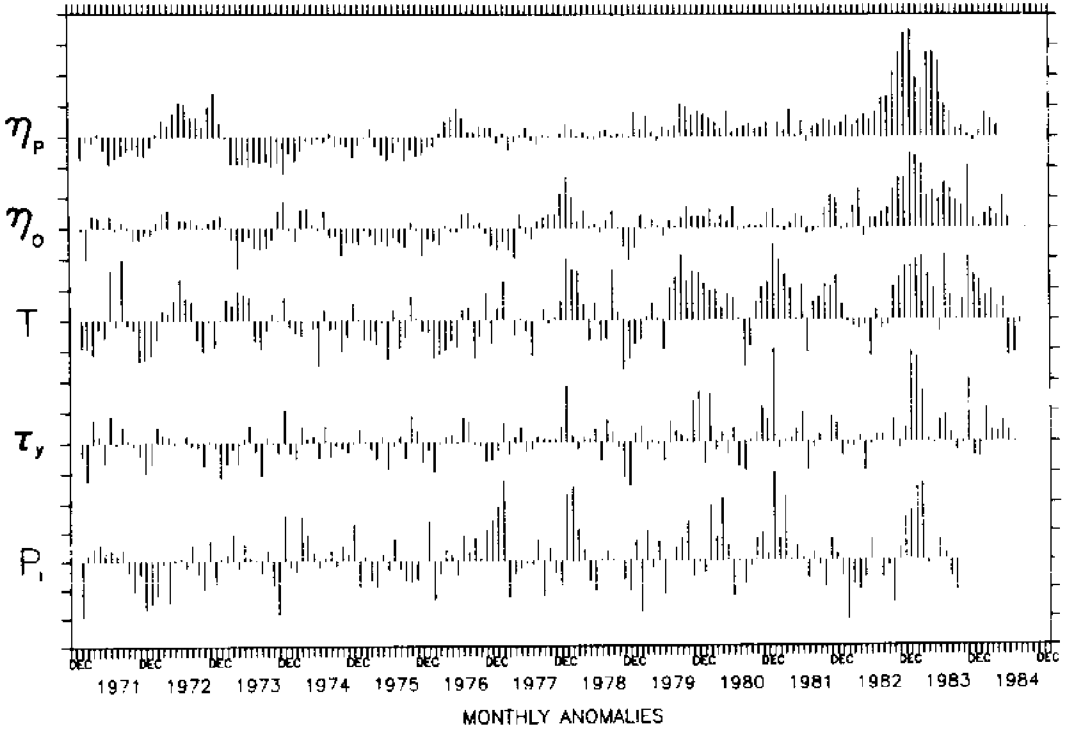

Figure 1. Monthly anomalies, beginning January 1971, of sea level at 12^{O}S on the Peru coast (η_p), sea level at 44.6^{O}N on the Oregon coast (η_o), sea surface temperature at 43.3^{O}N on the Oregon coast (T), alongshore wind stress at 45^{O}N, 125^{O}W (τ), and the amplitude of the large-scale North Pacific atmospheric pressure pattern (P_1). Ticks are 10 cm for sea level, 1C^O for temperatures and 0.5 dynes cm^{-2} for wind stress. One tick corresponds to a pressure anomaly of 5 mb at the center of the Aleutian Low.

Comparison of El Niño Events Off the Pacific Northwest

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Abstract

Observations show that El Niño events of 1940-41, 1957-58, and 1982-83 had large coastal effects off Washington and British Columbia. Subsurface temperature anomalies were comparable during the three episodes, and average profiles between the coast and 127°W had anomalies of about 1.5°C at 100 m; individual anomalies sometimes exceeded 3°C, with the highest values near the coast. Positive anomalies were observed to extend over 200 km offshore and to depths of about 500 m. These scales were similar to those farther north in the Gulf of Alaska and were about half the offshore extent off southern California. Monthly average sea level anomalies showed that the largest increases occurred almost simultaneously from California to Alaska. Thus we suggest these data support the concept that the events are initiated by long ocean waves but that subsequent development is strongly affected by anomalous coastal winds.

Introduction

During the 1982-83 El Niño event dramatic ocean temperature changes occurred off the coast of Washington at 47°N (Reed, 1983, 1984). Positive thermal anomalies were observed above 500 m and were greater than 1°C in the upper 200 m. Earlier, Enfield and Allen (1980) showed that during 1950-74 only the 1957-58 El Niño event resulted in large sea level and coastal sea surface temperature changes as far north as 47°N. In fact, some of the larger tropical events in the last 100 years have not been observed north of central California. The El Niño events of 1891, 1925, 1940, 1957, 1972, and 1982 all had very large effects in the tropics (Ramage and Hori, 1981; Quinn et al., 1978; Wooster, 1983). A recent compilation of sea level revealed little change from the 1891, 1925, or the 1972 events north of California, but large changes are clearly visible along the coast into southeast Alaska during 1941 and 1958 (Hicks et al., 1983; also see Roden, 1960).

The events of 1940-41, 1957-58, and 1982-83 thus appear to have been the only ones producing major changes in sea level off the Pacific Northwest. The purpose of this paper is to examine and document the offshore temperature changes at depth, as well as the historical record allows, during these sea-level events. Reed has presented some of the 1983 observations with which we will compare effects during 1941 and 1958. We have restricted the area of this study primarily to north of about 45°N because of our interest in the effects on fisheries in this region.

Sea-level Anomalies

Many of the previous inferences about El Niño effects at mid-latitudes in the eastern North Pacific have been made from sea level data (e.g., Enfield and Allen, 1980). For this study we have extended their 1950-74 period by using monthly mean sea level values through 1980 from Hicks et al. (1983) and for 1981-83 from manuscript data of the National Ocean Survey. The sea levels were corrected for changes in atmospheric pressure at nearby weather stations by first calculating the monthly atmospheric pressure anomaly from the long-term pressure mean for each station. This anomaly then was added to the monthly sea level values, and the data at each station were detrended by a straight-line least squares fit. Long-term monthly mean sea levels were computed for all available data through 1982, and monthly anomalies of sea level were calculated by subtracting the long-term monthly means from the corrected sea levels (Figure 1).

El Niño events that have had effects on sea level all along the west coast are indicated by vertical lines in Figure 1. The events of 1940-41, 1957-58, and 1982-83 are evident, but the 1972 event did not produce changes everywhere. The average magnitude of the sea level anomaly in early 1983 is slightly larger than that in 1958, and the 1982-83 event appears to be virtually simultaneous from La Jolla to Yakutat. The largest increases in adjusted sea level for the 1982-83 event (Figure 1) occurred during October-November 1982 for all three California locations, September-October 1982 for Neah Bay, December-January 1982-83 for Sitka, and November-December 1982 for Yakutat. The 1941 anomaly is broader than the others from Neah Bay northward. There also seems to be the suggestion of a very slow rise in sea level as far north as Alaska several months after the 1976 event in the tropics (see also Royer and Xiong, 1984).

In addition to the rise in sea level associated with these events, there also were large, but spatially incoherent, rises at other times. Lower than normal sea level seemed to occur before most of the major events. This is especially evident during 1955-57 at all stations. There was a sharp trough present from La Jolla to Sitka in 1939-40, but low values were less pronounced before the 1982-83 event. The rise in sea level during 1958 according to our data also was characterized by an offshore surface geopotential anomaly increase (relative to 1000 db) of about 15 dyn cm compared to 1957. Tabata (1984) noted a similar characteristic of the 1982-83 event.

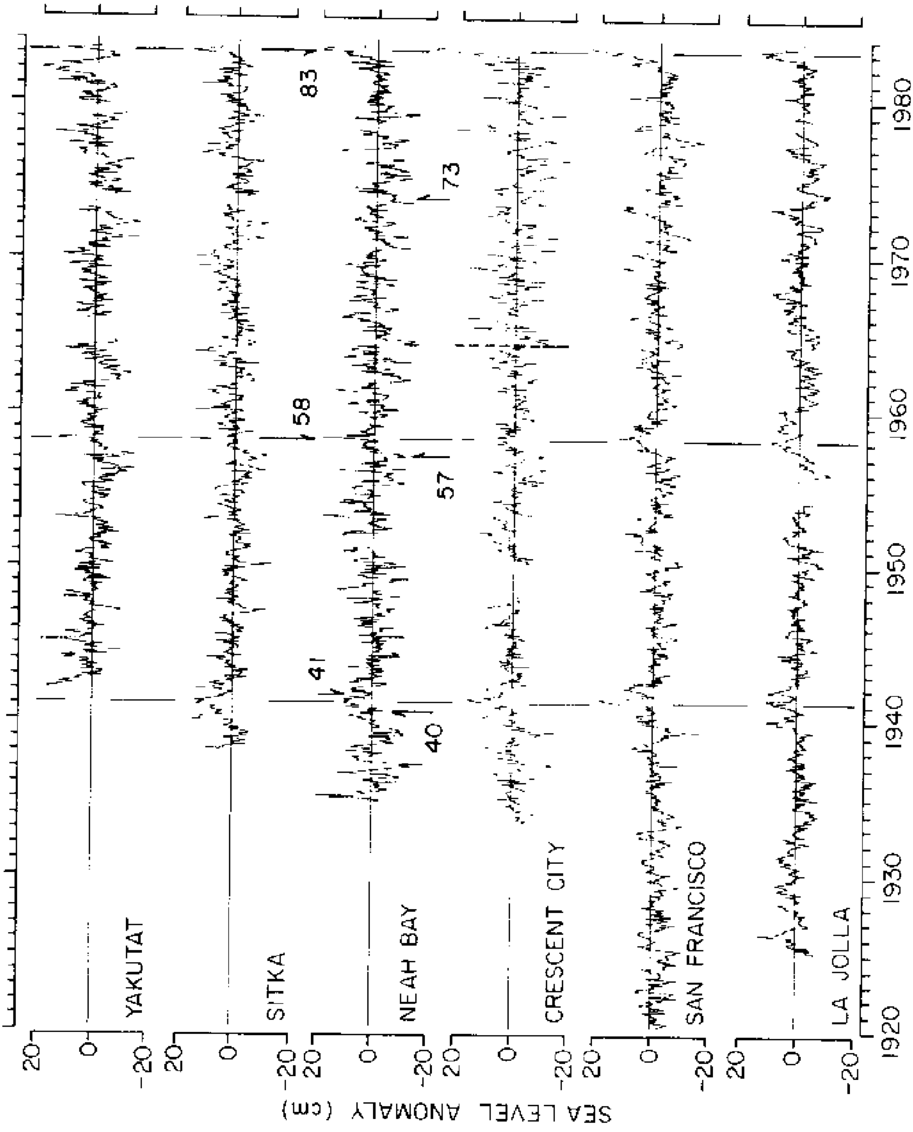


Figure 1. Sea level anomalies along the west coast of North America. Vertical lines indicate the El Niño events in 1941, 1958, and 1983. Arrows with dates indicate oceanographic observations off Washington referred to in the text. Atmospheric pressure corrections were not applied at Crescent City after 1964 (dashed vertical line).

Temperature Anomalies

Oceanographic observations were made off the coast of the Pacific Northwest by the University of Washington using the RV CATALYST in July of 1940 and 1941 and using the RV BROWN BEAR during 1957-58 as part of the IGY and are available in Oceanic Observations of the Pacific, Pre-1949, 1957, and, 1958 (published by Scripps Institution of Oceanography). Reed (1983) used observations along 47°N by the NOAA ship DISCOVERER in May 1983, and we have supplemented these with observations along the Ocean Station PAPA line (approximately 48°N) from Tabata (1984).

Reed (1983) calculated the vertical structure of the temperature anomalies by taking the temperature differences between stations along 47°N during the El Niño event (May 1983) and during a relatively normal time with comprehensive observations (September 1973; see Figure 1). He then averaged all the differences at the same depths between the coast and 127°W to form an average anomaly profile which is used here (Figure 2). Since the seasonal temperature signal is above 100 m (Dodimead et al., 1963), anomalies at this level and below were derived from reference data from different seasons where necessary. We calculated additional average anomaly profiles to supplement Reed's for 1982-83 along approximately 48°N using individual station data along the Ocean Station PAPA section presented in Tabata (1984) and referenced to a 1959-81 long-term annual mean (Figure 2, middle). The data used for 1957-58 are from stations along 46.9°N. Anomalies were calculated for various times using February 1957, one year prior to the peak of the event, as the reference (Figure 2, top). The 1940-41 data consisted of four stations each along 47.6°N in July of 1940 and 1941. Anomalies were calculated from the differences between the two years (Figure 2, bottom). Individual cruise data were used as references for our 1957-58 and 1940-41 data as well as for Reed's 1983 data because there were insufficient observations to form a climatological base at locations south of the PAPA line.

The average anomalies for February 1958 were calculated using four station pairs and were greater than 1°C in the upper 400 m and were 0.3°C at 700 m (Figure 2, top). The surface anomaly of almost 3°C is included because the reference month is also February (1957). Standard deviations from the mean anomalies at each depth were generally less than half of the means. Data from November 1957 (referred to February 1957) showed relatively small anomalies which indicates that the major warming occurred after then. In July 1958, five months following the sea-level anomaly peak, there still was a temperature anomaly of 0.5°C at 100 m and 0.4°C at 200 m.

The analogous buildup and decay of the 1982-83 event can be shown using Reed's (1983) average temperature-anomaly profile for May 1983 and average anomaly profiles we calculated from Tabata's (1984) individual profiles for November 1982, March 1983, and late June 1983 (Figure 2, middle), referred to mean annual conditions during 1959-81. Tabata's data are slightly north of Reed's but extend about the same distance offshore. The anomalies were

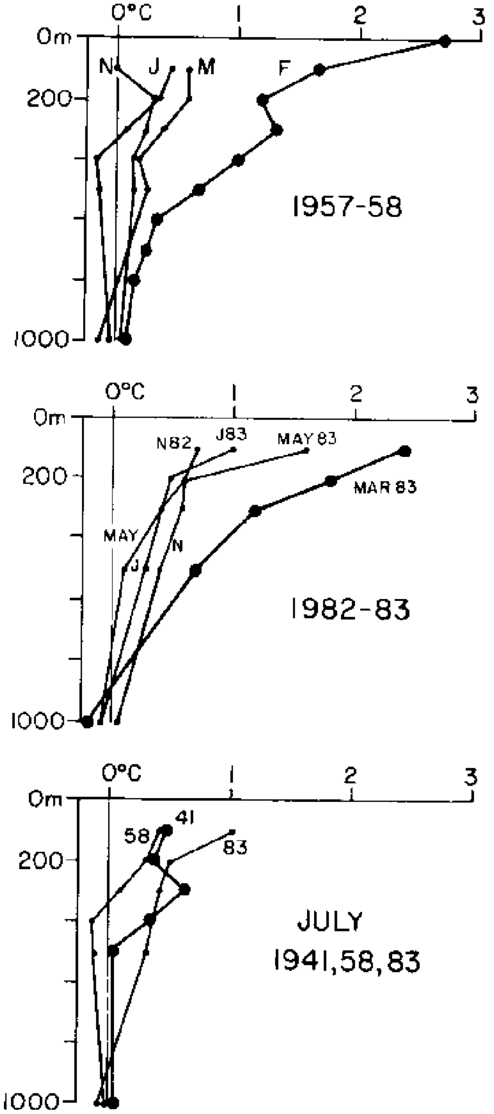


Figure 2. Average temperature anomalies between the coast and 127°W between 47 and 48°N. Top: November 1957, February (large dots), March, and July 1958 minus February 1957. Middle: November 1982, March 1983 (large dots), and June 1983 minus 1959-81 annual climatological mean (adapted from Tabata, 1984) and May 1983 minus September 1973 (from Reed, 1983). Bottom: July 1941 minus July 1940 (large dots) compared to July 1958 and late June 1983 anomalies from above.

greatest in March 1983 and were greater than 1°C in the upper 400 m. This was about the same as the February 1958 anomalies, the peak of that event. Comparison of the late June 1983 and the early July 1958 profiles suggests that the 1958 event may not have lasted as long as in 1983. The 1957-58 event, however, started about six months earlier in the year in the tropics than in 1982-83 (Quinn and Zopf, 1984).

Temperature anomalies also were calculated from four pairs of stations for July 1941 relative to the previous July (Figure 2, bottom). The anomalies were between 0.3 and 0.6°C in 1941; in 1983 the July anomalies extended to below 500 m, but those for July 1958 were detectable only to about 200 m. The peak in sea-level anomaly at these latitudes, however, occurred earlier in the year (winter) both in 1940-41 and 1957-58. Thus the temperature effects of the 1940-41 event may have been as large as the 1957-58 and 1982-83 events off the Pacific Northwest. However, data from other times could not be located.

The offshore and vertical extent of the 1957-58 El Niño event is shown by the temperature anomalies at individual stations along 47°N (Figure 3). The inset shows the corresponding surface temperature anomalies. The section is along the southernmost stations on the chart. The greatest values exceeded 3°C, and they were close to the surface near the coast. (This figure is unchanged if the 0-100 m interval is shown in more detail; in 1983, however, the maximum anomalies were at 100 m and decreased at 50 m according to Tabata, 1984.) The anomalies appeared to extend a little over 200 km offshore to 127°W. At the next station westward, anomalies greater than 0.5°C occurred only very near the surface. This is consistent with our choice of about 127°W longitude as an offshore limit for calculating the average temperature anomaly profiles along latitude 47°N in Figure 2. Anomalies greater than 1°C were associated with water of 8-10°C in February 1958; in February 1957 temperatures in this section were 8°C or less.

Discussion

The effects at mid latitudes (47-48°N) appear to have been similar for the 1957-58, 1982-83, and perhaps the 1940-41 El Niño events. The sea-surface temperature anomalies in 1958 were larger than in 1983; they occurred during winter, however, and did not persist through the following summer. During 1983, the surface temperature-anomaly peak occurred later (April), and warmer than normal temperatures extended through the summer.

The offshore extent of the anomalies was about the same in all three years (shown here for 1958 in Figure 3). Unusually warm water extended to about 127°W, more than 200 km offshore, which is about half the extent off California (Reid, 1960; Lynn, 1983; Simpson, 1983). However, this emphasizes that the effects are more than just a coastal phenomenon at the higher latitudes, which is all that can be determined from analysis of sea level data. In

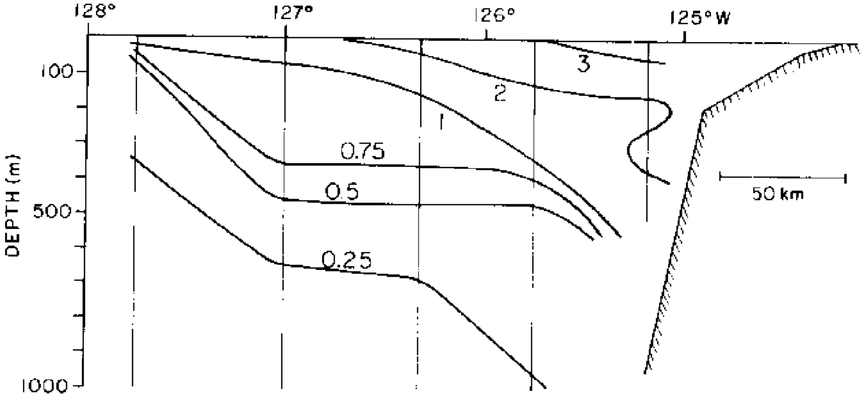
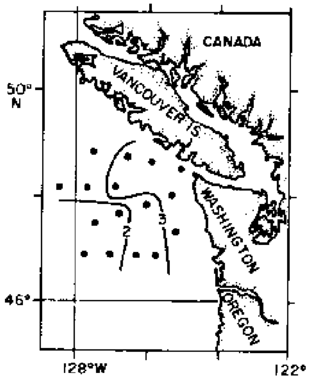


Figure 3. Top: Vertical section of temperature anomalies (°C, February 1958 minus February 1957) along approximately 47°N. Vertical lines indicate stations. Right: Chart of corresponding sea-surface temperature anomalies in °C. The section is across the southernmost five stations; the inshore station is north of the other four.



addition, the vertical extent (~500 m) of the warming indicates a large volume of water is involved.

Other studies have indicated El Niño effects farther north than the area examined here. Tabata (1961) showed at Ocean Weather Station P (50°N, 145°W) an increase in temperature between the surface and 1000 m for the first half of 1958 relative to the 1950-57 average and attributed the warmer water to northward transport into the region. Dodimead et al.'s (1963) maps of temperature on salinity surfaces showed about a 1°C increase in temperature from winter 1956-57 to winter 1957-58 in the upper 200 m from the Strait of Juan de Fuca northward to the head of the Gulf of Alaska. The offshore extent appeared to be about 200 km. Royer and Xiong (1984) observed positive thermal anomalies off Alaska in 1983, and Reed (1984) noted surface warming in the Gulf of Alaska and the Bering Sea in 1982-83.

Salinity anomalies for the data in Figure 3 during February 1958 were about -0.5°/oo at 100 m but were less than 0.05°/oo at deeper depths. In May 1983 the 100-m salinity anomaly was also negative, but slight positive anomalies were evident at 300-500 m (Reed, 1984). Tabata (personal communication), however, generally found positive subsurface salinity anomalies in late 1982 - early 1983. Reed's temperature-salinity analysis showed an increase over the normal percentage of equatorial water during May 1983, and the temperature sections examined for this study strongly suggested northward flow along the continental slope in February 1958. Thus it appears that the El Niño effects near the peak of the temperature anomalies were associated with a northward movement of water which extended offshore about 200 km. Simpson (1984), however, argued for onshore transport of Subarctic water off California instead of poleward transport. Large-scale wind patterns support more onshore flow off southern California, but more alongshore (northward) flow off the Pacific Northwest (Quiroz, 1983; M. Wallace, personal communication). Also, the anomalous wind patterns started later (January 1983) than the onset of the sea-level anomalies (September-December 1982) for the 1982-83 event. Furthermore, Smith and Huyer (1983) found anomalous northward currents starting in October 1982 off Oregon. Thus the onset of anomalous conditions occurred rapidly over a vast region before extreme atmospheric cyclogenisis, which suggests initial poleward advection by a long wave.

Other El Niño occurrences have not had major effects at high latitudes. For example, during the 1972 event the winds along the coast at the higher latitudes were opposite to the normal pattern and were to the south throughout the Gulf of Alaska (shown in Figure 4c, but not discussed, in Enfield and Allen, 1980). It seems possible that southward wind drift may have altered the normal northward flow expected during an El Niño event. On the other hand, winds were strongly northward during both the 1957-58 event (Enfield and Allen, 1980) and later stages of the 1982-83 event (Quiroz, 1983), which may have contributed to their considerable poleward extent.

Not all of the warming events which have been observed off the Pacific Northwest, however, are associated with El Niño episodes. In 1981 a surface warming, with anomalies as large as 3°C, was observed to propagate northward along the coast (Freeland and Giovando, 1982) and into the Puget Sound estuarine system (Mearns and Patten, 1982). Our comparison of data during this event with those at other times, however, indicate that this was only a surface phenomenon and did not extend to appreciable depth as was the case following the El Niño events.

Finally, our use of individual cruise data to calculate temperature anomalies points out the gap in observations sufficient to form a climatological data base between the northern end of regularly sampled CALCOFI stations (approximately northern California) and the Ocean Station PAPA section (Vancouver Island). In spite of this, we feel our data are sufficient to demonstrate, at least qualitatively, some offshore effects with depth of El Niño events at these latitudes.

Acknowledgments

Initial discussions with E. Bernard prompted our undertaking this study. A. Schoener in her investigations of biological effects kept encouraging us by asking about various physical changes during El Niño events. Contribution number 697 from the Pacific Marine Environmental Laboratory.

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El Niño Effects Along and Off The Pacific Coast of Canada During 1982–83

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Abstract

The anomalous warming of surface water and the anomalous rise of mean sea level along the Pacific coast of Canada in early 1983 indicated the effect of El Nino along the coast and there have been earlier El Nino signals evident in the large changes of temperature in the sub-surface waters off the coast before 1983. The 1982-83 episode is compared with the similar one that occurred during 1957-58.

Introduction

The El Ninos of 1940-41 and 1957-58 can be considered as the two major events that resulted in a widespread, anomalous warming along the Pacific coast of North America. Oceanographic data were scarce for the earlier event, but the later, 1957-58 event is well-documented (see for example, Sette and Isaacs, 1960). Along the coast of British Columbia (B.C.) sea-surface temperatures (SST) were anomalously high during the two periods (Fig. 1), and associated with the increase in SST were higher mean sea levels. Off the coast during 1957-58 warming was evident in the sub-surface layers (Tully et al., 1960) and extended at least as far as Station P (50°N, 145°W) (Tabata, 1961).

In addition to data available from the regular monitoring of coastal sea-surface temperatures and salinities, and sea level heights, oceanographic data taken between Station P and the B.C. coast are available at a few to several months intervals during 1981-83. The location of oceanographic stations taken during this period is shown in Fig. 2. These data form the basis for the present discussion on the El Nino effects along and off the coast.

Results

There has been an irregular, increasing trend of SST along the coast since the early 1970s, reaching its maximum in 1983 (Fig. 1). More detailed monthly anomalies of SST (Fig. 3) showed that an accelerated rise occurred during the winter of 1982-83, reaching maximum (+2°C)

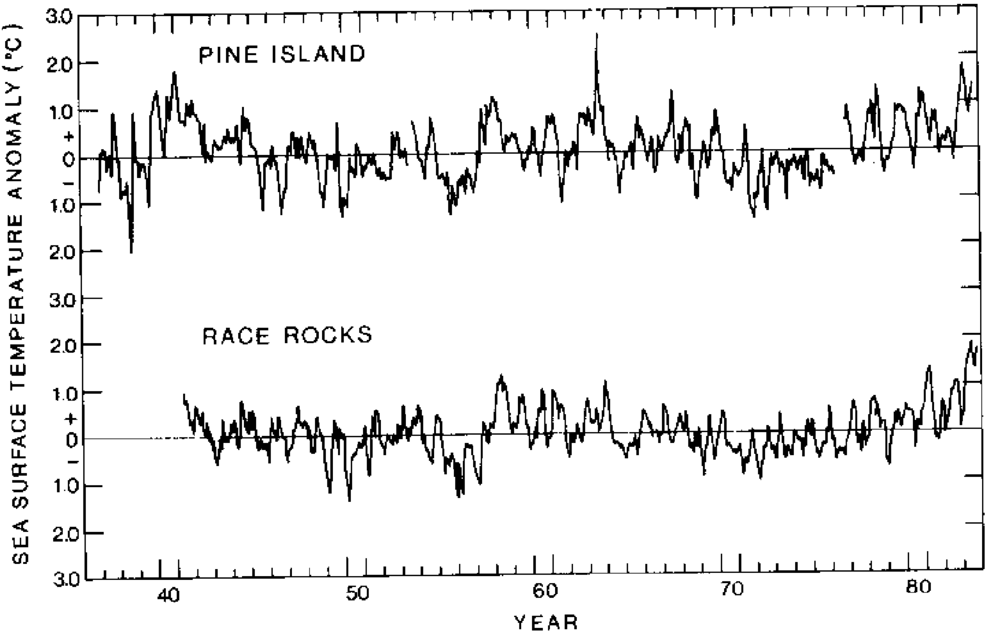

Figure 1. Anomaly of monthly mean sea-surface temperatures (°C) for Pine Island and Race Rocks along the Pacific coast of Canada, based on 33-year means (1950-82).

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in March-May 1983. Although they dropped during the remainder of 1983, positive anomalies (+1°C) persisted along the northern coast whereas they became "normal" or became negative along the southern coast. Sea level heights, on the other hand, although exhibiting a similar trend to that of SST, showed an appreciable rise in early 1982, followed by an even greater rise in early 1983, reaching maximum in February (Fig. 3). Thereafter the anomalies decreased until another sharp rise and fall occurred in the later part of 1983.

Continuous observations of SST along Line P (line between Station P and southern coast of B.C.) during November 1982 and March 1983 revealed that while the earlier data showed a large positive anomaly only within 30 kilometers (km) of the coast, later data showed a large anomaly (2-3 times the standard deviation) occupied an area within a few hundred km of the coast. The intrusion of warm water during this period is well-depicted in the satellite-derived SST, as shown in Fig. 4.

Away from the shore a remarkable warming occurred in the subsurface layers over the continental shelf and slope before November 1982 and in offshore waters in early 1983. This event can be examined by comparing the sequence of temperature profiles available for this period

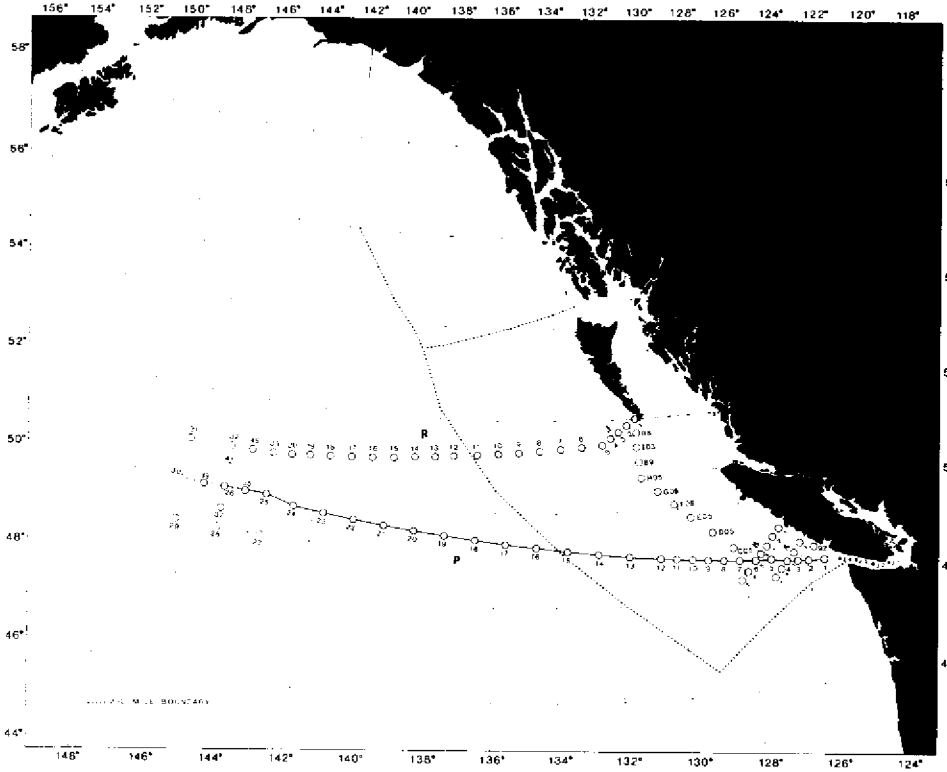

Figure 2. Oceanographic stations occupied during 1981-83 cruises. Not all the stations indicated were taken during each cruise.

(Fig. 5). During the period September to November 1982, an appreciable increase in the subsurface temperatures occurred over the continental shelf and slope in the upper 800 m depths, being largest at a depth of 200 m (Station P1-P6), in a relatively narrow band (100 km of the coast). An increase as much as 5°C occurred in the layer between 50 and 100 m over the shelf. No significant warming was noted beyond the continental slope during this period, but subsequently between November 1982 and March 1983 a spectacular increase in subsurface temperatures resulted in the offshore waters, particularly between Stations P6 and P12, a distance of only 100 km. The largest increase occurred in the layer between the depths of 125 and 175 m and was as large as 3°C. In terms of standard deviation, the increase represents 10 times at a depth of 150 m. While such a large increase occurred in the offshore waters, in contrast only a limited increase occurred in the inshore waters, at depths between 50 and 300 m, and a decrease occurred at greater depths by as much as 1°C. By end of June 1983 the large positive anomaly in the subsurface layers had either been reduced appreciably or in some cases had disappeared. However, along the northern

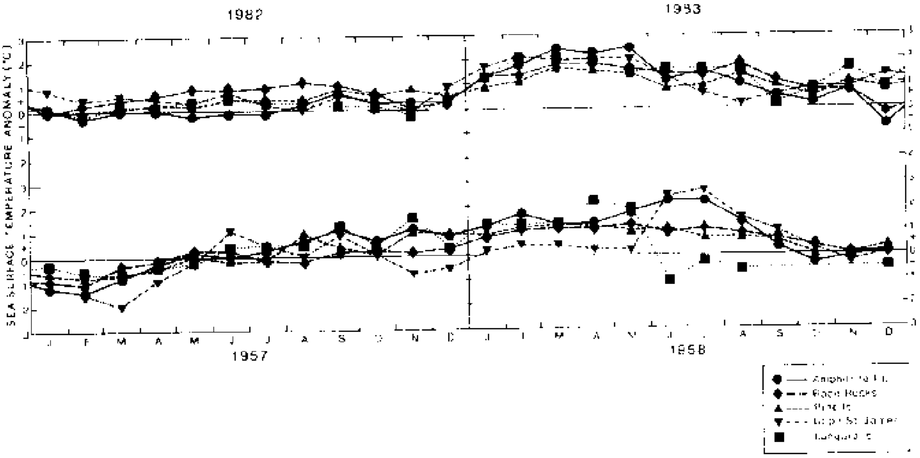

Figure 3a. Anomaly of monthly mean sea-surface temperature (°C) for exposed coastal stations for periods 1982-83 and 1957-58, based on 33-year means (1950-82).

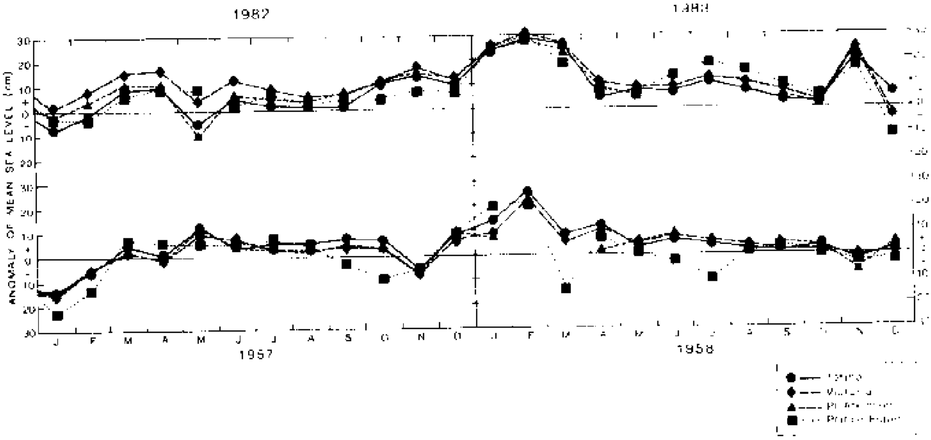

Figure 3b. Anomaly of monthly mean sea level heights (cm) for representative coastal tidal stations for periods 1982-83 and 1957-58, based on 33-year means (1950-82).

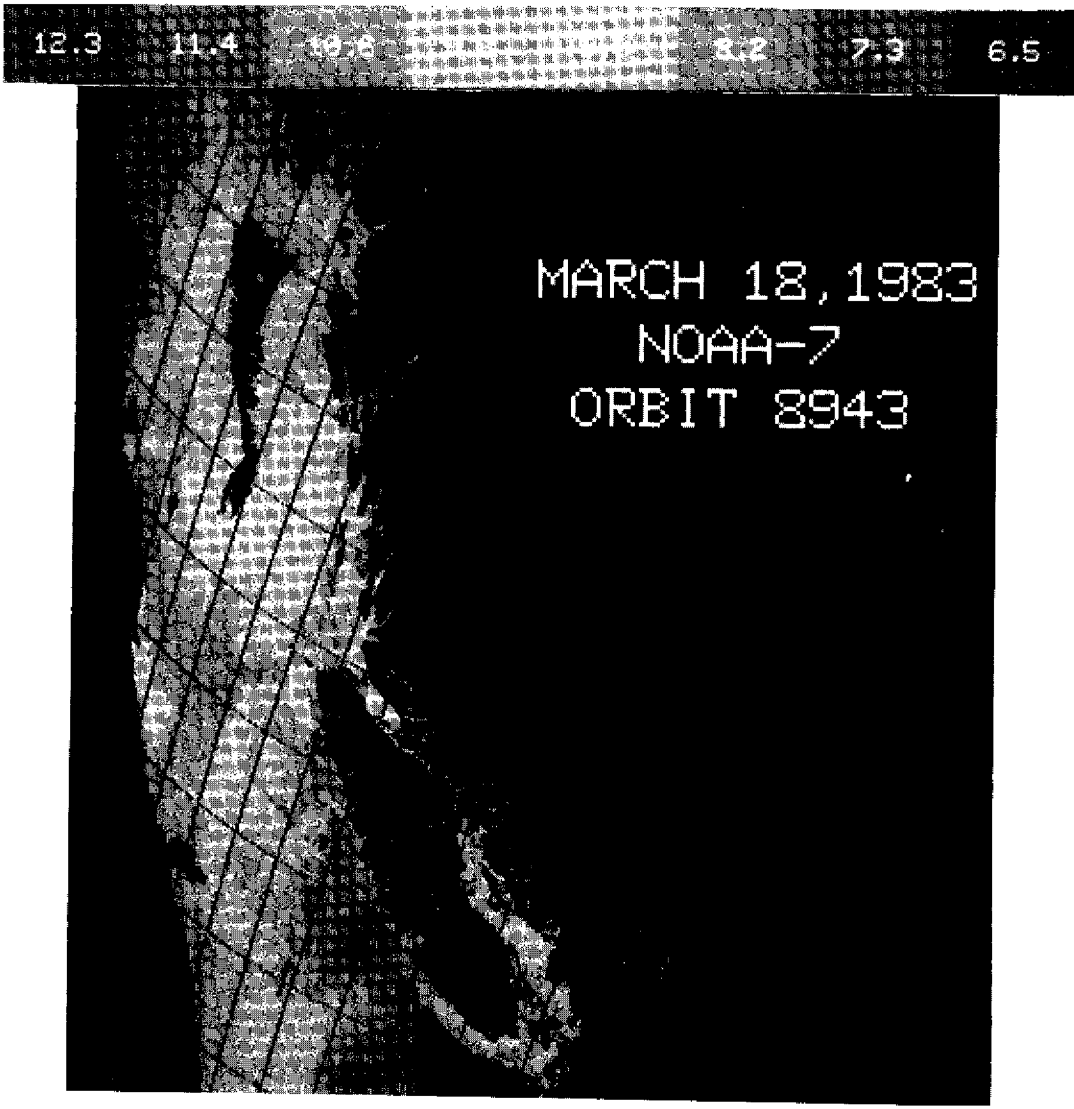

Figure 4. Satellite-derived sea-surface temperatures (°C) off the Pacific coast of Canada and State of Washington (Time: 22:01 GMT, 18 March 1983; NOAA-7, Orbit No. 8943). These temperatures were obtained through field-calibration, based on 74 SSTs taken by a research ship during 16-18 March 1983. The temperatures are estimated to have an accuracy of 0.3°C.

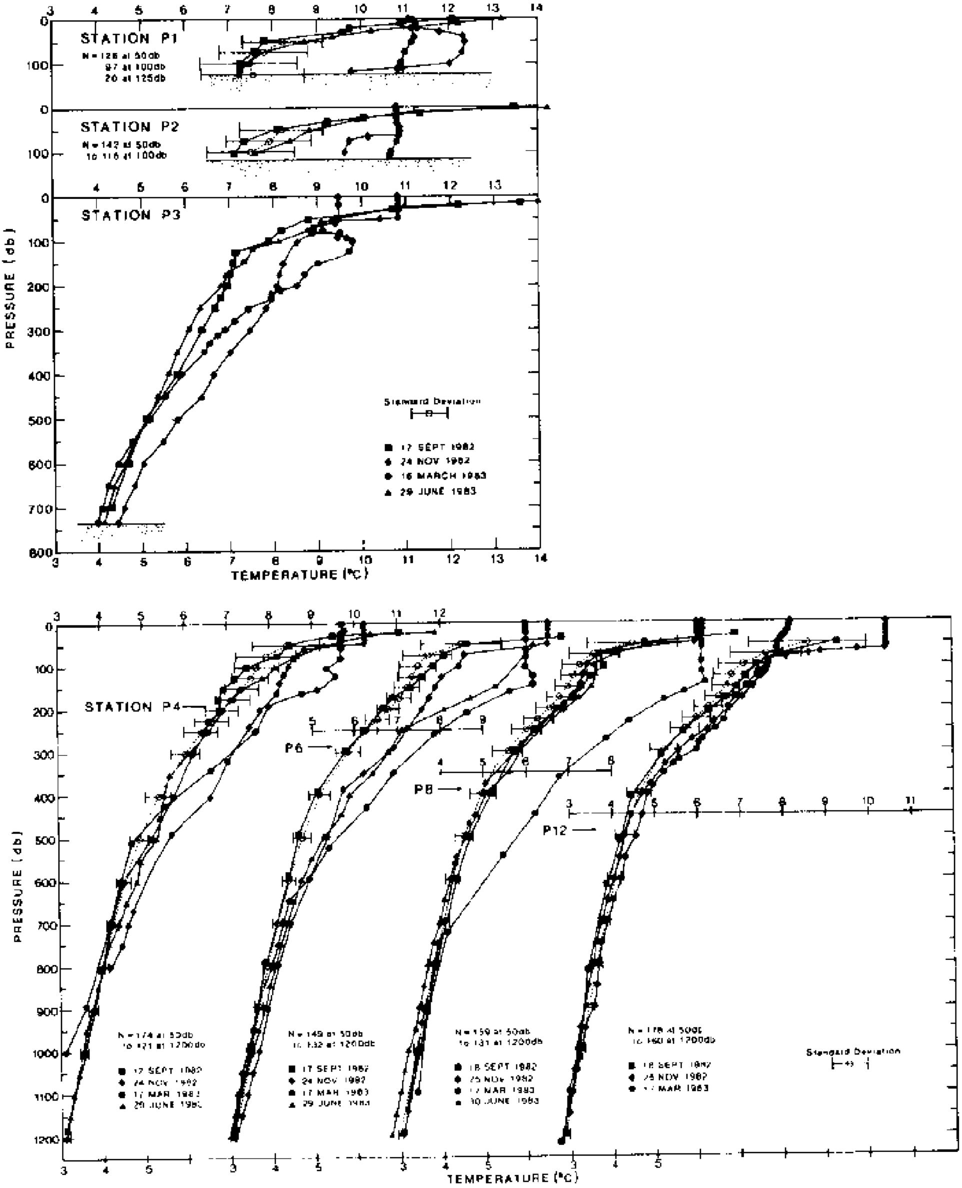

Figure 5. Representative temperature profiles (^{0}C) at stations along Line P and within a few hundred km of the coast for the period September 1982 - August 1983. The means and their associated standard deviations are based on all the data collected during 1959-1981.

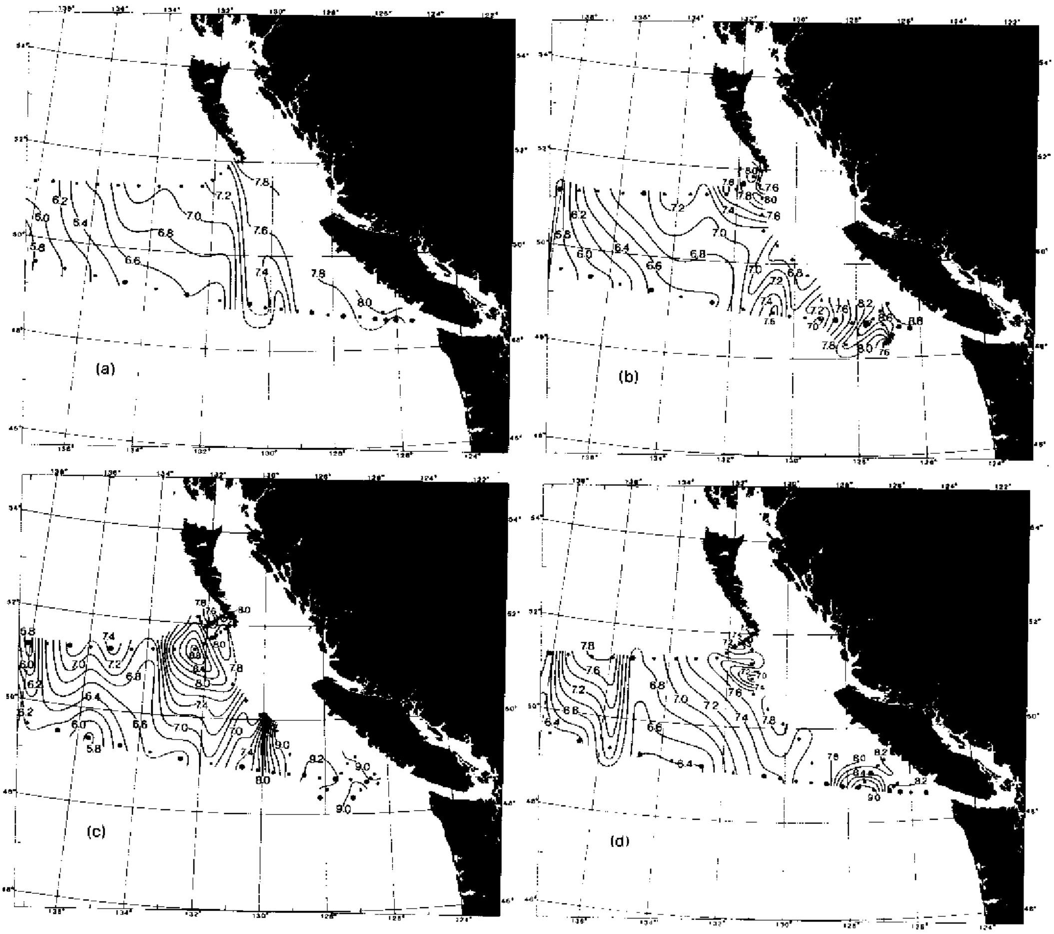

Figure 6. Distribution of temperature (^{0}C) along isopycnal, σ_t = 26.0:

(a) 17-30 September 1982
(b) 24 November - 5 December 1982
(c) 16-30 March 1983
(d) 17-26 August 1983

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line, warming continued during March-August 1983 in a narrow band (∿ 100 km) between Stations R10 and R13.

The areal extent of subsurface warming off the coast during the summers of 1982 and 1983 can be examined by comparing the temperatures along isopycnals such as on σ_t = 26.0 (Fig. 6) and 26.8 (Fig. 7) for successive periods. The depth of σ_t = 26.0 is about 100 m and of

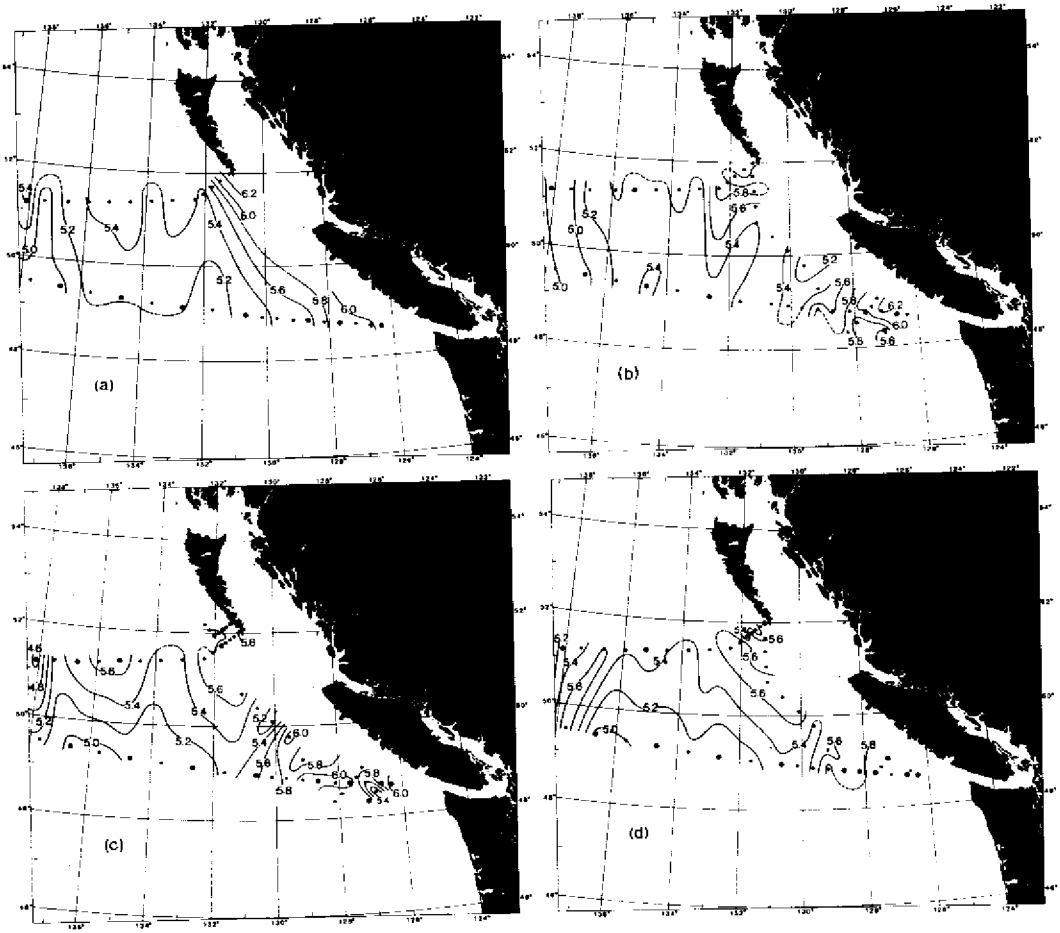

Figure 7. Distribution of temperature (°C) along isopycnal, $\sigma_t = 26.8$:

(a) 17-30 September 1982
(b) 24 November - 5 December 1982
(c) 16-30 March 1983
(d) 17-26 August 1983

$\sigma_t = 26.8$, 300-400 m (Fig. 8). As is evident from Fig. 6 warming between September and November 1982 is only conspicuous near the coast but between November 1982 and March 1983 a widespread warming occurred within approximately 200 km of the coast. By August 1983 the warm water off southern B.C. had retreated southward. The 9°C-water present in March 1983 now occupies a small area along Line P. It is uncertain where the warm water lying off the Queen Charlotte Islands to the north in March 1983 had gone by August 1983. It is speculated that it might have propagated westward as a consequence of baroclinic Rossby waves. Other data are being examined to see if this speculation has substance. In the deeper layer where σ_t = 26.8 the warming between November 1982 and March 1983 and the cooling between March and August 1983 are both present (Fig. 7). There is, however, still evidence of a presence of relatively warm water lying northwest of Vancouver Island in August.

The deepening of the isopycnal surfaces along the Pacific coast of North America is also considered an effect of El Nino (Fig. 8). The three isopycnals (σ_t = 26.0, 26.4 and 26.8) all show deepening between November 1982 and March 1983. However, there is some difference in the behavior of these isopycnals from one period to another and from one location to another. For example, at the two inshore stations (P4 and P6) the isopycnal, σ_t = 26.0 remained deep until August whereas at the offshore stations (P8 and P12) it had returned to "normal" depths by late June. A somewhat analogous trend is noted for the isopycnal, σ_t = 26.4; however, at Station P4 the deepening was evident earlier, between September and November 1982. The relatively deep σt = 26.8 isopycnal exhibited changes that were occasionally different from those of the other two. Here, while the large increase in the depths occurred between November 1982 and March 1983, as for the other isopycnals (σ_t = 26.0, 26.4), it was already deep compared to the corresponding long-term means in early 1982, particularly at the inshore stations (P4 and P6) and continued to remain deep until August 1983. It is to be noted that the deepening of the isopycnal at the offshore station (P12) is much less than at other stations inshore of it.

Comparison Between the Effects of 1982–83 and 1957–58

The 1982-83 and the 1957-58 warm episodes were similar in that during both periods the SST increased and the mean sea level rose along the coast (Fig. 3). However, some differences also occurred. For instance, the recent event is featured by a sudden rise of SST during the winter, reaching a maximum that persisted for a few months, and decreased gradually. The earlier one is characterized by a slow, gradual increase during 1957-58, reaching maximum in summer, then followed by a sharp drop. For the sea level heights the recent event had a sharp rise in early 1982, followed by a rapid decrease, and a rebound from whence it increased slowly until winter when a sudden increase occurred, with maximum in February. The peak in late 1983 is, at the moment, unexplained. The sea-level anomalies during the earlier event also increased earlier in the year (1957), followed by another increase in winter. During this event the maximum which occurred in February, as in the later one, lasted for only one month; then both events slowly decreased during the remainder of the second year. Both in terms of the anomalies of SST and sea level heights, the magnitudes for the recent event are larger than the corresponding values for the earlier events.

The recent warming in the subsurface layers is much larger than during the previous 1957-58 event. During the 1950s the poleward advance of the 8° isotherm on the isopycnal surface of σ_t = 26.0 started from the vicinity of California and Oregon coast in 1955-56 and reached the Washington coast in 1958, (Tully et al., 1960). Only later, in

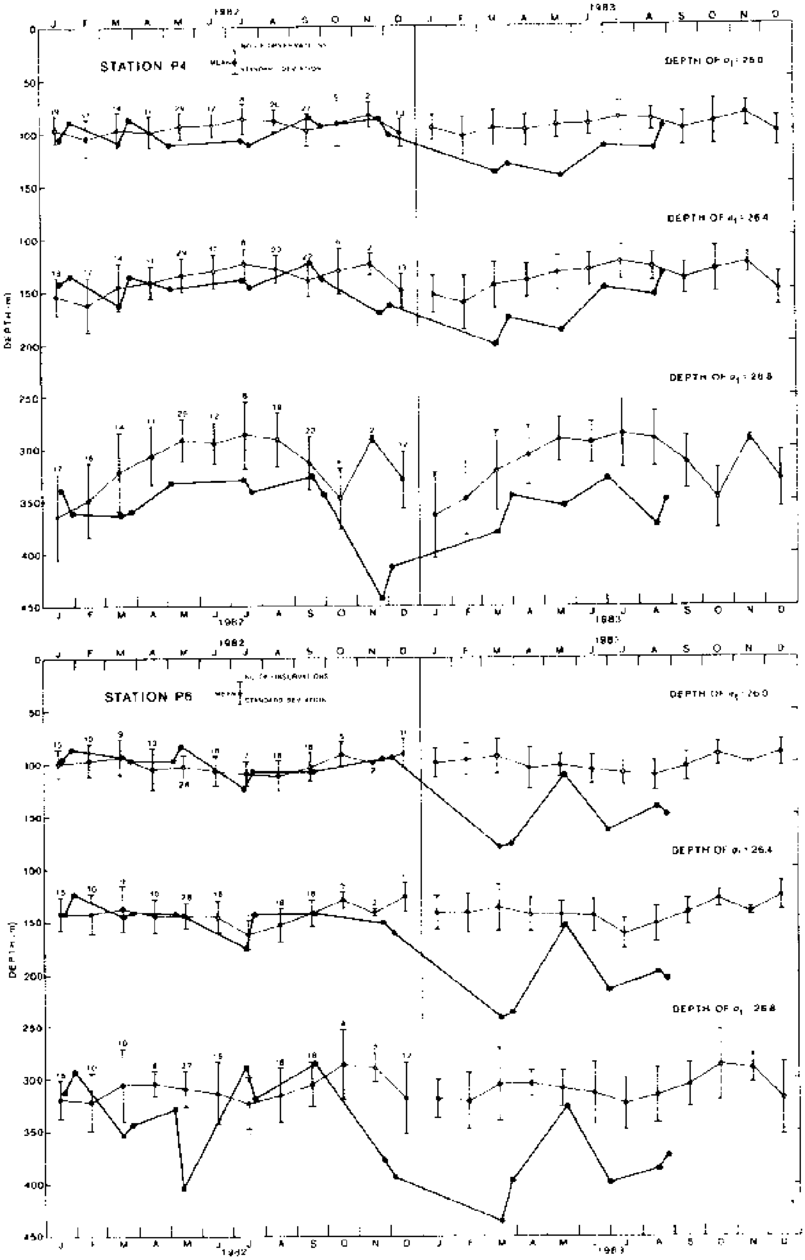

Figure 8. Depths (m) of isopycnals, σ_t = 26.0, 26.4 and 26.8 for period 1982-83. The means and their associated standard deviations are based on data taken during 1959-81.

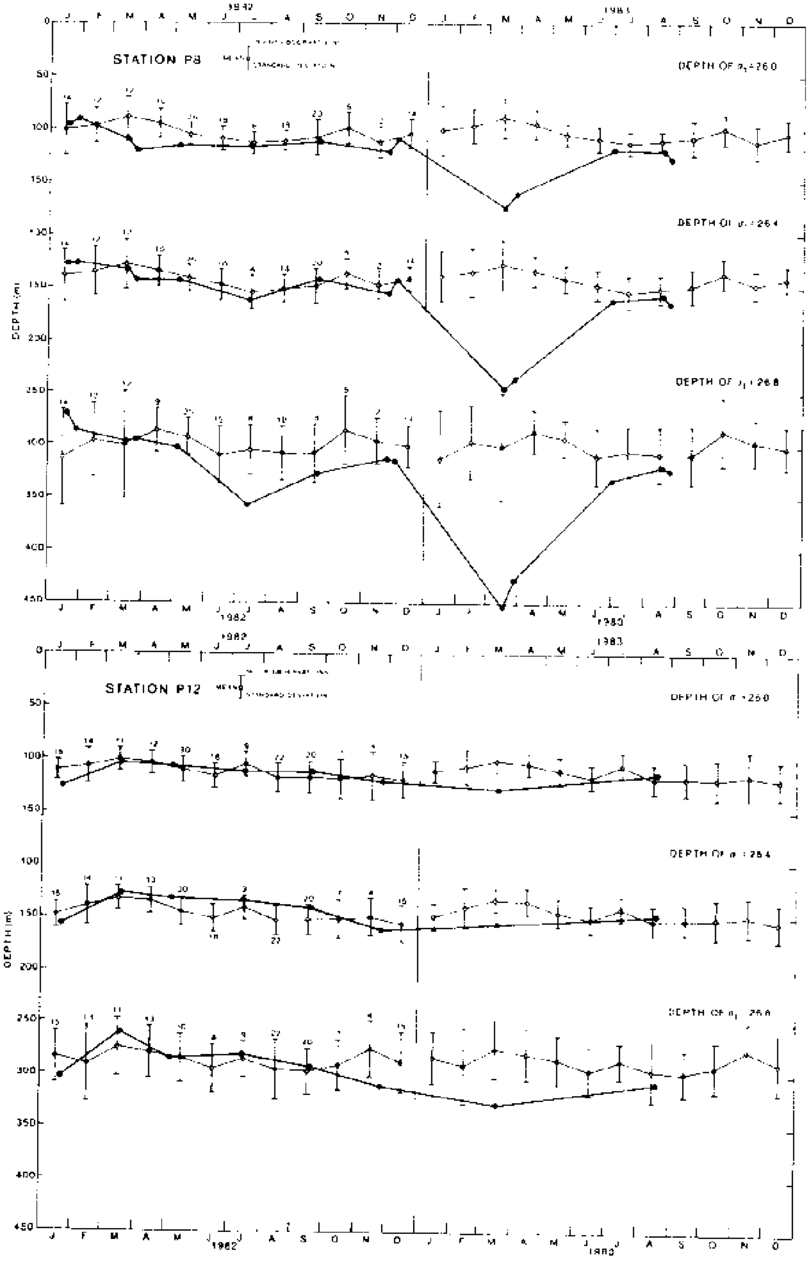

Figure 8. Continued.

the winter of 1959, was such an isotherm located off the B.C. coast. During the recent event such an isotherm was present off the B.C. coast by March and large temperatures greater than 9°C were encountered. In the deeper waters on the isopycnal surface of $\sigma_t = 26.8$, however, the isotherm 5.6°C appears to have extended farther northward during the earlier event than for the recent one. While the anomalous warming of the recent event is more intense than the earlier one, its area extent is smaller, being restricted to a few hundred kilometers of the coast. The earlier one, though not as intense in magnitude, had a much greater influence over a larger area of the northeast Pacific.

Acknowledgments

Grateful acknowledgement is made to the many people who persevered to obtain oceanographic data during 1982-83. Thanks are also due to Ms. P.M. Kimber for preparing the illustrations and Ms. A.L. Mathias for typing the manuscript.

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On the Interannual Variability of Eddies In the Northeast Pacific Ocean

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Introduction

Schumacher and Reed (1983) recently discussed some aspects of the interannual variability of the circulation, sea surface temperature, sea level and atmospheric conditions in the Gulf of Alaska. However, in their review, little attention was given to describing the year-to-year changes in the eddy field in this region. During the past few years a number of studies have shown that in the Northeast Pacific and its inshore waters, there is significant mesoscale activity whose occurrence and strength in any one location change interannually. Perhaps the best known example of this is the large, clockwise-rotating Sitka eddy, recently described in some detail by Tabata (1982). The main purpose of this note is to present observational and theoretical evidence which strongly suggests that the intermittent appearance of this eddy (at around 57°N, 140°W--see Figure 1) may ultimately be due to interannual changes in the North Pacific winter atmospheric circulation.

However, before giving this evidence we shall mention a few other cases of observed interannual variability of eddy energy in the Northeast Pacific. It is conceivable that some of the arguments presented in connection with the Sitka eddy phenomenon may also apply to these examples.

In their study of the low-frequency (periods of a few days) current fluctuations in Shelikof Strait, Alaska, Mysak et al (1981) noted that the amplitude level and time scale of this eddy energy changes from season to season and, for a given season, from year to year. The fluctuations were shown to be due to baroclinic instability of the along-channel mean flow, and since this and the mean stratification have a strong annual signal, the seasonal changes in the eddy field are understandable. However, the mean flow during fall 1976 was much stronger than in fall 1978, indicating the presence of significant interannual variability. Along with the reduction in mean flow, the peak eddy energy in Shelikof Strait dropped by several factors and shifted toward longer time scales. Some evidence of interannual changes in the subsurface eddy energy (periods of 10-25 days) and seasonal mean flow conditions in the central part of the Strait of Georgia has recently been reported by Yao et al (1984). However, the mechanism for producing the current fluctuations and the reason for the year-to-year changes in the mean flow are unknown and remain as a challenge to the theoretician.

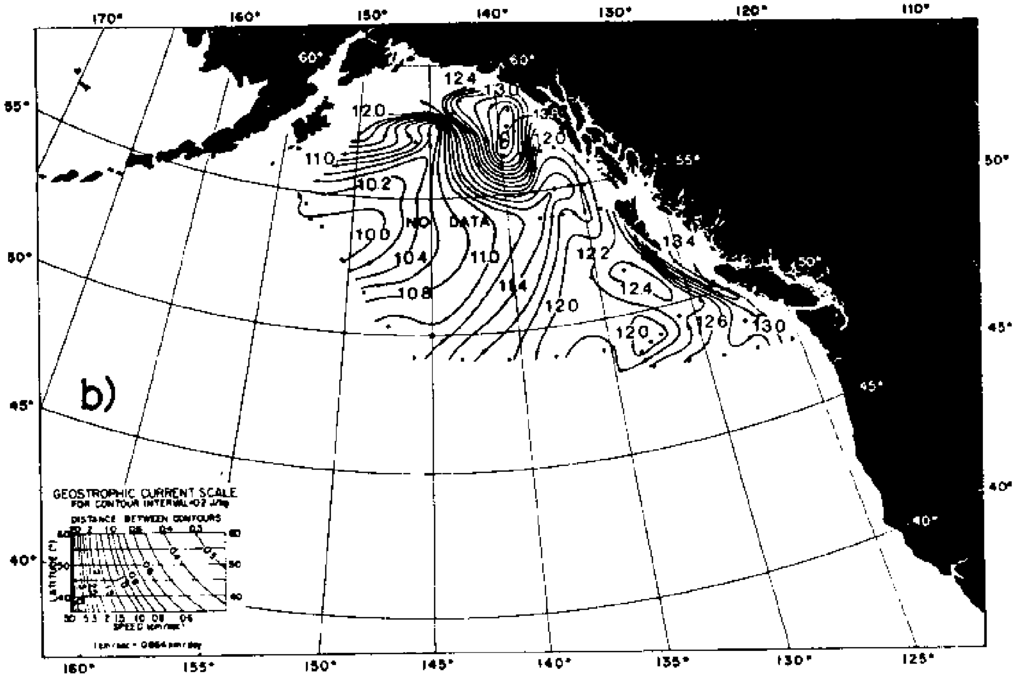

Fig. 1 Geopotential anomaly at the sea surface relative to the 1000 db surface (JK g^{-1}) in the northeast Pacific during March-April 1958 (from Tabata, 1982). The anticyclonic (clockwise-rotating) Sitka eddy is centered at approximately 57°N, 140°W.

In connection with the recent 1982-83 ENSO episode, Tabata (1984) noted the presence of a relatively large, warm-core subsurface eddy off Queen Charlotte Sound, British Columbia during spring 1983, the peak period of the local warming. Although the data is sparse for earlier years, it appears that like the Sitka eddy, this may be an intermittent phenomenon. However, its generation mechanism is not known. Further offshore, Emery et al (1984), in their study of satellite-tracked drogued buoys in the Gulf of Alaska, presented some evidence of the interannual variability in the near-surface eddy field during August 1981-March 1983. During winter 1982, when the atmospheric circulation was anomalously weak, the drogue tracks contained a considerable number of meanders. However, during the next winter, when the Aleutian low expanded and intensified, relatively straight tracks (and strong currents) were observed, especially along segments of the California-Alaska coast.

The seasonal variability of the eddy field off Vancouver Island has now been reasonably well established (Ikeda et al, 1984). However, since the formation and growth of the meanders (which later develop into the eddies) is due to baroclinic and (to a lesser degree) barotropic instability of the California Current system and the latter has significant interannual changes (Chelton et al, 1982; Simpson, 1983, 1984), it is conceivable that for a given season the eddy field off Vancouver Island should contain an interannual signal. The search for this signal would make an interesting topic for future research.

The Sitka Eddy and Its Generation

From an analysis of historical hydrographic data and satellite-tracked buoys (Kirwan et al, 1978) in the Gulf of Alaska, Tabata (1982) noted the occurrence, in a number of years, of a baroclinic, clockwise-rotating eddy a few hundred kilometers to the west of Sitka, Alaska (located at 57°N, 135°W). The eddy (hereafter called the "Sitka" or "Tabata" eddy) is typically 200-300 km in diameter, extends to a depth of about 1,000 km, and has a maximum (axial) speed on the order of 40 cm s^{-1} (relative to the 1,000 db surface). An example of a well developed Sitka eddy is shown in Figure 1.

In any year of occurrence the Sitka eddy generally first appears during the spring-summer period and then persists for up to one year, often moving slowly westward (at $\sim$ 1-2 km d^{-1}) during this time. Since the eddy is not observed every year, interannual effects appear to be important for its generation. In this spirit, Willmott and Mysak (1980) suggested that a generation mechanism for this and other Northeast Pacific eddies is atmospherically-forced interannual (period $\sim$ 5-6 years) baroclinic Rossby waves that undergo multiple reflections at the coastlines of British Columbia and Alaska. However, it was recognized (Willmott and Mysak, 1980; Tabata, 1982) that topographic irregularities off the Alaskan panhandle could also contribute to the production of the Sitka eddy. Recently, Swaters and Mysak (1985) have proposed a theory for the generation of the Tabata eddy by the interaction of a steady coastal current with a variable bottom topography.

The idealized bottom topography (Figure 2) used in the theory of Swaters and Mysak contains two bathymetric features found in the vicinity of the Tabata eddy: the collection of high seamounts centred around Pratt seamount (56°N, 143°W) and the broad seaward protrusion at the base of the continental slope off Baranof Island (on which Sitka is located). Starting from the conservation of potential vorticity on the f-plane, Swaters and Mysak (1985) showed that a northward-flowing baroclinic, latterally-sheared current representative of the Alaska current (see Figure 2) encountering this topographic configuration generates a large anticyclonic (clockwise-rotating) baroclinic eddy which possesses many of the characteristics of the Sitka eddy (e.g., horizontal and vertical structure, diameter and transport). An example of the surface flow pattern obtained by Swaters and Mysak is shown in Figure 3. For a moderate incident upstream current, two stratified Taylor columns get trapped over each topographic feature, but encircling both of these small anticyclonic eddies is a large anticyclonic eddy (diameter ~ 400 km). It is this circulation which probably approximates best the observed Tabata eddy.

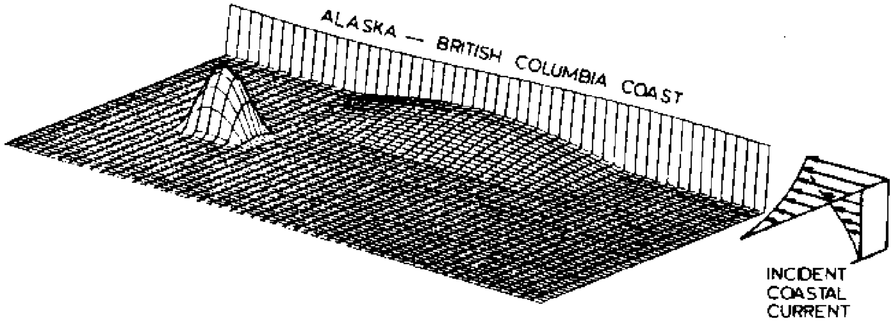

Fig. 2 Three-dimensional plot of topographic model used to generate the Sitka eddy by the interaction of an incident coastal current (shown at lower right) (from Swaters and Mysak, 1985).

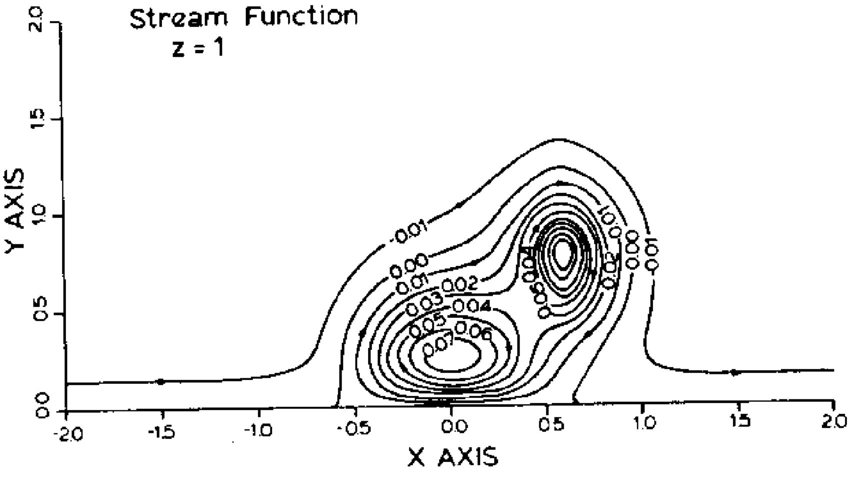

Fig. 3 Horizontal contour plot of surface stream function computed by Swaters and Mysak (1985) for an upstream current of 5.9 Sverdrups. The x axis points to the northwest and the topographic features are centered at (0, 0.25) (the slope protrusion) and (0.6, 0.75) (the "Pratt Seamount"). A unit distance on the axes corresponds to 400 km.

From a parameter sensitivity study, Swaters and Mysak found that for the eddy field to have closed streamlines (at the surface), the upstream surface current must be <u>less</u> than about 20 cm s^{-1}. Maximum axial current speeds occur, however, for an upstream current of about 5-7 cm s^{-1}. For upstream surface speeds less than this, the surface signature of the eddy is very weak. Thus the intermittent appearance of the eddy could be due to interannual changes in the strength of the upstream surface flow, which in turn could be caused by changes in the atmospheric forcing.

Interannual Variability of Upstream Conditions And Atmospheric Circulation

Figure 4 shows the baroclinic transports across Line P for the period 1959-1981. Since Line P cuts across the path of the northward-flowing Alaska Current (modelled by the coastal shear flow shown in Figure 2), the interannual variability of the transport across this line can be used as a measure of the year-to-year changes in the upstream current. Also indicated in Figure 4 are the times when eddy has been observed (arrow) and has not been observed (dashed line). The large number of years during which there are no lines or arrows arise because no data were available during these times. Although the evidence is limited, the data suggest that the Sitka eddy tends to form (in spring-summer) during or shortly after a slight relaxation of a strong upstream flow (an upstream transport of $6\text{-}7 \times 10^6 m^3 s^{-1}$, i.e., 6-7 Sverdrups). Such a condition will arise just after the occurrence of an expanded and intensified (or deepened) Aleutian low, a phenomenon which often happens during winter of the second year of a major El Niño episode, but also during non-El Niño years (e.g., 1977 - see Figure 5). When such a low occurs, the wind-driven upstream flow across Line P is very strong, and according to Swaters and Mysak, precludes the trapping of an eddy by the topography. However, when such a low weakens (in spring - see Hamilton, 1984), the transport across Line P will tend to decrease slightly (ocean spin-down effect) and hence produce a favorable (i.e., a moderate) coastal current for eddy production by mean flow-topographic interaction. According to Swaters and Mysak, this occurs when the upstream transport is about 6 Sverdrups. (The theoretical upstream transport associated with Figure 3 is 5.9 Sverdrups.) On the other hand, when the upstream transport is weak (e.g., winter 1962), the transport across Line P is relatively small (~ 3-5 Sverdrups) and consequently no surface eddy is formed because of a very weak mean flow-topographic interaction.

These results relating the Tabata eddy occurrence to the upstream transport and atmospheric circulation are summarized in Table 1, which also includes data for the 1982-83 El Niño event. In view of the pattern found in Table 1, Swaters and Mysak (1985) predicted that a Sitka eddy would be formed in spring 1983, following the occurrence of the expanded and intensified Aleutian low during winter 1983 (Simpson, 1983). Only a few weeks before this conference, this prediction was confirmed by Andrew Thomas who produced an infrared satellite image of the Sitka eddy from data collected and archived at U.B.C.'s Department of Oceanography remote sensing facility (see Figure 6). It is interesting to note the substantial

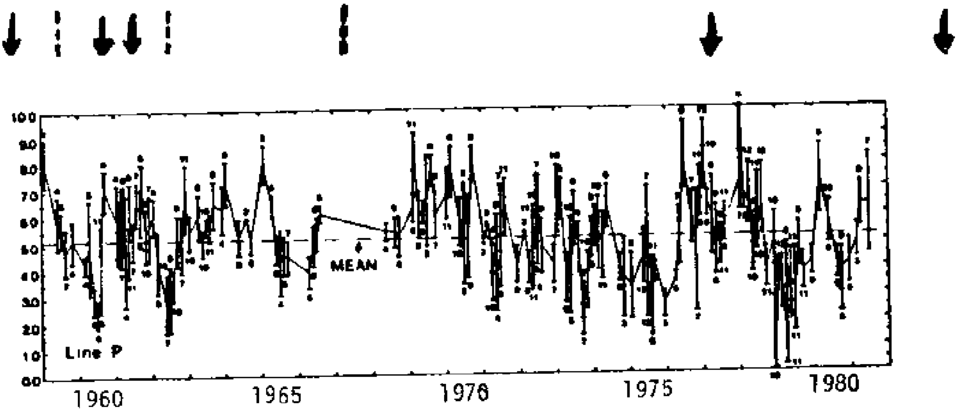

Fig. 4 Baroclinic transports ($10^6 m^3 s^{-1}$) across Line P (from 48°N, 126° 40'W to 50°N, 145°W) for the period 1959-1981 (from Tabata, 1983). Numerals denote the number of stations used to estimate transports. The arrows (dashed lines) at top indicate when the Sitka eddy has been (has not been) observed.

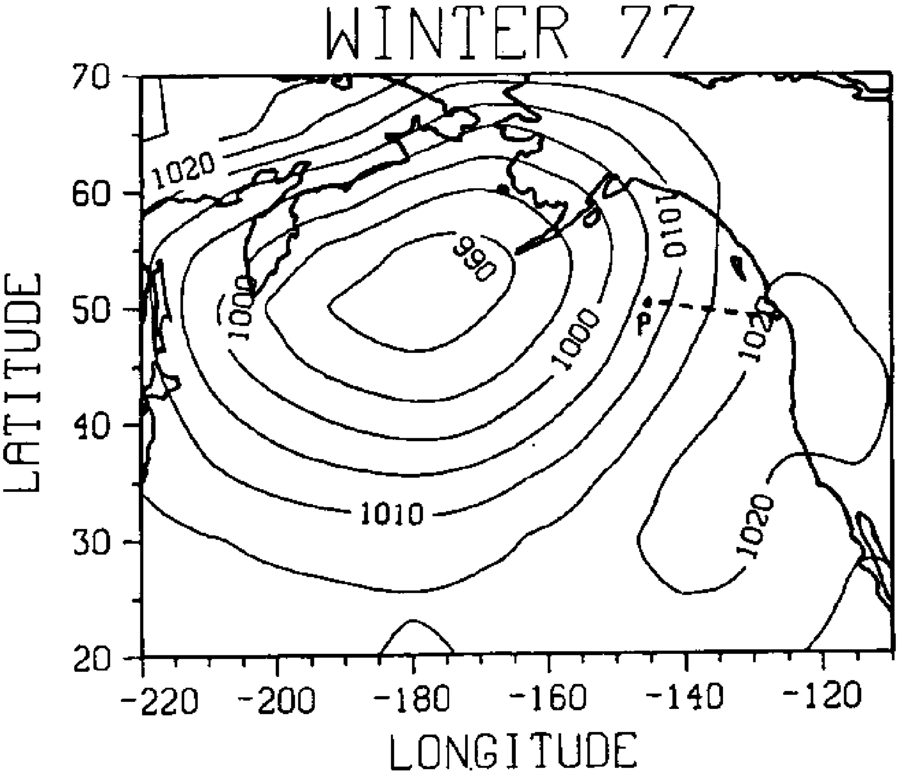

Fig. 5 Seasonal mean sea level pressure chart for winter 1977 (Emery and Hamilton, 1985). The dashed line denotes Line P.

entrainment of offshore cold water (light shade) along the north side of the eddy, a phenomenon consistent with a clockwise-rotating motion.

Summary

We have presented evidence which suggests that the intermittent occurrence of the Tabata eddy is due to the interannual variability of the upstream flow, which in turn is likely caused by changes in the sea level atmospheric circulation. In particular, we have shown

Table 1

Dates of eddy occurrence and corresponding Line P transport and sea level atmospheric circulation in the North Pacific. A strong winter circulation corresponds to an intensification of the climatological Aleutian low, whereas a weak circulation corresponds roughly to a weakened Aleutian low shifted westward and a weak high pressure intrusion from the southeast.

Date of Oceanographic Data[1]	Eddy present near Sitka	Baroclinic transport ($10^5 m^3 s^{-1}$) across Line P[2]	Winter (DJF) N. Pacific atmospheric circulation[3]
1954, Aug-Sept	Probably (data for region incomplete)	?	Moderate to strong
1956, May-June	No	?	Weak
1957, July-Aug	No	?	Weak
1958,[4] Mar-Apr (Fig. 1)	Yes	8(?)	Strong
June-Aug	Yes (but eddy observed further offshore		
1959, Jan-Feb	No, but 1958 eddy observed still farther offshore)	7	Moderate to weak
Aug-Sept	No	6	
1960, Jan-Feb	Starting to form	4.5	Moderate to strong
July-Sept	Yes	7	
1961, May-June	Yes	7	Strong
1962, May-June	No	3	Weak
1967, February	No	5.5(?)	Weak to moderate
1977, Mar-May	Yes	7	Very strong
1983,[4] March (Fig. 6)	Yes	?	Very strong[5]

[1] Tabata (1982); [2] Fig. 4 (from Tabata, 1983); [3] Emery and Hamilton (1985); [4] Second year of intense tropical ENSO espisode; [5] Simpson (1983)

that following the expansion and intensification of the Aleutian low during winter (e.g., in 1958, 1961, 1977 and 1983), the eddy was generated next spring-summer. Conversely, when the winter circulation was weak (e.g., in 1956, 1957, 1962 and 1967), no evidence of the eddy was found in the data examined by Tabata (1982). On the basis of this pattern and the recent study of the winter circulation in the North Pacific by Emery and Hamilton (1985), it appears reasonable to make the following predictions regarding the past appearance of the Tabata eddy in most of those years for which no published data are available. Emery and Hamilton (1985, Table 1) reported the existence of a strong North Pacific atmospheric circulation during the winters of 1953, 1963, 1964, 1970, 1978 and 1981 (in addition to the years given in our Table 1). Further, Figure 4 shows transports across Line P which are on the order of 6-7 Sverdrups during those years (except for 1953 - no data). Hence according to the pattern established in Table 1, the Sitka eddy should have been generated during those years. Conversely, during winters of 1947, 1949, 1950, 1965, 1968, 1969, 1971, 1972, 1980 and 1982, Emery and Hamilton classified the atmospheric circulation as weak (and also weak in the years noted in our Table 1). Also for the years in which data were available, Figure 4 shows Line P transports on the order of 4-5 Sverdrups (except for the years

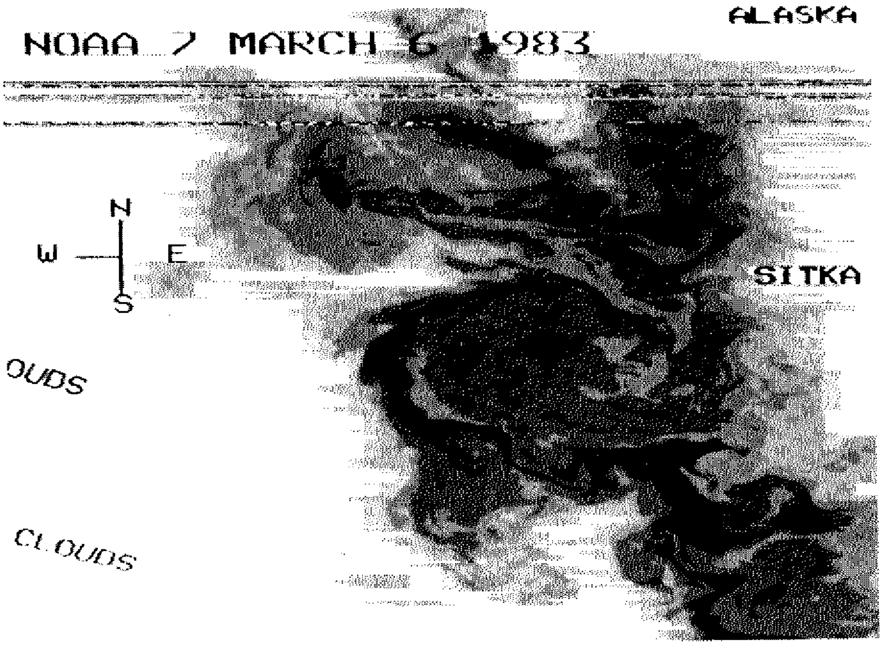

Fig. 6 Thermal infrared satellite image of the Sitka eddy, 6 March, 1983. Dark shades correspond to warm water and light shades to cold water. The maximum temperature change from the warmest to the coldest parts of the eddy is about 1°C.

1969 and 1980). Thus we infer that during the weak circulation years (but possibly excepting 1969 and 1980), no Tabata eddy was generated.

In practice, it may be difficult to separate the two generating mechanisms proposed for the Sitka eddy: topographic generation (Swaters and Mysak, 1985) and the superposition of forced Rossby waves (Willmott and Mysak, 1980). However, on the short-time scale (< 1 year), the initial formation of the eddy west of Sitka eddy could be due to mean flow-topographic interaction. But once the eddy is formed, long-time scale (several years) dynamics associated with interannual baroclinic Rossby waves becomes important and produces the slow, westward drift of the eddy, which has been observed by Tabata (1982). Also, during this time the eddy could decay due to friction and/or entrainment.

Fisheries Implications

According to P.A. Larkin (personal communication, 1984) the timing and return migration route of the mature Skeena River sockeye have been known to change from year to year, especially around the occurrence of a major El Niño espisode which affects the mid-latitudes. Since the return migration route of these sockeye passes near the Tabata eddy, it is conceivable that its occurrence or not could ultimately influence the distribution of the annual fish catch. (If the returning fish encounter anomalous currents due to the eddy, they may choose a different return route, away from the waiting fishing fleet which is anticipating the "normal" route.) The strength and nature of this physical-biological interaction is not known, but clearly, because of the economic implications, deserves further study.

Acknowledgments

It is a pleasure to thank Andrew Thomas for producing the satellite photograph shown in Figure 6. This paper was supported by the Natural Sciences and Engineering Research Council of Canada and the U.S. Office of Naval Research, Code P0422.

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Coastal Temperature and Salinity Anomalies In the Northern Gulf of Alaska, 1970–84

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Introduction

Coastal temperature and salinity measurements were collected on the continental shelf in the northern Gulf of Alaska from 1970 through 1984. These data have large seasonal signals with occasional warming associated with El Niño-Southern Oscillation events (ENSO) and a linear trend which results in an average increase of temperature throughout the water column of 1.5°C. This 14 year trend in temperature is accompanied by a slight decrease in the salinity at all depths to 250 m. The seasonal changes can be explained by the local influences of heating, coastal fresh water discharge and wind stress. The ENSO warming is apparently driven by large scale atmospheric changes over the Northeast Pacific rather than as a planetary wave in the ocean. The cause of the temperature elevation of 0.11°C/year is unknown.

The warming and freshening of the coastal waters of the Northeast Pacific could increase the dynamic height at the coast, possibly altering its cross-shelf gradient and hence increasing the flow of the Alaska Coastal Current. Advection of warmer water from the south will increase, enchancing this effect. The atmosphere should also be warmed, which might increase glacial ablation in the region which might also increase the intensity of the coastal current. However, the increased sea surface temperature will cause increased evaporation and possibly increased cloudiness. The decreased insolation could cause a growth of the glaciers in the region. The Aleutian Low could be affected by the warming, increasing its strength and altering its position, though global atmospheric circulation effects might be more important than this regional heating.

There are several reasons for the 1982-3 ENSO warming event in the Gulf of Alaska to have large effects on the biota. It has a relatively long duration (more than a year) and temperature amplitudes of greater than 2°C. It also occurs at a time when the local water temperature has experienced a long term increase over the past 14 years, allowing the temperature effects to be cumulative.

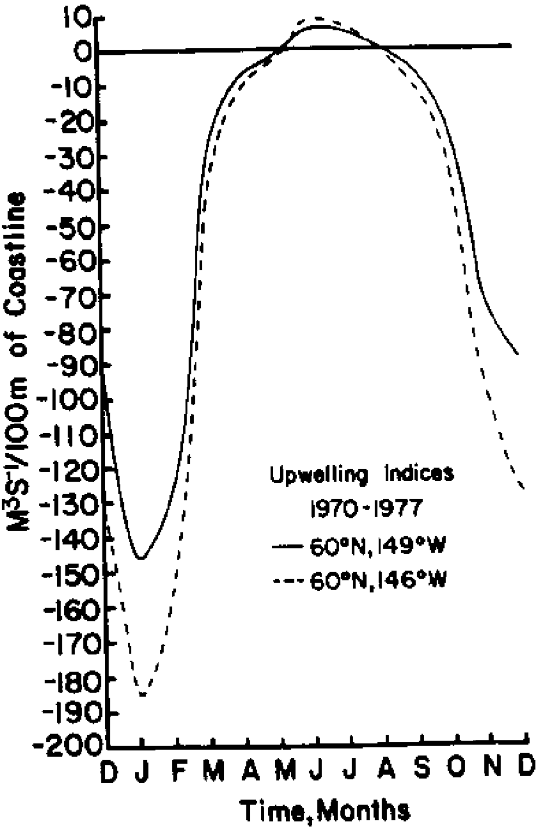

Figure 1. Onshore-offshore Ekman transport (upwelling indices) for two locations in the northern Gulf of Alaska (from Royer, 1983).

Seasonal Temperature Cycle

The northern Gulf of Alaska undergoes extreme seasonal variations in atmospheric conditions with intense downwelling in winter and very weak upwelling in summer (Fig. 1). In winter, low pressure atmospheric systems, usually designated as the Aleutian Low, often form in the central Pacific and propagate northeastward into the Gulf of Alaska. Their onshore movements are blocked by coastal mountain ranges and these storms usually stagnate in the Gulf of Alaska, though occasionally they continue southeastward along the North American coast. As the coastal waters are downwelled by the winds associated with the low pressure system, the central waters of the gulf are upwelled. In summer, the North Pacific High advances northward, pushing the Aleutian Low into the Arctic. Summer winds are very light and eastward in the northern Gulf of Alaska. Small coastal upwelling and slight central gulf downwelling often occur in summer.

The solar input in this high latitude region has a very large seasonal variation, too. In winter sun angles are low and the possible number of hours of sunlight are much less than in summer when solar heating is much more significant.

The seasonal fluctuations of the atmospheric circulation cause changes in the coastal precipitation rate and the rate of fresh water discharge along the coast (Royer, 1982). The maximum coastal fresh water influx occurs in fall, nearly concurrent with the maximum precipitation. There is a slight offset since in November, the air temperatures drop below 0°C which ties up the precipitation as snow, to be released at some later, undetermined time. In spring, precipitation rates are low but there is a slight increase in the fresh water influx from spring melting. This usually occurs in May. Depending on insolation, local air temperatures and albedoes, there can be a net annual storage or depletion of snow in the glacial fields that comprise about 20% of the coastal region.

The seasonal progression of water temperature and salinity throughout the water column at a station called GAK1 at the coast (59° 50.8' N, 149° 28' W) near Seward, Alaska is illustrated in Figure 2 (Xiong and Royer, 1984). The months assigned to the seasons are March, April and May for spring; June, July and August for summer; September, October and November for fall; December, January and February for winter. The hydrographic data used in this seasonal discussion was gathered at irregular intervals between December 1970 and July 1982. It is best to discuss the salinity and temperature structure together as they are dependent upon each other. In summer there is a halocline in the upper 20 m with a more uniform layer beneath. Within the halocline the salinity increase is about 0.17 ppt/m. At the bottom of the halocline the salinity increases from 30.9 ppt to 32.9 ppt at a depth of about 200 m and to about 33.0 ppt at the shelf bottom. The surface salinity is about 27.5 ppt. In winter, mixing causes the halocline in the upper 20 m to disappear with a salinity of about 31 ppt in this mixed layer.

A well developed thermocline exists simultaneously with the halocline in summer but the bottom of the thermocline is much deeper (75m) than the halocline (20 m). This suggests that there are different mechanisms causing the formation and decay of these two features. The temperature profile can be altered by vertical displacement of warmer water from either above or below (See Fig. 2) whereas the salinity changes monotonically with depth. At the surface, the average summer temperature is about 11°C. Below the thermocline, the temperature decreases gradually to a minimum of about 4.7°C at 150 m and then increases to to about 4.9°C near the bottom at 264 m. In winter, there is a temperature inversion between 15 and 200 m. This inversion begins much deeper (75 m) in spring. Spring is also the time of extreme values at the surface in both temperature (4°C) and salinity (31.4 ppt). The seasonal progression in temperature shows that the range at the surface is greatest, but also that the range of temperature at the bottom is greater than at mid-depth, such as at 150 m. Salinity has its largest range at the surface but its range decreases with depth throughout the water column. The minimum salinity in the upper 30 m occurs in August while at depths of 50 m and greater, the minimum

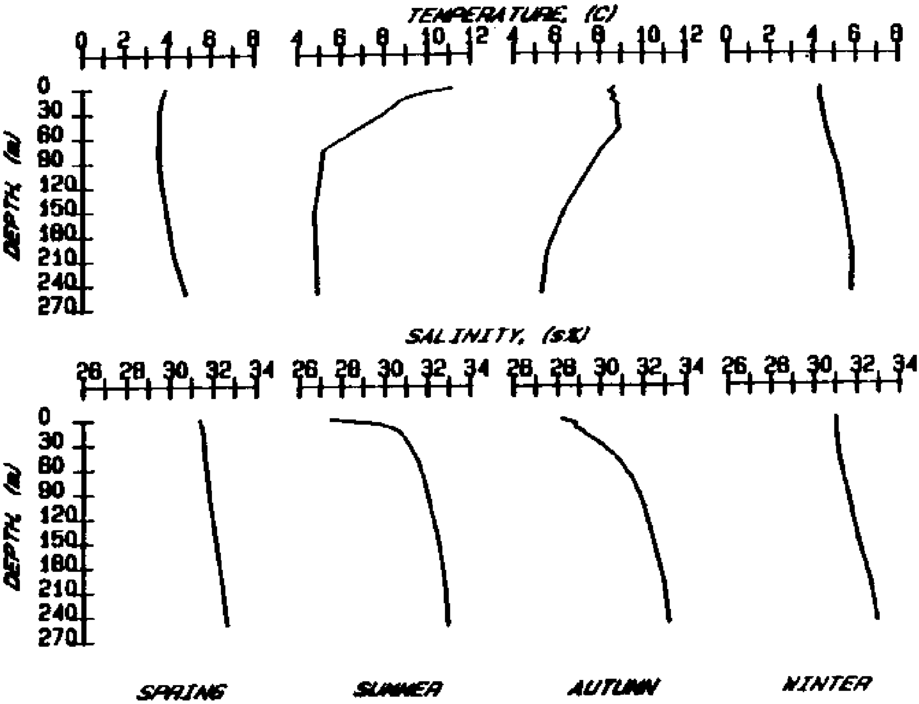

Figure 2. Seasonal cycles of temperature (upper panel) and salinity (lower panel) at GAK1 near Seward, Alaska (from Xiong and Royer, 1984).

takes place in November. This delay in the salinity minimum is a result of the upper layers being controlled by the fresh water discharge at the coast while at greater depths, it is the winds causing upwelling and downwelling which alter the phasing of the salinity cycle. This results in the salinity being a maximum in the lower layers in autumn not quite coincident with upwelling wind conditions. The salinity response is delayed by about a month, which could represent the time required for the higher salinity water to be advected across the shelf from the shelfbreak. The absence of strong downwelling conditions here will allow deep, nutrient-rich waters to be advected onto the shelf in the northern Gulf of Alaska. High production could be due to an *inactive* wind system, in contrast to productive shelves elsewhere that require an active, upwelling wind system.

Interannual Variability, 1970–1984

Using the seasonal temperature and salinity cycles as described in the previous section, the interannual variability of these parameters is determined by subtracting the seasonal signals from the original data set. The temperature anomalies are greatest at the surface (Fig. 3, upper panel) with a range of about 4°C. The temperature anomaly amplitudes are fairly uniform with depth beneath

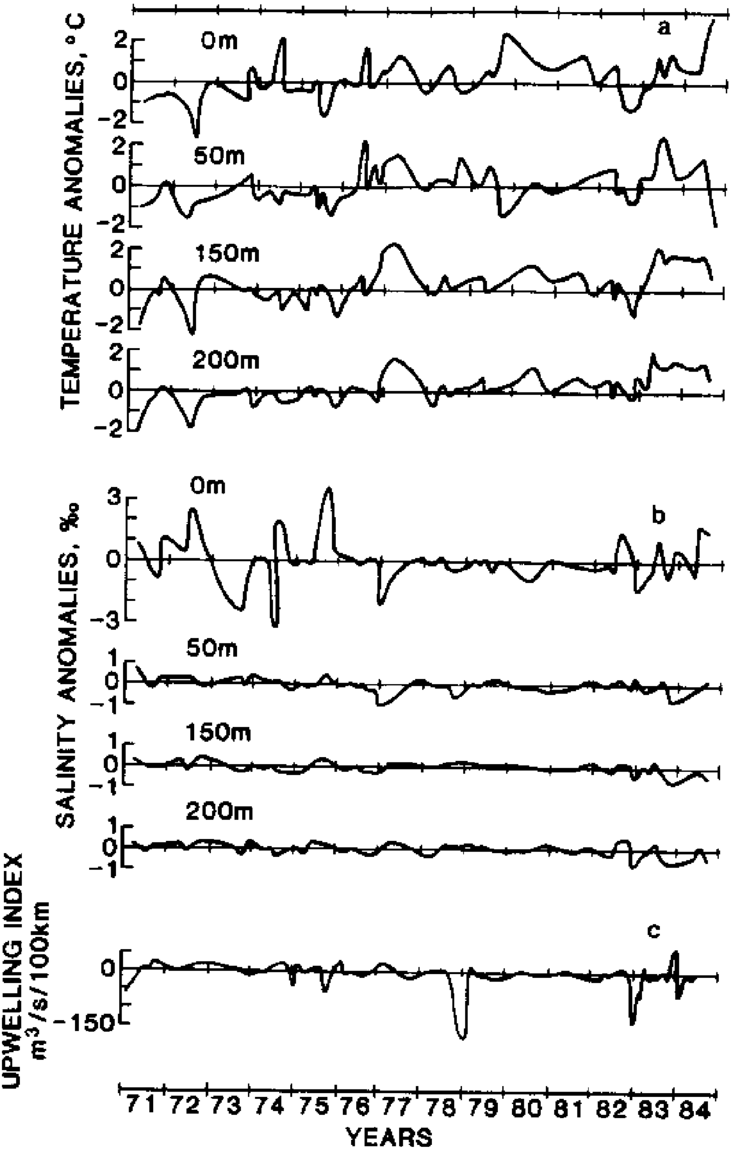

Figure 3. Time series of the anomalies of temperature, salinity, and upwelling index at GAK1 for 1970-1984.

the surface. In the early 1970's, the temperatures throughout the water column were less than normal with the largest negative anomalies occurring in 1971 and mid-1972. A "major" increase in temperature occurred briefly in 1976, followed by a sustained warming throughout most of 1977. This warming is best seen in the

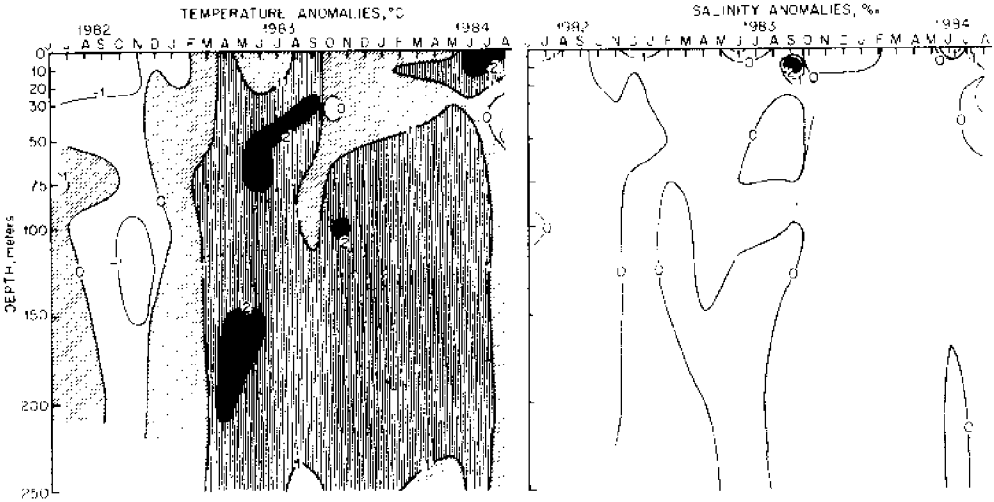

Figure 4. Temperature (left panel) and salinity anomalies at GAK1 from July 1982 through August 1984.

temperatures at 150 and 200 m. At the surface, the next warming took place in late 1979 but this event was not followed by temperature increases beneath the surface.

In early 1983 after less than normal temperatures in the fall of 1982, a sustained elevation in temperature began throughout the water column (Fig. 4). Higher than normal temperatures occurred at all depths, with the greatest anomalies found at depth. Maximum anomalies exceeded 2°C in summer 1983. By June 1984 the subsurface anomalies were less than 1°C though the temperature anomaly at the surface was greater than 2°C. A conclusion is that temperature anomalies are not the result of local effects since they do not propagate downward from the surface. Horizontal advection is a likely mechanism for the creation of these anomalies. The exact cause of these temperature anomalies is unknown, but their timing of 6-9 months after an ENSO event suggests a connection between them. Since 1970 there have been three El Niño Southern Oscillation events. With the exception of the 1972 event, all of the events during this time period have produced temperature anomalies at Seward. Enfield and Allen (1980) indicate that the 1972 event did not propagate to high latitudes, so it is reasonable that it did not appear in this record.

For the 1983-4 temperature elevation in the northern Gulf of Alaska, the salinity throughout the water column was below normal (Fig. 4). These conditions are in contrast to the temperature anomaly in 1976-7, when the 0 and 50 m salinities were below normal and the 150 and 200 m were above normal.

The salinity anomalies for the period of 1970-1984 show much less dramatic changes those of temperature (Fig. 3). There are very large salinity anomalies at the surface from 1970 through 1975. From 1976 to 1981, the salinity followed the expected seasonal cycle. If the surface salinity influenced by local runoff, one can assume that unusual runoff conditions occurred in the early 1970's.

The local wind conditions are estimated from the upwelling index (Fig. 3, lower panel) as determined by Bakun using the Fleet Numerical Oceanographic Central (FNOC) 3x3 degree sea level atmospheric pressure. There is little apparent relationship between the fluctuations of upwelling index anomaly and either the temperature or salinity anomalies, suggesting that the anomalies are not caused by local winds.

Interdecade Temperature Fluctuations

Though no other routine hydrographic data exist for the northern Gulf of Alaska, some extrapolations are justified based on the knowledge gained through the existing 14 year record. Xiong and Royer (1984) established that the air temperature at Seward and the sea surface water temperature anomalies for the time series are well correlated (r = 0.43; significant at 75% confidence interval). Because the air temperature data for Seward extends back to 1916, it is possible to construct a "proxy" record of sea surface temperature. For example, the air temperature over the southeastern and southern coasts of Alaska and the precipitation for these areas has been used to construct a hydrology model that predicts the coastal fresh water influx along this coast since 1931 (Fig. 5).

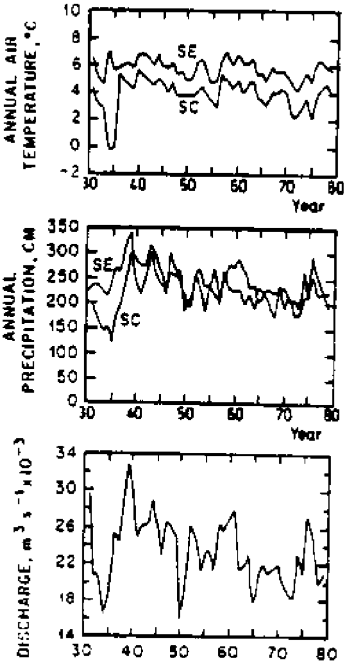

Figure 5. Annual mean air temperature (top) for Southeast Alaska (SE) and Southcoast Alaska (SC), precipitation (middle) and fresh water discharge (bottom) (from Royer, 1982).

A set of sea surface temperature observations for the entire North Pacific since 1947 has been compiled by Namias (Chelton, 1984). A comparison of those data for the Northeast Pacific with the hydrographic data for Seward reveal some similar trends. Looking again at Figure 3, a linear regression curve fit seems in order of the temperature and salinity anomalies. Those calculations reveal very high confidence levels to those fits, exceeding 99.95% for all depths. The best fit is for the 250 m temperature and the largest slope is for the temperature at 150 m where it is 0.126°C/year. The average temperature increase for the water column was about 1.5°C over the 14 years. Clearly this cannot continue indefinitely. By comparing the hydrographic data with the longer, Namias series for the Northeast Pacific (Chelton, 1984) and the air temperature data for the coast (Fig. 5), it can be seen that the temperature has been steadily increasing in each series since about 1970. This is a trend that will probably end in the near future. [The linear regression analysis on the salinity shows a decrease in the salinity over this same time period but the confidence interval is not as high as it is for temperature.] The close match of the sea surface temperature for the Northeast Pacific and the temperatures at depth near Seward is not surprising if one looks at the density surfaces for the two locations. The density surfaces slope upward as one progresses offshore in the Gulf of Alaska and they intersect the surface somewhere between the shelfbreak in winter and the central gulf in summer. Thus the surface temperature in the area from the central gulf to the shelfbreak are on approximately the same density surface as is the deep water (150-250 m) at the coast. This allows the possibility of reconstructing the deep water temperatures over the shelf in the Gulf of Alaska using the sea surface temperature. Unfortunately, the temperature features that have been associated with El Niño-Southern Oscillation events are not readily apparent in this "proxy" record, but the longer period interannual temperature fluctuations and their impact on the biota can be addressed.

Climatic Implications

Warming of the Northeast Pacific over the past 14 years should have some climatic influences. The most obvious is an increase in the local air temperature, which can be seen in Figure 5. The increase in water temperature will also increase the evaporation which should increase the cloud cover and the precipitation. This trend can best be seen in Figure 5 where from 1940 to about 1970 there was a decrease in the air temperature (sea surface temperature) accompanied by a general decrease in the precipitation. These trends have been reversed since 1970. The influence of the warming in 1956-8 can be seen in both the air temperature and the precipitation.

The increase in precipitation might result in an increase in the transport of the Alaska Coastal Current which is dependent on fresh water as a driving mechanism. However, the increased cloudiness might cause more water to tied up in the glacial fields, reducing the amount available to drive the coastal flow.

It is probable that that the increased water temperature will have some influence on the overlying atmospheric pressure systems. The intensity of the Aleutian Low and its position might be affected which would, in turn affect the position and intensity of weather systems elsewhere such as over North America.

The influence of the 1982-3 ENSO event on the biota in the northern Gulf of Alaska is probably enhanced because of the long term trend of increasing water temperatures over the past 14 years. Thus, the ENSO heating is combined with this other effect to produce temperatures of nearly 3°C above normal and more than a year of temperatures greater than one degree above normal.

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Southern Oscillation/El Niño Effects In the Eastern Bering Sea

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University of Alaska

Abstract

Five relatively long time series (18 to 30 years) of deviations from monthly mean atmospheric (surface winds and North Pacific Oscillation (NPO) and oceanic (sea surface temperatures (SST) and ice cover from the eastern Bering Sea) parameters are compared with a 30 year time series of a Southern Oscillation Index (SOI) (Trenberth, 1984). The SOI (Figure 1) is the deviations from the mean normalized Tahiti minus normalized Darwin, Australia surface air pressure, the SST (Figure 1) are from a 300 km square around the Pribilof Islands, the winds (Figure 1) are the north-south component of the surface winds from the Pribilof Island airport, the ice cover is the per cent ice cover for the eastern Bering Sea and the NPO is the Pribilof Island minus Edmunton, Alberta surface air temperatures. The data were all smoothed by a 9-month running mean and sampled every 4 months (J,A,J,O). The four Bering Sea data sets were then cross-correlated and lagged against the SOI (eg. Figure 2). The confidence levels were calculated using the Student's t distribution using an effective number of degrees of freedom (Neff) after Davis (1976) and Trenberth (1984) as shown in Figure 2.

The results for wind and SST vs SOI (Figure 2) show significant correlation peaking with SST and wind lagging SOI by 9 and 15 months respectively. Similar results were found for the other data sets with lags ranging 6 months to a year (Niebauer, 1984). Overall, this suggests that the ocean and the atmosphere in the region of the Bering Sea respond significantly to El-Nino-Southern Oscillation (ENSO) events with "warming" in the Bering Sea following an ENSO event. The physical mechanism is undoubtedly the deepening of the Aleutian Low and its movement south and east of its mean position over the Kamchatka Peninsula. This results in southerly flow from the North Pacific northward over the Bering Sea. Thus ENSO events tend to result in

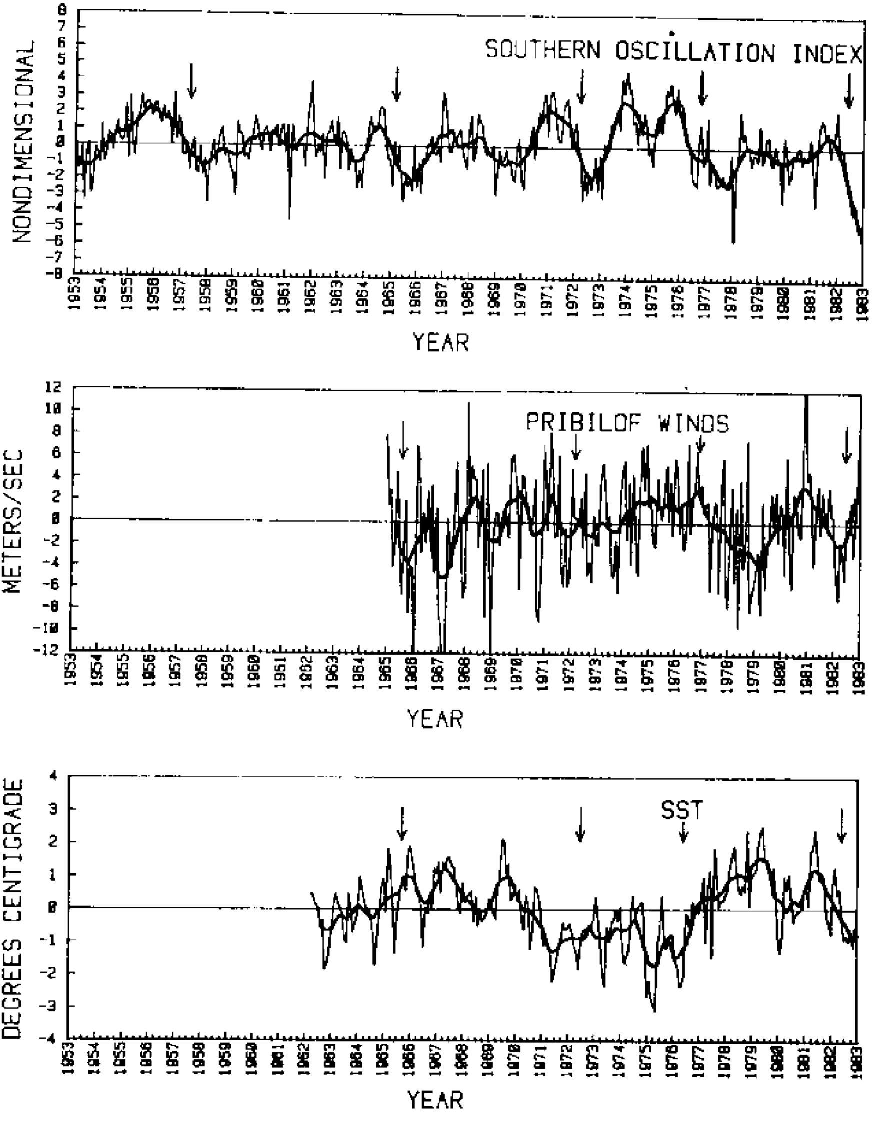

Figure 1. Southern Oscillation Index and sea surface temperature and north-south component of the surface winds from the eastern Bering Sea. Thin lines are the deviations from monthly mean, thick lines are 9-month running mean. Arrows are major El Nino events.

"warming" of the Bering Sea as shown by the sign of the correlation coefficients in Figure 2, that is, a decline in the SOI correlates with a rise in SST and a reduction in northerly winds.

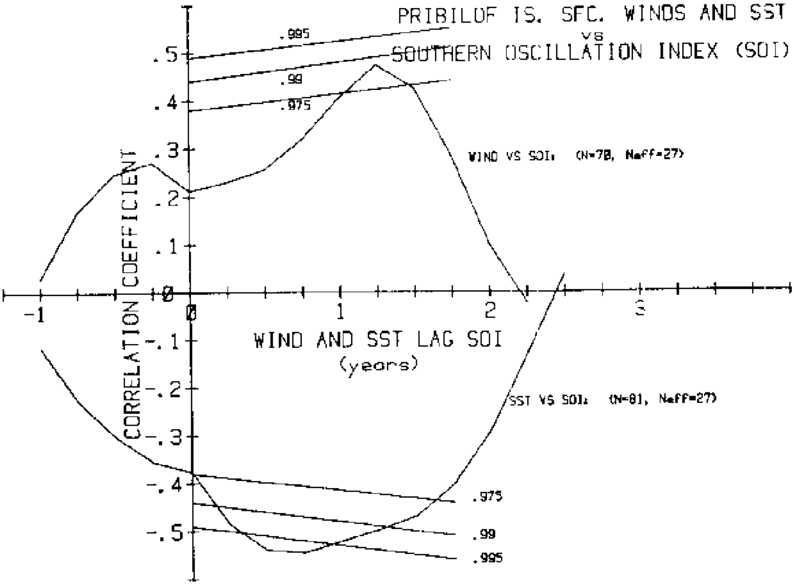

Figure 2. Lagged cross-correlation coefficients between the Southern Oscillation Index and Bering Sea winds and sea surface temperatures as shown in Fig 1. Significance levels are also indicated.

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THE BIOLOGICAL RESPONSE

A Case History of an Anti-El Niño to El Niño Transition on Plankton and Nekton Distribution and Abundances

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National Marine Fisheries Service

Introduction

The management of coastal pelagic schooling fishes is complicated by vast changes in recruitment and availability. While an El Niño event can be a tragic economic event in the history of a fishery, it can also be a natural experiment for biological oceanographic monitoring to gather important dynamic information. The motivation and funding to monitor an event like "El Niño" usually arrives after the onset is well in place (McGowan, 1984). To find a time when, by chance, the onset of an El Niño was well monitored, we must return to the 1955-9 event.

While there seems little doubt of the magnitude of the 1983-84 El Niño event, the anchovy population continued to spawn eggs at the same rate in 1983-4 as in 1980-2 (Fiedler, et al., MS) (Table 1). Although the process of spawning is energy intensive (Hunter and Leong, 1981), spawning continued as the apparent production of the anchovy habitat declined (McGowan, 1984; Fiedler, 1984). Local catches were also reduced for the coastal pelagic and continental shelf fishes and increased for tropical and temperate tunas as expected for these oceanic conditions (Table 2). The comparable increase of tropical fish catch in 1957 compared to the average of the previous five years was barracuda 2.4 x, yellowtail 4.6 x, bonito 5.6 x, yellowfin tuna 18.8 x skipjack tuna 82.3 x, and dolphinfish 876.6 x, for only the first nine months of the year. Young sardine were noted in the live anchovy bait catch along the entire coast from San Diego to Monterey Bay for the first time in years. (Anon. 1958).

Reexamination of a Case History

The 1957-9 El Niño was discussed in the "Rancho Santa Fe Symposium". The report of that meeting, and particularly the personal contacts between quantitative and theoretical meteorologists and oceanographers, launched the discipline of "air-sea interaction (Sette and Isaacs, 1960). A biological study of great magnitude (3,461 plankton observations on 20

Table 1. Northern anchovy (*Engraulis mordax*) central population reproduction parameters.

PART A Cruise	Spawning area (Sq. mi.)	Spawning biomass '000 t	 g/m^2	Mortality rate z	 %/d
Mar. 1980	19000	870	13	.453	36
Feb. 1981	23000	635	8	.138	13
Apr. 1981	17000	372	6	nil	nil
Feb. 1982	24000	415	5	.158	15
Feb. 1983	28000*	652	7	.184	17
Mar. 1984	18000	309	5	.170	16

PART B Cruise	Female weight g	Specific fecundity m-eggs/d/t	Mean interval days
Mar. 1980	17	30	7
Feb. 1981	13	33	9
Apr. 1981	16	34	8
Feb. 1982	19	33	8
Feb. 1983	11	24	11
Mar. 1984	12	42	6

*About half the area of the state of Washington.

cruises quarterly for five years separated into 18 taxonomic groups) was begun as a result of that climatic change (CalCOFI atlases by Isaacs, Fleminger and Miller, 1969; Isaacs, Fleminger and Miller, 1971; and Fleminger, Isaacs and Wyllie, 1974) and a principle components analysis was reported by Colebrook (19777).

I have divided the fishes of the CalCOFI region into those which occupy an area larger than the CalCOFI survey; those which inhabit the coastal currents of the eastern boundary; and those which are mostly confined to the continental shelf. Most of the fish we have studied are planktivorous so I have included a brief section on plankton. In the "High Seas" category, I have included the tunas, the jack mackerel, the saury, and the mesopelagic fishes. In the fishes of the coastal currents, I have included anchovy, sardine, and Pacific mackerel. The flatfishes and rockfishes are considered under the heading "continental shelf" fishes. Hake are included as continental shelf fishes for the purpose of this paper because that is where most of the feeding takes place (Bailey, et al., 1982). The primary reason for dividing the fishes into these categories is to more precisely interpret the effects of El Niño.

Table 2. Commercial landings from California waters.

Species	1982			1983			Weight ratio
	Rank	Weight	Value	Rank	Weight	Value	
Coastal Pelagics		117.5	18.8		59.1	12.8	0.50
Mackerel	1	54.9	10.1	1	48.8	9.1	0.89
Market squid	4	16.3	3.6	14	1.4	0.6	0.09
Northern anchovy	2	42.1	1.9	10	4.1	0.4	0.10
Pacific bonito	15	2.1	1.0	12	3.2	1.3	1.52
Pacific hake	21	1.0	0.2	17	1.0	0.2	1.00
Thresher shark	20	1.1	2.0	20	0.6	1.2	0.55
Shelf & Slope		76.8	67.1		54.5	43.8	0.71
Chinook salmon	11	3.3	18.8	25	0.4	1.8	0.12
Dover sole	6	10.0	5.1	5	8.4	4.1	0.84
Dungeness crab	12	3.0	7.2	18	0.9	3.1	0.30
English sole	18	1.4	1.0	15	1.2	0.8	0.86
Lingcod	19	1.4	0.7	19	0.8	0.5	0.57
Pacific herring	5	10.3	9.7	6	8.0	12.5	0.78
Petrale sole	22	0.8	1.0	23	0.6	0.8	0.75
Rex sole	25	0.7	0.5	21	0.6	0.5	0.86
Rock crab	unrank	-	-	22	0.6	1.1	+
Rockfish	3	21.8	10.6	4	14.0	8.6	0.64
Rockfish (b-c*)	14	2.3	1.0	11	3.5	1.8	1.52
Rockfish (t*)	16	2.0	1.0	13	1.7	0.8	0.85
Sablefish	7	9.5	5.2	8	6.1	3.2	0.64
Sea urchin	8	8.3	3.1	7	7.2	3.3	0.87
Shrimp (po*)	17	2.0	2.2	24	0.5	0.9	0.25
Temperate Tuna		3.4	4.7		4.5	5.7	1.67
Albacore tuna	13	2.7	3.9	9	4.5	5.7	1.67
Bluefin tuna	24	0.7	0.8	unrank	-	-	-
Tropical tuna		9.7	14.8		37.7	39.9	3.89
Skipjack tuna	10	3.9	3.7	2	18.8	15.3	4.82
Swordfish	23	0.8	5.1	16	1.0	5.7	1.25
Yellowfin tuna	9	5.0	6.0	3	17.9	18.9	3.58

Weight is in thousands of metric tons.
Value is in millions of dollars to the fishermen.
Mackerel is Pacific mackerel and jack mackerel combined.
b-c bocaccio and chilipepper rockfish.
po Pacific Ocean shrimp.
t thornyhead rockfish.

Nekton

High seas

Bluefin tuna. Yamanaka (1984) noted an inverse correlation between the catch rate of young bluefin tuna (*Thunnus thynnus*) off Japan and the United States. In particular there appeared to be a

Table 3. Crude composition of zooplankton in the upper 140 m of the California Current

Functional group	1956		1958		Weight Ratio	Change	%
	Rank	Weight	Rank	Weight			
Copepoda	2	27.9	1	14.2	0.51	-13.7	12
Chaetognatha	4	6.3	2	4.4	0.70	-1.9	2
Siphonophora	5	6.1	3	3.6	0.59	-2.5	2
Thaliacea	1	91.4	4	3.3	0.04	-88.1	74
Euphausiacea	3	7.1	5	3.2	0.45	-3.9	3
Medusae	6	3.1	6	1.2	0.39	-1.9	2
Decapoda	10	1.2	7	0.6	0.50	-0.6	
Pteropoda	14	0.3	8	0.6	2.00	0.3	
Radiolaria	9	1.4	9	0.4	0.29	-1.0	
Crustacean larvae	12	0.8	10	0.3	0.38	-0.5	
Amphipoda	7	1.8	11	0.2	0.11	-1.6	1
Larvacea	11	0.9	12	0.2	0.22	-0.7	
Ostracoda	13	0.4	13	0.2	0.50	-0.2	
Ctenophora	8	1.5	14	0.2	0.13	-1.3	1
Cladocera	17	0.02	15	0.2	10.00	0.18	
Heteropoda	15	0.1	16	0.1	1.00	=	
Mysidacea	16	0.03	17	0.01	0.33	-0.02	
TOTAL		150.35		32.91	0.22	-117.44	100

Weight is in grams per 1000 cubic meters to 140 meters depth.
Change is the difference in grams between 1956 and 1958.
% is the category change as a percent of sum of categories change.

low rate of return of juveniles to Japan during the El Niño periods. He postulated that during the El Niño more juvenile bluefin migrated to the Pacific coast of America than usual and then those fish migrated to the southern hemisphere off Chile. He also pointed out that the Japanese sardine migrated out to the albacore tuna fishing grounds during the recent El Niño.

Albacore tuna. Like the bluefin tuna, some albacore are trans-Pacific migrants in the temperate zone. The 1957-8 El Niño was associated with inverse trends in the California sport boat and Canadian jigboat catches; between 1955 and 1959 the annual catches of the sport boats was 577, 482, 304, 48, and nil tons, the Canadian jigboats nil, 17, 8, 74, and 212 tons (Laurs 1983). It is now thought that local water clarity may play a large role in determining the feeding migration patterns (Fiedler, Laurs and Montgomery, MS) of albacore and the catch by different method. Changes in prey distribution, vertical and geographic, and local temperature gradients must also have an effect on fishing success on albacore and the distribution of all the oceanic properties is altered by El Niño.

Tropical scombroids. Major predators from the tropics inhabit California Current waters warmer than 20°C. This includes skipjack, bigeye, and yellowfin tunas and the billfish (*Katsuwonus pelamis*, *Thunnus obesus*, *Thunnus albacares*, *Makaira indica*, and

Xiphias gladius). The northerly extent of these species appears to be limited by surface temperature. Blackburn (1965) found that the existence of a suitable temperature was not always accompanied by the presence of tropical predators. Schaeffer (1960) considered the chief cause of the occurrence of tropical tunas off California to be active migration during warm conditions because the warming at that time was due to heat exchange rather than advection of warm water.

Jack mackerel. The abundance of larvae of jack mackerel declined from an area averaged 2 per square meter in 1950-1957 to fewer than 0.3 per square meter between 1958 and 1960 (MacCall and Stauffer, 19883). The relative recruitment strength of the stock in 1958 was 2 times that in 1959 and 1960. It is obvious that the abundance of larvae of this species is not effective as an index of spawning biomass but is instead responsive to several environmental influences. Since the outer and northern range of spawning is not normally encompassed by the larval surveys, the variation may signal changes in the degree of overlap of the survey area and the spawning area. The change of temperature, alone, is probably incapable of exerting more than a two-fold influence on development rate, thus the 5-7 fold change is probably indicative of a change in fecundity rather than a change in spawning biomass. During the radical change between 1957 and 1958, the primary difference appeared to be the number of samples with large numbers of larvae, suggesting a change in reproductive per capita output (Ahlstrom, 1969). Cursory examination of the larval mortality rate between 3 and 11 mm does not reveal an obvious change between 1957 and 1959 but this constancy could be confounded with an abnormal growth rate.

It is not clear whether jack mackerel changes its distribution in relation to temperature directly to its temperature-related food. The food of another jack mackerel species in a similar current system off the Pacific coast of South America, (Konchina, 1983) consists of primarily Euphausiids (54%), fish (20%), decapods (12%), copepods (7%), and cephalopods (5%). Of the fish 40% were engraulids, 25% were gonostomatids, and 20% were normanichthyids. Almost all oft he euphausiid shrimps were Nyctiphanes simplex. The seasonal maximum of fish in jack mackerel was in August (Southern hemisphere winter) at 35% owing to the addition of Vinciguerria lucetia. He described the feeding interaction between hake and jack mackerel overlapping mainly in the feeding on engraulids and occasionally Vinciguerria lucetia. Thus, to understand the effect of El Niño on jack mackerel one would have to observe changes in euphausiids, and at least 3 groups of fish.

Saury. Saury spawning below 30° north latitude virtually ceased between 1957 and 1960. Either the adult fish were not there or they were unable gain sufficient surplus energy to spawn. This species exhibits a trans-Pacific distribution and is thought to be a zooplankton feeder (Smith and Ahlstrom, 1973). There was also a small decline in the abundance of eggs off southern and central California. This could be explained by more rapid hatching time in the warmer water. Another explanation would be that the zooplankton abundance was lowered which changed the per capita rate of spawning. Also, the northward migration of tropical predatory birds, fish and mammals could be a contributing cause of the decreased abundance of eggs by predation on the spawning adults or consumption of egg masses. Off Japan saury may be replaced by incursions of *Scomber japonicus* (Schaeffer, 1980); although this occurred in 1958 off Japan it was determined whether some oceanic boundary of the saury habitat shifted or the Pacific mackerel population expanded its range into the saury habitat.

Mesopelagic fishes. Even though the main effects of the El Niño may be above the habitat of the adult mesopelagic fishes, the larvae of some mesopelagic fishes inhabit the upper mixed layer. An examination of an atlas of the most common mesopelagic fishes (Ahlstrom, 1972) reveals several different responses to the onset of the 1957-59 El Niño.

Three of the mesopelagic species have epipelagic (100 m or less) larvae. One of the most massive distributional changes occurred with *Vinciguerria lucetia*. Its major concentrations were restricted to south of 30°N in the anti-Niño period 1955-56 and it spread to the oceanic areas off San Francisco to 35 north latitude by 1960. Primarily because of its increased "overlap" with the CalCOFI survey area, the abundance of *V. lucetia* increased an order of magnitude between 1956 and 1959. In a similar but less extensive change of geographic distribution larvae of *Triphoturus mexicanus*, tripled in apparent abundance through a 240 nautical mile northward shift. Larvae of a third species, *Stenobrachius leucopsaurus*, did not appear to respond in any way to either the anti-Niño or Niño; the southern limit of distribution remained off San Diego through the entire period.

Two of the mesopelagic species also have mesopelagic larvae. The number of larval *Leuroglossus stilbius* declined by 6-fold between 1957 and 1958; this appeared to be caused by the decline in spawning in a southern center off Punta Eugenia, Baja California as the northern limits did not appear to shift. *Bathylagus wesethi* larvae doubled in apparent abundance during the niño period, apparently by slight increases in abundance in spawning centers and by drawing closer to the coast. The larvae of *Bathylagus ochotensis*, a subarctic species, decreased slightly during the warming apparently due to a withdrawal from the coast and to the north. The depth distribution of this species is not well known.

Engraulis. The onset of El Niños in 1957-9 (Fig. 1) and 1982-3 (Table 1) had remarkably little effect on the apparent production of eggs and larvae. In fact the "anti-El Niño" with its colder waters and invasion of subarctic fauna appears to have a negative effect on the abundance of these planktivorous fishes. In 1957-9 increase with the onset of El Niño. There were large increases in the abundance of larvae off central California and moderate increases off the southern California coast more than 300 km. In the egg production time series from 1980 to 19884 there continued to be production rates of more than 200 eggs per square meter per day throughout the Los Angeles Bight. In addition, during El Niño in 1983, there were more than 100 eggs produced per square meter per day from 200 km to 250 km offshore. Similar rates were sustained in 1984 out to 200 km. Therefore, the prediction of diminished northern anchovy fecundity caused the apparent low zooplankton volume and chlorophyll (McGowan, 1983; 1984) has not been substantiated. Similarly, in 1957-9, the diminished primary production and zooplankton volume was met with equal or greater spawning of northern anchovy (Smith and Eppley, 1982) in the Los Angeles Bight area.

Sardinops. As with the anchovy, the sardine Sardinops caerulea, appears to be adversely affected by the cold "anti-El Niño" and favored by El Niño (Fig. 2). Murphy (1960) used temperature as a "convenient index" for other oceanic properties in his discussion of the sardine. He stated that "...cooler temperatures along the California Current are associated with accelerated southward transport, and more vigorous upwelling with its attendant offshore movement of water. Plankton densities are increased." He noted that the warm years of the late 30's and early 40's appeared to have been favorable for sardine recruitment and the cooler years 1943-1956 were accompanied by a precipitous and sustained decline in the species. The species reached a spawning biomass of 2 million tons during the El Niño of 1941. However, in the El Niño of 1982-3 off Chile, the large Sardinops population failed to recover its normal fat content in the summer and in the next spawning season the fat content of the population was again reduced by a factor of 2 (Vidal, Chile Pesquero, December 1983 p. 13).

Scomber. A high rate of parent per capita recruitment occurred in the years 1958-60 (Parrish and MacCall, 1978; Schaeffer, 1980). While the catch records of Pacific and jack mackerel are frequently combined for statistical purposes, the species are radically different. The life span of the jack mackerel is several times that of the Pacific mackerel and the adult phase of the jack mackerel is found in transitional waters between the Central Water Mass of the North Pacific and the West Wind Drift and California Current. Juvenile jack mackerel school with Pacific mackerel in the coastal currents off California but at the age of 3 or 4 they resume the high seas distribution characteristic of their parents. There they live for about 25 years (MacCall and Stauffer, 1981). Pacific mackerel live in the coastal current region of the subtropical and temperate zone of the Gulf of California, Baja California and southern California. The maximum age of Pacific mackerel is 11 years (Schaeffer, 1980) and they probably remain in the coastal currents region.

Despite the increased recruitment of Pacific mackerel in the 1957-9 Niño the sport catch off California was 1/2 normal in this period. The Mexican catch of Pacific mackerel declined by a factor of 5 in 1957 and declined yet another factor of 5 in 1958. These conflicting facts are probably explained by a more northerly distribution of this species at this time so that they are unavailable to the fishery from the traditional ports.

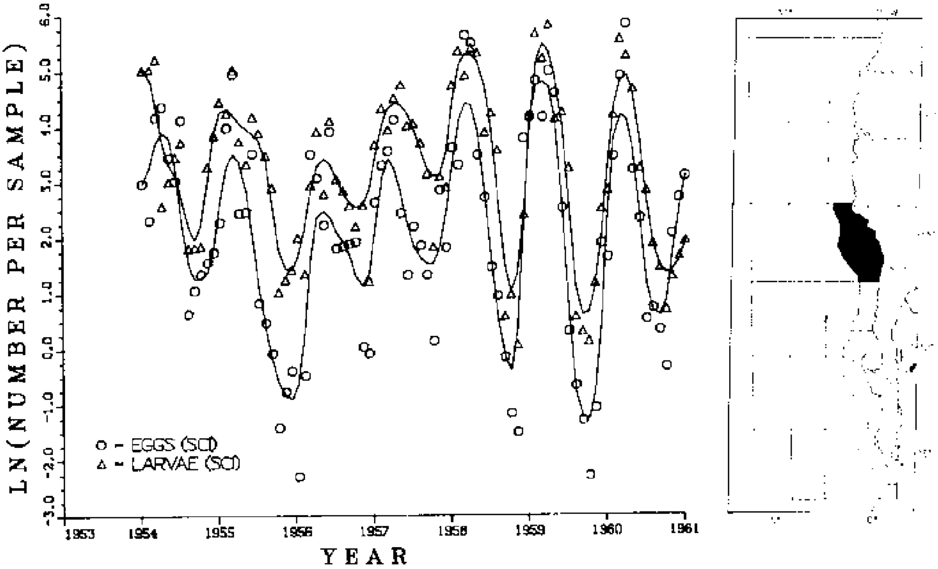

Figure 1. The increase of anchovy spawning between 1954 and 1960 in the southern California inshore region. The circles are at the natural log of the monthly average egg abundance for all stations in the region. The triangles are at the natural log of the monthly average larvae abundance for all stations in the region. The line is a resistant non-parametric smoother for these points (Velleman, 1980).

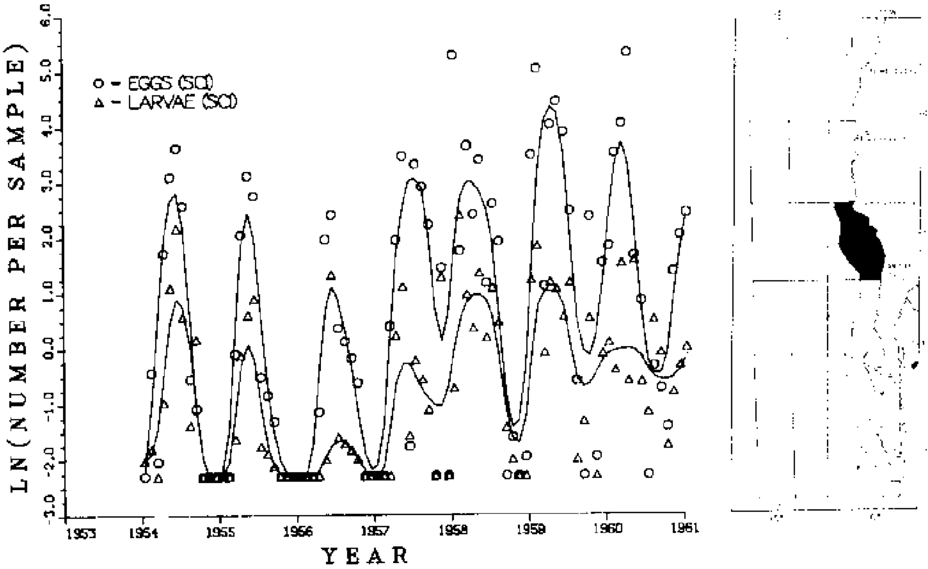

Figure 2. The increase of sardine spawning between 1954 and 1960 in the southern California inshore region. The circles are at the natural log of the monthly average egg abundance for all stations in the region. The triangles are at the natural log of monthly average larvae abundance for all stations in the region. The line is a resistant non-parametric smoother for these points.

Detailed studies of growth have not been conducted on the Pacific mackerel so changes in length at age which are observed for this species (smaller during El Niño) may be due to greater survival of the smaller members of the cohort, or smaller members of the population transported in from the southern, more subtropical sectors of the distribution (Klingbeil, pers. comm.) or larger fish migrating to the north.

Pleuroncodes. The red crab, *Pleuroncodes planipes*, is a benthic animal of the Gulf of California and the south Baja California continental shelf (Longhurst, 1966). During most years the juvenile pelagic phase drifts back and forth in the coastal currents over the adult habitat but important numbers of offspring are entrained in the California Current extension and carried into the tropics. During El Niño, similarly important numbers are carried north as far as southern California in a band 160 km wide and in a narrow coastal strip into waters off central California. New data from trawling for anchovy adults shows a similar northerly transport (Fig. 3) of red crab juveniles offshore. Although sightings of red crab are at the surface, it is not known at what depth the organisms are transported. Since the adults live in depths as great as 300 meters it is conceivable that some transport is in the California Undercurrent. The pelagic phase of red crab is about 2 years in duration but mature individuals have not been collected off Alta California thus the origin of all the young is considered to be at 25°N latitude or 1000 km south of where many young are transported (Boyd, 1967).

Shelf Fauna

The fishes and invertebrates of the continental borderland are likely to exhibit some diversity of response to El Niño. Planktivorous species or older organisms may be in part be isolated from the immediate effects of a brief El Niño. In general hake are mesopelagic spawners which feed on the continental shelf, the rockfish as a group are pelagic over canyons and around islands and the flatfish are demersal over the gentler slopes of the continental margin. The time series of larval catches of these species may permit identification of some changes associated with El Niño.

Merluccius. The Pacific hake does not continuously occupy the zone of coastal currents (Bailey et al., 1982). During the spring and summer, the adult population migrates 1000 km northward to feed on the continental shelf of the north temperate eastern north Pacific. Depending on the age structure and the temperature at depth (Smith, 1975), the hake migrate to various distances to the south in the fall and spawning is conducted in winter. Since the onset of the El Niño was in April 1957, the first year of effect on hake larvae was in 1958. An index of larvae from winter abundance in 1954-1960 was 5, 8, 14, 21, *8*, *2*, 3. That portion of the larval index in the region seaward of about 300 km for the same years is 2, 4, 11, 15, *3*, *.1*, and .9. The survival of the 1957-9 spawn to fishable age was low relative to 1960 and 1961.

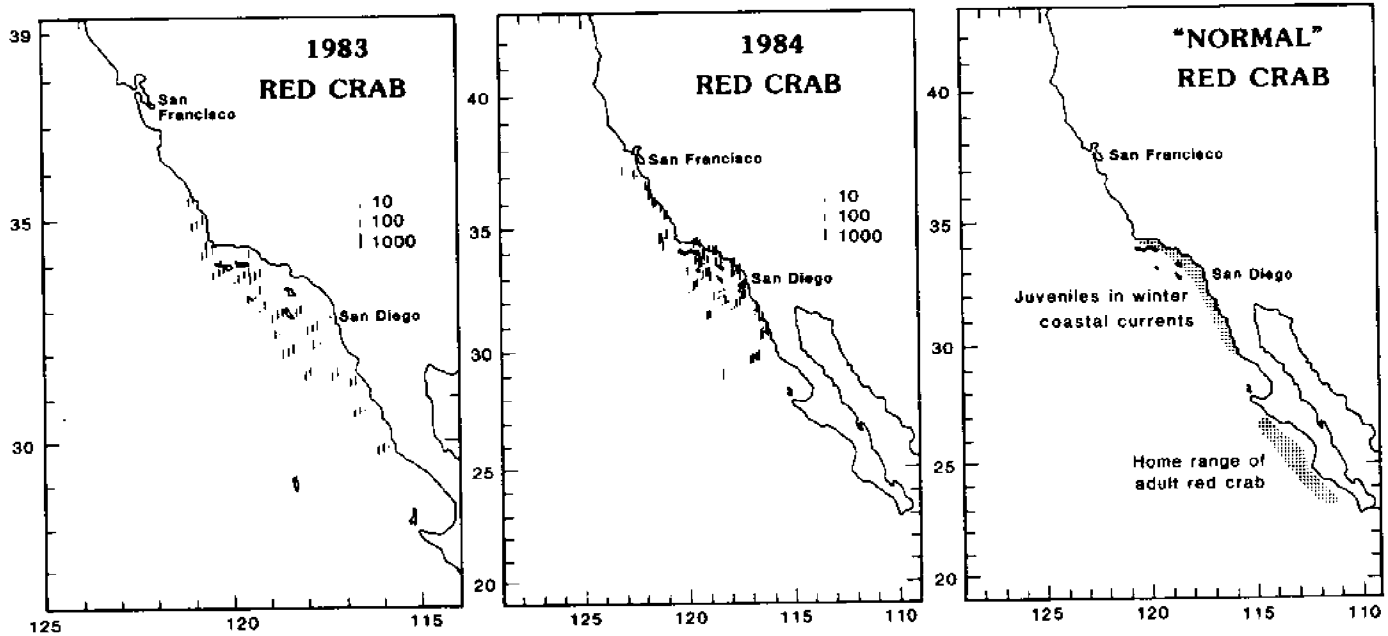

Figure 3. Temperate distribution of red crab. a) juveniles caught in near surface trawls in 1983; b) juveniles caught in near surface trawls in 1984; c) normal range and adult habitat. For maps of trawling effort see Picquelle and Hewitt, 1984 and Hewitt, 1984.

Since the larval index was high in 1957, the per capita survival of spawn must have been extremely low for that year.

Rockfish. The first effects of the 1957-9 El Niño on the production of rockfish larvae were noted in 1958. Since the onset of El Niño condition was in April of 1957 after the most rockfish births (rockfish bear live young) had occurred for the year. At 42°N there was an apparent increase in the number of rockfish larvae in 1958. At 37°N there were moderate decreases in 1958 and 1959. At 32°N the number of rockfish larvae per stations decreased by more than half in 1958 and again by a factor of three in 1959. The decline of larvae was similar at 27°N. There were no obvious effects of El Niño on the commercial fishery. The decline in larval abundance may have been caused by the decline of the productivity of the waters adjacent to the continental shelf. The El Niño may have had a profound effect on the reproductive rate of this group of species. A description of these time series is found in Ahlstrom, Moser and Sandknop (1978). This arctic to temperate genus has 69 species in the eastern North Pacific and about 40 species are taken in commercial and sports fisheries in California.

Flatfishes. Of eight kinds of flatfishes that Ahlstrom and Moser (1975) analyzed only four showed major declines in abundance during El Niño of 1957-9. The species which declined less than 2-fold (possible temperature/development rate effect) were the California halibut, Paralichthys californicus, English sole, Parophrys vetulus, Rex sole, Glyptocephalus zachirus, and the Dover sole, Microstomus pacificus. The species which appeared to change more drastically were the speckled sanddab, Citharichthys stigmaeus, other sanddabs, Citharichthys spp., slender sole, Lyopsetta exilis and the turbots, Pleuronichthys spp. It would be interesting to know the feeding habits of these two groups and what mechanism differentiates their response to El Niño.

Plankton

The plankton sampling program of CalCOFI was designed to quantitatively capture the eggs and early larval stages of fishes which occupy the euphotic zone. Thus, observations of organisms which occur in and deeper than the 140-m depth of the CalCOFI oblique tows must be interpreted cautiously. For example, the adults of many euphausiids substantially evaded the bridled ring-net, even at night, and most euphausiids range throughout the upper 600 meters (Brinton and Townsend, 1981). Important amounts of copepod biomass were not retained by the .505 mm mesh apertures of the CalCOFI standard net. Important fractions of the zooplankton are totally destroyed by contact with the filtering surface under tow and others are extruded from the mesh during vigorous washing. Thaliaceans shrink greatly before the displacement volume is taken in many samples the large thaliaceans were discarded before fixation owing to the lack of adequate containers and fixative (Thrailkill, pers. comm.). Planning and sample design, like that conducted for the eggs and larvae of sardine, would be a prerequisite for a quantitative analysis of any of the 500 or so populations now captured in the fish egg and larva surveys. Still the regularity of the sample techniques has permitted advanced analysis and important conclusions about widespread biological oceanographic phenomena and much of the interpretation is based on the strength of the non-seasonal changes during the 1957-9 Niño and the cooler period which preceded it (Bernal, 1981).

As pointed out by Smith (1971) most of the change in zooplankton volume during the El Niño of 1957-59 was caused by a radical diminution in the volume of thaliaceans (salps, pyrosomes and doliolids) and larvaceans. This category comprised 75% of the zooplankton in October of 1956 and by April of 1958 this category was only 7%. The crustaceans had during the same period risen from 17% to 60%. These relative changes in plankton group composition cannot be interpreted in terms of productivity since changes in standing crop merely represent changes in the relative rates of natality, growth and mortality. One would need to know much more about the demographics of the planktonic populations and the vulnerability of the life stages to sampling to make useful inferences about zooplankton production.

Thaliaceans dominated plankton collections in the California Current region in 1956 being more than triple the quantity of copepods and 13 times the volume of euphausiids. The rank order was thaliaceans, copepods, and euphausiids. By 1958 the copepods had decreased to 50%, the euphausiids had decreased to 45%, and the Thaliaceans had decreased to 4% of their volumes. Table 3 lists these functional groups with the other 14 for comparison. Following the climatic shift, copepods became the most abundant group in the biomass and the thaliaceans and euphausiids were nearly equal at fourth and fifth rank abundance. The chaetognaths had risen from fourth to second rank and the siphonophores had risen from fifth to third rank.

Thaliaceans. Thaliaceans were most abundant seaward of 150 km in the main branch of the California Current (Figure 4). The annual average reached a maximum of 200 grams per 1000 m^3 in 1956 and decreased to less than 10 grams per 1000 m^3 by 1958 and in 1959. The annual average temperature shifted from 14 to 16.5° degrees in this outer region over the same period (Fig. 5). Alongshore thaliaceans changed from 140 cc per 1000 m^3 in 1956 to nil in 1958 and remained there in 1959 in the Vizcaino Bay region (Fig. 6). There were parallel temperature rises along the entire coast (Fig. 7).

During the actual onset of El Niño in April of 1957, the thaliacean displacement volume declined 20-fold between April and July. In a similar period in 1956 the thaliaceans increased 5-fold in the southern California section.

Copepods and Euphausiids. Across the coastal currents and main branch of the California Current the annual average abundance of copepods decreased from about 50 and 10 grams per 1000 m^3 in 1955-57 to about 20 and 6 grams per 1000 m^3 in 1958-9 (Fig. 8).

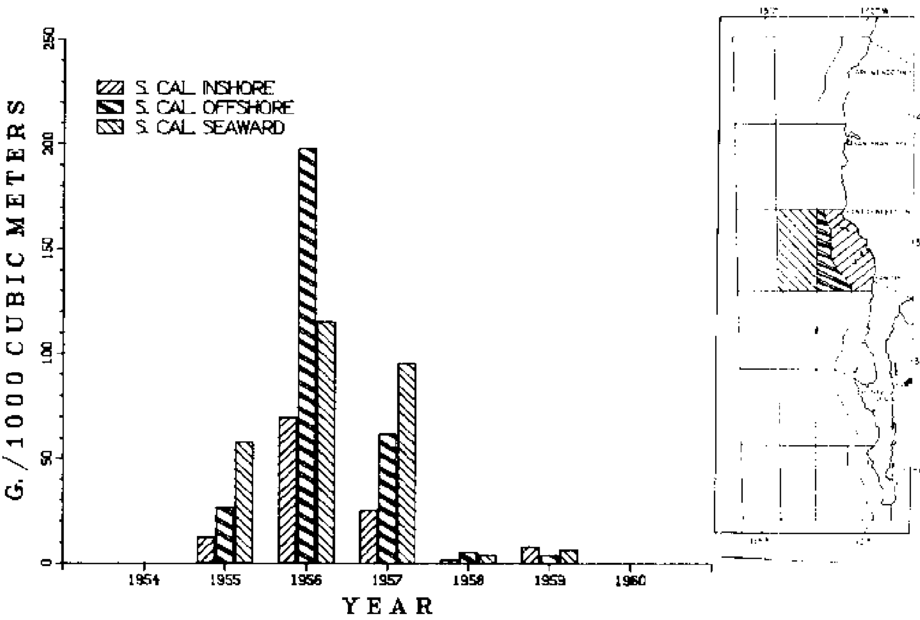

Figure 4. The decrease of thaliacean displacement volume between 1955 and 1959. The first bar is the volume calculated from the average of all stations in the southern California inshore region for the entire year. The second bar is the same value for the southern California offshore region. The third bar is the same value for the southern California seaward region.

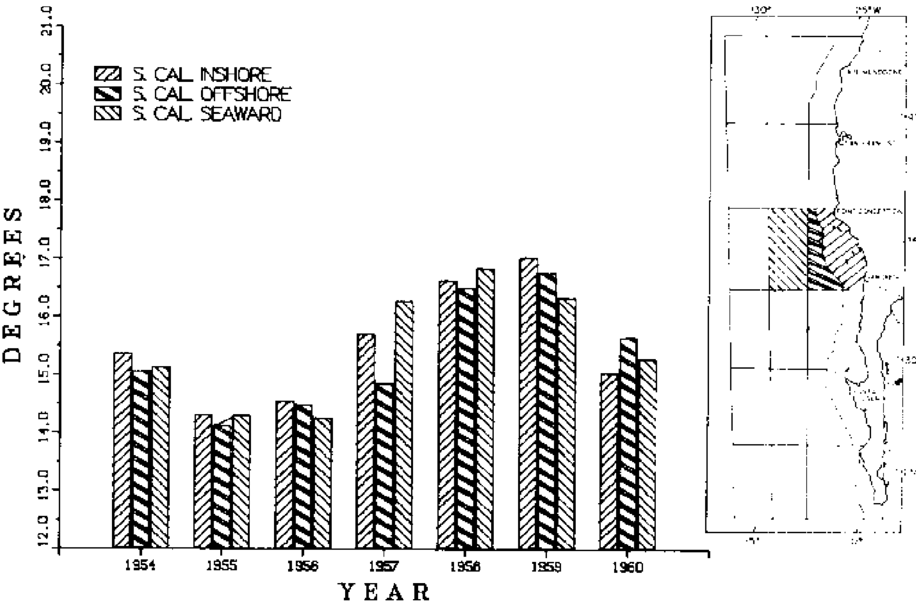

Figure 5. The increase of 10 meter temperatures between 1954 and 1960. The first bar is the 10 m temperature calculated from the average of all stations in the southern California inshore region for the entire year. The second bar is the same value for the southern California offshore region. The third bar is the same value for the southern California seaward region.

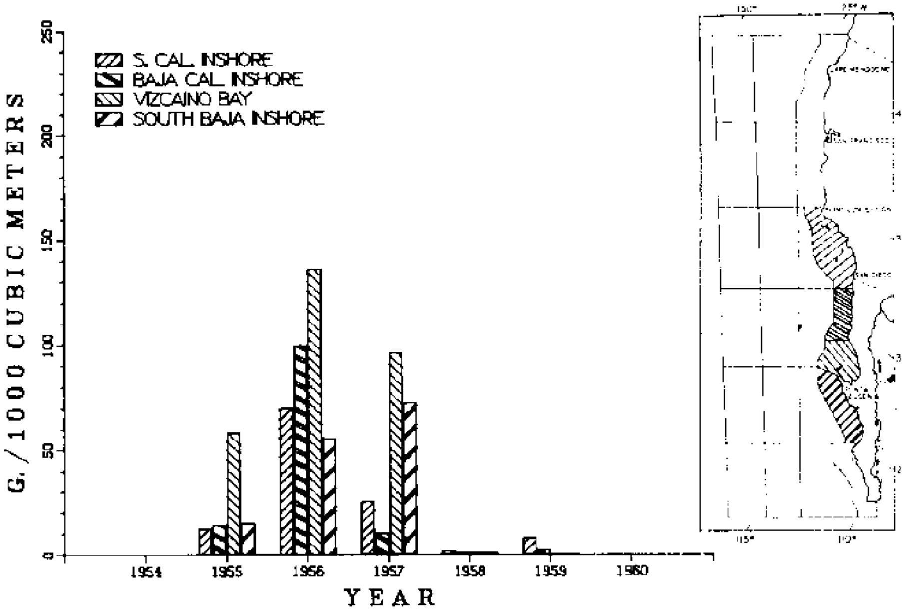

Figure 6. The decrease of thaliacean displacement volume between 1955 and 1959. The first bar is the volume calculated from the average of all stations in the Southern California inshore region for the entire year. The second bar is the same value for the Baja California inshore region. The third bar is the same value for the Sebastian Vizcaino Bay region. The fourth bar is the same value for the south Baja inshore region.

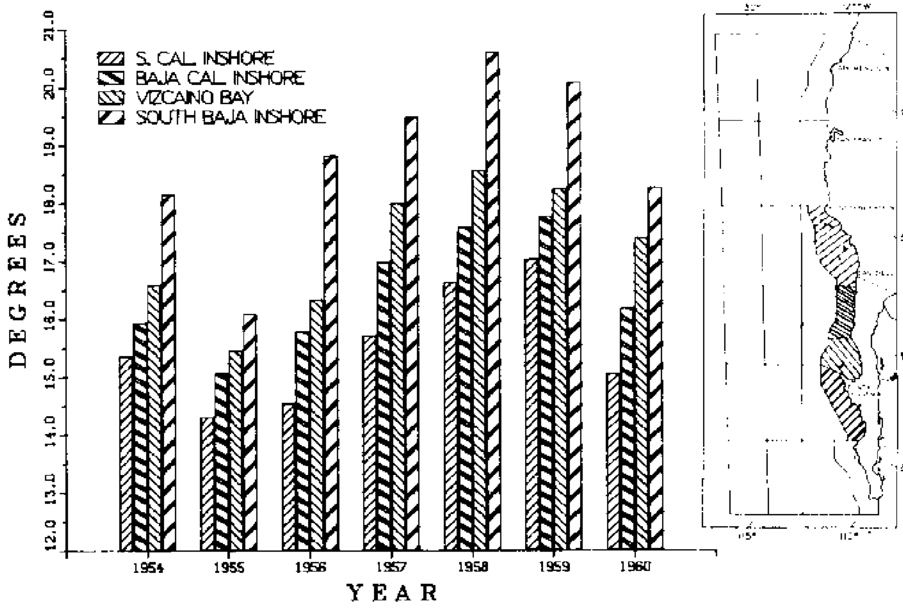

Figure 7. The increase of 10 m temperatures between 1954 and 1960. The first bar is the average 10 m temperature calculated from all stations in the southern California inshore region for the entire year. The second bar is the same value for the Baja California inshore region. The third bar is the same value for the Sebastian Vizcaino Bay region. The fourth bar is the same value for the south Baja inshore region.

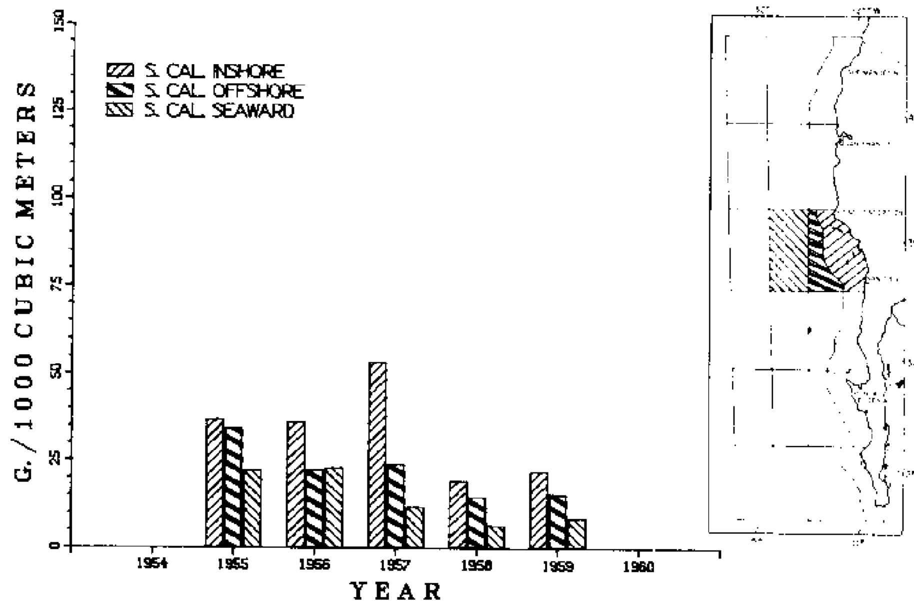

Figure 8. The decrease of copepod displacement volume between 1955 and 1959. The first bar is the volume calculated from the average of all stations in the southern California inshore region for the entire year. The second bar is the same value for the southern California offshore region. The third bar is the same value for the southern California seaward region.

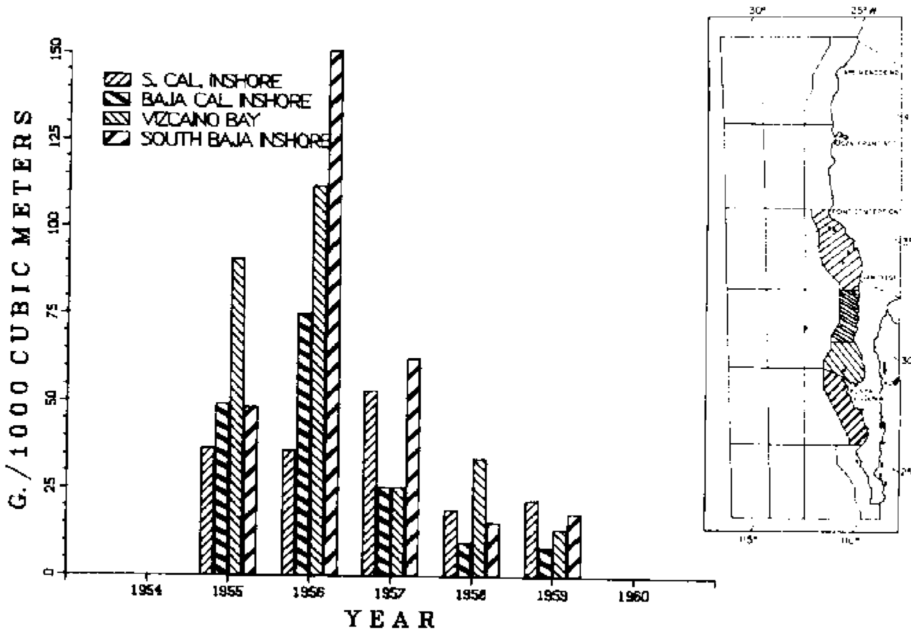

Figure 9. The decrease of copepod displacement volume between 1955 and 1959. The first bar is the volume calculated from the average of all stations in the southern California inshore region for the entire year. The second bar is the same value for the Baja California inshore region. The third bar is the same value for the Sebastian Vizcaino bay region. The fourth bar is the same value for the southa Baja inshore region.

Southward along the coast in the coastal currents zone the decrease in the southerly regions was more dramatic for the copepods, from 140 grams per 1000 m^3 to 20 (Fig. 9). Euphausiids decreased by a factor of three (Fig. 10 and 11).

During the onset of El Niño in April 1957, the inshore copepods decreased by a factor of 4 and the euphausiids decreased by a factor of 3 by July. In the same period in 1956 the volumes were equal over the 3 month span in the southern California inshore area.

Presumed Secondary Production

While secondary production is difficult to infer from zooplankton displacement volume, it may be interesting to note that the slope of the seasonal increase of zooplankton is similar in the southern California inshore area in the years 1955 through 1959 (Fig. 12 and 13). One can infer from this that the reproductive capacity less the predation rate favored increases in zooplankton volume both when the system was dominated by thaliaceans and when dominated by copepods. The second figure is a display of the adjacent month differences displayed as ratios. In this area one can expect sustained increases from 10 to 60% per month in the winter and spring months whether the system is dominated by thaliaceans or copepods and at either the 14° temperature of the 1955-56 period or the 16.5° temperature of the Niño period. Since the currents are sluggish in this area one would expect local growth to dominate over transport as a factor in this rate of increase, transport in the gyre is largely from the south and west with only minor entrainment of the California Current as indicated from the offshore position (270 km at line 90) of salinity less than 33.4% (Bernal, 1981).

Primary Production

Unfortunately, there were no primary production estimates at the time of the 1957-9 El Niño. There are no spatially and temporally coherent time series of an area the size of the California Current region. A coastal time series reported by Smith and Eppley (1982) did capture one extremely high phytoplankton production rate of 1.41 g C per m^2 per day in June of 1975 and a relatively low value of 0.1 g C per m^2 per day in October of 1976 and February 1977. Assuming the Scripps Pier Temperature Anomaly was related to primary production in the same way in the years 1955-59, the annual average production declined from 0.4 to 0.2 g C per m^2 per day and December minima of 0.1 were obtained in 1957 and 1958. There appeared to be moderate agreement in the change in values of zooplankton volume over the same period Table 4.

Summary and Recommendation for Future Study

Re-examination of the more thoroughly sampled transition from anti- to El Niño conditions in 1955-9 suggests answers to the question "Why was the effect on anchovy spawning so moderate in

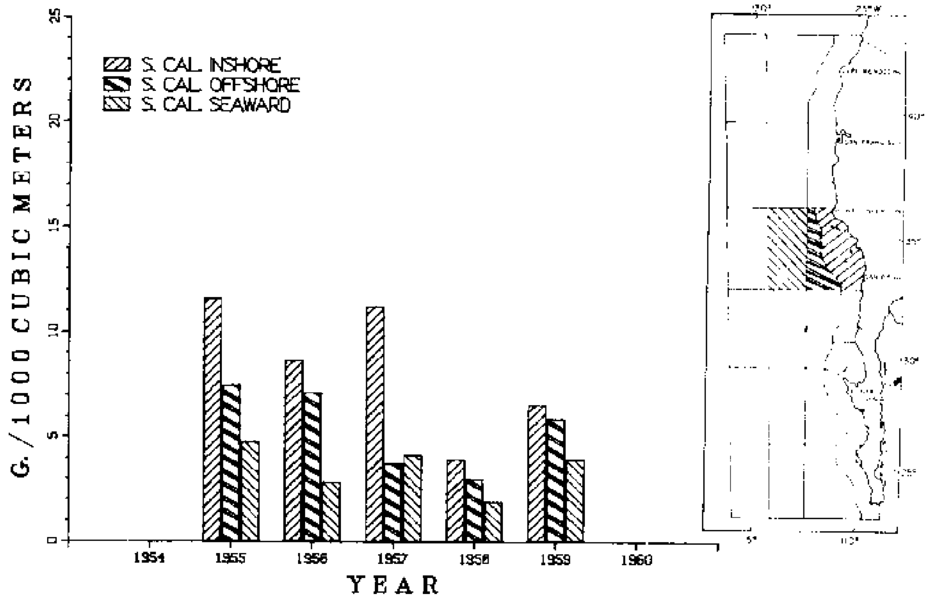

Figure 10. The decrease of euphausiid displacement volume between 1955 and 1959. The first bar is the volume calculated from the average of all stations in the southern California inshore region for the entire year. The second bar is the same value for the southern California offshore region. The third bar is the same value for the southern California seaward region.

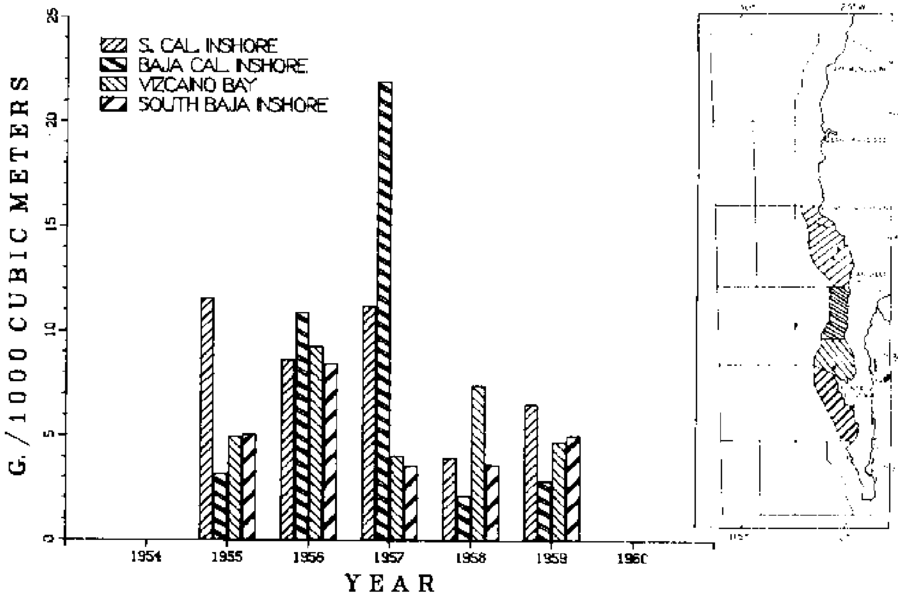

Figure 11. The decrease of euphausiid displacement volume between 1955 and 1959. The first bar is the volume calculated from the average of all stations in the southern California inshore region for the entire year. The second bar is the same value for the Baja California inshore region. The third bar is the same value for the Sebastian Vizcaino Bay region. The fourth bar is the same value for the south Baja inshore region.

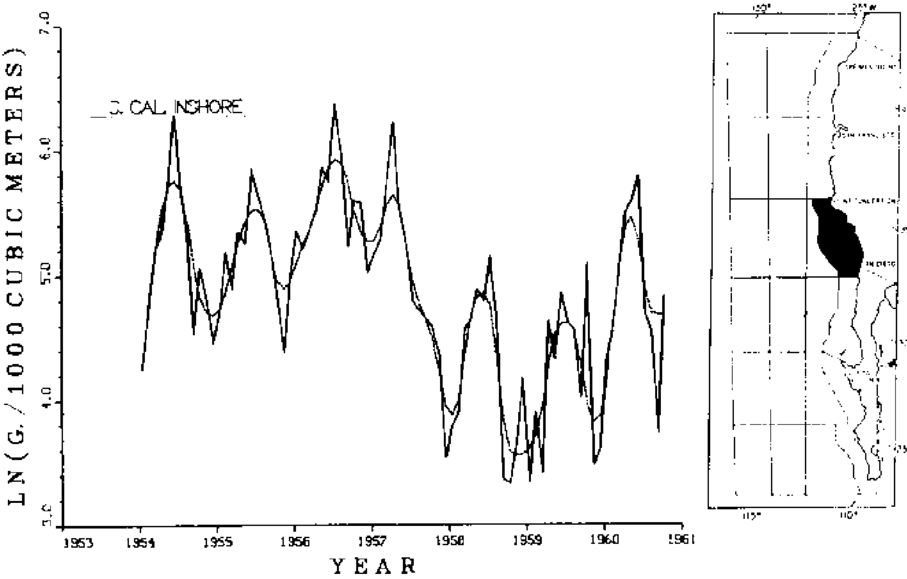

Figure 12. The time series of small zooplankton volume between 1954 and 1960 in the southern California inshore region. The jagged line is the natural log of the average of all stations on a monthly interval with missing values (about 10% mostly August or September) interpolated linearly. The smooth line is a resistant non-parametric smoother for these points. The similarity of seasonal slopes in anti-Niño (1954-60) and Niño (1958-59) years is an indication that the growth rate per unit initial zooplankton volume is similar for both conditions.

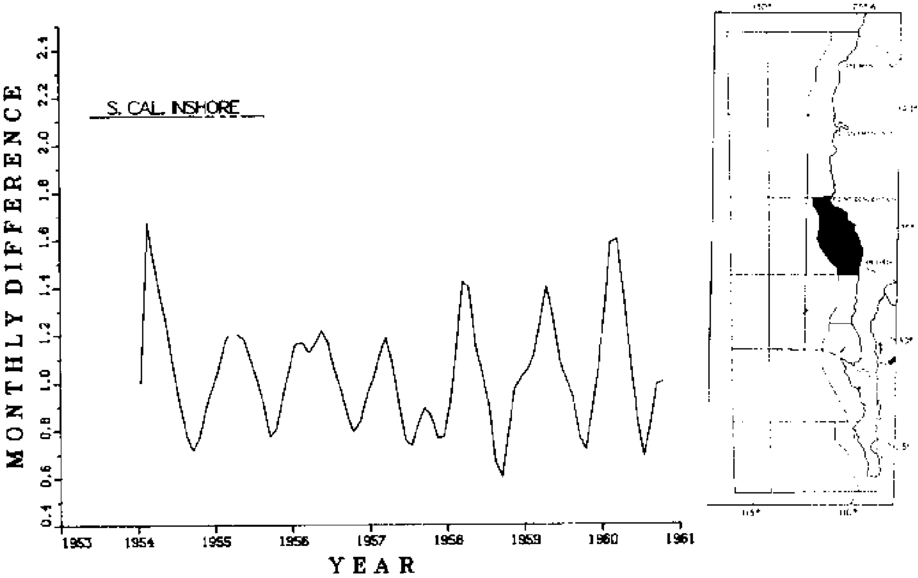

Figure 13. The time series of monthly differences of small zooplankton volume expressed as a ratio between the displacement volume of a given month and that of the previous month in the southern California inshore region from 1954 to 1960. Raw, interpolated and smoothed data in Figure 12.

Table 4. Comparison of estimated primary production and zooplankton standing stock during the 1955-9 transition from anti-Niño to Niño.

		Primary production g C/m^2/day	Zooplankton standing stock g/m^2	Change g/m^2/qtr
1955	March	0.5	11	-
	June	0.7	25	14
	September	0.3	13	-12
	December	0.3	13	0
1956	March	0.5	17	4
	June	0.7	42	25
	September	0.4	23	-19
	December	0.2	23	
1957	March	0.3	17	-6
	June	0.5		
	September	0.3	6	-8
	December	0.1	5	-1
1958	March	0.2	7	2
	June	0.6	11	4
	September	0.3	2	-9
	December	0.1	2	0
1959	March	0.2	5	3
	June	0.3	9	4
	September	0.2	7	-2

1983-4?" The energy required for anchovy spawning could have been "gleaned" from local island and coastal enriched areas which would be inadequately represented in wide-scale oceanic surveys. Anchovy, Pacific mackerel, and sardines may draw substantially on stored reserve energy from preceding seasons (Smith and Eppley, 1982) and may delay growth (Table 1b.) Another possibility is that diminished populations of salps, dalialids and pyrosomes (thaliaceans) allowed greater production of other herbivores, like crustaceans which are in the anchovy food chain.

Given these elements of resilience in the anchovy, Pacific mackerel, and sardine populations, one can speculate on why the spawn production of jack mackerel and saury was so low following the 1957 onset of El Niño. The jack mackerel spawning adults occupy the same habitat as the thaliaceans. This area is so broad and homogeneous that the twenty-fold decline in thaliaceans signaled a similar seven-fold decline in larval production by jack mackerel. This could have been mediated by the production of crustacea on which jack mackerel depend in part, or by the withdrawal of key mesopelagic fishes toward the north without equivalent replacement from the south. I would favor the mesopelagic fish explanation because the zooplankton predator, saury, did not change its spawn production rate markedly. Thus the mobility of the jack mackerel was not adequate to compensate for the scale of El Niño event in the main and outer branches of the California Current.

The responses of the hake, rockfish and flatfish to the onset of the El Niño appear similar. The hake feeds along the continental shelf of the British Columbia, Washington, Oregon and northern California coastlines. In the 1955-59 anti-and El Niño transition the main branch of the California Current impinged on these continental borderlands and the rockfish and flatfish are permanent members of that continental border. Thus the similarity of response was probably mediated by the interruption of the usual high rate of primary and secondary productivity usually ascribed to these coastal areas. Since these fishes and the jack mackerel all prey on the sardines and anchovies, one must assume that the predation withdrawn to the north roughly counterbalanced the added predation from the tropical and temperate tunas during the Niño.

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El Niño and the Early Life History And Recruitment of Fishes In Temperate Marine Waters

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Introduction

El Nino events can have drastic ecological and economic consequences for fisheries. This has been most widely recognized from fluctuations in the fishery for the Peruvian anchovetta (Cushing 1982), but abundances of other species are affected as well. A tropical El Nino is characterized by anomalous environmental conditions often detectable along the west coast of North America as increases in surface and near-surface water temperature, a rise in coastal sea level, an increase in depth of the thermocline, and anomalous coastal currents (Enfield and Allen 1980, Huyer 1983, Lynn 1983, Smith and Huyer 1983, Reed 1984, Tabata 1984, Cannon and Reed, this volume). Changes in the planktonic community also occur (McGowan 1984). These physical and biological changes may alter the distribution and extent of spawning effort and the transport and survival of eggs and larvae. To the extent that some of these conditions are extreme compared to the range of conditions encountered by fish stocks, particularly successful or unsuccessful year classes may result.

Unfortunately, little is known about the effects of El Nino on subarctic (cold temperate water) fishes. Most documentation on subarctic effects involves records of subtropical species occurring in subarctic regions such as reported by Squire (1983) and Schoener (this volume). Our discussion of other possible effects therefore must remain quite speculative. First, we present an overview of how an El Nino event potentially influences spawning and egg and larval stages of temperate marine fishes. These potential effects include changes in: 1) distribution of highly migratory species during spawning; 2) fecundity of spawning fish; (3) physiological condition of eggs and larvae; (4) transport of eggs and larvae; and 5) the predator-prey community to which eggs and larval stages are exposed. Examples are given where data are available. Since there are few data on El Nino effects on subarctic fishes we draw heavily from what is known about subtropical (warm temperate) fishes, including those from the southern hemisphere. Second, we examine historical data on recruitment of fish stocks from the eastern and northeastern Pacific Ocean to consider possible impacts of past El Nino events, and we suggest general patterns which seem to apply to these data. Even for the better documented subtropical stocks, cause and effect relationships appear equivocal. The patterns we describe based on the limited but available data therefore must be viewed as preliminary.

Potential Effects of El Niño on Reproduction and Early Life History

Meteorological and oceanographic conditions during an El Nino event are detailed in other papers in this volume. There is now adequate evidence to suggest that most El Nino events are associated with anomalously warm sea surface temperatures (SST) north of the subarctic boundary (see Cannon and Reed, this volume; Tabata 1984). The precise combination of factors responsible for positive temperature anomalies along the west coast of North America are not well quantified and probably vary with latitude and between events. Warm anomalies begin during autumn or winter and probably are initiated by a coastally trapped wave with concomitant increases in poleward flow of water (Enfield and Allen 1980; Smith and Huyer 1983). After this, several factors may be equally important in maintaining or increasing the positive SST anomalies. These include the following: (1) poleward flow of water may continue due to unusually persistent southerly winds; (2) coastal upwelling may become established later than usual, may be weaker than usual, or may not develop; (3) even if upwelling becomes established, the thermocline may be deep enough that upwelled water is warmer than usual. Finally, at some latitudes, there may be shoreward movement of oceanic water. Salinity may provide a clue to the source of surface water along the coast, but interannual changes are generally small and may be masked by local modifications due to climate. The source of apparent warming and attendant rates and direction of transport are important in considering the interactions of early life stages with their environment.

The El Nino of 1983 is summarized as an example of the physical anomalies along the west coast of North America. Off California, SST was elevated up to 4° C (McLain 1984) and salinity increased by 0.1-0.2 ppt above normal (Lynn 1983). Sea surface temperature was 2° C above normal off Oregon, where salinity possibly was lower than average (Huyer 1983). Shelf waters off Canada were up to 5° C warmer than usual, and positive temperature anomalies were observed down to 150 m (Tabata 1984). Royer and Xiong (1984) report positive temperature anomalies of 2° C in the northern Gulf of Alaska during summer 1983. Extremely strong northward currents were observed along the California and Oregon coasts during summer 1983 (Smith and Huyer 1983).

The potential mechanisms of impact of El Nino conditions on recruitment success of fishes can be considered first by grouping species according to migratory behavior. For sedentary or "homing" species (Table 1), which remain in, or return to, the same area regardless of El Nino, there can be a direct physiological impact of temperature on spawning effort involving effects on fecundity, timing of spawning and condition of spawned eggs. There will be direct physiological impacts on eggs and larvae involving rates of development, metabolism, etc. Changes in abundance, species composition and/or temporal dynamicsof the prey community can be expected, due either to the intrusion of a different water mass or to the effect of increased temperature on local species assemblages. This could affect spawning effort of fish, depending on the nature of the adults' diet and patterns of energy storage and mobilization for reproduction. After spawning and hatching of eggs, the quantity and type of prey would affect larval feeding conditions. Planktonic predators also may change because of a new water mass or because of local warming, and these changes have the potential to affect egg and larval stages. Also, it is well documented that migratory vertebrate predators (fish, birds) change in response to ocean warming (e.g., they travel further north than customary); thus a new cast of vertebrate predators may be present as a result of El Nino.

Table 1. Summary of potential effects of El Nino conditions on sedentary or "homing" species.

1. Impact of elevated temperatures on spawning effort
   - fecundity
   - timing of spawning
   - condition of eggs

2. Effect of changes in food abundance on spawning effort (depends on nature of prey and spatial and temporal pattern of energy storage and mobilization for spawning)

3. Elevated temperature effects on eggs and larvae
   - physiological tolerance
   - development time
   - metabolism

4. Indirect effects of elevated temperatures on eggs and larvae: predator and prey communities
   - abundance
   - species composition
   - timing

5. Effects of new water mass on eggs and larvae
   - same as above

6. Effects of migratory vertebrate predators that follow ocean warming, and which may feed on eggs and larvae
   - timing
   - new species

For highly migratory species of fish (Table 2), physiological impacts of temperature can be minimized or avoided by migrating with appropriate conditions, but spawning then would take place in a different water mass and/or at different latitudes than usual. The planktonic and nektonic communities encountered by the spawned eggs and larvae of these species may or may not be unusual depending on whether the migration occurred within a water mass or followed temperature patterns which propagated faster than the advective rate of poleward-moving water. The latter condition would result in an overlap of communities which ordinarily remain more distinct, and both conditions would result in a temporary, northward expansion of range for spawning. The new territory thus encountered provides opportunity for colonization (successful recruitment) but could also prove hostile to the egg, larval or post-larval stages.

In contrast to the species considered above, adult fishes inhabiting deeper slope waters may be isolated from El Nino conditions in the upper water column. Nonetheless, shallow pelagic eggs and larvae of such species still would be exposed to anomalous conditions of temperature, predators and prey. At present, neither the extent of biological change nor its likely consequences are adequately understood.

Table 2. Summary of potential effects of El Nino conditions on highly migratory (nomadic) or mobile species.

These species may minimize adverse physiological impacts of elevated temperatures on adults, but there are costs, including:

1. Extra energetic expenditure on migration which may affect spawning effort
   - fecundity
   - timing of spawning
   - condition of eggs

2. Spawning may take place in a different water mass than usual
   - predator and prey communities may be different (abundance and species composition)
   - local dynamics (timing) may be different

3. Spawning may take place further poleward
   - opportunity for "colonization" or "expansion" may be successful or unsuccessful
   - new interspecific interactions
   - colonized area may be physically inhospitable after El Nino conditions subside

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Finally, for all species, anomalous transport of planktonic stages is likely to be a factor in recruitment success. Transport processes are considered important in recruitment of several subarctic and subtropical stocks (Hayman and Tyler 1980; Parrish, et al. 1981; Methot 1984).

Effects of El Niño Conditions on Reproduction And Early Life History: Examples

Reproductive physiology.

The influence of El Nino events on egg production by adult subtropical fishes is fairly well documented. Most of the examples we present are for anchovetta or sardine, but many similar effects can be expected for subarctic stocks when the event extends its influence into their range. The most immediate effect on reproduction appears to be a decline in reproductive output. This may happen as a result of fewer fish in the population maturing their gonads (Tsukayama and Alvarez 1980), a shortened spawning season (Tsukayama and Alvarez 1980) or a failure to utilize fat reserves for the production of gonads (Santander 1980). A recent example for a North American species is from the 1983 El Nino, when blue rockfish (Sebastes mystinsus) in Monterey Bay lost weight and had low gonadal output (D. VenTresca, Calif. Dept. Fish and Game, Monterey, CA, pers. comm.).

Several examples of altered spawning times exist. During an El Nino anchovies and sardines appear to spawn earlier than during other years (Ahlstrom 1967; Santander 1980). However, English sole (Kruse and Tyler 1983) and Pacific hake (Bailey, unpublished data) appear to experience delayed spawning. The effect of unusually early or late spawning on survival is unknown, but either presumably influences the match or mismatch of larval food availabilty to feeding readiness, a condition conceivably critical to larval survival and to recruitment success of many species (Cushing 1975).

Distributional changes.

Changes in spawning distribution of adults during El Nino are well documented. Several species shift spawning locations poleward during such events, including hake (Bailey and Francis, in press), anchovetta (Santander 1980; Walsh et al. 1980; Fiedler 1984) and sardine (Ahlstrom 1967; MacCall 1979; Anon. 1984). For stocks which spawn in localized habitats or that are homing and spawn in specific locations, such as salmon, possibly herring (Blaxter and Hunter 1982) and some rockfishes (D. Ventresca, Calif. Dept. Fish and Game, Monterey, CA, pers. comm.), El Nino conditions might prevent return of spawning fish to their home habitat during a period or in physiological condition which favors success for their progeny.

Changes in the geographical distribution of eggs and larvae during El Nino conditions result either from displacement of spawning adults out of their normal spawning region or from advection of eggs and larvae by anomalous current patterns. There is ample documentation for changes in spawning range of adults (e.g., Fiedler, 1984), but little documented evidence of changes in ichthyoplankton distribution due to advection. One possible exception involves the observed high abundance of larval anchovy, normally found offshore, at sampling stations near the Oregon coast during 1983, which Brodeur et al.(1984) speculate was due to anomalous onshore transport.

Changes in community structure and production.

A major effect of El Nino events is altered production of food for planktivorous life stages of fish. This is best documented for the California Current system, where El Nino results in reduced planktonic production. During the 1983 El Nino off California, nutrient concentrations were low, primary production was reduced and the chlorophyll maximum layer deeper than normal. In the normal area of peak zooplankton abundance, approximately 150 km offshore, zooplankton biomass was about 5% of normal (McGowan 1984). Most fish larvae eat copepod nauplii early in their feeding history. Since naupliar production depends largely on the abundance of adult copepods and the phytoplankton standing crop, it appears a safe conclusion that naupliar abundance was extremely low off California during 1983 compared with most other years. The decrease in zooplankton production was translated into little or no growth for adult fishes such as anchovy and rockfish (Parrish, cited in McLain 1984; Mais 1983a,b; D. VenTresca, Calif. Dept. Fish and Game, Monterey CA, pers. comm.). McLain (1984) hypothesized that even though El Nino caused a decrease in production off California, production in subarctic waters may have been enhanced due to warming, increased stability and reduced offshore transport. This hypothesis is supported in part by a 23 year time series of zooplankton biomass at Ocean Station P in the Gulf of Alaska, showing that 1958-60 had anomalously high biomass, with 1958 showing the maximum biomass in the time series (Frost 1983). By contrast, 1958-59 were years of extremely low zooplankton biomass off the California coast (Bernal and McGowan 1981). However, Frost (1983) points out that while the subarctic Pacific and California Current systems appear from existing data to be out of phase with respect to zooplankton biomass, this contrariety is not necessarily linked to a common cause.

Community species composition differs between offshore and nearshore areas in the subarctic Pacific (Lebrasseur 1965), Bering Sea (Cooney and Coyle 1982, Smith and Vidal 1984) and off Peru (Walsh et al. 1980; Santander 1981). Latitudinal changes also occur, such as between subtropical waters off California and subarctic waters farther north. Santander (1981) reported striking changes in the species composition of copepods during the 1976 El Nino in Peru. Changes in the prey community due to enhanced poleward flow and/or onshore transport during an El Nino event could be important to fishes. For example, Cushing (1982) attributed changes in growth, maturity and recruitment of herring in the North Sea to a shift in the dominant copepod species from small calanoids to larger species. Such shifts would be important to larval fishes that depend on certain species or sizes of microzooplankton for food (e.g., Lasker 1975; Checkley 1982). However, El Nino may not always be bad for larval feeding conditions. Barber and Chavez (1983) reported a bloom of Gymnodinium splendens off Peru during the 1976 El Nino, and this dinoflagellate appears to be suitable food for larval anchovy (Lasker 1975).

Changes in predator communities also have been documented. Onshore transport during El Nino can result in increases of several species of predators, such as siphonophores and euphausiids, in the larval nursery (Santander 1981). Some siphonophores (Purcell 1981) and euphausiids (Theilacker and Lasker 1974) are important predators on fish larvae. During the 1972 El Nino, blooming populations of medusae and voracious pelagic crabs (Euphilax dovii), probably originating from the north and west, occurred in the anchovetta nursery grounds off Peru (Valdivia 1978). In addition to planktonic predators, which are transported, many larger pelagic predators may invade subarctic or coastal waters during El Nino. Examples are squid, which prey on young anchovy, and rockfishes, such as Canary rockfish and boccacio (Henry, cited in McLain 1984), which eat small fishes (T. Echevarria, Southwest Fisheries Center, Tiburon, CA, pers. comm.). Another consideration is that if zooplankton are less abundant, pelagic predators may switch from their normal prey to feed on greater numbers of fish larvae. Finally, El Nino sometimes results in a collapse of some important predator populations, such as birds and pinnipeds (Barber and Chavez 1983), the former being important predators on early life stages of some fishes.

Physiology of eggs and larvae.

Eggs and larvae of subarctic fishes that are spawned or entrained in waters with subtropical or oceanic characteristics are subject to new conditions that can influence physiological processes. These conditions include increased temperature and salinity, and possibly decreased oxygen concentrations. Little is known about the ambient oxygen concentrations required for normal development of eggs and larvae of most temperate Pacific fishes. Alderdice and Forrester (1971a) give 2-3 ppm oxygen as a lower limit for development of cod eggs and larvae, which seems low relative to ambient concentrations of 4-5 ml O2/l (6-7 ppm) in subtropical waters off Peru reported by Walsh et al. (1980) However, Santander (1981) reports concentrations of 1 ml O2/l (about 1.5 ppm) during an El Nino. Since oxygen demand increases with higher temperature and oxygen concentrations decrease with warming, Santander (1980) noted that oxygen concentration during an El Nino could influence survival of anchovy larvae. Brett (1970) commented that even at 100% saturation, oxygen may limit performance of salmon fry when temperature and activity are high.

The hatching success of fish eggs with changes in temperature and salinity varies by species. Many species, such as herring, are euryhaline and eurythermal (Fig 1a, from Alderdice and Velsen 1971). By contrast, Petrale sole is stenothermal and stenohaline (Fig. 1b, from Alderdice and Forrester 1971b) and Pacific cod is stenothermal and euryhaline (Alderdice and Forrester 1971a). Consequently, larvae of sensitive species such as Petrale sole that are spawned or entrained in warm and saline water should have reduced survival in habitats that are impacted by El Nino.

Increases in temperature (below lethal limits) result in shortened egg hatching time, higher metabolic rates and faster utilization of yolk reserves by recently hatched larvae. Herring eggs, for example, developing under warmer conditions hatch larger larvae, but at the expense of their yolk reserves. Larger larvae have larger mouths,

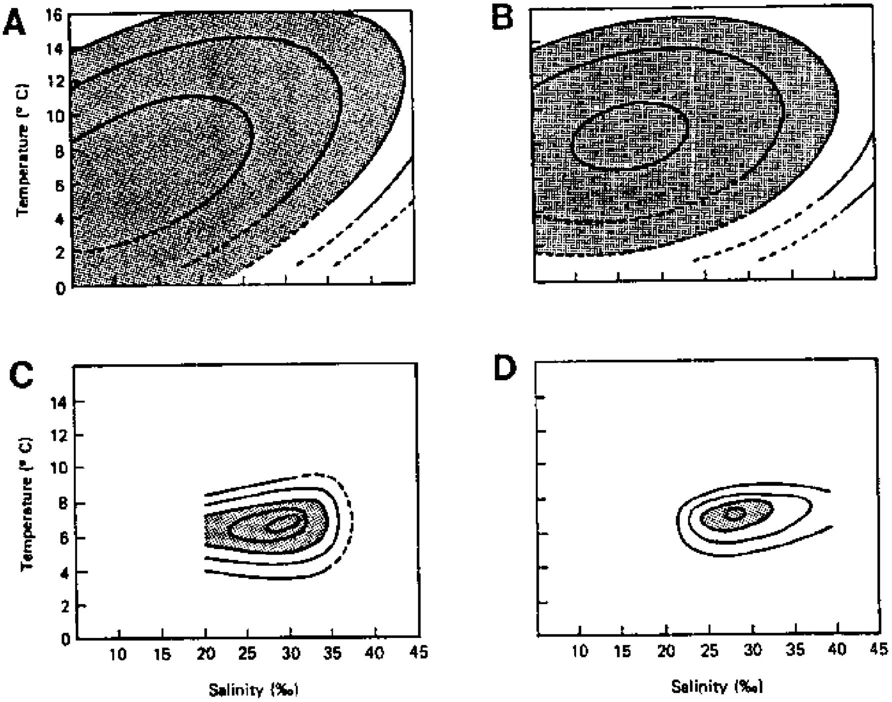

Fig. 1. A comparison of calculated isopleths of percent total hatch and percent viable hatch in relation to salinity and temperature of incubation for eggs of herring and petrale sole (from Alderdice and Forrester 1971, and Alderdice and Velsen 1971). A. Isopleths of percent total hatch of herring, B. isopleths of percent viable hatch of herring, C. isopleths of percent total hatch of petrale sole, D. isopleths of percent viable hatch of petrale sole.

which increases the size spectrum of prey which can be ingested; they swim faster and have more advanced visual ability, which increases food searching and capture potential compared with smaller larvae (Blaxter and Hempel 1963; Blaxter and Hunter 1982). Consequently, the feeding abilities of larger larvae should be improved over small larvae. Studying larval turbot, Rosenberg and Haugen (1982) found that smaller larvae do appear to be more vulnerable to starvation compared with larger larvae reared under the same conditions. Larval growth rates are temperature dependent (Laurence 1978; Hunter and Kimbrell 1980) with faster growth and higher RNA/DNA ratios (Buckley 1982) at higher temperatures. However, growth rates also depend on food availability and decline when metabolism consumes too much of the daily ration (Brett et al. 1969). Ryland and Nichols (1967) showed a temperature dependent optimum in growth of larval plaice. At low temperature, metabolic rates were low, but enzymes required for digestion were not efficient. At high temperature, most energy was used in respiration. Finally, given

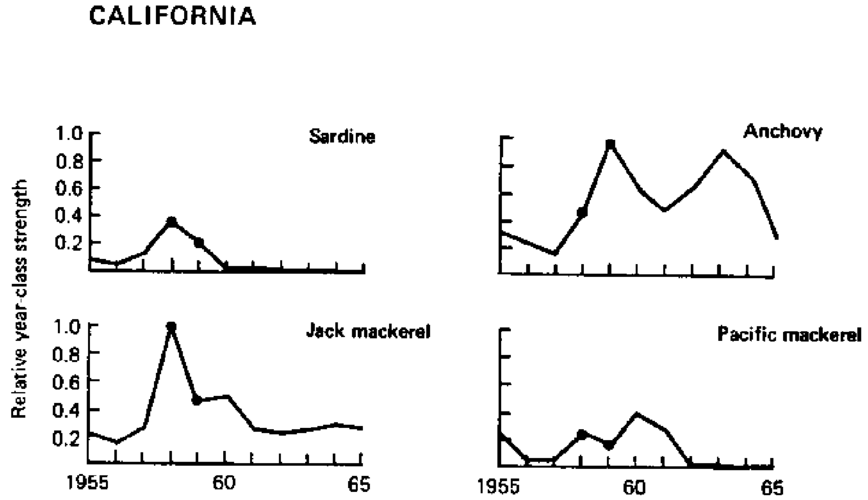

Fig. 2. Relative indices of year class strengths from cohort analyses and other analyses of fishery data of California fish stocks, 1955-65.

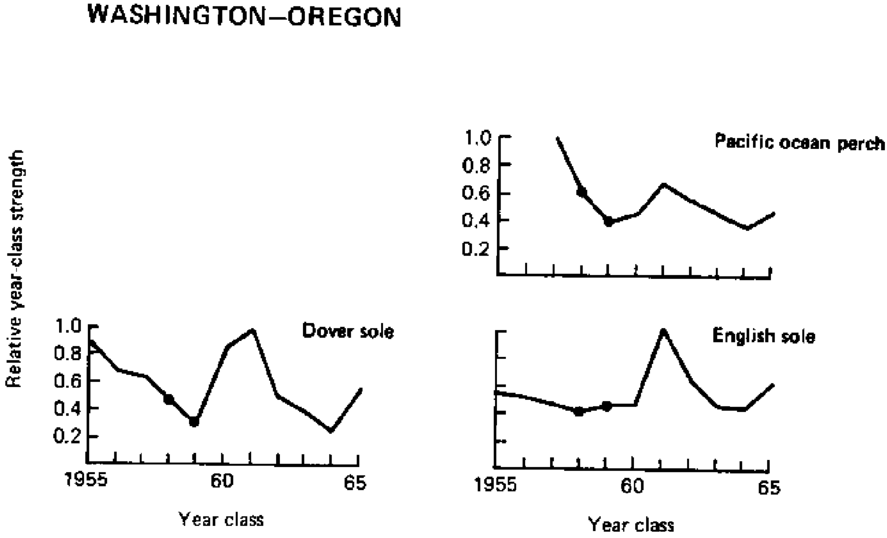

Fig. 3. Relative indices of year class strengths of Washington-Oregon fish stocks, 1955-65.

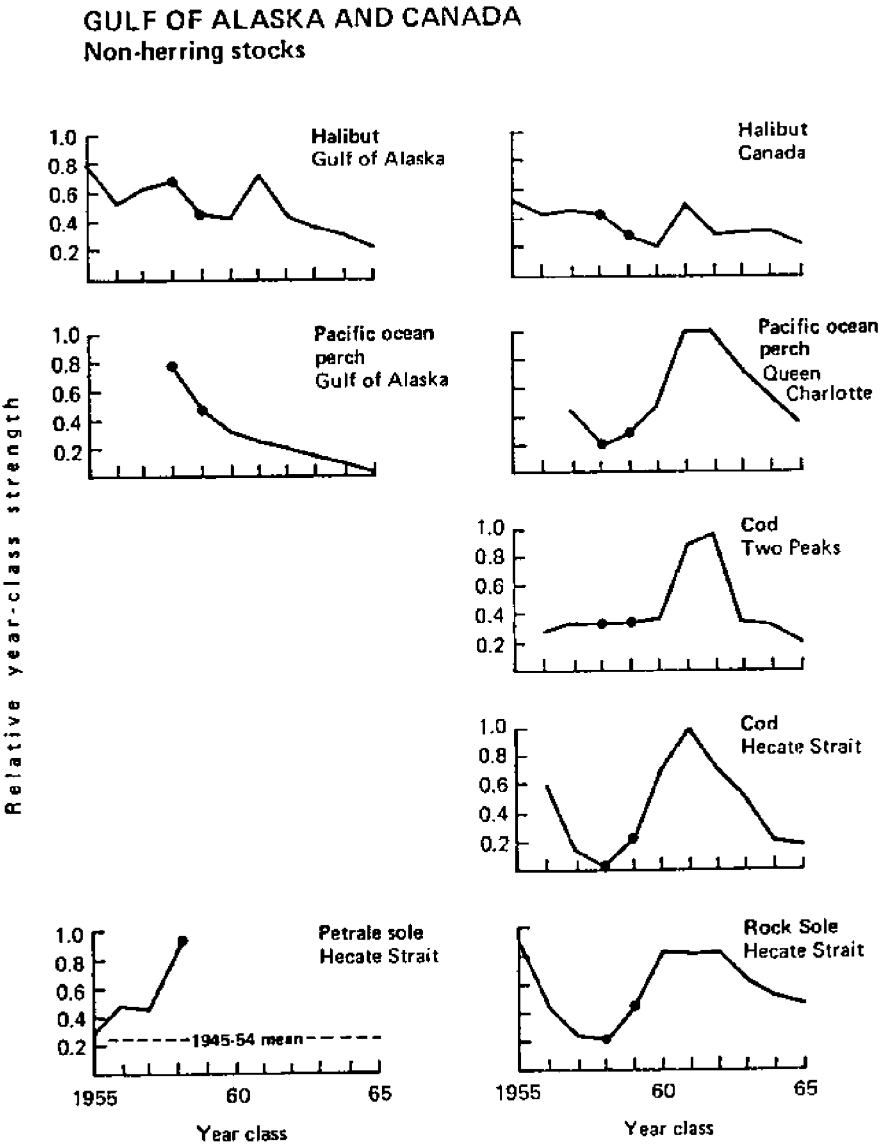

Fig. 4. Relative indices of year class strengths of Gulf of Alaska and Canada fish stocks, 1955-65.

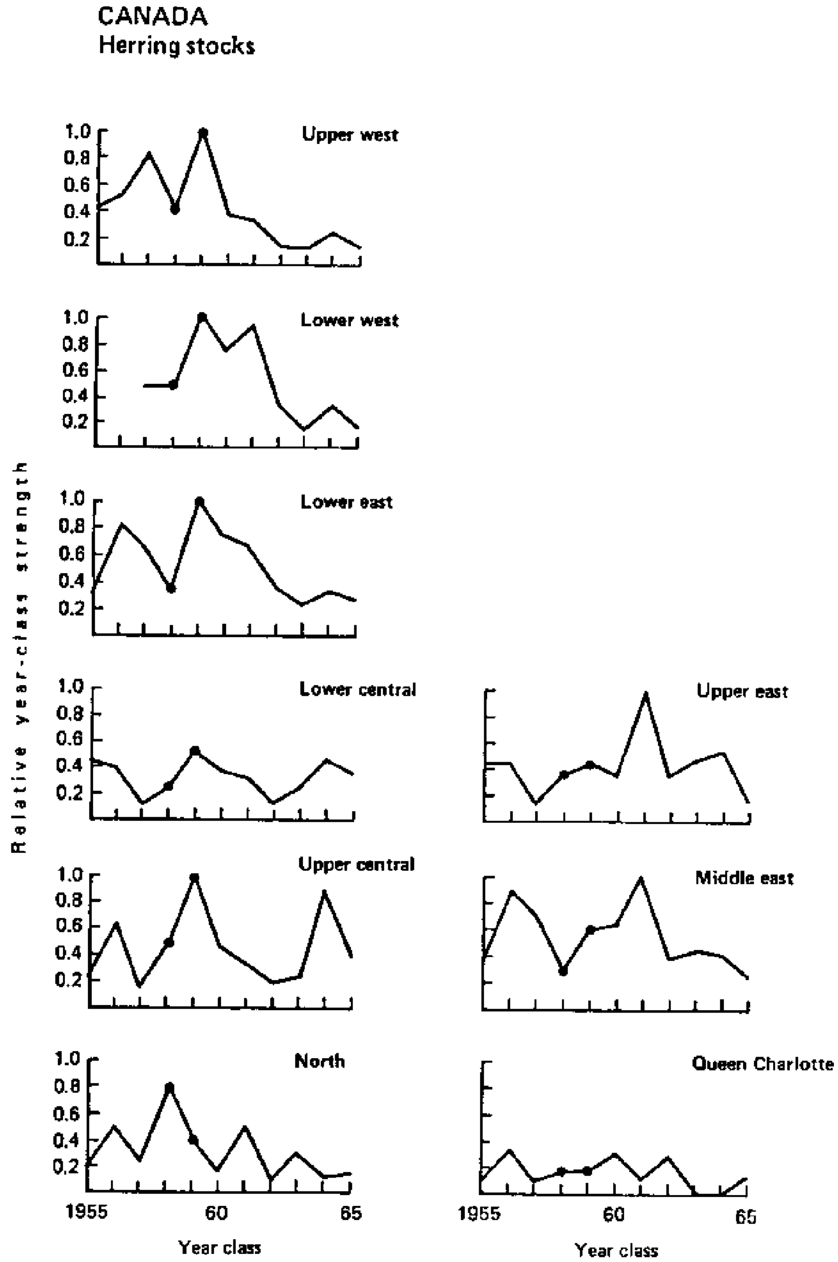

Fig. 5. Relative indices of year class strengths of Canadian herring stocks, 1955-65.

ample food and faster growth rates in higher temperatures, the time to metamorphosis is decreased (Laurence 1978). Other things being equal, this should reduce losses to predation.

Effects of the 1958–59 El Niño on Recruitment of Subarctic Stocks

Data on recruitment of 38 fish stocks along the west coast of North America have been compiled by Hollowed, Bailey and Wooster (unpublished manuscript). Relative values of recruitment from 1955-65 are available for 23 stocks (Figs. 2-5). These estimates of recruitment strength are derived from cohort analyses or from age frequency analyses, and reflect relative year class strength when entering the fishery. The data originate from published and unpublished literature, and from numerous personal communications. The various pitfalls and assumptions involved in using these data, as well as the complete time series for each stock and sources of data, are given in the above manuscript. In the present analysis, the 23 stocks have been divided into three geographical regions: the California coast, the Oregon-Washington coast, and the Canada to Gulf of Alaska coast. Very little information is available from the Bering Sea during this time period.

Off California, information is available for four pelagic stocks. The 1958-59 El Nino resulted in relatively strong recruitment of the 1958 year class to stocks of Pacific sardine and Jack mackerel. In fact, these were the strongest year classes recorded for the 11 year period. For Pacific mackerel, 1958 was a stronger than average year class, markedly stronger than either 1956 or 1957, but also not as strong as the 1960 year class. For the anchovy, 1958 was a weak year class, whereas 1959 was a strong one.

Off the Oregon-Washington coast there is recruitment information for three stocks. For all three coastal stocks: Pacific Ocean Perch, Dover sole and English sole, the 1958 and 1959 year classes were below average in strength.

More historical data on stock dynamics is available from Canada due to the early pioneering efforts of Ketchen, Forrester. Alderdice and Stevenson. Petrale sole, for which only a few years of data are available, was the only demersal stock showing an increase in recruitment during the 1958-59 El Nino. The 1958 and 1959 year classes of halibut, POP, cod and rock sole were poor in this region.

Further to the north in the Gulf of Alaska, the 1958 year class was strong for both halibut and POP, whereas 1959 resulted in moderate to weak year classes.

The largest collection of data on year class strengths for any species exists for Pacific herring off Canada. Herring spawn in the near coastal zone. Of 9 stocks, 5 had strong year classes in 1959 and one had a strong 1958 year class. Of the three remaining stocks, 1958 and 1959 were moderate year classes, except for 1958 in the middle east stock, which was weak.

It is interesting to note that 1961 stands out in the above statistics for many stocks. For the 12 stocks not demonstrating strong year classes from the 1958-59 El Nino event, 10 showed exceptionally strong year classes in 1961. According to McLain and Thomas (1983) this was a year of a deepened mixed layer and onshore and northward transport that was apparently unrelated to disturbances in the tropics.

Some discernable patterns exist in these data. For example, stocks showing strong 1958 and/or 1959 year classes are those towards the northern end of their geographical ranges. These stocks include Petrale sole off Canada, and anchovy, sardine and Jack mackerel off California. This pattern also is seen with POP and halibut in the Gulf of Alaska, which had relatively strong 1958 and 1959 year classes compared with stocks of these species further south off Canada. Stocks at the southern end of their geographical range tended to have relatively poor recruitment of the 1958 and 1959 year classes; these include halibut, Dover sole, POP, English sole, rock sole and cod from Oregon to Canada. Either adults from these stocks spawned north of their normal range, or egg and larval survival was poor in their normal resident habitats. Most of the above stocks, possibly excluding Dover sole, have fairly narrow temperature and salinity tolerance for survival of eggs and larvae.

Data for herring tend to conform to the above pattern. Most herring stocks off Canada exhibited unusually strong year classes in 1958 or 1959, and strong 1958 and 1959 year classes of herring also appeared in the Gulf of Alaska. Favorite and McLain (1973) related these strong year classes in the Gulf to warm water conditions. The 1958 year class of herring in the eastern Bering Sea also was the strongest in a 21 year time series (Wespestad 1982). At the southern end of the range of herring, off central California, catches declined markedly during the early 1960's (Spratt 1981) indicating that recruitment failures probably resulted from the 1958-59 El Nino and later warming which occurred through 1961. Preliminary evidence (J. Spratt, Calif. Dept. Fish and Game, Monterey, CA, pers. comm.) indicates that the 1983 year class of herring in central California appears to be of moderate to weak strength, and 1984 may be a weak year class. Whereas the other species considered above may be relatively nomadic, spawning within water of certain characteristics, herring may exhibit some location-specific homing behavior (Blaxter and Hunter 1982). Since herring eggs and larvae are eurythermal, direct temperature impact on these stages may not have been the critical factor.

Some preliminary data from research surveys for juvenile fishes of several stocks are available to examine the effects of the 1982-83 El Nino. These data indicate that the 1983 and 1984 year classes of sardine and Jack mackerel are strong but the 1983 and 1984 year classes of Pacific mackerel and 1983 year class of anchovy are moderate to poor (Mais 1983a, 1983b). Data from these same surveys indicate that the 1983 El Nino resulted in a year class failure for hake. Hayes (Northwest and Alaska Fisheries Center, Seattle, WA, pers. comm.) reported an unusually high abundance of juveniles of the 1983 year class of Pacific cod around Kodiak Island, Alaska. It still is too early to determine strengths of the 1983 year classes of groundfish stocks off Canada (A. Tyler, Pacific Biological Station, Nanaimo, B.C., pers. comm.).

Discussion

El Nino-like warming events appear to have significant effects on production of some fish stocks via effects on early life stages. Conditions that eggs and larvae encounter depend partly on the response of spawning adults to warming and other environmental changes. These responses range from adults being nomadic, either migrating with the advancing subtropical water mass or away from it, to adults being sedentary, releasing eggs or larvae into ambient conditions. Other variations on adult responses include homing adults, deep living adults that may not detect pelagic conditions that their larvae will encounter, and slowly migrating stocks.

The most important inluences of El Nino on early life stages are warming, altered food production and changes in transport regimes. We expect that the most significantly affected stocks are sedentary, homing or slowly migrating ones; nomadic stocks are able to search for better conditions (Sharp 1980). Some stocks, such as herring, seem able to overcome large natural changes in local conditions by their tolerance of changes in salinity and temperature, adaptations to living in an environmentally variable coastal zone. We speculate that populations of Dover sole and sablefish, reflecting their ubiquitous distributions, are also tolerant of changes in environmental conditions. However, like herring, they may be sensitive to altered food production.

El Nino events appear to have disastrous effects on recruitment of some stocks in some areas, especially those living near the southern end of their geographical range, such as cod off the Canadian coast. Cod eggs are stenothermal, and temperature increases of up to 4° C could be lethal. Cod eggs spawned in these waters may die, or alternatively, adult cod migrate northward into cooler water to spawn. Consequently, recruitment in southern areas would be low, but recruitment could be higher in newly colonized areas. As we noted earlier, the 1983 year class of cod around Kodiak Island appears to be strong. There also is some evidence for stronger year classes from El Nino years in northern stocks of halibut and Pacific Ocean perch.

Strong year classes of herring from several stocks off the Canadian coast, in the Gulf of Alaska, and in the Bering Sea resulted from the 1958-59 El Nino, whereas herring off the California coast seem to have experienced year class failures. Several alternative rationales exist. First, the 1958-59 El Nino off California resulted in drastically reduced zooplankton abundance there (Bernal and McGowan 1981). In contrast, northern areas, such as the Gulf of Alaska had high levels of zooplankton biomass in 1958-59 (Frost 1983). Thus, warm water combined with increased production in northern areas may have been beneficial to feeding and growth of larvae in the northern part of their range. Second, herring might have migrated northward to colonize more favorable nursery areas. Third, the normal migratory patterns of birds, some of which are important predators on herring eggs (Palsson 1984), may have been disrupted, resulting in lower predation pressure.

El Nino sometimes appears to be good for some subtropical stocks spawning at the northern end of their range, such as sardine and Jack mackerel off California during both 1958-59 and 1983 El Ninos. On the other hand, El Nino often, although not always, causes poor year classes in anchovy. This same pattern is sometimes observed in other areas of the world, for example, the 1972 El Nino resulted in recruitment failure of Peruvian anchovetta, but that year was highly successful for sardines (Csirke 1980). During that year sardine spawning expanded from the usual small area on the northern Peruvian coast to include the entire coast (Santander 1980). MacCall (1979) reported that the strong 1958 year class of sardine off California resulted from higher than average spawning by stocks normally living to the south. However, it appears that the 1983 El Nino resulted in recruitment failures for both anchovy and sardine off Peru (Anon. 1984). In contrast, there are preliminary indications that the 1983 year class of sardine off South Africa may be strong; however, warm events do not always result in strong year classes of sardines in the region (Shannon et al. 1984). Santander (1984) hypothesizes that El Nino is favorable for larvae of warm water and offshore species such as mackerels, and is less favorable for coastal species like anchovy.

Differences in recruitment strength of anchovy and sardine in the same year may result from subtle differences in the spawning response of adults to El Nino conditions or possibly from physiological requirements of larvae. For example, Smith (1981) states that the Northern anchovy can withstand colder temperatures than the Pacific sardine. MacCall (1983) commented that the anchovy/sardine species replacement off California probably was due to large scale environmental influences. This is somewhat consistent with long-term recruitment patterns for sardines in northern Japan. Kondo (1980) notes that the warm water year 1972 was a year of anomalously good recruitment for the Japanese sardine and also the mackerel. Off Japan, sardine spawn in a region of the warm Kuroshio current bordering the coastal water mass. Kondo hypothesized that in 1972, larval sardines were able to colonize favorable inshore nursery areas because the Kuroshio meandered northward and close to the coast of Honshu. Conversely, he says that the collapse of the sardine occurred in the 1940's probably was because the Kuroshio was far offshore, and the colder Oyashio intruded into the coastal areas. In these years sardine spawned offshore and larvae starved under poor feeding conditions.

Representative of stock responses to environmental anomalies are examples from the eastern North Atlantic, similar to the responses we have noted off our own coast. These examples are from Cushing (1975, 1982), and include observations that, in the North Sea, recruitment of gadids, herring, and plaice, all at the southern end of their range, increased during cooling periods and declined during warming periods. However, in the colder waters off Iceland, strong year classes of cod (at the northern end of its range) appeared during warm years, as did strong year classes of cod and herring in Norway. Pilchards (sardines), at the northern end of their range in the North Sea, increased during warming years around Britain, and mackerels declined during cooling years.

Environmental changes associated with El Nino have important consequences for regional stocks; while for scientists El Nino provides a rare opportunity to observe response to an extremity in the range of environmental conditions experienced by marine fishes. Many authors have recently proposed conceptual models linking variability in recruitment to environmental conditions, including such conditions that occur during an El Nino event. For example, Cushing (1975, 1982) attributes recruitment variations to large-scale changes in the timing and magnitude of the production cycle. This is somewhat similar to Lasker's (1975) hypothesis that food abundance and quality, as influenced by environmental factors are critical to larval survival. Skud (1982) pointed out that stock abundance responds to changes in the physical environment, but interspecific interactions also need to be considered. The preceeding examples deal more with temporal interactions of environmental events and larval survival. Several other authors consider interactions on spatial scales. For example, Walsh (1978) proposed that changes in fish abundance during El Nino events and other transient climatic events are a result of spatial shifts in geographic patterns, or latitudinal ecotones, and that marine communities engaged in these shifts are responding to global oscillations in climate. On a smaller scale, Iles and Sinclair (1982) hypothesized that larval habitat size can restrict the size of stocks via survival of early stages. Parrish, et al. (1981) state that in the California Current, appropriate spawning habitat is limiting, and that the apparent dependence of spawning strategies upon regional transport characteristics suggest that variations in recruitment of many species in the California Current region result from surface drift anomalies.

In an insightful review, Sharp (1980) combines many of the above ideas in a conceptual model that includes spatial and temporal considerations. He hypothesizes that successful colonization (or recruitment) depends on availability of suitable larval habitat. Species restricted to reproducing in small home ranges are seriously affected if the larval habitat area ceases to be appropriate, whereas nomadic species have the advantage of colonizing areas quickly. When suitable larval habitat boundaries shift due to environmental conditions, either an increase or decrease in local population size subsequently occurs. Therefore, larval distribution as influenced by the oceanographic environment is the initial condition and is mediated by adult migrations or by planktonic transport of early life stages; successful larval colonization occurs as a result of temperature and properties of community structure and production within the habitat.

Sharp's (1980) model is consistent with observations of recruitment resulting from the 1958-59 El Nino, as noted in the preceeding discussion. In a warming event, areas can be opened up for colonization by nomadic subtropical stocks through an extension of their spawning range. This assumes that suitable larval habitat exists poleward of their normal range (cf. Walsh et al. 1980). Subarctic

Table 3. Partial list of fish and shellfish stocks currently monitored for populaton abundance by region.

California

- Sardine
- Anchovy
- Jack mackerel
- Pacific mackerel
- Herring
- Ling cod
- Chilipepper
- Boccacio
- Dungeness crab
- Shrimp

Washington-Oregon

- Hake
- Dover sole
- English sole
- Petrale sole
- Halibut
- Sablefish
- Herring
- Pacific Ocean perch
- Ling cod
- Yellowtail rockfish
- Canary rockfish
- Widow rockfish
- Dungeness crab
- Shrimp

Canada

- Herring
- Pacific cod
- Rock sole
- English sole
- Dover sole
- Petrale sole
- Halibut
- Pacific Ocean perch
- Ling cod
- Sablefish

Gulf of Alaska

- Pacific cod
- Halibut
- Pacific Ocean perch
- Flounder
- Sablefish
- Pollock
- Atka mackerel
- Herring
- King crab
- Shrimp

Bering Sea

- Pacific cod
- Pollock
- Pacific Ocean perch
- Halibut
- Herring
- Yellowfin sole
- King crab
- Tanner crab
- Shrimp

Oceanics

- Albacore
- Bluefin tuna
- Bonito
- Yellowtail tuna
- Skipjack tuna

stocks at the northern end of their range also benefit from warm conditions because of an increase in physiologically suitable larval habitat, which may include increased planktonic production. Stocks at the southern end of their range have reduced recruitment in those areas during warming. A test of this conceptual model of El Nino effects on fish recruitment will be possible as information on the 1983 year classes of fish stocks accumulate. For pelagic stocks the effects of the recent El Nino will be known within a few years; however, for most of the demersal species, indices of recruitment may not be available for 3-8 years. Nevertheless much more information should be available than ever before, with good information on recruitment now accruing for 58 stocks in the northeastern Pacific (Table 3).

Throughout all of the above discussion we have stressed events and conditions affecting adult spawning migrations and reproductive physiology as well as transport and survival of early life stages.

We emphasize these as initial conditions important in determining the potential for particularly large or small year classes. Subsequent processes, notably predatory and other losses of juveniles, can be expected to play occasionally important roles as interannually varying modifiers of year class strength.

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El Niño 1983 in the Southern California Bight

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Introduction and Background

The population sizes of pelagic organisms vary greatly in both time and space on a broad spectrum of scales. Many oceanographers and fishery biologists wish to understand the causes of these variations. It can be argued that much of the population variability is primarily of biological origin. Experimental and theoretical studies show that competitive contests can first favor one species, then another, with only small changes in environmental or model parameters. Predator-prey populations can be made to "cycle" in both experiments and models, disease epidemics can cause population crashes, and nutrient recycling within systems can be reallocated in a variety of ways, including stochastically. Finally man's activities such as overfishing can be evoked as a disturbance which affects the entire ecosystem.

On the other hand there is also general agreement that variations or heterogeneity in the physical environment can strongly influence carrying capacities. Everything from small-scale physical turbulence to global climatic shifts have been implicated in the regulation of populations.

I recognize the dangers of attempting to characterize a phenomenon so complex as natural population variability in simplistic ways, for such variations are, no doubt, due to multiple causes, some of which may be independent. But it is possible, by comparing population and physical time series, to ask, "To what degree are population trends and physical trends related in time and space?" and thereby, through statistical inference, get some appreciation for the role of physics in natural population biology. Of course lack of correlation could mean that the wrong physical parameters have been measured, or the wrong scales are being compared, or it could also mean that the state of the populations in question is chiefly influenced by biological rather than physical processes. Since this is the issue to be resolved, it is important that serious attention be paid to the choice of properties to be measured and the time-space scales on which to measure them. There are additional reasons for wishing to know the degree to which physical changes affect populations or communities. Such changes may perturb the organization of the biological system in such a way that diversity may be enhanced or even induce a new set of dominance relationships between populations (Holling, 1973).

Populations of marine organisms generally have spatially extensive ranges, but within these there are large variations in abundance in localized areas or patches (Haury et al., 1978). Locally there may be rapid growth, declines or even extinctions. While what happens at these individual locales may be interesting, it is not necessarily indicative of what is happening to the entire population on the larger scale. One can therefore be misled in attempting to compare the results of a local (and often short-term) set of measurements to a larger-scale phenomenon such as El Niño. Therefore even to describe population variability on something near the "correct" scales, one should have a large, space-averaged, time series of measurements to account for the problem introduced by patchiness where such patches may be out of phase with one another. Such a series is essential if the amplitude of the population event is to be measured. This is generally expressed as a departure from, or an "anomaly" of, the long-term mean. Further the frequency of the anomalies should be estimated if we wish to compare them to environmental or climatic events which themselves have characteristic frequencies and amplitudes. Both of these objectives require temporally extensive sets of measurements.

Biologists seldom have such measurement programs or data available. The large-scale population estimates from commercial fisheries catches can be and have been used in this way (Cushing, 1982), but the results are always equivocal because the response of fish populations to disturbances or perturbations is slow due to their long generation times and because man's interference, i.e. the catch itself, is frequently a large, added source of mortality that may obscure natural processes. Of the few appropriate time series programs, the California Cooperative Fisheries Investigations in the California Current has provided a data set which can be used for the study of the effects of the 1983 El Niño on the plankton of the Pacific coast of North America.

This time series of zooplankton, temperature, salinity and oxygen began in 1949 and covered a large spatial domain at monthly intervals until 1961, at which time the sampling frequency was reduced to quarterly intervals. In 1969 the plan reverted to one of semimonthly coverage, but only every third year (fig. 1). In spite of the changes in sampling frequency (due mainly to financial constraints), the program has provided a time series for the study of low-frequency biological events, as indicated by macrozooplankton, and physical events as indicated by temperature, salinity and the parameters that can be derived from them.

The data have been analyzed in this way (Bernal, 1979; Chelton, 1981; Bernal and McGowan, 1981; Chelton et al., 1982), and it is evident that there are large-scale, low-frequency biological and physical variations which are spatially coherent over the entire

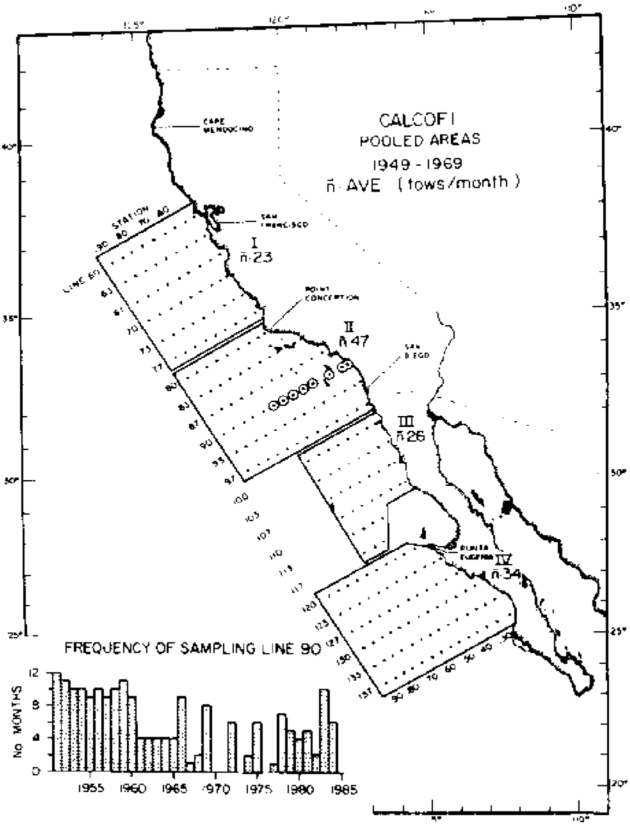

Figure 1. The California Cooperative Fisheries Investigations' sampling scheme showing the most frequently sampled stations in the four major subdivisions of the area. The Southern California bight is within Area II and the circled station positions on line 90 are those used in this study. The inset shows the number of months in a year that measurements were made at these stations from 1951 to 1984.

current system. These biological and physical anomalies from the long-term mean are highly intercorrelated in the low-frequency part of the spectrum. Further, the spectrum appears to be very red, that is, the low-frequency variability (and variance) is large (Bernal, 1979). One of the outstanding features of this time series is the very large anomalies in all properties from mid-1957 through 1959: the "years of warming" which coincided with a major equatorial El Niño (fig. 2).

The salient features of that event in California were: a significant rise in sea level, anomalously high SST over large areas, a depression of the thermocline, a vast reduction in macrozooplankton abundance and, nearshore, the widespread occurrence of some nekton, normally found well to the south, off central Mexico (viz., Red Crabs, Pleuroncodes planipus) (Sette and Isaacs, 1960).

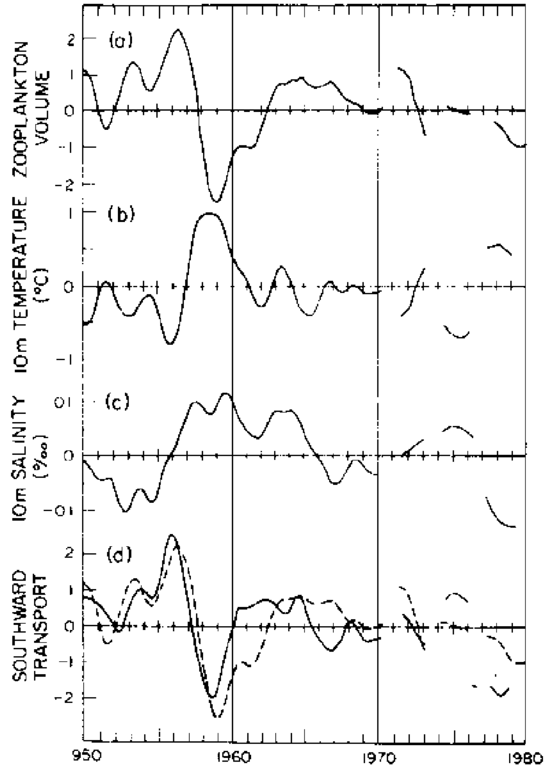

Figure 2. Low-frequency, nonseasonal departures from the long-term (1950-1980) mean of temperature, salinity, zooplankton biomass and southward transport, over areas I, II, III, and IV, from Chelton, Bernal and McGowan (1982). The dashed line is zooplankton biomass (a) repeated. The graphs show that anomalously warm, high-salinity water was present during the 1958-1959 El Niño. There was also greatly decreased southward transport and during this time there was much smaller zooplankton biomass.

In the autumn of 1982 it was evident that monthly mean sea level at San Diego had increased significantly above the long-term mean (Fig. 3), that there were "blobs" of water offshore where SST was well above the long-term mean (fig. 4) and there was a very large El Niño developing along the equator. In the next few months, sea level continued to increase, the blobs began coalescing into larger blobs (fig. 5), the equatorial El Niño intensified and pelagic "red crabs," tuna, marlin and other warm-water fish, normally found far to the south, began appearing nearshore off southern California. In spite of all of these early warnings which so resembled the 1957-59 California El Niño, it wasn't until March of 1983 that we managed to schedule a ship, obtain funds and recruit help to study the rapidly developing event.

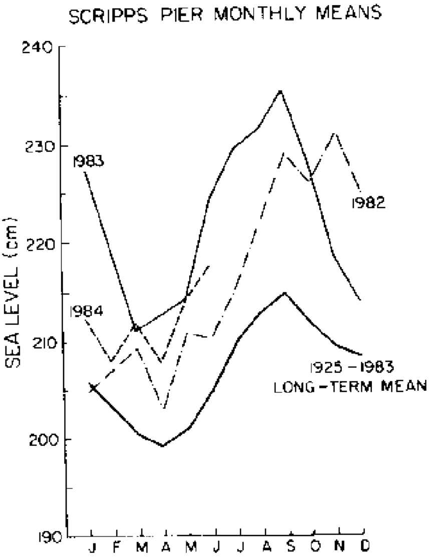

Figure 3. Sea level at Scripps pier. The 1982 and especially 1983 sea level was much higher than the long-term mean. Sea levels at Scripps pier are correlated with offshore steric heights, indicating a much reduced southward component to the transport within the bight in 1983.

Our tactics were to make a series of measurements on a line of stations which had been very frequently occupied during the previous 30 years (line 90, station 90.28 to 90.65, fig. 1). We measured the same properties (T, S, O_2, macrozooplankton), in the same way as in the time series but added a suite of nutrients (NO_3, NO_2, PO_4, SiO_3), chlorophyll a, and "phaeophytin" to the routine. Other additional measurements such as net phytoplankton were also done on some stations.

However, the question arises as to the degree to which measurements taken at these nine locales are representative of the larger system. The mean zooplankton volume (all months, n=140) from stations 90.28 through 90.65 (n=9) is 191.2 ml/1000 m^3, while that of Area 11 (fig. 1) is 205.9 (n=140, mean stations per month, n=47). The correlation coefficient, 0.86, is highly significant (fig. 6). Thus, in this case, the mean zooplankton abundance on line 90 (stas. 90.28 through 90.65) and the month-to-month variations in that mean are good indices of zooplankton variability throughout the Southern California "Bight" (Area 11). No such comparisons have been done for the other properties, but there are good reasons to assume that variables such as T, S, and nutricline depth are much more spatially coherent (i.e. less patchy) than zooplankton and therefore that our line 90 data are representative of a larger area. Ten-meter temperature anomalies from the mean on line 90 stations seem very similar in amplitude and frequency (by visual inspection) to those of the bight (Area 11) in general (CalCOFI Atlas No. 1, 1963; Chelton et al., 1982).

There have been 16 patterned CalCOFI cruises on which water column chlorophyll and nutrients have been measured as a matter of routine on line 90. These are too few to "establish" a long-term mean from which creditable anomalies may be derived analyzed and compared to

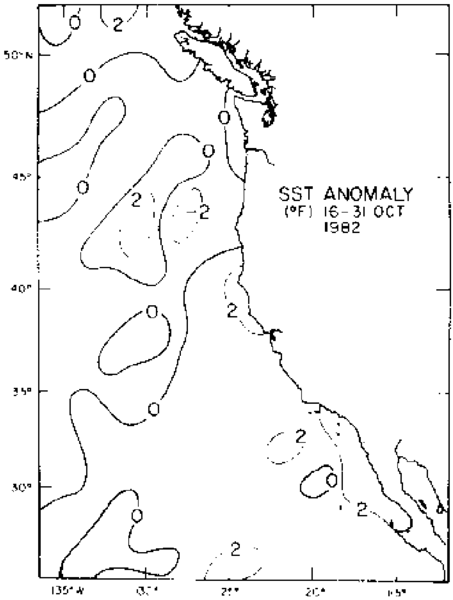

Figure 4. Sea surface temperature anomalies (in °F) for 16 to 31 Oct. 1982 showing patches or blobs of anomalously warm (by 2°F) surface water, both nearshore and offshore.

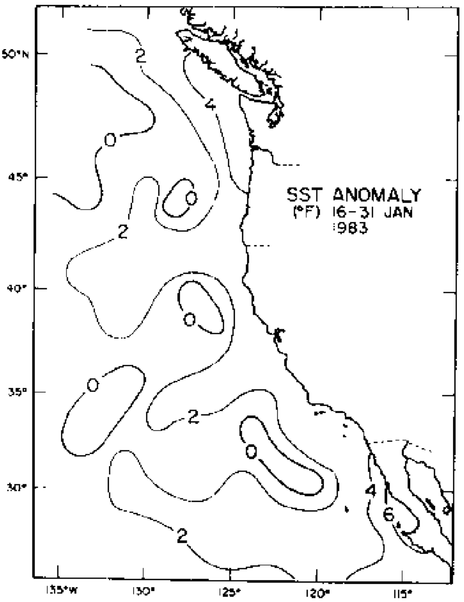

Figure 5. Sea surface temperature anomalies for the second half of Jan. 1983, three months after Fig. 4. Much of the California Current surface water is now anomalously warm by 2°F, and nearshore in the south and north +4° or even +6° anomalies were present.

those of other properties. However, since these are the only background, non-El Niño data available, they will serve as the "historical" basis for chlorophyll and nutrient averages to which our El Niño data is compared. We do not, of course, know, nor can we now determine the degree to which variations in integrated water column chlorophyll concentration or nutrient patterns, as measured on line 90, are indicative of the rest of the bight. There are strong reasons to believe, from remote-sensing studies, that in normal years part of this area has generally lower "surface" chlorophyll concentrations than more offshore areas, but the entire southern California sector of the California Current is quite heterogeneous and on a broad spectrum of scales (Peláez-Hudlet, 1984).

The following is a summary description of events in the California Current during the spring, fall and early winter of 1983 as determined by data collected at nine stations on CalCOFI line 90. It is not the full story of the present El Niño because at the time of writing the bio-physical system has not yet returned to its "normal"

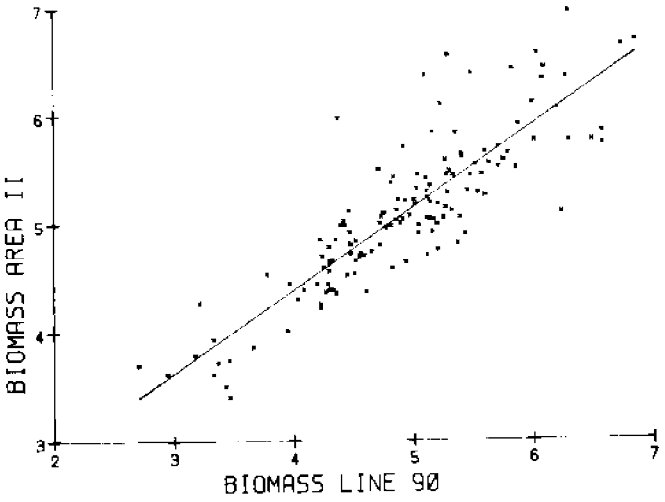

Figure 6. The mean monthly biomass from stations 90.28 through 90.65 (n=9) from the years 1950 through 1983 as a function of the mean monthly biomass of Area II (as shown in Fig. 1). The regression line departs significantly from a slope of zero. Units on axes are natural logarithms of the biomass in ml/1000 m^3.

state. A more complete description including a relaxation phase is necessary before an analysis of this great natural ecological experiment can yield substantial insight into how a perturbation of this kind affects the state of the biological system and how, and if the system returns to its former state.

Findings

By early March of 1983 sea surface temperature (SST) in the Southern California bight was systematically well above the long-term seasonal mean, especially nearshore (fig. 7). But this warming was even more spectacular in the subsurface waters where anomalies of 4°C occurred at depths of 50 m or more (fig. 7). The normal thermocline was depressed, and the nearshore (but not offshore) T-S curves departed very much from normal (fig. 8). By late March the thermocline was depressed along the entire section from the coast seaward 300 km (and no doubt farther) with 4°C anomalies at 70 m offshore, a core of water 8 to 10 standard deviations above the mean at depths of more than 100 m (fig. 9). By now the T-S curves departed from normal almost everywhere, and it seemed evident that the area was flooded with a large intrusion of anomalously warm but anomalously fresh water, i.e., there were significant negative salinity anomalies both offshore and nearshore (fig. 10). Simpson (1984) has attributed these changes in structure to a displacement shoreward of low-salinity water masses more typically found 600 km or so offshore. While this does explain the deepened thermocline and negative salinity anomaly, this offshore water is thought to originate from the Subarctic or Transition Zone (Sverdrup et al., 1942; Dodimead et al., 1963; Reid et al., 1958). If so, then those

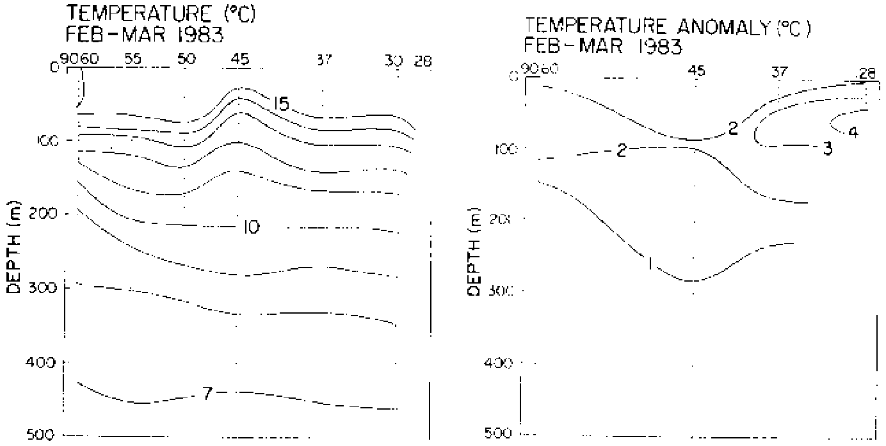

Figure 7. Feb.-Mar. 1983 temperature section and anomalies from the 30-yr mean for the season. The thermocline, especially near-shore, is much deeper than normal.

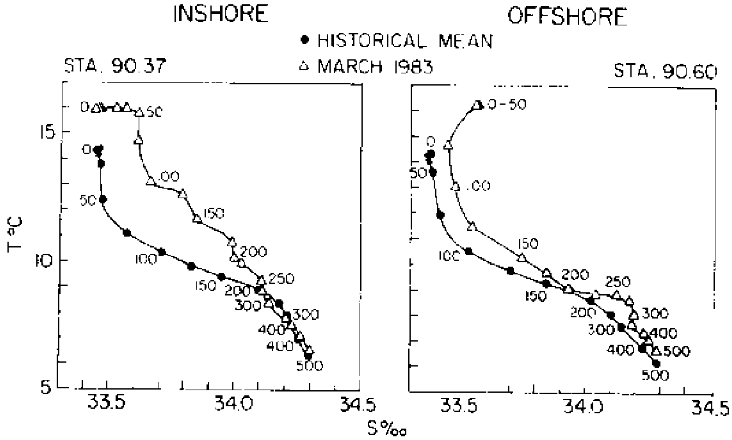

Figure 8. Nearshore (90.37) and offshore (90.60) T-S diagrams from Feb.-Mar. data as compared to the historical (30-yr) mean.

areas must have been anomalously warm as well. This strongly implies that El Niño '83- is very different from El Niño '57-'59, because during that event both temperatures and salinities were anomalously high (fig. 2).

Although these physical changes were very clear and large, the biological response, at this time, was quite modest. The departures from the historical norms in the shape and depth of the nutricline, chlorophyll and phaeophytin maxima were not great and probably not significant. The spring nutricline normally is at depths of about

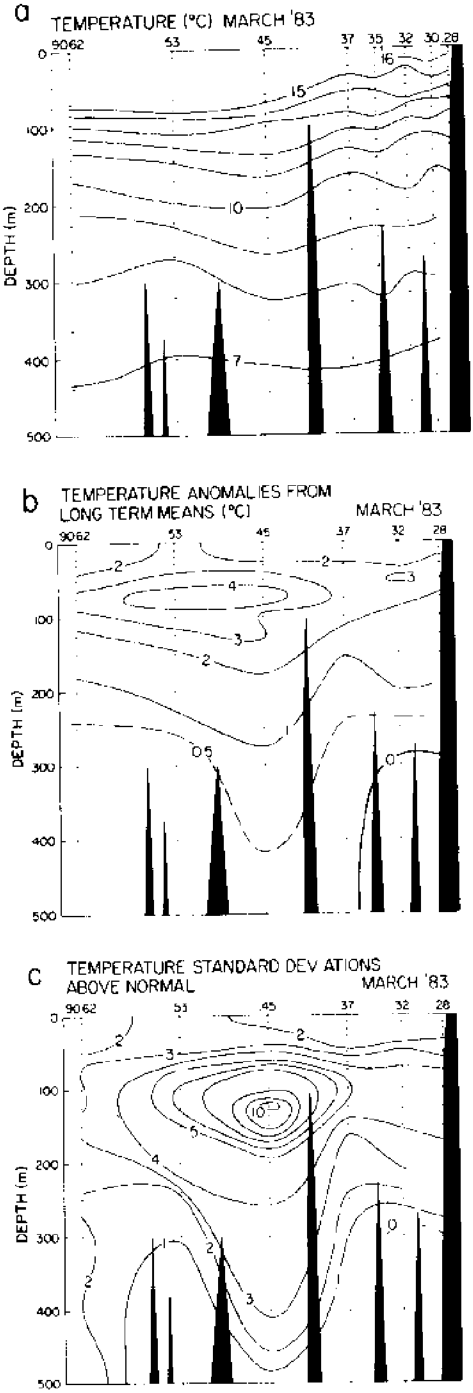

Figure 9a. Temperature (°C) section, line 90 for 17-19 Mar. 1983.
9b. Temperature anomalies (°C) line 90 based on a 30-year mean.
9c. Standard deviations of temperature from the long-term mean. Data as in a and b.

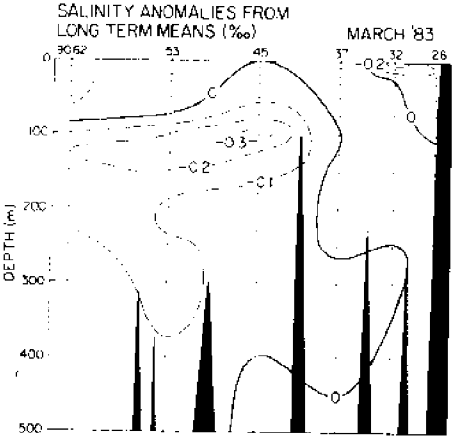

Figure 10. Salinity anomalies (‰) for line 90, Mar. 1983 based on 30-year mean.

50 m in the offshore sector and tilts upward to depths of less than 20 m very nearshore. But in March-April 1983 it had deepened considerably (>80 m) offshore while still retaining an onshore upward slope (fig. 11). In spite of this structural change, plant abundance was not greatly altered.

Spring chlorophyll in the upper layers (<30 m) is normally high very near the coast and there is a strong secondary offshore maximum (fig. 12 and Peláez-Hudlet, 1984). In March-April of 1983 the nearshore pattern was normal, but offshore (>90 km) the offshore maximum had all but disappeared.

The long-term (1949-1984) series of macrozooplankton data from line 90 shows that a clear seasonal increase does not begin until April but is quite strong by May (fig. 13). Presumably such a "bloom" of macrozooplankton (>500 μm) would depend on the primary productivity of the previous few months. Zooplankton biomass for 1983 was well below the long-term monthly means for the area and significantly less than the long-term monthly medians (fig. 13). While the non-seasonal anomalies were negative, they were not the lowest values recorded for the spring months.

Thus although the spring physical signals were strongly indicative of rather large changes which appeared to be due to intrusions of structurally different water masses, the biological response, while evident, was not great. This, however, changed dramatically by late summer.

By August 1983 there was a very strong biological signal. The nutricline was quite deep everywhere and sloped downward from a depth of 75 m nearshore in a very unusual pattern as compared to that of previous years (fig. 14). The spatial patterns and characteristic large-scale features of plant biomass were very different from those of the more normal years. The expected summer pattern, based on about 20 spatially extensive sampling grids (CalCOFI

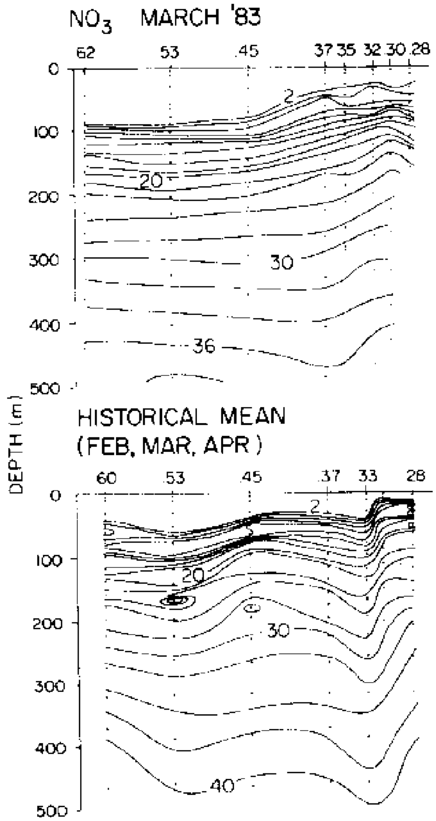

Figure 11. Nitrate concentration in mg-at/m^3 in Mar. 1983 as compared to the historical spring mean.

cruises) and an extensive satellite, remote-sensing study (Peláez-Hudlet, 1984; Guan et al., 1985), is the presence of a narrow band very nearshore, high in surface chlorophyll, typically about 1 to 2 mg/m^3 and 10 to 15 km in width, a second zone about 100 km wide with low surface values of about 0.25 to 0.5 mg/m^3 and then a broad offshore maximum about 100 km wide with surface values similar to those of the narrow, coastal strip. Beneath this coastal, surface feature is a wider, subsurface maximum. The broad offshore surface feature has a subsurface secondary maximum. Both the surface and subsurface maxima are spatially separated by an oligotrophic zone (fig. 15). During the summer of 1983 this picture was greatly altered. Surface values of chlorophyll were very low everywhere ($\leq$0.16 mg/m^3) on line 90, but the subsurface maximum persisted. This maximum, however, was deeper than normal and coincided with the top of the nutricline. Judging from our monthly series of measurements, this transition from the early spring (March) situation to that of midsummer (August) was not gradual but happened rather suddenly sometime in July. Thus the broad offshore band that occupies most of the photic zone and is so evident in both maps and satellite pictures from normal years disappeared in the summer of 1983 and was replaced by a deep, subsurface maximum that extended

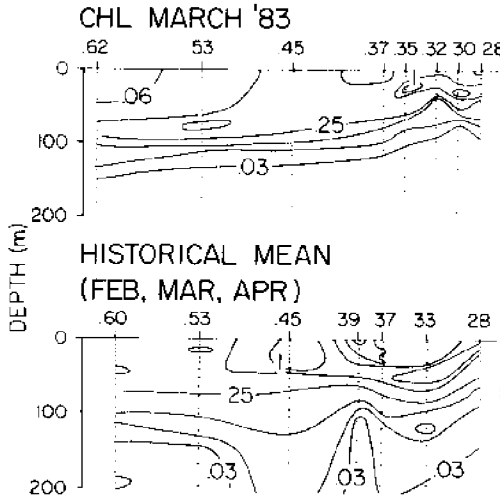

Figure 12. Chlorophyll (mg/m^3) for line 90, Mar. 1983 as compared to the historical spring mean.

over most of the section. This situation persisted until (at least) December 1983 (fig. 16). This biolobical "response" lagged far behind the original physical signals but developed rapidly once some critical point was reached.

By midsummer the macrozooplankton biomass was greatly reduced. There was a depression of the normal summer bloom (fig. 13) and the offshore maximum (Bernal and McGowan, 1982), that coincides so well with the offshore chlorophyll high, was totally missing (fig. 17).

By late summer the pycnocline and nutricline depth, gradient and slope became "stuck" in the August position, and the chlorophyll and zooplankton patterns followed suit. There were very few changes in any of these properties for the next four months, a season when we normally expect a shift to winter conditions.

Discussion

This is a brief account of the onset of El Niño in the Southern California bight as observed from a single, rather short, line of stations. Although we have evidence that variations in properties measured at these stations are representative of a much larger area, the lack of greater spatial coverage is clearly a disadvantage. We do not, of course, have much evidence for the coherence of our line 90 data with the California Current north of Pt. Conception or south of Pta. Descanso, Baja California. But it is clear from a large number of sources that this El Niño was widespread along the entire Pacific coast of North America, that it had a very large spatial component.

Beginning in January of 1984 seven spatially extensive CalCOFI cruises (SIO Refs. 84-18, 84-23, 84-25, 84-30, 1984; SIO Ref. 85-1, 1985) were done, and in 1985 a new quarterly time series on lines

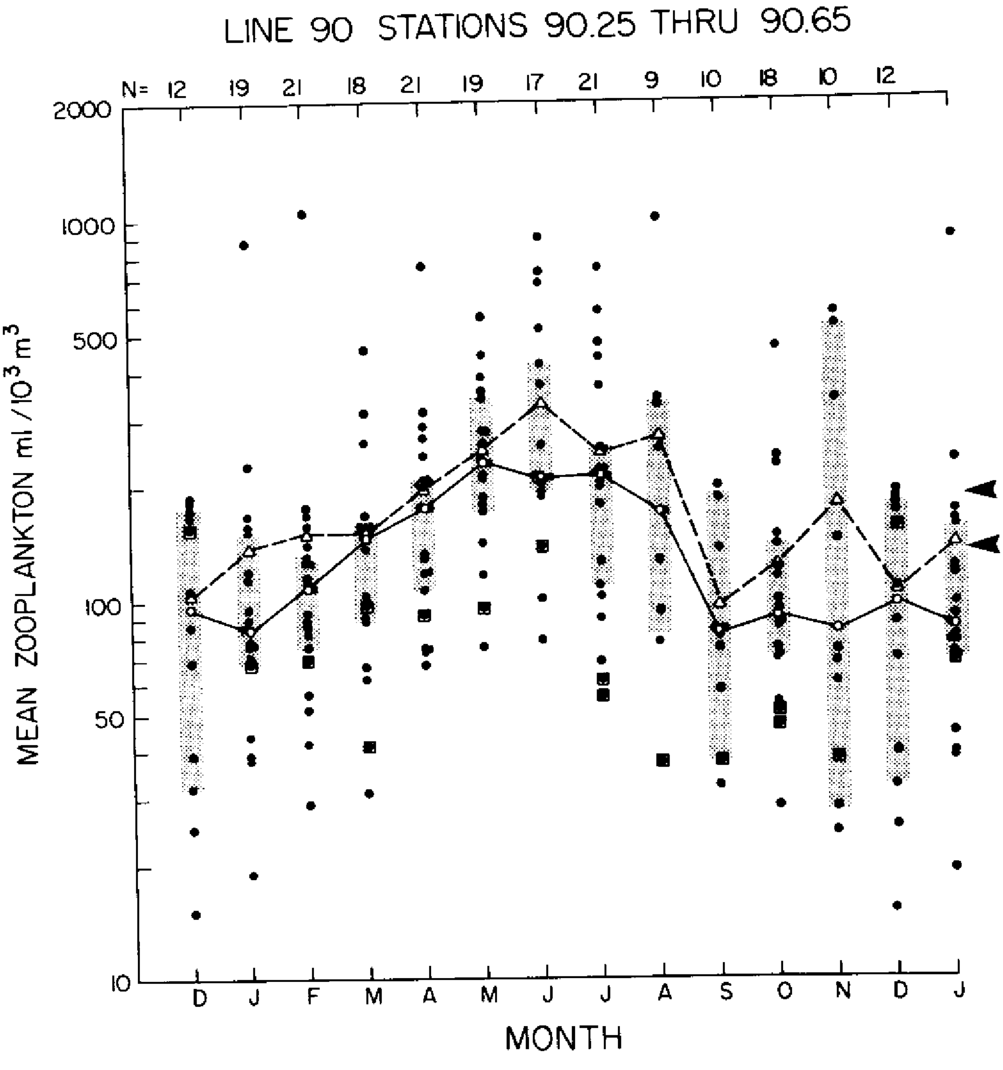

Figure 13. The long-term (1950-1984) seasonal abundance of macrozooplankton averaged over line 90 (90.25 to 90.65) in ml/1000 m^3. Each point represents the mean of five to nine stations on line 90 in a particular year. The solid line connects the monthly medians (open circles). The dashed line connects the monthly means (open triangles). Arrows point to the overall median (132) and mean (186). The 1983 and 1984 data are marked by squares. Vertical bars show the 95% confidence limits of the median.

77, 80, 83, 87, 90, and 93 was begun. These cruises should provide the data necessary to describe the relaxation phase of El Niño and a return to normal conditions in the California Current. Taken together with the 1983 results, described here, we should have a set of data and samples which will allow an analysis of the effects

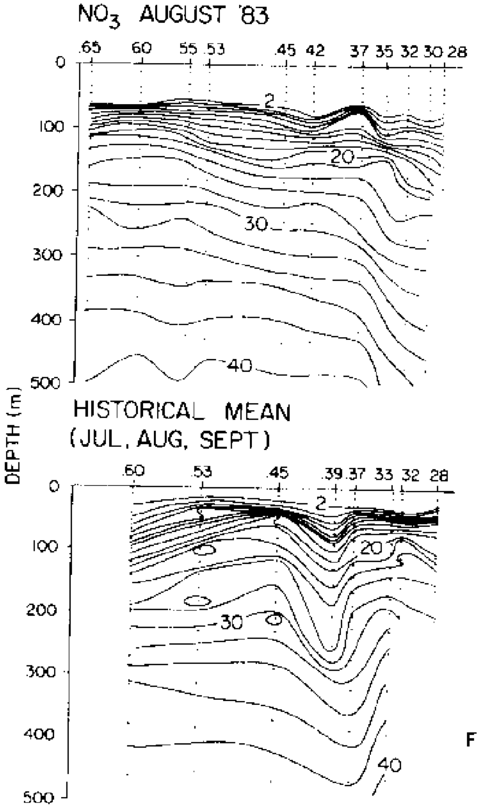

Figure 14. Nitrate concentrations mg-at/m along line 90 in Aug. 1983 as compared to the historical summer mean.

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of a major perturbation on a large, complex but well known (or at least well measured) pelagic ecosystem. Episodic "perturbations" are thought to be one of the main organizing forces for ecosystems (Holling, 1973; May, 1976; Paine and Levin, 1981), but there is very little observational information on this subject or even speculation on the magnitude and direction of perturbation necessary to cause a reorganization or reorientation of the system. The 1984 and 1985 data have not as yet been analyzed to the degree necessary for use in such a study but should be helpful in testing these theoretical expectations.

The main attributes of El Niño 1983 were a pronounced deepening of the thermocline, the timing of which differed inshore and offshore, accompanied by (or preceded by) a significant warming of the mixed layer. While it is tempting to attribute this to an intensification of water transport from the south, the presence of water of anomalously low salinity throughout our section, and presumably the entire bight, argues against this. Simpson (1984) has suggested that this relatively fresh water nearshore indicates an onshore intrusion of the offshore California Current low-salinity "core." One might have expected to see the larger nutrient loads and plant

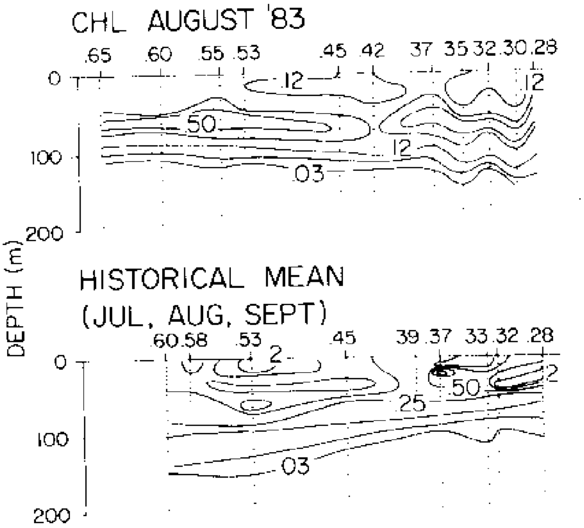

Figure 15. Chlorophyll concentrations (mg/m^3) along line 90 in Aug. 1983 as compared to the historical summer mean.

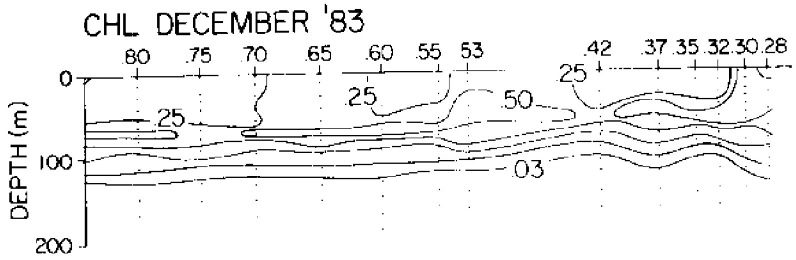

Figure 16. Chlorophyll concentration (mg/m^3) along line 90 in Dec. 1983.

and animal biomass normally associated with such water (Bernal and McGowan, 1981; Chelton et al., 1982). However, this did not occur; instead, all nutrient concentrations were extremely low in the euphotic zone, the plant biomass was spatially redistributed and zooplankton biomass reached record lows for the 30-year history of measurement. If intrusions, transport and/or advection of waters normally found well to the south or west was responsible for these changes, then their flora and fauna, especially their plankton, should give us some hint of this, since southern water and western water do differ in species list and relative abundances. If, on the other hand, the west coast El Niño was primarily an *in situ* phenomenon (i.e. local heat exchange problem), then we should expect little or no change in the planktonic biota. The local indigenous species may have decreased, increased, changed dominance structure or undergone other *in situ* changes due entirely to

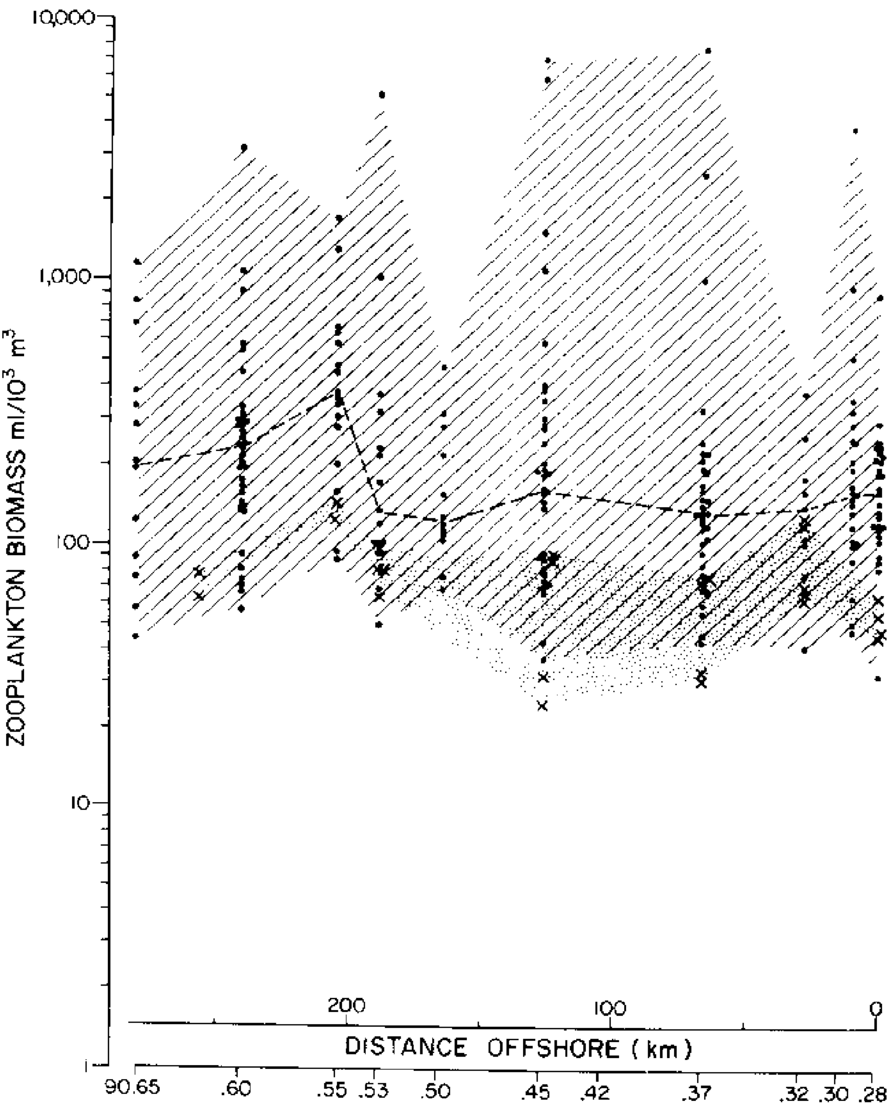

Figure 17a. Zooplankton biomass vs distance offshore along line 90. All samples taken in years 1949-1969 (not including 1957-1959 El Niño) in the months March, April, May are shown. Data from 1983 are shown as x and their range stippled. The dashed line connects the station medians.

local forcing. On the other hand, intrusions of exotic water from the south or west should bring planktonic flora and fauna which are also exotic. The invasions of the bight by tuna, marlin and other warm-water fish are uncertain indicators of such water movement

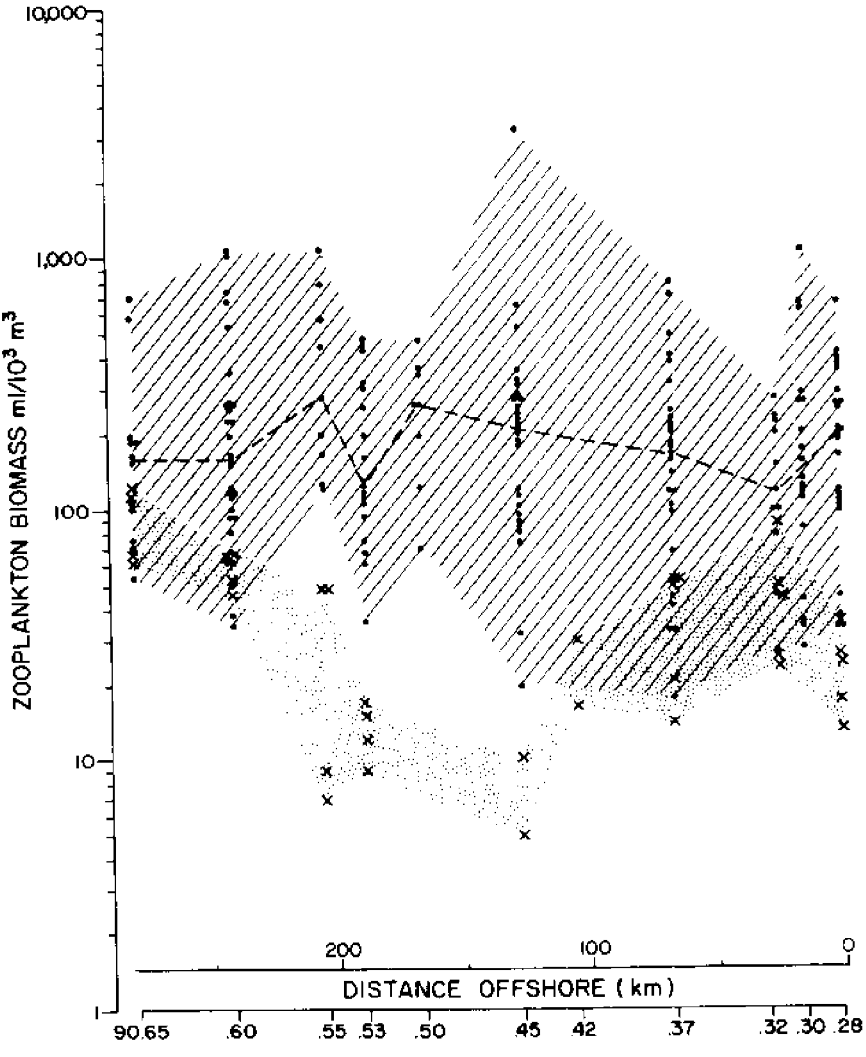

Figure 17b. As in a for July, August, September.

because of the great mobility and relatively sophisticated behavior of these and other nekton.

Since Sector II of the California Current normally has a mixed fauna with northern, southern and western species present, the determination of an intrusion by use of indicator species will depend on our ability to detect a significant change in proportions. Although this may be difficult, it is an important point. The issues are twofold: whether or not there was an intrusion, and whether the disturbance or perturbation forced a change in local biological "state variables" (Holling, 1973) or merely represents a shift in biogeographical species boundaries that might accompany an intrusion.

Acknowledgments

This study was supported by the Marine Life Research Group of the Scripps Institution of Oceanography, and by rapid-response grants from the Office of Naval Research and Sea Grant. I am very grateful to Mr. Walt Bryan, who was chief scientist on all of the 1983 cruises, and to Mr. Arnold Mantyla, who processed the physical data so rapidly and who prepared all of the vertical sections of temperature, salinity and their anomalies. Mrs. P. Walker provided the analysis and charts of long-term zooplankton abundance and its variability.

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Response of the Zooplankton and Ichthyoplankton Off Oregon to the El Niño Event of 1983

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Richard D. Brodeur, and William G. Pearcy
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Well before our first observations in April 1983, a thick lens of warmer than usual water lay over the Oregon shelf and slope out more than 100 nautical miles. This was a northern manifestation of the El Nino of 1982-1983, as reported in this volume generally. In response to the event we undertook some zooplankton sampling from a 35 foot boat at a traditional set of stations: 1, 3, 5, and 10 nautical miles from shore at Newport. We did CTD lowerings, 5-depth chlorophyll casts, and two net tows. Tows were oblique from near the bottom to the surface at each station with 1) a 1/4 m square net of 202 um mesh, and 2) a 70 cm ring net of 333 um mesh.

While there were some upwelling-favorable winds during 1983, they did not dig through the lens of warm water, except for a single event in mid-August. Typical summer sea surface temperatures in this most inshore zone off Oregon are 7 to 11°C, and isotherms usually tilt sharply upward. In 1983 temperatures were consistently above 12°C, and they went to almost 18°C in July. Isotherms lay almost flat across the inner shelf throughout the season, except in the brief August upwelling.

When there is strong upwelling over the Oregon shelf, the peak of chlorophyll concentration is located at the surface and is displaced offshore of 10 km, the usual location of the "upwelling front". When it is not upwelling, there is usually a subsurface chlorophyll maximum at 10 to 25 m depth extending right to shore. In 1983 the non-upwelling pattern of chlorophyll distribution was found throughout the summer, except for the few days in August when some upwelling did occur. On that occasion there was a remarkably rapid shift of the plant pigment distribution to the upwelling pattern.

Zooplankton of the Oregon shelf shift in a regular way with the changing seasons. Californian forms appear in fall, carried north by the Davidson Current, and they persist as the dominants through the winter. They are replaced by northern species after the spring transition to north winds and southward flow. Copepods dominate the assemblages of all seasons. The southern representatives in usual order of importance are *Ctenocalanus vanus*, *Paracalanus parvus*, several species of *Clausocalanus*, and a long list of others. Northern species are *Pseudocalanus* sp., *Acartia clausi*, *Acartia longiremis*, and *Centropages abdominalis*. Typically the winter species disappear altogether during the summer.

During 1983 the overall density of zooplankton over the shelf in spring and summer was low, about 30% of that in non-El Nino years. Usual water column averages for abundance of all copepods are 10^4 to 10^5 per cubic meter. In 1983 they stayed close to the lower figure. In April of 1983 at both inshore (1 n.mi.) and offshore stations (10 n.mi.) the fauna was dominated by southern species. This is typical of all Aprils. By May we expect some transition to northern species, but in May 1983 it did not happen to any significant degree. In June there was a partial transition to the usual summer fauna, but the winter species, particularly *Paracalanus parvus* were still abundantly present, and they were numerically dominant inshore. This southern species remained the dominant form through July, but it shared prominence with another southern form, *Acartia tonsa*. *Acartia tonsa* is carried into the Oregon area in occasional winters, and in some summers, including 1983, it develops a large local stock. It had also done so in 1969, which was not a particularly warm year and had about average upwelling intensity. Population density of *Acartia tonsa* was a record high in 1983.

A more typical summer zooplankton dominated by *Pseudocalanus* sp. developed during August 1983 at the offshore end of the transect. However, southern species continued to do very well at the inshore stations with dominance by *P. parvus* and *A. tonsa*. In addition there was an unusually great density of *Noctiluca* sp. during August. This large, predatory dinoflagellate appears in September and October of most years in small numbers, although they can be an important faunal component in the coastal estuaries. Our sampling ended in mid-September, when there were huge numbers of *Noctiluca* sp. inshore, and the usual summer and usual winter copepods shared dominance both inshore and offshore. The prolonged persistence and recurring dominance of the zooplankton by winter species through the whole summer and into fall has not been seen before the El Nino year of 1983.

Our coarse mesh samples were examined for euphausiids and larval fish. There were many occurrences of *Nyctiphanes simplex*, previously recorded no farther north than central California. Late larval, juvenile, and adult stages all were present. The relative abundance of *Thysanoessa spinifera*, the usual dominant, neritic euphausiid off Oregon, was lower than in most years.

Richardson and Pearcy(1977, Fishery Bulletin 75: 125-145) have shown that there are inshore (inside 15 to 20 nm) and offshore (beyond 15 nm) groups among the fish larvae commonly found over the Oregon shelf. In 1983 the larvae found inshore belonged predominantly to the usual offshore group. In particular, there was very early and very heavy spawning of the Northern Anchovy, *Engraulis mordax*. Its eggs and small larvae were present in high numbers in April off Newport. Anchovy usually spawn in mid-August, and the bulk of them spawn offshore in the Columbia River plume. Almost certainly the warm conditions of 1983 triggered a much earlier spawning than is usual. Most inshore larval fish in most years are species of the family Osmeridae. Larvae of those species were virtually absent from stations along our transect.

Effects of the 1983 El Niño on Coastal Nekton Off Oregon and Washington

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Introduction

The 1982-83 El Nino event in the northeastern Pacific has been associated with significant changes in sea temperatures, vertical thermal structure, coastal currents and upwelling (this volume). Such physical changes may affect the species composition, abundance or availability of fishes and other nektonic animals in a variety of ways: e.g.,

1) passive advection of water and animals and active migration of nekton, resulting in changes in species composition;
2) changes in the vertical distribution of species in response to warm surface waters that result in low availability near the surface, movement offshore into deeper water, or modified migration patterns;
3) decreased productivity or availability of prey, and concomittant adverse effects on growth, reproduction or survival; and
4) changes in inshore-offshore environmental gradients and frontal structure that concentrate fishes in narrow bands where predation or competition may be intensified.

Such responses of nekton have been described off Peru during the 1982-83 El Nino event (Barber and Chavez, 1983). Similar effects either occurred or were anticipated along the west coast of North America. This paper evaluates possible effects of the recent El Nino on distributions and abundances of fishes and other nekton along the coast of Oregon and Washington. Our observations are based on collections of unusual animals, systematic purse seining and commercial landings.

Methods

Our observations came from several sources. In early 1983, we initiated "Fish Watch '83" to alert fishermen and residents along the coast to the possible occurrence of unusual animals in the coastal ocean and to encourage the collection, preservation and return of animals to university or state personnel. Publicity stimulated by this program, by the subsequent discoveries of rare animals, and by the El Nino event in general resulted in more reports than in previous years. The degree that this public awareness increased the number of reports, and hence biased our results, is unknown. However the news media publicity on El Nino subsided months after waning of the major physical effects, making 1984 a better "control" year than 1981 or 1982.

Our purse seining for juvenile salmonids during the summer months of 1979-1984 provided samples of nektonic animals in surface waters off Oregon and Washington. The purse seines were large (475-495 m long) and fished to a depth of 30 to 55 m. All seines had 32-mm (stretch) mesh. A summary of the number and location of the 843 round haul sets along inshore-offshore transects, from the 37-m contour to 46 km offshore, is given in Table 1. Only June cruises were completed off Oregon in 1979 and 1980. In subsequent years, three or four cruises were made in different months (see Pearcy, 1984). Cruises extended from Cape Flattery off northern Washington south to Yachats or Coos Bay, Oregon in 1982, 1983 and 1984. All nekton were identified and samples were preserved for species verification and laboratory analyses.

Data on the commercial landings were provided to the Oregon Department of Fish and Wildlife and the Pacific Fishery Management Council.

Table 1. Summary of sampling by cruise from 1979 to 1984. Number of sets includes only quantitative, round hauls taken within 56 km of the coast.

Year	Dates of Cruise	Latitudinal (°N) Range Sampled	Number of Sets
1979	June 18-29	46°20'-43°18'	49
1980	June 20-28	46°20'-44°30'	33
1981	May 16-25	46°35'-44°30'	63
	June 9-19	46°35'-43°11'	67
	July 9-19	46°35'-44°25'	71
	August 8-19	46°35'-43°11'	66
1982	May 19-June 2	48°20'-44°00'	62
	June 7-22	47°20'-44°20'	56
	Sept. 4-14	47°20'-44°20'	40
1983	May 16-27	48°20'-44°20'	57
	June 9-27	48°20'-43°00'	58
	Sept. 15-24	48°20'-43°28'	52
1984	June 6-20	48°20'-43°28'	66
	July 19-30	48°00'-44°00'	40
	Sept. 1-15	48°20'-44°00'	63

Results

Range extensions and rare species

Northern range extensions were reported by Fish Watch '83 for four species of fishes (Table 2). None of these species was previously known to occur north of California (Eschmeyer et al., 1983). The finescale triggerfish and California lizardfish were reported even farther to the north, to Willapa Bay and Puget Sound respectively, after they were collected in Oregon (Schroener and Fluharty, this volume). Not included in Table 2 are northern records of the mollusk the sea hare (Aplysia californica) taken off the Yaquina Bay jetty on October 14 and 19, 1983.

Four other species are listed in Table 2 as "rare occurrences" off Oregon. Although they have been reported in waters off or to the north of Oregon in previous years, these fishes are usually uncommon north of California (Eschmeyer et al., 1983).

Some of these occurrences (i.e., larval and juvenile California tonguefish, small California lizardfish and sea hare) were probably advected to the north by the intensified California Countercurrent (McLain, 1984; Huyer and Smith, in press) as pelagic eggs or larvae. With the exception of the yellowtail, none of these species listed in Table 2 is noted for long, swift migrations, and most are associated with the sea floor.

During 1983-84 about half of the animals reported to us were known from the ocean off Oregon, though sometimes uncommon near the coast (e.g., the brown cat shark Apristurus brunneus, smalleye squaretail Tetragonurus cuvieri, white croaker Genyonemus lineatus). With the exception of a pilotfish (Naucrates ductor) caught off Oregon during the summer of 1984 (C. E. Bond, pers. comm.), there were no reports of rare fishes later than January 1984 despite the continuing wide publicity that El Nino received in this year.

Purse seine catches

The rank order of abundances (ROA) of the 10 most common species in the purse seine catches for June 1979-1984 (Table 3) shows some interesting trends. Pacific mackerel (Scomber japonicus), followed by jack mackerel (Trachurus symmetricus), were the two most abundant species in 1983 and 1984. With the exception of 1982, when jack mackerel ranked 8th, neither species ranked in the top ten species caught during June of other years. Jack mackerel occurred in low numbers during August 1981, June and September 1982, and May and September 1983. Only two Pacific mackerel were captured, both in June 1982, on the nine cruises before 1983. Pacific mackerel were also common in May of 1983 when they ranked second in overall abundance, and a few were caught in September 1983.

Other species showed marked changes in ROA, 1979-84. The rank of spiny dogfish (Squalus acanthias) increased from ninth and tenth in 1979 and 1980 to third in 1983 and 1984. Loligo opalescens, the market squid, on the other hand, ranked first in abundance in purse

Table 2. Rare fishes reported in 1983-84 by Oregon State University's Fish Watch '83.

A. Northern Range Extensions SPECIES	SL-mm (or No.)	Date	Location	Lat. N, Long W	Depth of Capture (m)	Gear
Echinorhinus cookei Prickly shark	1365	Jan 22, '83	off Moolack Bch.	46°11'; 124°40'	439	otter t.
Synodus lucioceps California lizardfish	62	Apr 6, '83	off Moolack Bch.	44°42'; 124°04'	11	beam t.
	75	Jun 23, '83	off Newport	44°37'; 124°05'	9	beam t.
	167	Jan 14, '84	off Astoria	46°09'; 124°11'	73	shrimp t.
Pristigenys serrula Popeye catalufa	181,198	Apr 6, '83	off Newport	44°38'; 124°07'	40	otter t.
	203	Jan 15, '84	No. of Brookings	42°03'; 124°15'	52	otter t.
Balistes polyepis Finescale triggerfish	273	Sept 4, '83	off Yachats	44°19'; 124°07'	15	crabpot
	277	Dec 23, '83	No. of Coos Bay	43°31'; 124°17'	55	crabpot
B. Rare Occurrences						
Genyonemus lineatus White croaker	(1)	Apr 6, '83	off Moolack Bch.	44°42'; 124°04'	11	beam t.
	14	May 3, '83	off Moolack Bch.	44°41'; 124°02'	8	beam t.
Medialuna californiensis Halfmoon	210-247 (12)	Sept 17, '83	off Grays Hbr.	46°56'; 124°33'	0-40	purse s.
Seriola lalandi Yellowtail	(1)	Aug '83	off Port Orford	42°44'	0	troll
Symphurus atricauda California tonguefish	21	Mar 11, '83	Yaquina Bay	44°37'; 124°03'	Fl	beach s.
	27	Mar 22, '83	Yaquina Bay	44°37'; 124°03'	3	beam t.
	24,25	Apr 6, '83	Yaquina Bay	44°37'; 124°03'	3	beam t.
	57,64,85	Dec 13, '83	Yaquina Bay	44°37'; 124°02'	6	beam t.

Table 3. Rank order of abundance of nekton in purse seine catches during June cruises, 1979-1984.

1979	1980	1981	1982	1983	1984
LOLIGO	LOLIGO	LOLIGO	LOLIGO	PAC. MACK.	PAC. MACK.
COHO	SEBASTES	SEBASTES	COHO	JACK MACK.	JACK MACK.
SEBASTES	HERRING	COHO	HAKE	DOGFISH	DOGFISH
HERRING	COHO	SABLEFISH	DOGFISH	COHO	COHO
CHINOOK	ANCHOVY	DOGFISH	HERRING	ANCHOVY	LOLIGO
WOLFEEL	CHINOOK	ANCHOVY	CHINOOK	LOLIGO	CHINOOK
STEELHEAD	SAURY	CHINOOK	CHUM	HERRING	HERRING
CHUM	OSMERIDS	KELP GREENLING	JACK MACK.	CHINOOK	HAKE
DOGFISH	STEELHEAD	CHUM	SEBASTES	OSMERIDS	ANCHOVY
OSMERIDS	DOGFISH	STEELHEAD	SOCKEYE	SEBASTES	SEBASTES

seine catches in 1979, 1980, 1981 and 1982, but dropped to sixth and fifth in 1983 and 1984, respectively. Juvenile rockfishes (Sebastes spp.) also decreased in ROA during this period. They ranked second or third in 1979-81 and ninth or tenth in 1982-84.

The total numbers of several species caught in quantitative purse seine sets from all cruises 1981-1984 are shown in Table 4. (Note that the total number of collections is not equal, and catch per set was not estimated.) Pacific mackerel, the most common species in 1983 and 1984, were caught in larger numbers in 1984 than 1983. Jack mackerel were also more common in 1984 than 1983. The large catches of these two species of mackerel in 1984 after return to near-normal conditions are evidence for a shift in distribution of some species that persisted after the 1983 El Nino. Whether these nektonic fishes returned to Oregon-Washington waters after retreating to the south in the winter of 1983-84 or whether they stayed in waters off the Pacific Northwest is unknown. Squid fishermen off Oregon reported many schools of fishes on echosounders in the spring of 1983 that they believed were mackerel, suggesting that mackerel may have resided here through the winter.

Pacific butterfish (Peprilus simillimus), though not abundant, also appeared to be more common in 1983-84 than 1981-82. The Pacific sardine (Sardinops sagax) was caught twice, both in 1984. It was once abundant off Oregon, but in recent years the sardine has only been common from California southward.

Table 4. (A) Total numbers of some species of fishes in purse seine catches and (B) landings of some fishes in Oregon; 1981-1984.

	1981	1982	1983	1984
A. Total Caught (No. Sets)	(267)	(158)	(167)	(169)
Pacific mackerel	0	2	11,037	18,427
Jack mackerel	8	110	1,764	3,818
Pacific butterfish	0	1	7	12
Pacific sardine	0	0	0	5
Blue shark	14	4	9	9
Thresher shark	0	2	0	2
Ocean sunfish	3	5	7	13
Pacific saury	130	2	1194	240
Pacific whiting	155	1268	41	748
Juvenile Salmonids - June only				
Frequency of Occurrence (%)	69	75	48	75
Coho - Catch per set	8.8	15.7	3.9	3.2
B. Oregon Landings (pounds)				
Pacific bonito	0	0	1,462	0
Pacific and Jack mackerel	26	83	18,253	6,761
Skipjack tuna	0	290	18	0
Albacore ($x10^6$)	7.2	1.9	3.4	1.6

We received reports that species normally found in warm, offshore waters in the summer, such as the ocean sunfish (Mola mola), were common in inshore waters during the summer of 1983 (Schoener and Fluharty, this volume). We therefore expected these offshore species to be more numerous in our catches in the summer of 1983 in absence of cool, upwelled waters along the coast. With the exception of Pacific saury (Cololabis saira) which was taken in large numbers in 1983, such a trend was not apparent from our limited purse seine catches of other species. Ocean sunfish, thresher shark (Alopias vulpinus) and blue shark (Prionace glauca) showed no obvious increase in our catches in 1983.

Pacific whiting (Merluccius productus) were less common and occurred less frequently in purse seine catches in 1983 than other years. This species is commonly associated with waters at the edge of the continental shelf but intrudes into shallower, nearshore waters. It also migrates toward the surface at night. Warm surface waters may have restricted its shallow-water incursions and made them less available to our purse seining in the upper 50 m in 1983 than other years.

Purse seine catches of gelatinous zooplankton were noted in 1982 and 1983. Table 5 shows that the scyphomedusa *Aurelia aurita*, the salp *Thetys vagina* and the heteropod *Caranaria japonica* occurred more frequently in 1983 than 1982. Medusae such as *Chrysaora fuscesens* and *Aequorea victoria*, on the other hand, occurred more often in 1982 than 1983. Literally tons of these medusae were caught in purse seine sets before 1983 when dense concentrations occurred close to shore (Shenker, 1984).

Table 5. Comparison of purse seine catches of gelatinous macrozooplankton from 1982 and 1983. All data expressed as percent frequency of occurrence (J. Shenker, unpublished data).

Species	1982 (161 sets)	1983 (168 sets)
SCYPHOMEDUSAE		
Aurelia aurita	6.2	22.6
Chrysaora fuscesens	53.4	30.3
*Cyanea capillata/ Phacellophora camtschatica**	50.9	36.9
HYDROMEDUSAE		
Aequorea victoria	59.6	26.1
Other (mostly *Eutonina indicans* and *Vellela vellela*)	14.9	1.2
CTENOPHORA		
Beroe spp. and *Pleurobrachia* spp.	6.8	1.8
SALPIDAE		
Salpa fusiformis	7.4	---
Thetys vagina	---	30.9
HETEROPODA		
Caranaria japonica	---	8.9

*No distinction was made between these two species in the field.

Commercial landings

Data from commercial landings in Oregon also indicate distinct changes in the relative abundance or availability of some species (Table 4). No Pacific bonito (*Sarda chiliensis*) were reported in the landings of 1981 and 1982, but 663 kg (1,462 pounds) were landed in 1983. Mackerel, including both Pacific and jack mackerel, were much more numerous in 1983 than 1981 or 1982 landings. Mackerel were also common in 1984 landings. Albacore (*Thunnus* alalunga) were not landed in large numbers in Oregon in 1983 despite the warm water temperatures close to shore. High catches of albacore are known to occur along the offshore boundaries of thermal and color fronts or "edges" produced by coastal upwelling (Laurs et al., 1984). Because of the absence of cold upwelled water, such fronts were thought to be poorly developed in 1983. A few skipjack tuna (Euthynnus pelamis) were caught off Oregon in 1983. The larger landings in 1982 were presumably caught in warm waters far south of Oregon (L. Hreha, pers. comm.).

One species of rockfish, Sebastes rufus, appeared to increase in bottom trawl catches in 1983 compared to other years. This species comprised 2.3% of the weight of rockfish caught in bottom trawls from Cape Perpetua to Cape Blanco from April-December 1983 but was not reported in the catches in either 1981 and 1982. During April-July 1984 it comprised 0.1% of the catch compared to 3.0% for the same period in 1983, suggesting that it was most common in the 1983 El Nino year.

Salmon

Juvenile salmon. Juvenile salmon were less common in nearshore waters off Oregon and Washington during the summer of 1983 then previous summers. The frequency of occurrence of juvenile salmonids in purse seine catches was lower in June and September 1983 than any of the previous ten cruises, and the average catch per set of juvenile coho salmon, the most abundant species in our catches, was lower during June 1983 than during June 1981 or 1982 from Willapa Bay to Alsea Bay, but it was slightly higher than the average catch per set in June 1984 (Table 4; Pearcy, 1984). The average catch per set in September 1983 was the lowest found for any prior cruise, 1979-1982 (Table 5 in Pearcy, 1984).

Chung (1985) found higher purse seine catches of juvenile coho salmon farther inshore and to the north in June 1983, when upwelling was weak and sea surface temperatures were elevated, than in June 1982, when upwelling and offshore Ekman transport were more pronounced. Major differences in sea surface temperatures and surface chlorophyll concentrations are illustrated for June 1982 and 1983 in Figure 1. North-south distributions of juvenile coho in September 1982 resembled those of June 1983. In September 1983, catches were very low along the coasts of Oregon and Washington, except for the northern-most stations off Cape Flattery, Washington where large catches were made. Juvenile coho salmon occupied waters that were several degrees warmer in May and June of 1983 than 1982. The relationship between catch per set and temperature was similar, however, in September 1982 and 1983 (Chung, 1985).

The lower catches of juvenile coho in 1983 than in 1979-82 could reflect differences in numbers of smolts migrating to sea, or their mortality or availability. Numbers of yearling coho smolts released by hatcheries in the Columbia River and along the Oregon coast have remained fairly constant since 1979. Total smolts released in these regions (yearling plus age 0) were about 15% lower in 1983 than 1982 (Oregon Department of Fish and Wildlife, 1985),

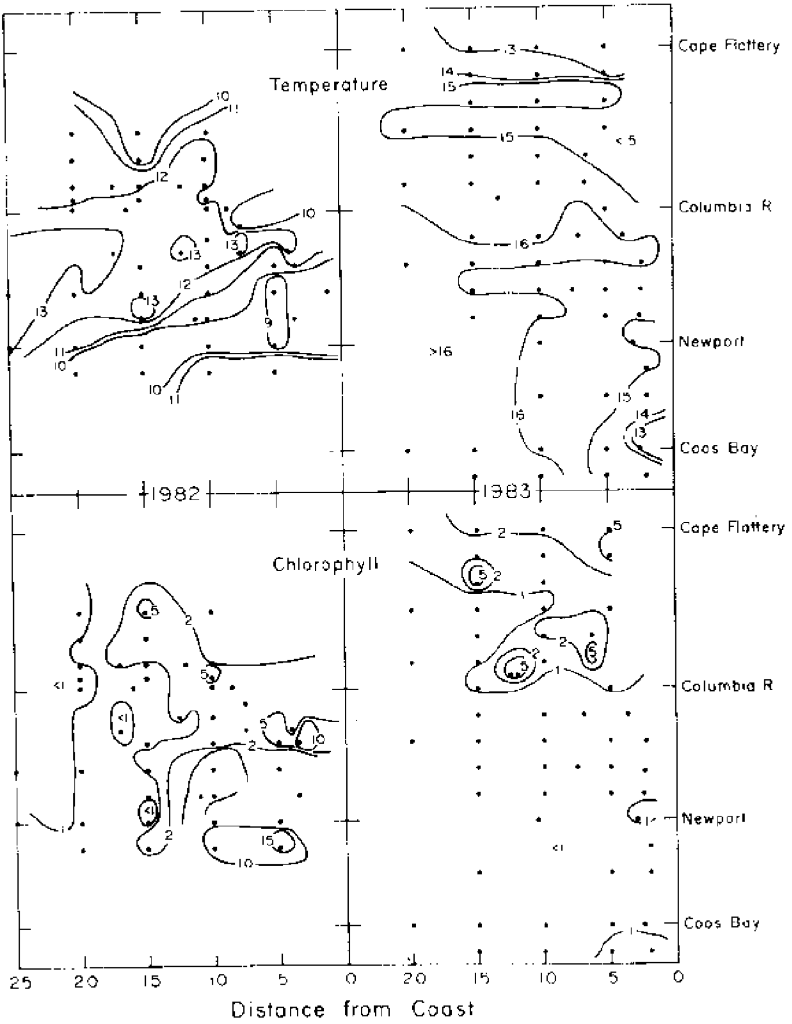

Figure 1. Contours of surface temperature and cholorphyll, June 1982 and 1983. (Note expansion of horizontal scale.)

not nearly enough to explain the four-fold decrease in juvenile coho caught in 1983. The fact that 1983 catches of juvenile coho were highest off southern Washington in June and northern Washington in September may be an indication of northward movement out of our sampling area. Northward migrations of juvenile coho salmon along the Oregon-Washington coast have been reported based on recovery of tagged juvenile coho (Pearcy, 1984). However, the number of sexually precocious male coho salmon (jacks) returning to the Columbia River and coastal index streams during the fall of 1983 was the lowest on record since 1969. These trends indicate that environmental conditions associated with the 1983 El Nino apparently caused poor survival of coho smolts in the ocean.

Table 6. Growth rate estimates for marked jacks returning to the Anadromous facility at Coos Bay based on mean weights and days at liberty.

Year	No. Jacks	Weight at release (g)	Weight at recapture (g)	days at liberty	Growth (g/day)
1980	126	33.1	600	152	3.7
1981	1335	36.6	730	132	5.3
1982	173	31.5	530	120	4.2
1983	157	44.1	350	106	2.9

How were growth rates and body condition of juvenile salmon affected by the El Nino? We examined growth rates of juvenile coho by three methods: a) average changes in lengths of age I coho between June and August or September (age-0 was not used since they have a more prolonged period of release), b) differences between lengths at time of capture and lengths at ocean entrance (back-calculated from scales) of marked fish collected 60 days or more after release, and c) increase in length between release and recovery of 2-year old coho jacks returning to the private hatchery, Anadromous Inc. at Coos Bay. The first two methods did not reveal a drastic difference in growth between 1983 and 1981-82. The average growth rates for 1981, 1982 and 1983 were 1.2, 1.4 and 1.2 mm/day, respectively, from the average changes in lengths of age I coho, and 0.9, 1.4 and 1.2 mm/d from marked fish. The average size and growth rate of jacks returning to the Anadromous facility, however, were appreciably lower in 1983 than in 1980-1982 (Table 6). Thus 1983 appeared to be a year of below average growth for these coho jacks.

Length-weight relationships calculated for juvenile coho salmon were not significantly different in either slope (P>0.1) or the intercept (P>0.5) between 1982 and 1983. The condition of survivors caught off the coast did not reflect adverse effects of El Nino. Therefore, although survival of coho smolts off Oregon apparently was poor, the body condition and perhaps growth rates of smolts surviving to be caught in our purse seines were not abnormally low.

Fullness of stomachs of juvenile coho salmon also indicated little difference between 1983 and 1982 (Fig. 2, K-S test, P>0.05). The composition of food of juvenile coho salmon was different between these years however (Table 7). Larval northern anchovy were the most common prey of coho smolts in 1983 but were not even a major prey category in 1982. This agrees with the observation that larvae of northern anchovy were much more numerous in inshore plankton samples in 1983 than earlier years (Brodeur et al., in press). The

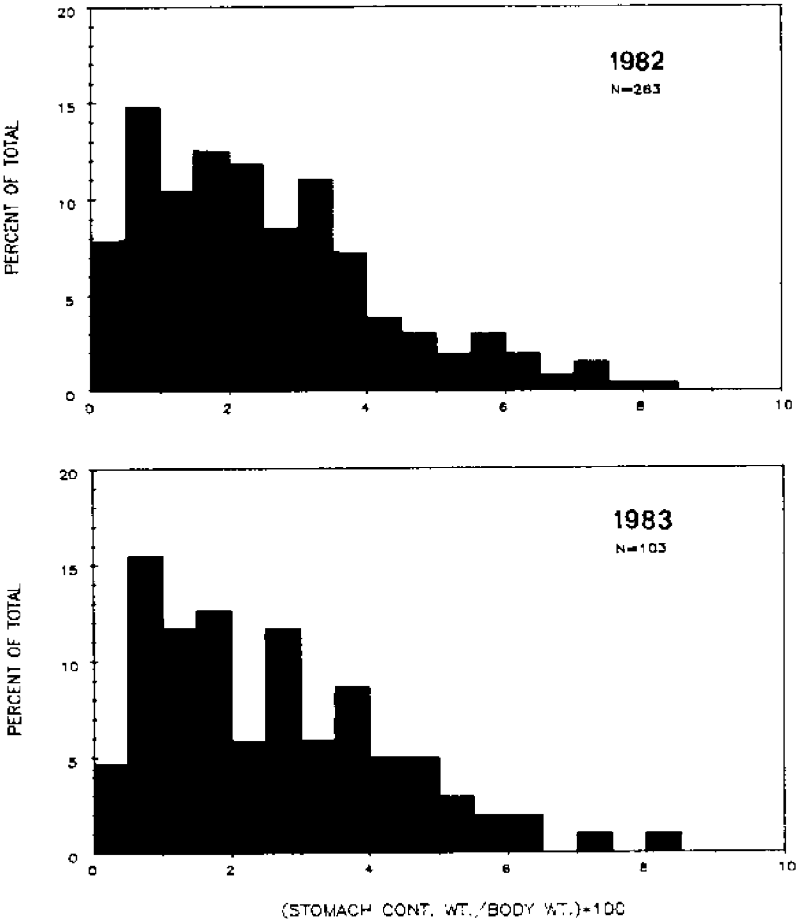

Figure 2. The weight of stomach contents expressed as a percentage of body weight of juvenile coho salmon collected during June 1982 and June 1983.

euphausiid Nyctiphanes simplex, a southern species previously found off central California only during warm years such as 1957-59 and 1977-78 (Brinton, 1981), was the most common euphausiid prey of juvenile coho in 1983. Dungeness crab (Cancer magister) larvae and megalopae were a major prey in 1982 but not in 1983.

Adult Salmon. The 1982-83 El Nino was associated with a disastrous fishing season for salmon off Oregon, California and Washington. The anomolous ocean conditions are believed to be responsible for increased ocean mortality of many salmon stocks and a marked decrease in the average size of adult salmon in 1983 (Pacific Fishery Management Council, 1984).

Table 7. Rank order of abundance of major prey of juvenile salmon in 1982 and 1983.

1982	1983
FISHES (LARVAE AND JUVENILES MOSTLY)	
Ammodytes hexapterus (sand lance)	*Engraulis mordax* (northern anchovy)
Hemilepidotus spinosus (red Irish lord)	*Sebastes* spp. (rockfishes)
Psettichthys melanostictus (sand sole)	*P. melanostictus*
Osmeridae	*A.* hexapterus
Microgadus proximus (tomcod)	*I. isolepis*
Clupea harengus (Pacific herring)	*Parophrys jordani* (English sole)
Sebastes spp. (rockfishes)	*Ronquilus jordani* (northern ronquil)
Hexagrammidae (greenlings and ling cod)	*H. spinosus*
Isopsetta isolepis (butter sole)	*Lyopsetta exilis* (slender sole)
EUPHAUSIIDS	
Thysanoessa spinifera	*Nyctiphanes simplex*
Euphausia pacifica	*E. pacifica*
AMPHIPODS	
Hyperoche medusarum	*Hyperoche medusarum*
Vibilia spp.	*Hyperia medusarum*
Parathemisto pacifica	*Phronima sedentaria*
Primno macropa	*Vabilia* spp.
Atylus tridens (gammarid)	
DECAPOD LARVAE	
Cancer magister (Dungeness crab)	*Cancer oregonensis* (rock crab)
Pandalus jordani (pink shrimp)	Porcellanidae (porcellanid crabs)
Pinnotheridae (pea crabs)	Pinnotheridae
	Pugettia spp. (kelp crabs)
	Crangon spp. (sand shrimp)

The average weights of coho salmon landed in 1983 in the Oregon commercial troll and Columbia River gillnet fisheries were the lowest on record since statistics are available in 1952 (Fig. 3). The average weight of chinook caught in Oregon by the commercial troll fishery was also the lowest since 1952. Adult coho salmon caught by Columbia River gillnets averaged only 3.0 kg, more than 1.0 kg below the 1957-82 average. For California and Oregon the average size of the troll-caught coho was 28-46% below the 1971-75 average and the average chinook was 5 to 33% below the 1971-75 average (Pacific Fishery Management Council, 1984).

Coho and chinook salmon also exhibit poorer condition factors in 1983 than non-El Nino years. For example, the dressed weight of a 60 cm coho averaged 1.9 kg in 1983 and 2.4 kg in previous years. Chinook salmon collected near the mouth of the Rogue River in 1983

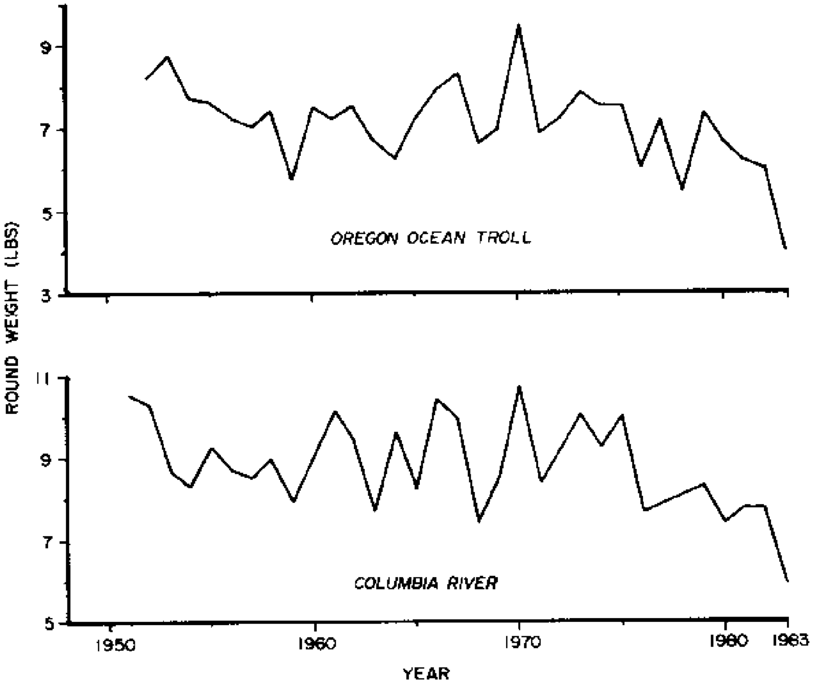

Figure 3. The average round weight of coho salmon landed in Oregon by the commercial troll fishery (July-August) and Columbia River gillnet fishery (Sept-Oct) from 1951-83. Average weight of Columbia River fishery in 1951-56 includes some fish caught in August.

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weighed about 0.9 kg less than chinook of equal length sampled in 1974-76 (Johnson, 1984).

Because of large variations in the gonad weights of coho salmon of the same length categories, differences were not apparent between size-specific gonad weights measured in 1983 and earlier years. However, the average number of eggs per female coho salmon returning to public hatcheries in Oregon was 24-27% lower in 1983 than in 1978-82, largely because of the smaller size of returning females. The average egg size of coho was also smaller at some hatcheries than in past years (Johnson, 1984).

A predictive index of the stock size of coho salmon in the ocean south of Willapa Bay, Washington has been developed based on the number of precocious 2-year old males (jacks) returning in the previous year. As seen in Figure 4 this relationship has been a fairly accurate prediction of the abundance of 3-year old coho returning the following year. Mortality rates of year classes are usually similar between the time of jack return, after the first six months in the ocean, and the time of return of 3-year old

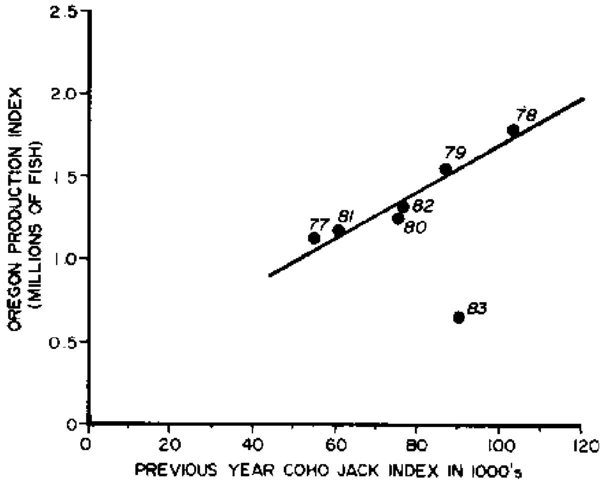

Figure 4. Relationship between the numbers of 2-year-old coho jacks returning to the Columbia River and streams of Oregon and California and the catch and escapement of 3-year-old coho (Oregon Production Index) 1977-83.

adults; hence adults return in a similar proportion to jacks in the prior year. In 1983, the prediction of the expected stock size was 1,553,600 (excluding private hatchery coho) based on return of jacks in 1982. The actual stock size was only 657,900 fish, 42% of the estimate based on the jack predictor (Pacific Fishery Management Council, 1984). The 1983 El Nino presumably was responsible for the unexpectedly high mortality of adult coho salmon during their final year in the ocean. The 1983 harvest of coho salmon was the lowest since 1961, and stream counts of coho on spawning grounds in Oregon were the lowest since surveys began in 1949 (Johnson, 1984).

The El Nino also affected the returns of many Oregon and California chinook stocks (Pacific Fishery Management Council, 1984). The abundance of chinook stocks from southern Oregon streams and some Columbia River stocks were far below predicted levels (Table 8). The numbers of chinook salmon returning as 2-year old jacks were at record lows in the Columbia River and Rogue River, predicting low returns of 3-year old chinook in 1984. Stocks that migrate to the north, such as coastal stocks north of Elk River and upriver fall chinook in the Columbia, usually had lower adult mortality than stocks having localized or southern distributions and were apparently less impacted by the El Nino conditions off Oregon and Washington (Pacific Fishery Management Council, 1984).

Conclusions

The 1982-83 El Nino was a major oceanographic event that had obvious biological consequences. Off Oregon and Washington it was correlated with a) occurrences of rare and unusual fishes from

Table 8. Comparison of the abundance of adult chinook in 1983 with the 1978-82 average for various Columbia River and Oregon coastal stocks.

Stock	Abundance Index	1978-82 mean	1983	% Change
Rogue Spring	Dam Count	29,841	7,688	-74%
Rogue Fall	Seining CPUE	1.58	0.57	-64%
Umpqua Spring	Dam Count	5,841	4,021	-37%
Elk River	Hatchery and Wild River Escapement	5,652	10,150	+80%
Columbia River Tule Fall	Ocean catch and escapement	849,000	479,000	-44%
Columbia River Upriver Fall	River catch and dam counts	78,100	83,200	+7%
Lower River Spring	River catch, dam counts α hatchery returns	96,100	99,600	+4%

southern waters, b) changes in the relative abundances of animals in purse seine collections, c) changes in the catches of some commercial species, d) poor growth and survival of coho salmon during their final summer in the ocean and e) low numbers and northerly distributions of juvenile coho salmon.

The warm ocean conditions and reduced upwelling of nutrient-rich, cool water apparently had severe effects on the production or availability of food, and hence growth of salmon that esided in coastal waters off Oregon, California and Washington.

Interestingly, the catches of Pacific and jack mackerel in purse seine sets off Oregon and Washington were higher in 1984 than 1983. Catches of juvenile coho salmon were low in both 1983 and 1984 in this region. Positive temperature and sea-level anomalies persisted from late 1982 into early 1984 off California (Norton et al., this volume) and off Oregon (Huyer and Smith, in press). By April and May 1984, thermal and sea level properties seemed normal in coastal waters (Huyer and Smith, loc. cit.). Sea-surface temperatures during our purse seining cruises off Oregon were several degrees cooler in June 1984 than June 1983.

This trend for the distributions and abundances of large pelagic animals to be affected beyond the subsidence of the physical manifestations of El Nino was also obvious for pelagic red crabs

(Pleuroncodes planipes) off California. Pelagic red crabs were found farthest to the north in the California Current in early 1960, following the 1957-58 El Nino, when massive strandings were observed in Monterey Bay (Glynn, 1961; Longhurst, 1967). Pelagic red crabs also moved north during the 1982-83 event, and again were reported farthest north (Fort Bragg) in early 1985 (D. McLain, pers. comm.). Such prolonged biological changes off California, as well as the ones we observed off Oregon and Washington, may be related to long-term changes in sea level and thermal structure in coastal waters along the west coast of North America (McLain, 1984; Norton et al., this volume), as well as to the transient El Nino event itself.

Acknowledgments

Many persons contributed observations for this paper. We thank them all, especially Larry Hreha and Jerry Lukas for data on landings of mackerel, tuna and bonito; Jim Golden, Neil Richmond and Betsy Hunt for data on rockfish landings; Ron Gowan for providing data on the sizes of coho jacks returning to Anadromous facility in Coos Bay; Bruce Mundy and Al Mirati for collection and reporting of fishes; Bruce Mundy and Carl Bond for identification of fishes; and to all the fishermen who saved specimens of unusual animals.

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Effects of the 1982–83 El Niño on Reproduction of Six Species of Seabirds in Oregon

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Anomalous oceanographic conditions developed off the coast of Oregon during 1983 (Huyer, 1983; Reed, 1983; Fielder, 1984). Concurrently the 1983 breeding season was an exceptionally poor one for at least three of Oregon's nesting seabird species.

Nest abandonment by cormorants was widespread during the 1983 breeding season. By 12 July 1983 a total nest abandonment had occurred at two Brandt's Cormorant colonies at Coquille Point Rocks (43° 06' N), where on 11 July 1979, 196 nests had been occupied (Pitman et al. in press). At a colony north of Sea Lion Caves (44° 07' N) by 17 July 1983 49% of the Brandt's Cormorant nests that were occupied on 24 June 1983 had been abandoned. Brandt's Cormorants do not fledge until around the second week of August in Oregon (Scott, 1973), thus our 0.58 chicks present/nest built (Table 1) for 17 July may over represent actual fledging success, nevertheless this possible over estimate is considerably lower than Scott's (1973) figure of 1.56 chicks fledged/nest built, and indicates that on colonies where birds did not abandon their nests completely, chick production by Brandt's Cormorants was low in 1983.

Pelagic Cormorants were also not as successful in 1983 as in previous years. At a colony south of Coos Bay (43° 19' N) the number of nests constructed in 1983 was not significantly different from previous years, but the percentage of successful nests was considerably lower (Table 1). Fledging success was also lower in 1983. Similar results were seen in 1984, although the number of nests in which at least one chick fledged was not different from the 8 year mean (Table 1), but the number of chicks fledged/nest in 1984 was considerably lower than the 8 year mean (Table 1).

Both reproductive success and adult survival of Common Murres were reduced in 1983. Common Murre colonies in the south of the state had many fewer individuals present in 1983 than in 1979 (Table 2). Colonies in the north of the state did not show this decrease.

Table 1. A summary of the 1983 reproductive success of Brandt's and Pelagic Cormorants, Pigeon Guillemots and Western Gulls in Oregon with comparisons to other years.

Species	Colony Location	Year	No. of Nests Constructed	% of nests Successful[a]	Mean Clutch Size	Mean no. of Chicks Fledged/ Nest built[b]	Mean no. of Chicks fledged/ successful nest[ab]
Brandt's Cormorant	44° 07' N	1983	84	51%	N/D	0.58	1.23
Pelagic Cormorant	43° 19' N	8 yr mean[c] 1973-1982	35 ± 12	80 ± 10%	N/D	2.30 ± 0.44	2.70 ± 0.42
Pelagic Cormorant	43° 19' N	1983	42	48%	N/D	0.65 ± 0.70	1.35 ± 0.72
Pelagic Cormorant	43° 19' N	1984	44	80%	N/D	1.36 ± 0.89	1.71 ± 0.62
Pigeon Guillemot	44° 29' N	1983	11	91%	1.55	1.27 ± 0.65	1.44 ± 0.53
Pigeon Guillemot	43° 22' N	1982	110	59%	1.76[d]	0.73 ± 0.69	1.23 ± 0.43
Pigeon Guillemot	43° 22' N	1983	89	63%	1.57[d]	0.74 ± 0.65	1.19 ± 0.39
Pigeon Guillemot	43° 22' N	1984	108	58%	1.64	0.68 ± 0.63	1.15 ± 0.36
Western Gull	43° 06' N	1982	28	N/D	N/D	1.71	N/D
Western Gull	43° 06' N	1983	37	N/D	N/D	1.59	N/D

N/D - no data
a - a successful nest is one in which at least one chick reached fledging size.
b - mean ± standard deviation
c - does not include 1974 or 1979
d - 1982 v 1983 t = 6.56 d.f = 197 $p<0.001$

Table 2. Number of Common Murres on six colonies in Oregon determined by aerial censuses, conducted by U.S. Fish and Wildlife Service, Finley Wildlife Refuge, Corvallis, Oregon.

Colony location	Number of Common Murres	
	1979^a (date)	1973 (date)
45^o 54' N	3750 (7/16)	4500 (7/3)
44^o 45' N	3200 (7/16)	2000 (7/3)
44^o 40' N	3000 (7/16)	2769 (7/3)
43^o 06' N	3500 (5/21)	800 (7/3)
42^o 40' N	6600 (7/11)	133 (7/3)
42^o 03' N	1850 (7/11)	0 (7/3)

[a] data from Pitman et al. (in press)

Mortality of Common Murre adults during the breeding season was significantly higher than in the previous five years (Table 3). Chick production was low; less than 1 chick/km was seen off Coos Bay on 12 July and 4 August 1983. In 1982 3.6 chicks/km were seen on 13 July and 6.9 chicks/km on 5 August.

The reproductive success of Pigeon Guillemots and Western Gulls was not significantly different in 1983 than in previous years (Table 1). In the Coos estuary (43^0 22' N) the clutch size of Pigeon Guillemots was significantly lower in 1983 than in 1982 but fledging success was not significantly different (Table 1). We checked 30 Leach's Storm-Petrel burrows at Hunters Island (42^0 18' N) in mid August 1982 and 1983; 67% of the burrows were occupied in 1982 and 63% in 1983, suggesting the anomalous ocean temperatures present during 1983 did not adversely influence nesting.

In the northeastern Pacific reproduction in marine birds is strongly tied to the oceanographic conditions that generate the plentiful food resource prior to and during the breeding season. El Niño episodes in the eastern tropical Pacific result in decreased primary productivity (Cowles et al., 1977; Barber and Chavez, 1983) and subsequent disruption of coastal food webs. Such a disruption during the unusual oceanographic conditions off Oregon in 1983 could explain the lowered reproductive success of Common Murres and Brandt's and Pelagic cormorants. Common Murres and Brandt's Cormorants in Oregon feed primarily on fish (Scott, 1973; Ainley et al., 1973 and Matthews, 1983). Many of these fish species are planktivores and as such are likely to be rapidly affected by a decrease in primary productivity.

Table 3. Adult Common Murre mortality assessed by numbers of dead birds/km from a 7.4 km beach in Lincoln County, Oregon.

	No. of Common Murre adults/km				
Year	April	May	June	July	August
1978-1982[a]	0.15 ± 0.18	0.16 ± 0.11	0.21 ± 0.16	0.25 ± 0.10	0.74 ± 0.75
1983[a]	0.63	0.74	0.72	3.38	1.42

[a] ANOVA of 1983 v other years $p<0.001$

During the breeding season Pigeon Guillemots feed on epibenthic fish (Ainley and Sanger, 1979; Hodder and Graybill, unpub. data), many of which are detritivore feeders (Hart, 1973) and thus may not have been so rapidly affected by a decrease in primary productivity.

The diverse feeding habits of Western Gulls (Hunt et al., 1979) allows them to switch to alternative sources should one become unavailable and this may account for their success in 1983. Two factors may have contributed to the ability of Leach's Storm-Petrels to nest successfully in 1983; first they feed offshore in areas that are not influenced by coastal upwelling (Ainley et al., 1974; Harris, 1974); and secondly their embryos are able to tolerate considerable incubation neglect (Wilbur, 1969).

Acknowledgments

We thank Bob Loeffel for use of his data on seabird mortality and the students of the University of Oregon's Institute of Marine Biology who have helped monitor the Pelagic Cormorant colony since 1973. The 1983 research on Pigeon Guillemots was funded by a grant from the non-game wildlife fund of the Oregon Department of Fish and Wildlife.

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Biological Anomalies off Washington in 1982–83 And other Major Niño Periods

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Nino years off Washington are characterized by anomalously warm waters extending to depths of several hundred meters and by high stands of sea level. Such events can be expected to alter productivity of the marine ecosystem and to influence the distributions of marine organisms. It might be expected that all Nino occurrences would have similar ecological effects, but lack of adequate time series of data make it difficult to compare the consequences of different events. We present here some observations from the three most conspicuous Ninos of recent decades, those of 1982-83, 1957-58, and 1940-41.

Our study is confined to the marine waters of Washington State. While this region is not a distinct biogeographic entity, it should provide an adequate sample of conditions for the zone 45°-50°N. Data for the earlier Ninos are derived from published records. For the 1982-83 event, observations came primarily from the fishing, recreation, and scientific communities. Identifications of unusual species were accepted only if confirmed by qualified scientists. Details of observations are available (Fluharty, 1984).

While changes in oceanic conditions accompanying El Nino might be expected to have a variety of biological consequences, the most obvious are likely to be changes in distributions and abundances. Such observations during the 1982-83 event will first be summarized, after which comparable information from the earlier Ninos will be discussed.

Distributional Changes Observed in 1982–83

Three kinds of distributional changes were seen, (1) range extensions in which species were recorded for the first time, (2) range anomalies where organisms were found significantly beyond their usual ranges, and (3) habitat anomalies where organisms were found shallower (deeper) or closer inshore (offshore) than normal. The observations discussed below are summarized in Fig. 1.

Figure 1 Inter-Nino Comparison of Observations

E Range extension
A Range anomaly
H Habitat anomaly
C Change in abundance (+ or -)

Species	1940-41	1957-58	1982-83
INVERTEBRATES			
Crassostrea gigas Pacific oyster		C+	
Emerita analoga sand/mole crab	E	A	A
Loligo opalescens Pacific squid	C+	C+	C+
Siliqua patula Pacific razor clam			C+
Velella velella by-the-wind-sailor		C+	C+
FISH			
Allosmerus elongatus whitebait smelt			H
Alopias vulpinus thresher shark			A
Balistes polylepis finescale triggerfish			E
Chilara taylori spotted cusk-eel			E
Cololabis saira Pacific saury			C+
Coryphaena hippurus common dolphinfish		E	
Cynoscion nobilis white seabass		A	A
Engraulis mordax anchovy			C-
Icostenus aenigmaticus fantail ragfish			H
Medialuna californiensis halfmoon			E

Species	1940-41	1957-58	1982-83
Mola mola ocean sunfish		C+	C+
Psychrolutes phrictus blob sculpin		H	
Sarda chiliensis Pacific bonito			C+
Scomber japonicus Pacific/chub mackerel			C+
Seriola dorsalis yellowtail		A	
Sphyraena argentea barracuda		A	
Symphurus atricauda California tonguefish			E
Synodus lucioceps California lizardfish			E
Thunnus thynnus bluefin tuna		C+	
REPTILES			
Dermochelys coriacea/schlegelii leatherback turtle			A
BIRDS			
Fregata magnificens magnificent frigatebird			A
Pelecos occidentalis brown pelican			C+
Thalasseus elegans elegant tern			E

Source: Based on review of literature by A. Schoener and observations reported to the El Nino Task Force - Fluharty, 1984. Commercial species (salmon, albacore) are discussed in text.

Range extensions

Fishes

a) *Balistes polylepis*. Fine-scale triggerfish were collected from Willapa Bay, on Washington's outer coast. The triggerfish range is from lower California to South America (Barnhart, 1936; Miller and Lea, 1972). Isolated records occasionally place it at San Clemente, California (Fitch, 1947) and San Pedro, California (Walford, 1931). We are not aware of any records north of the California region until the present.

b) *Chilara taylori*. The spotted cusk-eel, generally found from Baja California north to northern Oregon (Eschmeyer, *et al*. 1983), was collected from Willapa Bay, Washington during 1983.

c) *Symphurus atricauda*. The most northerly record of the California tonguefish was Yaquina Bay, Oregon until 1983 when six were captured near Grays Harbor, Washington. Another specimen was caught in Samish Bay (North Puget Sound) in 1984 (Dinnel, pers. comm.).

Birds

a) *Thalasseus elegans*. Elegant terns are considered regular autumn visitors along the southern California coast, making northward excursions from their breeding grounds in Mexico (Robbins, *et al*. 1966). They were observed in 1983 along the Washington coast.

Range anomalies

Invertebrates

a) *Emerita analoga*. Permanent colonies of the sand, or mole, crab occur from Oregon to Mexico and in Peru, Chile and Argentina (Hart, 1982). This species was collected on the Washington coast during the summer of 1983, and has been noted even farther north on a few occasions during and following Nino years (Banner and McKernan, 1943; Butler, 1959 and Hart, 1982).

Fishes

a) *Synodus lucioceps*. The California lizardfish is found from California to Mexico at moderate depths and is uncommon (Barnhart, 1936; Miller and Lea, 1972). In 1983, it was caught off Dash Point, Puget Sound, Washington. Another specimen was caught near Seattle in 1975 (Miller, pers. comm.).

b) *Cynoscion nobilis*. A white seabass was caught at Westport, Washington in 1983, although it is uncommon north of SanFrancisco, California (Hart, 1973). It was noted at Willapa Harbor, Washington, in 1958 (Washington State Department of Fisheries, 1958). Two specimens were caught in S.W. Washington waters in 1957 (Radovitch, 1961). Clemens and Wilby (1961) note its capture in British Columbia, Canada, in the years 1892 and 1906.

c) Alopia volpinus. The thresher shark, a pelagic species of warm temperature and subtropical seas, has occasionally been reported from more northerly latitudes (Hart, 1973). Among these reports are Coos Bay, Oregon (Hubbs and Schultz, 1929) in 1926 and British Columbia in 1937 (Clemens and Wilby, 1961). Two specimens were caught off Westport, Washington in 1983.

d) Medialuna californiensis. The halfmoon was taken in Grays Harbor in 1983 (Pearcy *et al.*, this volume).

Birds

a) Fregata magnificens. The magnificent frigatebird breeds on islands along the west coast of Mexico and ranges along the west coast to northern California (Gabrielson and Jewett, 1970). It has been noted as a rare straggler in Oregon (Ibid.) in 1935. It was observed at Westport, Washington during the summer of 1983.

Habitat anomalies

Fishes

a) Psychrolutes phrictus. The blob sculpin is a rare species generally found in very (840-2800m) deep waters from the Bering Sea to southern California (Eschmeyer *et al.*, 1983). It was caught on sport salmon troll gear in shallow water during the summer of 1983 off Westport, Washington. The specimen is archived at the College of Ocean and Fishery Sciences, University of Washington.

b) Icostenus aenigmaticus. Generally considered an oceanic species, this fantail ragfish was caught in Hood Canal, a part of Puget Sound, Washington during 1983. It is normally found in the north and mid-Pacific (Eschmeyer *et al.* 1983).

c) Allosmerus elongatus. The whitebait smelt is a coastal species seldom caught in Puget Sound. It is found from Vancouver Island, British Columbia, Canada, to Central California (Eschmeyer *et al.* 1983). It was caught in Puget Sound during 1983.

Abundance Changes Observed in 1982–83

Unless a species is subject to periodic sampling (e.g., in a commercial fishery), its variations in abundance are difficult to verify quantitatively. In the material that follows, some reports are based on the subjective impressions of knowledgeable observers while others came from annual censuses. Information available from commercial fisheries will be discussed in a later section.

Invertebrates

a) Velella velella. Velella, a siphonophore, occurred in large numbers in 1983 and 1984, washing up on beaches in the Strait of Juan de Fuca, and northern Puget Sound, particularly near Port Townsend. Historically, there have been many years in which this species has beached in unusual numbers. Hubbs and Schultz (1929) report large numbers of Velella from Oregon to British Columbia in 1929. LeBrasseur (1965) lists sighting at least a few Velella in all but one year during the 1956-1964 period at Station P in the northeast Pacific. Specimens in the University of Washington School of Oceanography museum were obtained in 1934, 1956, 1957 and 1959 (D. Henry, pers. comm.). Favorite (1973) reports mass strandings in 1927, 1965 and 1970. The 1981 abundance on the Washington coast was also unusually high (T. Schaeffer, pers. comm.). Wood (1975) reports that the winter arrival of Velella is received by beachcombers as common and as indicative of beaching glass floats and other debris.

b) Siliqua patula. The Pacific razor clam, underwent an apparent massive decrease on the Washington coast in 1983 (Simons, pers. comm.).

Fishes

a) Mola mola. The ocean sunfish was reported numerous times in 1983. Miller and Lea (1972) consider this a species found in both warm and temperate seas and mention records in British Columbia, Canada. Hart (1973) includes the British Columbian and Alaskan reports and adds that ocean sunfish are quite frequently observed along the coast and in the outside inlets off British Columbia. Hart also mentions two specimens caught from Puget Sound, Washington. Ocean sunfish were reported in Puget Sound in 1919, 1959 and 1962 (Miller and Barton, 1980).

b) Scomber japonicus. The northern hemisphere range of Pacific chub mackerel is from Mexico to the Gulf of Alaska. It is sometimes fairly abundant off the west coast of Vancouver Island (Hart, 1973; Miller and Lea, 1973). Catches in 1983 indicate increased abundance off the Washington coast and in Puget Sound. It was caught in Puget Sound in 1919 and 1963 (Miller and Borton, 1980).

c) Sarda chiliensis. The Pacific bonito appeared more abundant than usual off Washington during 1983. In anomalously warm waters, bonito may be numerous as far north as northern California (Radovich, 1961), and occur northward to coastal Alaska. Pacific bonito occurs rarely in Puget Sound, Washington: One record reports two caught near Seattle, Washington in 1962 and 1963 (Patten et al. 1965) and another notes catches in 1919 and 1972 (Miller and Borton, 1980).

d) Cololabis saira. The Pacific saury is widely distributed in the offshore waters of the Pacific, from the Southern Pacific through the Gulf of Alaska. Commercial fishermen reported Pacific saury to be far more prevalent in stomach contents of salmon in 1983 than the normal pelagic food species like herring.

Reptiles

a) Dermochelys coriacea/schlegelii. The leatherback turtle is considered to be the most widely distributed of all reptiles (Pritchard, 1980). While leatherbacks nest in tropical areas, they migrate to areas well outside the tropics and even to Alaska (Hodge, 1979). Active turtles have been found in waters as cold as 11.7°C in the Queen Charlotte Islands (McAskie and Forrester, 1962). Several sightings of this species were reportec in the summer of 1983 from the outer Washington coast. Leatherback turtles were observed in Barkeley Sound, B.C., in 1958 (Radovich, 1961).

Birds

a) Pelecos occidentalis. The brown pelican is sometimes observed along Washington's outer coast following the spring/summer breeding season and makes rare appearances in the Strait of Juan de Fuca (Angell and Balcomb, 1982). Brown pelicans were observed to linger at various places in western Washington during the late fall of 1982 (Hunn and Mattocks, 1983). In 1983, the brown pelican was observed along coastal Washington from August through mid-November - at times in numbers of up to 1,000. A total of 36 separate sightings were verified for Washington State during 1983. In contrast, during 1982, 20 separate sightings of pelicans were made. Sightings for 1981 and 1980 were only four each year, with 20 to 50 birds maximum per sighting. In 1979, five reported sightings of pelicans involved only 30 birds (Mattocks, pers. comm.).

Comparison with Other Niño Events

Using the criteria of anomalously high sea surface temperature and sea level, only the events of 1940-41, 1957-58, and 1982-83 affected coastal waters north of Oregon (R. Reed, pers. comm.) since suitable data were available. Both physical and biological data are more abundant for the later events. Enough exist for a crude comparison of biological changes in these three periods.

The principal ecosystem alterations that might be expected as a result of El Nino are decreases in primary and secondary productivity, changes in distributions, and changes in abundances, reproduction, survival and growth rates. Unfortunately, there are no systematic measurements of productivity off the Washington coast that could be used for interannual comparisons.

Changes in distributions

Information on distributional changes is summarized in Fig. 1. One of the most consistent changes is the appearance of Emerita analoga at subarctic latitudes (Hart, 1982). These have been collected on Washington beaches in 1941 and 1942 (Banner and McKernan, 1943) and on Vancouver Island in 1959 (Butler, 1959). Hart (1982) considers these records to be a temporary result of northward drift of the planktonic larvae. The adults persisted for several years thereafter. Incursions have only been recorded for Washington during the Nino periods under consideration.

In 1983, more than 10 species of fish normally occurring off California were observed off Washington. Some of the same species were observed in both 1957-58 and 1982-83 (e.g., white seabass, ocean sunfish). However, many of these seen in 1983 differed from those reported in previous Nino periods. It is noteworthy that there were no reports of unusual sightings from the Washington coast in 1940-41. Perhaps the Nino of those years had less impact there, or reporting may have been less adequate in these early war years.

Only for the 1982-83 Nino are reasonably adequate ornithological reports available, so inter-Nino comparison is not possible. However, Radovich (1961) does refer to changes in migratory bird species off California and on weather station P in the central Gulf of Alaska in 1957-58, and it seems reasonable to suppose that sea bird distributions will in the future be good indicators of Nino effects.

Leatherback turtles were reported off southwestern Washington in 1983. Salmon trollers who have operated there for many years consider the presence of leatherbacks as very unusual although that area is included in their range. Radovich (1961) reports unconfirmed sightings of Chelonia mydas, green sea turtles, in 1957-58 as far north as Nootka Sound. Without positive identification, they may also have been leatherbacks.

Changes in abundance

As noted earlier, information from commercial fisheries is of some value for interannual comparisons of abundance. However, while commercial fisheries sample target stocks periodically so that time series of catches can be developed, the magnitude of catch in any year is affected by many factors in addition to abundance. Catch per unit of effort is a better, although often misleading, estimator of abundance; however, such data were not used in this study. Since time did not permit an elaborate analysis of the fishery statistics, we restricted our treatment to a simple examination of trends for evidence of any obvious relation to El Nino.

Washington landing data were examined for the following fisheries: squid, albacore, and five species of salmon (coho, chinook, chum, pink, sockeye) (Figs. 2 and 3). Evidence for Nino effects was as follows:

Squid: Catches are large during or shortly following Ninos, while in other years the fishery is small or non-existent.

Albacore: A slight increase in landings appears to follow the 1957-58 event, and values for 1983 were double those in 1982, but the major feature in the record, the large increases in the 1970s, are unrelated to the Nino events being compared.

Coho: While landings were low after each of the three events, variability is large, and major declines occur in other periods.

Chinook: The pattern resembles that of coho except for 1940-41 where there was no apparent effect.

Chum: No relation to Nino events is apparent.

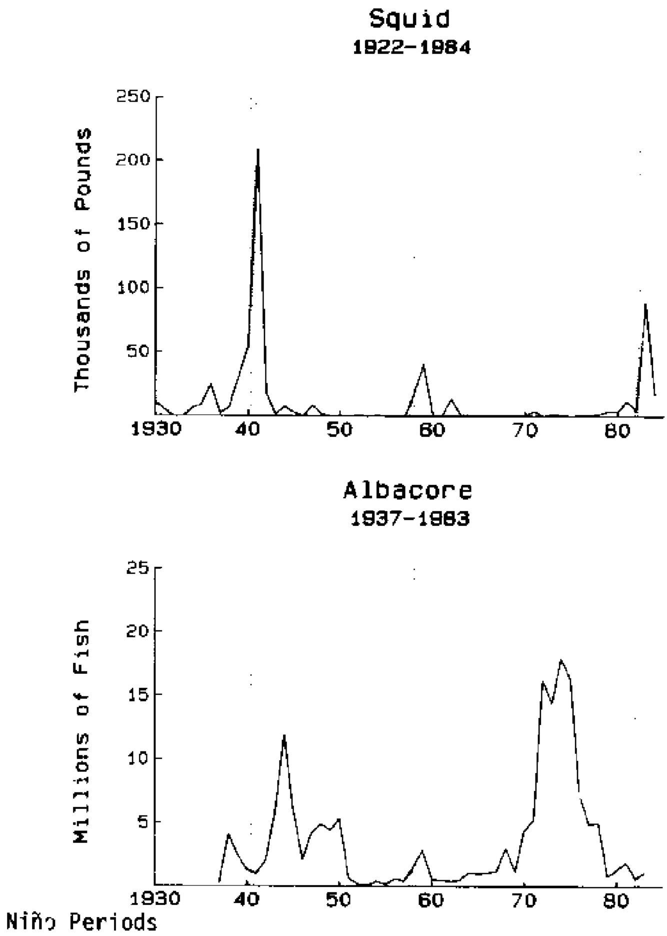


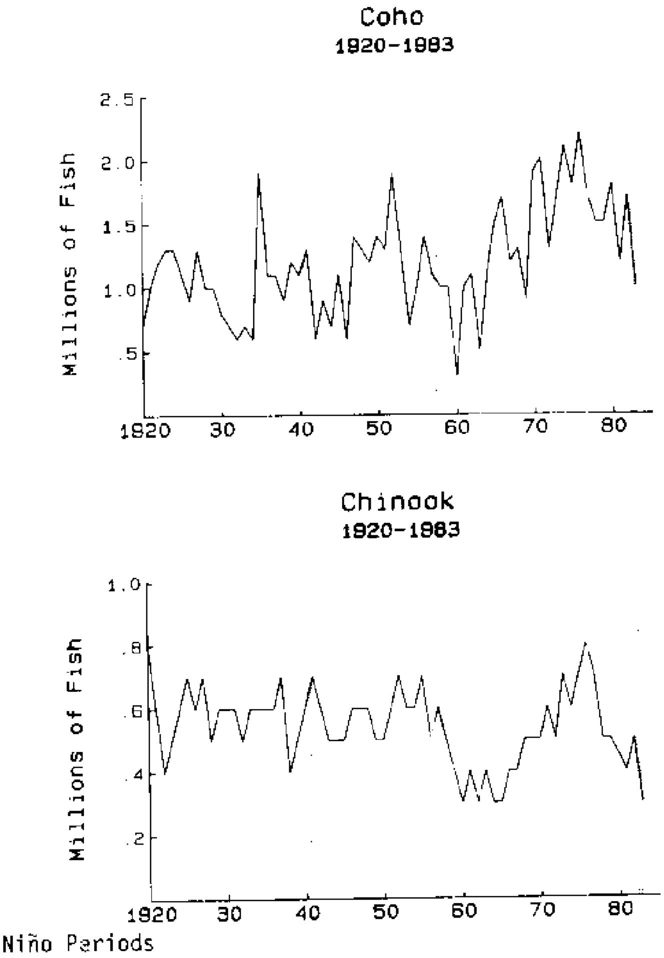
Fig. 2 Commercial Harvests of Squid and Albacore off Washington

Source: Squid
Sara Maupin, personal communication.

Source: Albacore
Data from 1937-1957 reported from Pacific Marine Fisheries Commission files by Northwest Pulp and Paper Association, A Summary of Fisheries Statistics of the Pacific Coast, Toledo, Oregon, December 1959. 1958-1983 data are from PMFC, Annual Report 1983, Portland 1984. (Compiled by Brian Culver).

Pink: The major catches, in odd years, decline during the Nino periods, but in each case the declines began in earlier years.

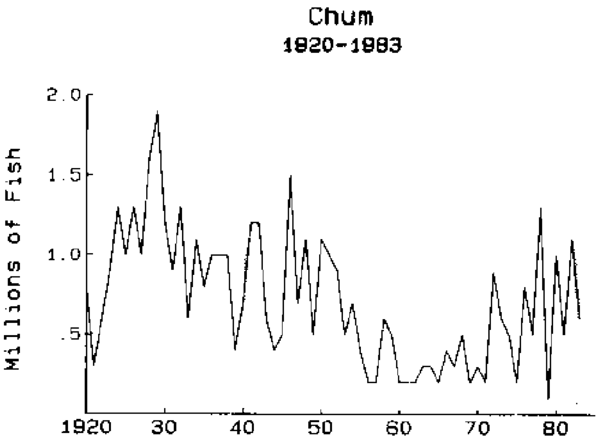
Sockeye: While maximum landings appear to be related to Nino periods, the maxima are no greater than in other years.


Coho
1920-1983

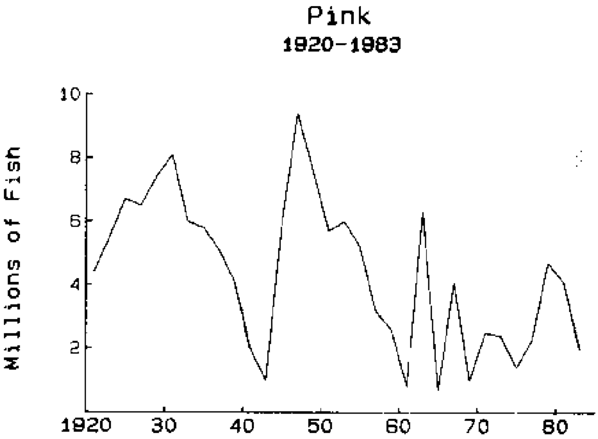
Chinook
1920-1983

Fig. 3 Salmon Harvests Off Washington

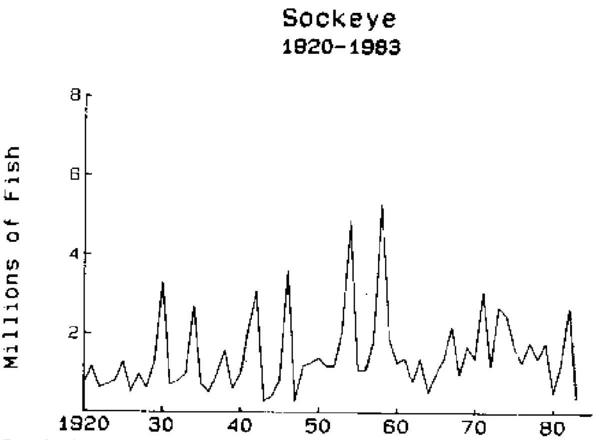
Source: 1920-1976, International North Pacific Fisheries Commission, Historical Catch Statistics for Salmon of the North Pacific Ocean, Bull.39, Vancouver, B.C. 1979. 1977-1983: Pacific Fishery Management Council, A Review of the 1983 Ocean Salmon Fisheries and Status of Stock and Management Goals for the 1984 Salmon Season of the Coasts of California, Oregon and Washington, March 1984.



Chum
1920-1983



Pink
1920-1983



Sockeye
1920-1983

Niño Periods

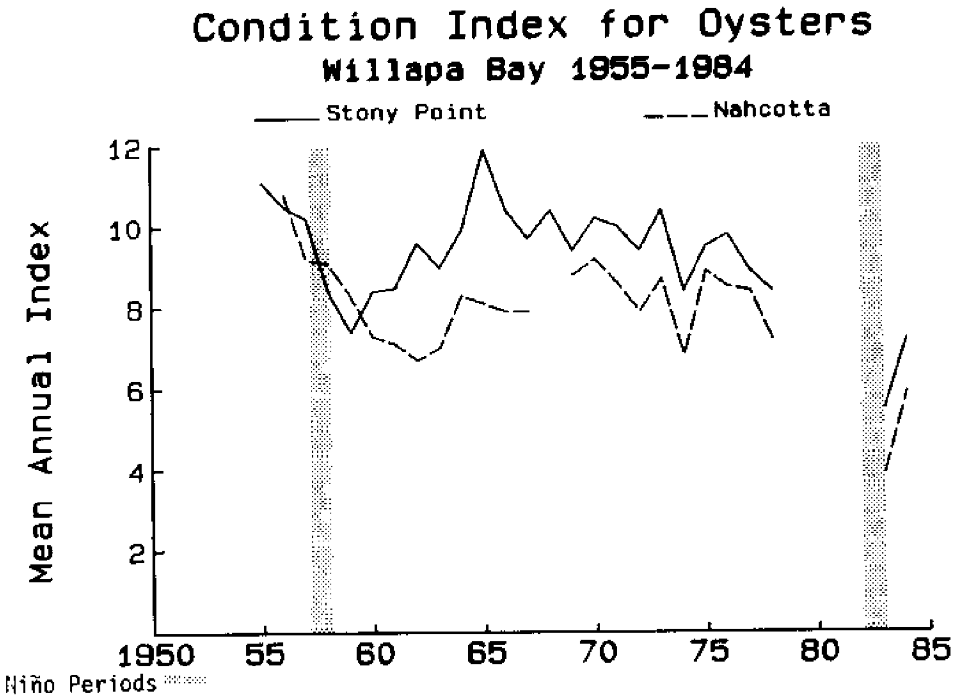


Fig. 4 Condition Index for Oysters Willapa Bay 1955-1984

Source: D. Tufts, personal communication.

Other changes

One other measure from Washington fisheries contributes to interannual comparison of Nino effects. The condition index of oysters at Stony Point and Nahcotta in Willapa Bay has been monitored since the mid-1950s except for a brief interruption in 1978-82 (Fig. 4). The index value for oysters in both locations was very low during and following the 1957-58 event. In 1983, all-time lows were recorded. The data for years preceding the most recent Nino are lacking, but sources familiar with the oyster industry in the region confirm that no decline in oyster conditions was noticed prior to 1983.

While the case for ascribing a Nino-related cause to variation in oyster condition index is at least plausible, the situation is less clear for razor clams. Razor clam populations along the Washington coast in June 1983 were estimated by the Washington Department of Fisheries to total 20.2 million clams. By August, the population had dropped to 6.4 million clams (Simons, pers. comm.). Because of the drastic decline, fall 1983 and 1984 sport clamming seasons were cancelled. In 1958, on the other hand, clam digging was the best in a decade (Washington Department of Fisheries, 1958).

Discussion

Observations of anomalous occurrences, distributions, and abundances of organisms off Washington in 1982-83 which occupy the bulk of this paper, while interesting, are insufficient to answer many questions about Nino effects at mid and higher latitudes. Comparisons with other major events would help but are difficult to make because time series of comparable data do not exist.

It is particularly unfortunate that productivity measurements are so infrequent and occasional, because important harmful effects of El Nino are often ascribed to reduction in the supply of nutrients to the surface layer and a consequent reduction in productivity. Reductions in growth and decreases in abundance farther along in the food chain are then said to result. But the productivity data do not exist to prove the point.

The most obvious effects of these grand environmental perturbations are changes in distributions which can be detected without quantitative data. For plankton and other drifting organisms, transport by altered currents presumably brings about the observed redistribution of southern fauna into more northern latitudes, and of oceanic fauna into more coastal regions. Animals capable of directed motion probably migrate in pursuit of favorable physical conditions or preferred food.

Abundance effects are more obscure. Abundance is usually poorly measured, even in commercial fisheries which have at least the virtue of repeated sampling over many years. But only in the case of squid, a species presumably redistributed during Nino years, was any clear Nino relationship apparent. For other commercial species, the data and simple analysis used were insufficient to demonstrate any such relationship. For species that are not harvested, observations of abundance are largely uncontrolled and anecdotal, and nothing definitive can really be said about Nino effects off Washington.

Acknowledgments

We would like to thank the following persons who have discussed, provided editorial comment, or supplied information for this paper. We appreciate their help, but accept resonsibility for any errors of fact, interpretation or omission: William Aron, Murray Hayes, Ken Henry, Roger Mercer, Sara Maupin, Tom Dark, Alan Shimada, Northwest and Alaska Fisheries Center, National Marine Fisheries Service; Paul Dinnell, Dora Henry, Bruce Miller, Ted Pietsch, Warren Wooster, College of Ocean and Fishery Sciences, University of Washington; Phil Mattocks, Department of Zoology, University of Washington; Greg Bargerson, Bill Simons, Dennis Tufts, Washington State Department of Fisheries; Alan Mearns, Ocean Assessments Division, National Oceanic and Atmospheric Administration; and Ron Reed, Pacific Marine Environmental Laboratory.

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Salmon Management in Response To the 1982–83 El Niño Event

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Introduction

Chinook salmon (Oncorhynchus tshawytscha) and coho salmon (O.kisutch) are the target species in the ocean salmon fisheries of Washington, Oregon, and California. Both species spawn in freshwater rivers and streams, juveniles live and grow in freshwater habitats from a few months to years, smolts then descend to the ocean where they migrate widely and grow rapidly, and finally, adults return to their stream of origin to spawn and begin a new cycle.

Ocean survival is quite variable and fisheries oceanographers have not yet developed successful predictive models. This situation results, in part, from our rudimentary understanding of the complex time-area stock migratory patterns of Pacific salmon. Each separate group of fish "runs different gauntlet" of environmental conditions. Yet salmon biologists are convinced that ocean environmental conditions are the determinants of such variable returns and seek methods to factor environmental variables into their predictive tools.

In 1983, salmon abundance and inshore escapements from the ocean fisheries of Washington, Oregon, and California were below preseason projections. In addition, returning salmon were smaller than expected, showed unusual migratory patterns and were in poor condition on the spawning grounds. These results have been interpreted as manifestations of poor ocean survival and growth caused by an adverse ocean environment resulting from the 1982-83 Nino event. Using information on 1983 performance, the Salmon Plan Development Team (SPDT) adjusted abundance projections for 1984 to anticipate Nino effects. This paper describes the 1983 experience, adjustment procedure for 1984, and provides some preliminary observations on the success of the adjustment procedure.

Salmon Management

Salmon management is a very complex process. The ocean salmon fishery is managed by the Pacific Fishery Management Council with technical input from its Salmon Plan Development Team (SPDT).[1] While each species and freshwater habitat unit consitutes a separate reproductive stock, the mixture of salmon in the ocean requires practical stock units for management. Such management units are defined to reflect the dominant species and freshwater habitat units present in each specific fishing area during harvest. These major ocean management units have been defined by careful analysis of the many stock units that contribute to the harvest. A continuing program of coded-wire tagging enables scientists to identify the stock composition contributing to each fishery. For the ocean salmon fishery areas off Washington, Oregon, and California, these units are shown in Figure 1:

Chinook Fisheries

South of Cape Viscaino - managed for California Central Valley fall chinook.
Cape Viscaino to Cape Blanco - managed for California Klamath River fall chinook and some southern Oregon local stocks.
Cape Blanco to Cape Falcon - managed for Oregon coastal wild and hatchery stocks.
North of Cape Falcon (numerous stock groups) - managed primarily for Columbia River fall chinook.

Coho Fisheries

North of Cape Falcon - managed for Washington coastal stocks
Oregon Production Index Area (OPI) - Columbia River area (Ledbetter Point to Cape Falcon) - managed for historical proportion of OPI stock.

South of Cape Falcon including California - managed for historical proportion of OPI stocks

While the details of salmon management are very complex, the overall concept is quite simple. Salmon stocks are managed to allow escapement that will produce the optimum return to the fishery over the long run. To accomplish this purpose, salmon managers analyze data on catch and escapement from each year's fishery to compare performance with plan and to produce estimates of the abundance of fish to be expected in the following year. Once these projections are developed, management options to produce the escapement targets and to allocate the allowable catch among user groups are developed. Management options are selected that will meet or rebuild escapements and that will allocate catch among user groups according to patterns adopted by the Council. Following this annual rule making process, the fishery proceeds and is monitored so that regulations can be adjusted to meet the plan.

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[1] Salmon are managed under provisions of "Fishery Management Plan for Commercial and Recreational Salmon Fisheries off the coasts of Washington, Oregon, and California, commencing in 1978" together with annual "Ocean Salmon Fisheries Reviews" and Plan Amendments. This series of documents (or the latest iterations) is available from the Pacfic Fishery Management Council, 526 S.W. Mill Street, Portland, Oregon, 97201.

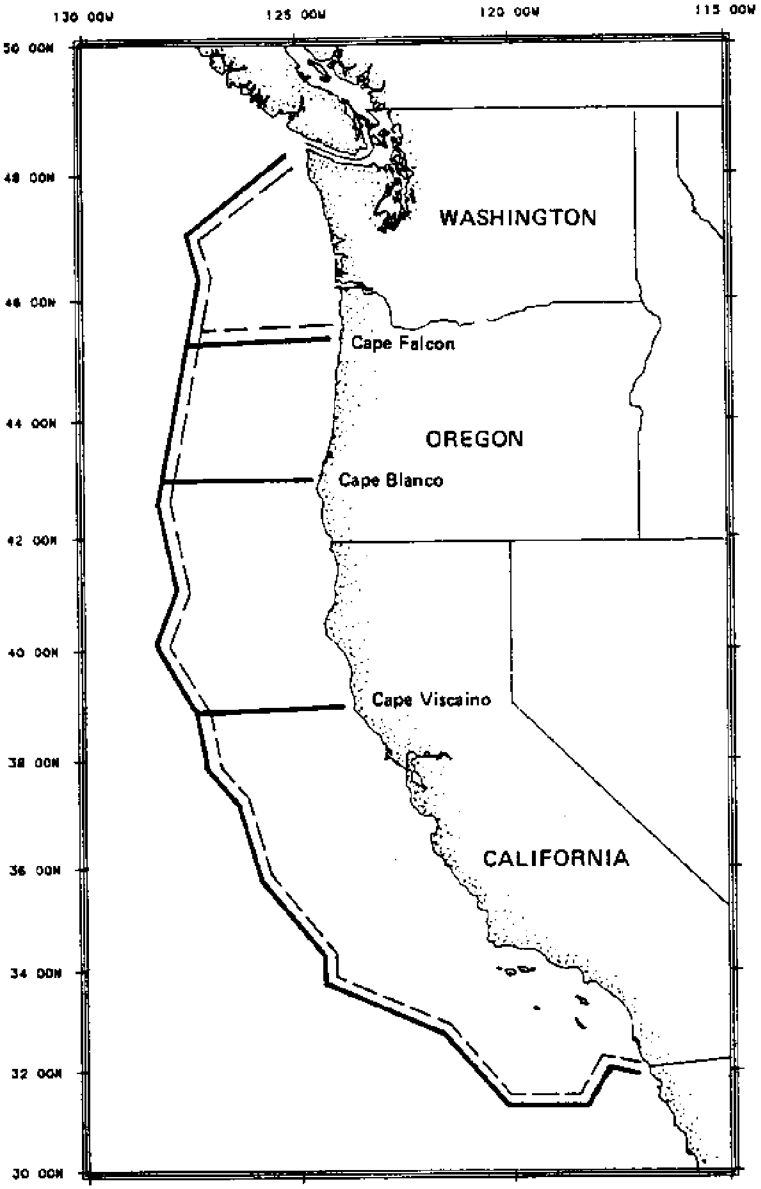

Figure 1.--Generalized chinook (solid lines) and coho (dashed lines) management area.

The 1983 Salmon Fishery

In this section we shall discuss the 1983 ocean salmon fishery in the context of performance versus plan during the 1982-83 El Nino event. All data are taken from the reviews of the 1983 and 1984 ocean salmon fisheries by the Council's Salmon Plan Development Team.

Chinook Fisheries

South of Cape Viscaino - The stocks in this area are managed for Central Valley fall chinook salmon. For management purposes, an abundance index for Central Valley chinook is computed as the total of ocean landings south of Point Arena together with the combined Central Valley adult chinook spawning escapements. The preseason forecast for Central Valley chinooks was projected to equal the 1982 abundance index of 756,000 fish. The 1983 abundance index was 350,000 fish or about 46% of the preseason estimate. The SPDT concluded "that the amount of error in the 1983 abundance forecast was due in large measure to the unquantified impact of the 1983 El Nino event on ocean natural mortality".

Cape Viscaino to Cape Blanco - The stocks in this fishery area are managed primarily for Klamath River fall chinook but include smaller coastal stocks of the northern California-southern Oregon coast. Ocean catches in this area come from mixed stocks and are not considered good indicators of Klamath River chinook abundance. Consequently the best indicator of stock condition is the in-river run size which includes an Indian net harvest, recreational harvest, and escapement to hatcheries and natural spawning areas. The preseason abundance forecast was for an in-river run size of 70,100 compared to the 1983 ocean escapement of 57,900 fish. For this fishery area the SPDT concluded "these declines are the apparent result of El Nino conditions prevailing along the west coast in 1983".

Cape Blanco to Cape Falcon - The stocks of chinook salmon in this fishing area consist of a mixture of local fall and spring runs to both hatchery and wild stocks. Most of the natural stocks from this area are north migrating stocks and also contribute to ocean fisheries off Washington, British Columbia, and Alaska so catch data must be interpreted carefully. The preseason forecast for chinook returns to area streams were projected to be similar to recent years. Ocean troll and recreational catches in the fishing area from Cape Blanco to Cape Falcon totaled 57,600 chinook or 63% of the 1971-75 average--and this smaller harvest resulted with increased fishing effort in 1983. Escapement counts to index streams were lower than the 1980-82 experience but high water conditions in 1983 may have reduced the effectiveness of the surveys. The SPDT concluded that "local salmon stocks were depressed in 1983...El Nino conditions were probably responsible for these decreased catches."

North of Cape Falcon - Chinook harvests north of Cape Falcon are composed of numerous stock groups but lower Columbia River fall chinook predominate in this area. A chinook harvest quota of 114,000 fish was established for the 1983 troll season. Total season landings for this ocean fishery area were 54,700 fish, or 48% of the quota. For the recreational fishery, a quota of 88,000 chinook was established but harvests totaled only 51,700 fish, or 59% of the quota. Abundance of the in-river run for lower Columbia River chinook was 135,500 fish as compared to the preseason estimate of 283,100 fish, or 48% of the preseason projection.

Coho Fisheries

Oregon Production Index area - This is the primary unit in management of the ocean salmon fisheries off Oregon and north of the Columbia River to Ledbetter Point (Willapa Bay). The OPI is simply the combined number of adult coho that can be accounted for within the area south of Ledbetter Point, Washington. It includes 1) the ocean sport and troll catches in the Columbia River area off Oregon and California, 2) Oregon coastal hatchery returns, 3) Columbia River in-river gillnet catch, Bonneville Dam and Willamette counts, hatchery returns to the Columbia River below Bonneville Dam, and 4) California hatchery returns. The OPI is judged to account for 90 to 95% of the actual stock size. A preseason abundance predictor for the OPI Index has been developed based on the number of two year old jack coho (precocious males) returning to selected hatcheries the year preceding. Based on the relationship using the 1977-82 database and the adjusted jack count of 90,200 fish returning in 1982, the total number of three year old adult coho to be expected to return in the OPI area in 1983 was predicted to be 1,553,600 fish. The actual or observed stock size in 1983 was 663,000 fish or 43% of the preseason prediction. The SPDT concluded "This large-scale difference is primarily the result of the extremely unfavorable ocean conditions brought on by the El Nino off the west coast in 1983".

North of Cape Falcon - Coho stocks in this area are a complex mixture of OPI area stocks, Washington coastal stocks, and stocks originating in the Strait of Juan de Fuca and Puget Sound. There are significant fisheries inshore of the ocean fishery and management must allow escapement from the ocean fisheries to provide for spawning escapements, Indian treaty obligations and inside fisheries. Preseason abundance estimates for coho were made for each major area or river system. In terms of percentage achievement of the preseason estimates postseason estimates of returns were 40% in Willapa Bay, 55% in Grays Harbor, 29% to 150% for natural runs in certain Washington coastal rivers, and 80% in the Strait of Juan de Fuca and Puget Sound.

Management in 1984

Review of results of the 1983 ocean salmon fisheries and escapements to the inside fisheries, hatcheries and spawning streams demonstrated that, coastwide, salmon were smaller than average and abundance was much less than preseason estimates. The SPDT concluded that oceanographic conditions associated with the El Nino were responsible for these severe impacts on ocean salmon production. The SPDT did not attempt to define the exact mechanism through which El Nino events affect salmon production nor did they attempt to predict oceanographic conditions for the upcoming season. Rather, the team considered the results of the 1983 fishery to be an estimate of the El Nino impacts and used that estimate to adjust their preseason estimates of stock abundance for 1984. It is important to remember here that all of the adult salmon to return in 1984 were in the ocean in 1983 and subject to the environmental conditions that affected the 1983 returns.

Management in 1984

The run size forecasts employed by the SPDT are based on observed relationships betwen adult production and resource indicators specific to each managemment unit. For example, the OPI estimates the abundance of adult coho from jack returns to defined index areas the year before; Columbia River chinook abundance forecasts are based upon relationships among in-river returns of fish at different ages within a cohort; other predictors are based on average return per spawner and a few include environmental affects such a stream flow conditions. Basic to the adjustment procedure is the assumption that the predictive relationships used are unbiased estimates derived from data collected under "normal" environmental conditions. Consequently, they will overestimate run sizes when ocean mortality exceeds the "average" such as that observed during the 1983 El Nino.

The procedure employed by the SPDT to adjust the preseason expectations for 1984 was to estimate the additional monthly stock mortality due to El Nino (from 1983 experience) and apply this for the period of time that El Nino conditions continued after the time at which stock predictors were measured. To determine this time, SPDT used elevated sea surface temperature as the best available indicator of El Nino affects. The team reviewed the available SST data and selected the period from May 1983 thru January 1984 as the time during which El Nino would have had an adverse impact on salmon stocks in the ocean.

A number of other assumptions were necessary to this analysis:

1. Run size estimates employed for regulation of the 1983 ocean fisheries are unbiased and represent accurate expectations of abundance under normal environmental conditions.

2. Deviations for predicted run sizes in 1983 are largely the result of El Nino and reflect differential stock impacts.

3. Impacts are not age specific within a cohort subjected to El Nino conditions.

4. El Nino increased the instantaneous rate of natural mortality by a constant amount regardless of time of the year.

5. The median times of river returns of coho and chinook jacks are September 15 and September 1, respectively; the median times of ocean entry of coho and chinook smolts are May 1 and June 1, respectively.

Figure 2 shows the estimated extent of the impact of the 1982-83 El Nino on different periods of life history by brood year and species. The procedure followed was to calculate an increased monthly mortality estimate based on the difference between predicted and actual 1983 run sizes. This monthly mortality figure (see (1) below) was then applied to estimated 1984 run sizes for the number of months (see (2) below) included in Figure 2 and presented in Table 1. The specific adjustment procedure was:

Adjustment Procedure

$$(1)\quad E = \frac{\ln(\text{postseason abundance estimate/preseason expectation})}{t}$$

where: E = instantaneous rate of increased monthly mortality attributed to El Nino impacts

t = time in months that adults returning to rivers in 1983 were subjected to increased water temperature after the time associated with parameters employed in the 1983 preseason run size forecasts.

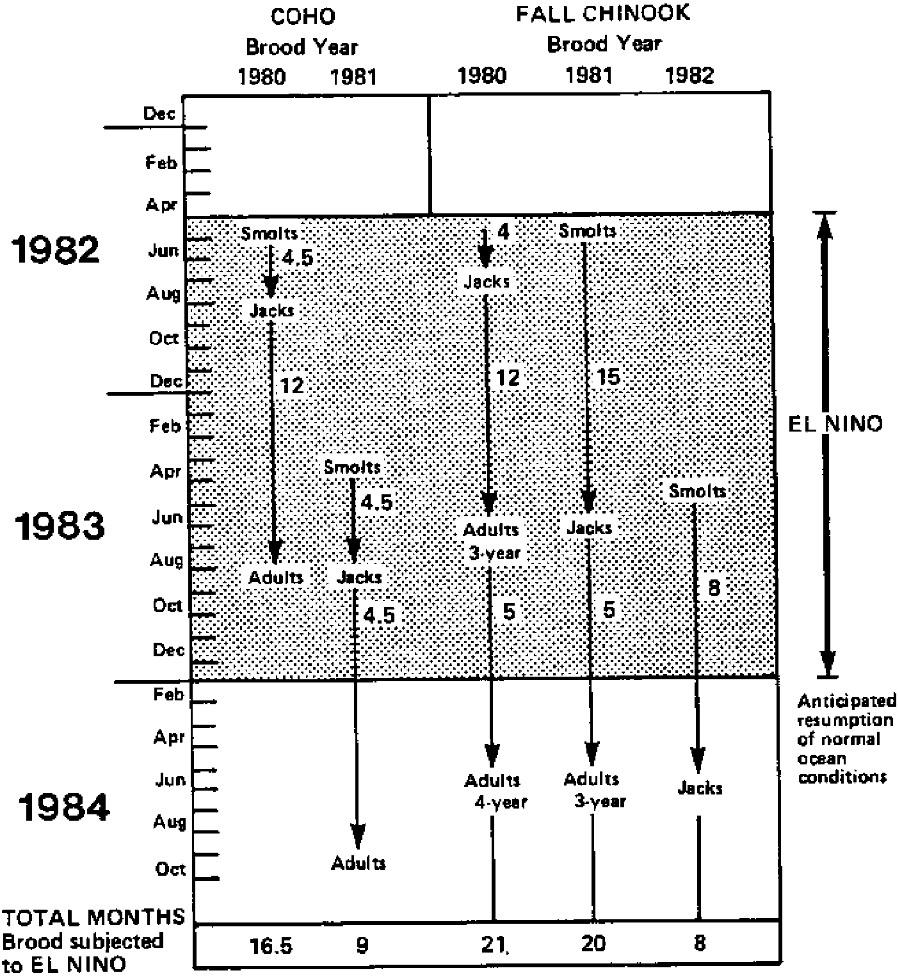

Figure 2.--Timing of elevated water temperatures associated with the 1983 El Nino event relative to life history of 1980-82 broods of chinook and coho salmon.

(2) Adjusted preseason = (exp(E x v)) x (unadjusted preseason expectation) run size expection
where: v = time in months after the 1984 preseason run size forecasts were made during which adults returning in 1984 are expected to be subject to increased ocean water temperature.

Values for t and v used in the adjustment procedure are provided below:

Forecast type	t	v
Coho		
OPI	10.7	4.5
Jack to terminal run	12.0	4.5
Average return/spawner	16.5	9.0
Average return/release	16.5	9.0
Escapement/streamflow	16.5	9.0
Fall chinook	12.0	5.0

There has been considerable discussion and criticism of some of the team's assumptions. Data has been presented indicating that temperatures may have returned to "normal" conditions before February 1984. Also, the assumption that impacts are not age specific has raised some concerns. Finally, even the team concedes that the impacts may vary considerably from stock to stock.

Preliminary 1984 Data

We can now look at some of the preliminary data for the 1984 salmon season to see how they fit in with the preseason expectations.

Size of salmon was a significant factor in the 1983 runs with fish being exceptionally small. As seen in Table 2, it is apparent that the coho salmon in 1984 are much larger than they were in 1983, even larger than average, indicating good growing conditions. Chinook salmon in 1984 were somewhat below average size. This condition, at least in part, was probably due to poor growth in 1983 and the consequent small size from last year carrying over into the start of 1984. They still were larger than they were in 1983.

There also were other indications that salmon abundance might be greater in 1984 than expected. Early returns from those salmon stocks with more northerly ocean migration patterns produced relatively better returns than those with more southerly ocean migrations. In the Columbia River, improved runs of steelhead, sockeye salmon and upriver chinooks occurred whereas the runs of lower river tule chinook again were poor in 1984. For coho, early indicators were that preseason run-size predictions would be reasonably close to actual performance.

The May chinook fisheries off Washington reached their quotas in only a few days; a seven-day fishery for the trollers and only a three-day fishery for recreational fishermen. California reported a large number of coho shakers in their chinook only fishery and requested that a coho fishery be permitted. California also

Table 1.--Estimated adjustments for anticipated impacts of El Nino to 1984 stock abundance forecasts by area and stock.

Area/Stock	1983 Abundance Estimates (1000 Fish)		Post-season / Pre-season	El Nino Adjustment Factor	1984 Abundance		
					Forecasts (1000 Fish)		
	Pre-season	Post-season			Unadjusted	Adjusted	Post-season
Coho							
OPI	1,553.6	657.9	.42	.69	806.6	556.6	658.7
Private Hatcheries	NA	NA	NA	.71	119.0	84.0	119.5
Willapa	70.0	27.8	.40	.61	52.3	31.9	88.6
Grays Harbor	103.3	56.3	.55	.72	56.4	40.6	NA
Washington Coastal	40.8	32.7	.80	.85	44.4	37.7[a]	72.8
Puget Sound	1,213.7	1,154.2	.95[b]	.89	1,187.8	1,064.8	NA
Chinook							
California Central Valley	756.6	350.6	.46	.72	651.9	469.4	504.3
Klamath	70.1	57.9	.83	.93	55.0	51.0	43.3
Columbia River							
Lower River							
Natural	26.4	18.3	.69	1.00[c]	NA	16.7	12.9
Hatchery	162.5	86.4	.53	.50[c]	NA	69.6	81.5
Upriver Brights	77.8	81.5	1.05	1.00[c]	NA	90.1	159.1
Bonneville Pool Hatchery	94.2	30.8	.33	.50[c]	NA	21.3	34.9

[a] Grouped data: team analysis by five units.

[b] Grouped data: adjusted for absence of Area 20 fishery.

[c] Calculated by Columbia River Management Group.

Table. 2--Average weight (pounds dressed) of troll caught salmon in 1984 compared with 1983 and 1971-75 average for California.

Months	1971-75 Average	1983	1984
	Chinook		
May	9.2	6.7	7.6
June	10.7	7.2	8.8
July	10.4	7.6	8.4
August	11.3	8.2	8.6
	Coho		
May	4.5	--	--
June	5.7	4.1	6.7
July	7.3	4.5	7.8
August	8.8	4.8	6.7

presented correlation data that suggested that coho abundance would be well above levels predicted for 1984. Also, the recreational fishery south of Cape Falcon, Oregon, which began on July 9 off Oregon, exceeded the coho quota of 106,000 by August 7. Finally, the July-August recreational fishery north of Cape Falcon reached its coho quota of 43,000 in only 12 days, while the troll fishery coho quota of 24,800 was exceeded by about 50% in only three days. These high harvests caused considerable concern that the El Nino adjustments had been unnecessary.

It was only after a complete compilation of catch and escapement data that a more accurate assessment of the lingering impact of El Nino on the 1984 salmon runs could be properly evaluated. Table 1 lists the actual returns for 1984 comparison with the adjusted estimates.

The conclusions of the SPDT were that for Chinook stocks, lingering effects of El Nino in 1981 seemed to have an inconsistent impact. Some stocks returned at levels above expected run sizes, while other stocks such as the Klamath River fall Chinook returned at lower than anticipated abundance.

For coho salmon, the SPDT noted that El Nino appeared to effect these stocks in a number of ways:

(1) Terminal run timing was highly unusual, (2) the size of coho in

the catch moderated potential stock differential impacts--Coho off California were almost twice as large in 1984 as in 1983 while coho off the entrance to the Strait of Juan de Fuca and late-run Columbia River stocks were unusually small, and (3) abundance of resident components of Puget Sound production were far lower than expected.

For OPI coho, the 1984 unadjusted, forecasted run size was 806,600. The forecast, after an adjustment for El Nino, was 556,600. Preliminary data indicates that the actual size of the 1984 OPI will be about 659,000 coho, at 18% below the unadjusted estimate but also 18% above the adjusted estimate.

The SPDT indicates there is little data in which to quantify any adjustments for negative El Nino impacts in Chinook run returning in 1985, but it is anticipated that El Nino will have little or no effect on coho runs returning in 1985.

Interannual Shifting of the Subarctic Boundary and Some of the Biotic Effects On Juvenile Salmonids

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Introduction

Zoogeographic boundaries of regionally distinct species assemblages have been described for the Oceanic Pacific by McGowan (1971, 1972). These unique regional pelagic fauna groupings are maintained and preserved by physical mechanisms such as semi-enclosed gyres which tend to conserve water mass characteristics. In addition to these established assemblages there are species or species groups found "down-stream" from centers of stable populations which must respond to more transient environmental states to maintain themselves at their range boundaries. These groupings, in contrast to those maintained within distinct water types, experience dynamic and seemingly unpredictable fluctuations.

Extensive field programs in the 50s and 60s led to the definition of smaller oceanographic subdivisions or "domains" within the Pacific Subarctic water mass (Fig. 1) based on analysis of temperature, salinity and oxygen measurements (Dodimead et al. 1963; Favorite et al. 1976). The Subarctic current system (Fig. 2) divides as it crosses the North Pacific; one portion proceeds in an cyclonic direction to form the Alaskan gyre; the other portion flows in a anticyclonic direction to form the California current. Chelton (1984) postulated that much of the observed interannual variability of ocean climate in the Northeastern Pacific is related to the relative proportions of northward and southward flowing water. Wickett (1967) correlated the interannual variability of zooplankton volumes in the California Current system from 1951 to 1960 with the input of nutrients via the southerly component of Ekman transport at 50°N, 140°W, 1200 miles "upstream" in the previous year. He estimated that fifty to sixty percent of the observed variance of the annual concentration of zooplankton off California was due to advection of nutrients.

Within the Pacific Subarctic water mass each domain can be characterized by general biological features. In the Central Subarctic domain for example, phytoplankton standing crops are relatively low and phytoplankton production is believed to be

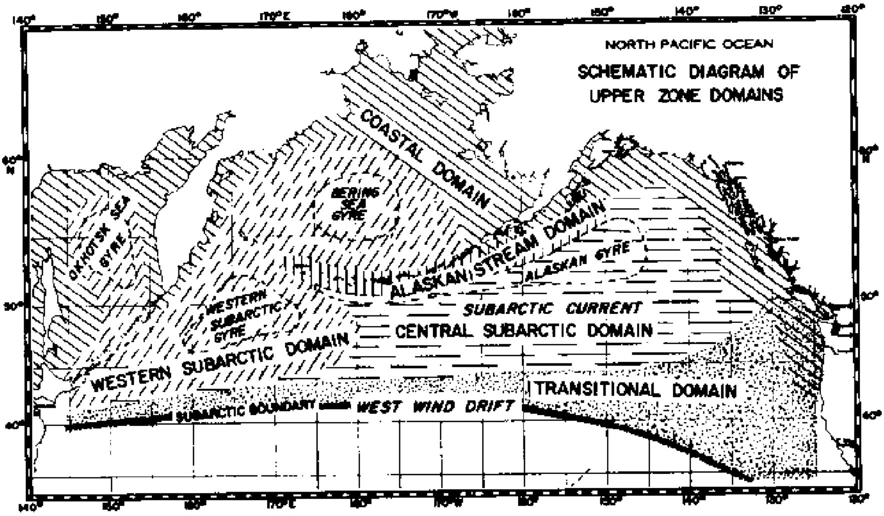

Figure 1. Schematic diagram of upper zone domains (from Oodimead et al. 1963).

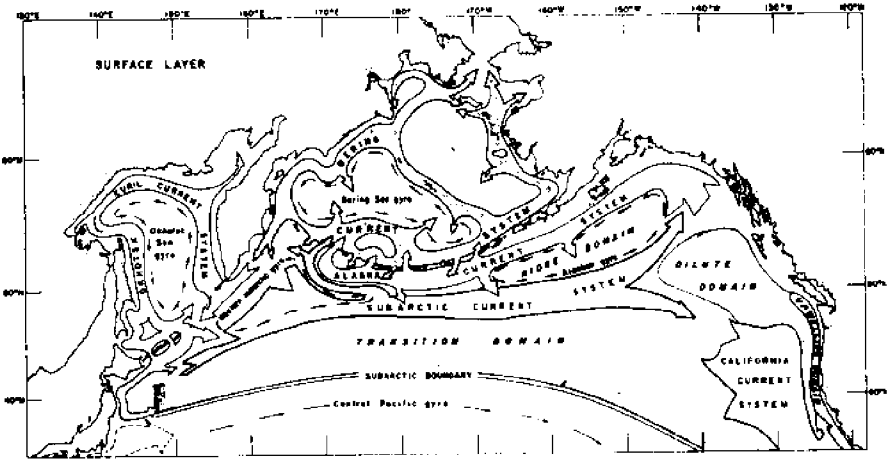

Figure 2. Schematic diagram of surface currents in the Subartic Pacific region (from Favorite et al.1976).

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controlled by zooplankton grazing (McAllister et al. 1960; Frost 1983); two relatively large herbivorous copepods (*Neocalanus plumchrus* and *N. cristatus*) make up 70-80% of the coarse mesh (.350 mm) zooplankton (LeBrasseur 1965; Miller et al. 1984) and finally, the endemic commercially important carnivores in the system are anadromous fishes (salmon) which enter the ocean at a relatively large size and change from plankivores to piscivores as they grow (LeBrasseur 1972). In contrast, in the California Current system which is made up of varying proportions of water from the transitional, Central Subarctic and Coastal domains, the phytoplankton standing crop may be high and is not limited by grazing; many species of small copepods (e.g. *Calanus* spp., *Mesocalanus* spp., *Paracalanus* spp., *Clausocalanus* spp., *Acartia* spp.) make up a relatively smaller portion of the zooplankton biomass which is generally lower than in the Subarctic (Fleminger, Issacs and Wyllie 1974); and the commercially important fish endemic to the system, the Pacific sardine (*Sardinops sagax*) and the northern anchovy (*Engraulis mordax*), are planktivorous (herbivorous and omnivorous).

This report illustrates some of the effects that variations in intensity of ocean circulation may have on some faunal distributions. Extreme northward shifting of the Subarctic boundary occurs during EL NINO years such as 1957-58. A number of Central Subarctic species are carried southward by the California current system during "normal" years; some exhibit relatively stable populations which may have become genetically or physiologically distinct from the parent population (eg. *Calanus pacificus* var. *californiensis*); some may form breeding populations which expand and retreat in unison with the strength of the southward transport (eg. *Euphausia pacifica*) (Brinton 1962); and still others rely on annual recruitment from the Central Subarctic water domain (eg. *Neocalanus cristatus* and *N. plumchrus*) (Bowman and Johnson 1973). This pattern of responses within the system is also supported by biomass data from large scale plankton surveys made between 1956 and 1963 (LeBrasseur 1965a). We postulate that planktivorous fish living in the open ocean adjacent to the west coast of North America) are affected by interannual fluctuations in southward transport of zooplankton biomass. We hypothesize major shifts in the particle size spectrum (see Parsons 1969) of the zooplankton community has a greater impact on planktivorous fish than do changes in biomass alone.

Methods

Approximately 5,000 zooplankton samples were collected during oceanographic and exploratory fishing surveys from 1956 to 1964. Vertical plankton hauls were made from 150 m to surface with a standard NORPAC net with a mouth opening of 0.16 m^2 and a mesh of .330-.350 m white nitex (Fulton 1983). Samples were preserved in 4% formaldehyde.

In the laboratory major taxa were identified and weights estimated as a percentage of the total sample weight. Organisms larger than 4 cm, including fish and squid, were weighted separately. The remaining sample was weighed to the nearest 0.1 g after draining and blotting on paper towelling. The estimated weight of phytoplankton, coelenterates, thaliacea and detritus was subtracted from the sample wet weight to arrive at zooplankton wet weight. For plotting zooplankton biomass distributions data were pooled into time intervals covering the spring bloom (April through June).

We define the boundary between the Central Subarctic and the transitional domains (Dodimead et al. 1963) as a line which separates biomass estimates greater or lesser than 80 mg/m^3 during the time period encompassed by the spring bloom of zooplankton as observed at Ocean Station P (50°N, 145°W). The value of 80 mg/m^3 represents the minimum annual biomass peak observed at Station P over a 26 year period (Fulton 1983). We assumed that Station P was always within the Central Subarctic Domain (Fig. 1). Biomass estimates for the California current region were taken from Fleminger et al. (1974) but adjusted by subtracting the thaliacea biomass in order to be comparable with the present sampling protocol.

As a measure of the relative strength of southward transport of Central Subarctic water (Table 1) we have chosen the annual mean meridional Ekman transport at 50°N, 130°W (Ballantyne and Wickett 1978).

Table 1. Zooplankton biomass in the Northeastern Pacific during the period April through June, compared with April biomass in the CalCOFI region. Ekman transport is shown to indicate the relative volume of the southwards flow. Figures in brackets indicate the number of observations; N/S indicates no samples taken; ? indicates no distinct boundary conditions.

Year	Subarctic biomass mg/m^3	Transition biomass mg/m^3	April CalCOFI biomass* mg/m^3	Annual Mean Ekman transport @ 10 metric T/sec/km
1956	183(36)	14(6)	102(172)	-15.3
1957	155(168	51(5)	69(205)	-10.0
1958	131(81)	45(6)	32(264)	-0.7
1959	218(65)	31(30)	34(247)	-18.4
1960	43(32)?	N/S		-12.0
1961	64(46)?	?		-12.8
1962	154(330)	38(50)		-13.9
1963	211(177)	N/S		-5.3
	$\bar{X}$=147(854)	$\bar{X}$=35(97)	$\bar{X}$=72(888)	$\bar{X}$=-11.1

*CalCOFI biomass is estimated from Fleminger et al. 1974 (Fig. 4) omitting THALIACEA biomass for comparison with sampling methods used in LeBrasseur (1965a).

@Annual mean Ekman transport at 50°N, 130°W is from Ballantyne and Wickett (1978). Negative values indicate southwards flow.

Results

For the spring bloom period between 1956 and 1963 (LeBrasseur 1965a) we examined eight zooplankton biomass charts. The boundary between the Central Subartic and the Transitional domains could be identified by the above criterion in six cases. The mean biomass within the area defined as the Central Subarctic was 147 mg/m^3, for the Transiction domain 35 mg/m^3, and for the California Current System 72 mg/m^2 (Table 1). Biomass in 1960 and 1961 (the two years when no boundary could be defined) for all positions sampled in the Central Subarctic domain was generally as low as the average Transition biomass (35 mg/m^3). Biomass which we consider to be of Subarctic origin (>80 mg/m^3) extended southward to the coasts of Washington and Oregon in 1957 (Fig. 3) and again in 1963 (Fig. 5).

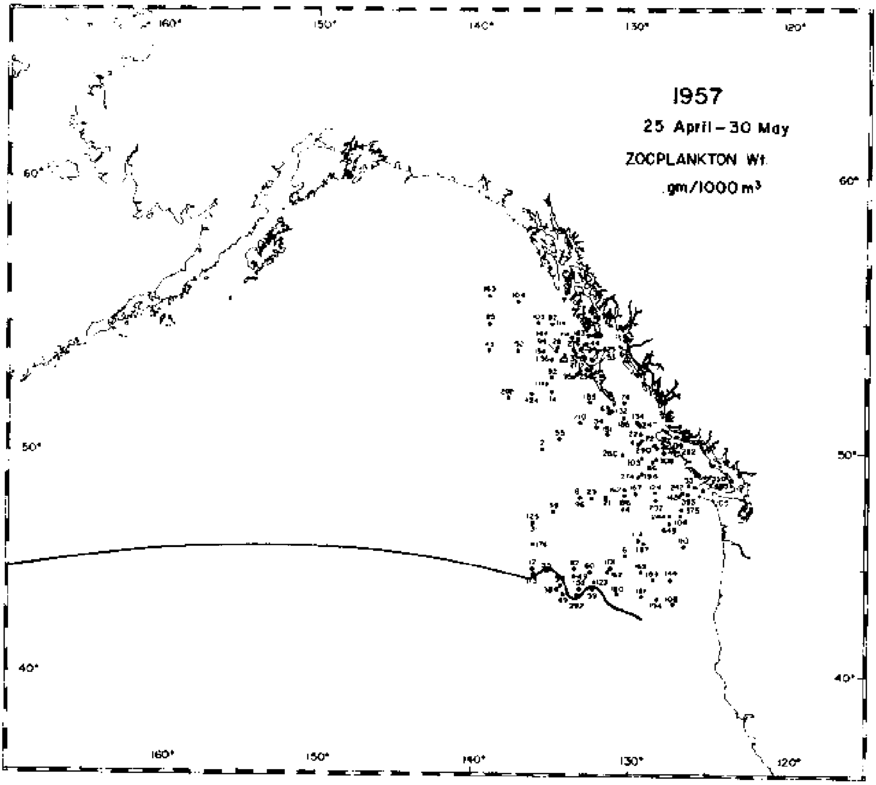

Figure 3. Distribution of zooplankton biomass - 1957.

In 1963 the Subarctic origin of this biomass was clearly identified by the presence of large numbers of <u>Neocalanus cristatus</u> and <u>N. plumchrus</u> which made up more than 80% of the wet weight; in 1956-61 zooplankton species were not identified. In 1958 during the period 22 May-10 June, biomass characteristic of Transitional water occupied a band about 500 km wide, extending northwards from about 45°N to the Queen Charlotte Islands (52°N) (Fig. 4). This northern extension of the Transitional domain was independently confirmed by physical measurements (Dodimead et al. 1963).

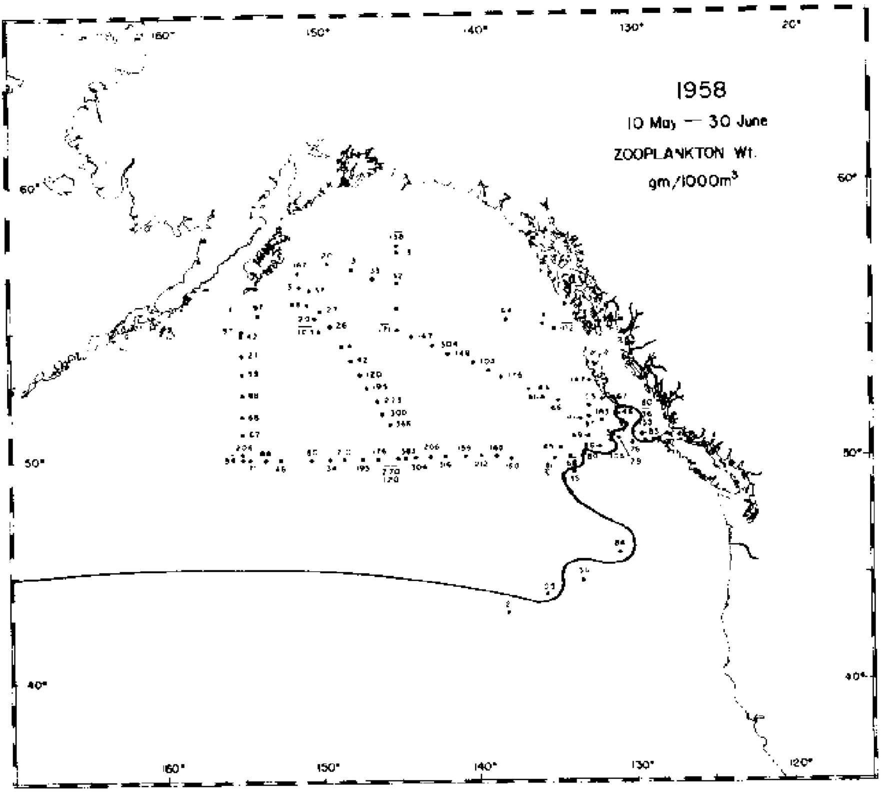

Figure 4. Distribution of zooplankton biomass - 1958.

Discussion

Greater than average southward transport of Central Subarctic water has been shown to affect secondary production in the California current system (Reid 1962; Wickett 1967; Colebrook 1977; Chelton et al. 1982). Suggested mechanisms have emphasized advection of nutrients from the Central Subarctic and entrainment of subsurface nutrients in proportion to the strength of the current. Nutrient transport appears to be accompanied by transport of Central Subarctic fauna and biomass. For example, Neocalanus plumchrus and N. cristatus both are present, sometimes in high numbers, south of Cape Mendocino (Fleminger 1964; Bowman and Johnson 1973). Our data show interannual variability of zooplankton biomass and, in the two years for which we have data which include species counts as well as biomass estimates (1962 and 1963), a corresponding shift in the species (size spectrum) of zooplankton along the coast of North America from at least the Queen Charlotte Islands to Cape Mendocino (Fig. 6).

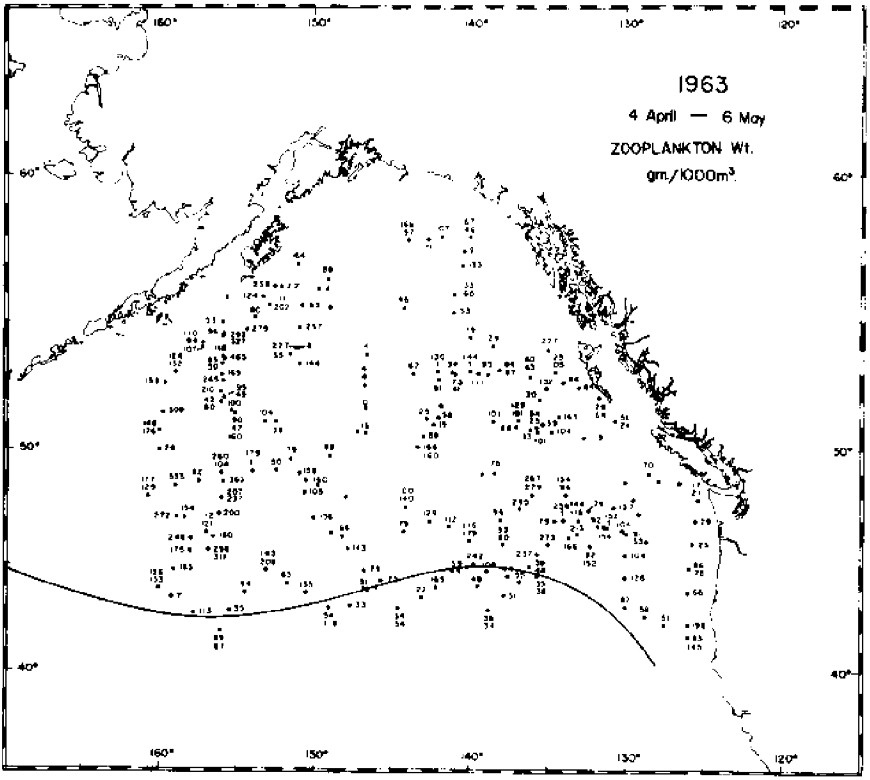

Figure 5. Distribution of zooplankton biomass - 1963.

Salmonids feed opportunistically in marine environments (see, for instance Healey 1980). In general, prey size is limited on the upper end by the gape of the mouth and on the lower end by the ability to detect and capture prey. It has been shown experimentally that juvenile pink salmon (Oncorhynchus gorbuscha) can meet their feeding requirements most efficiently on large food particles (Parsons and LeBrasseur 1970). Juvenile pink salmon fed rations of N. plumchrus (ca. 2.5 mg) obtained theoretical food requirements at prey concentrations of approximately 4,000 copepods/m^3 (10,000 mg/m^3) while those fed rations of Pseudocalanus minutus (ca. 0.1 mg) could not meet theoretical food requirements at prey concentrations of >670,000 copepods/m^3 (>67,000 mg/m^3). Although basic requirements of predator/prey models are violated by the restricted space in small aquaria (i.e. the predator should search an "infinite" optical field), these results indicate that N. plumchrus is closer to the optimal prey size for juvenile salmonids (ca. 5-10 g) than is P. minutus or other small copepods We speculate that a decrease in biomass further exaggerated by a reduction in zooplankton particle size would cause reduced growth and, possibly, reduced survival of juvenile salmonids.

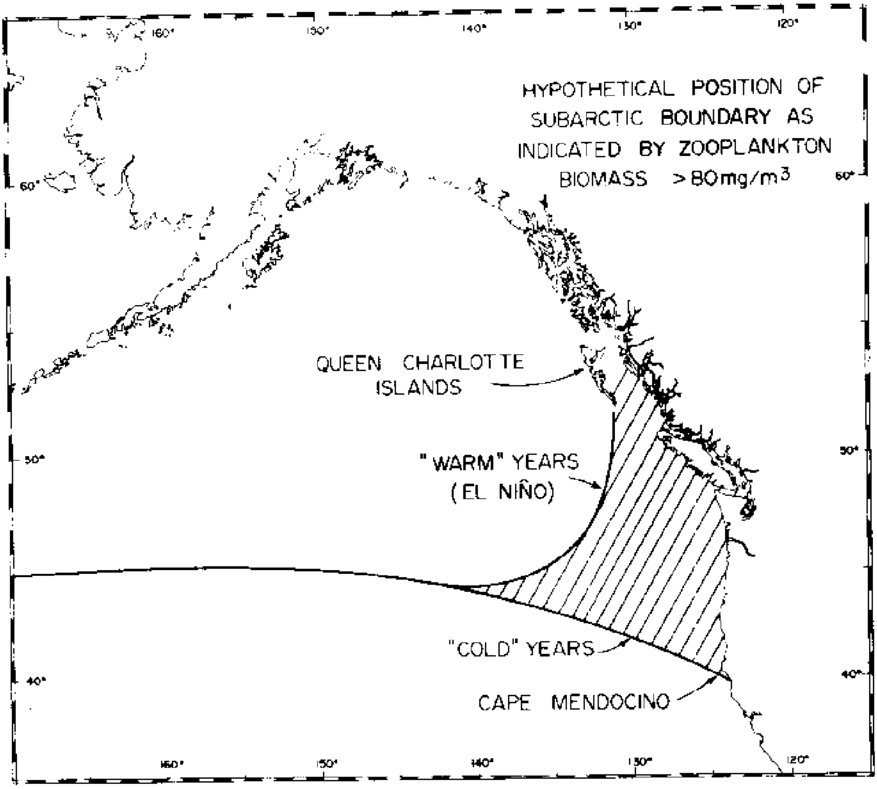

Figure 6. Schematic diagram of the area affected by shifting of Subarctic boundary.

Extreme northward shifting of the Subarctic boundary occurs during El Nino years such as 1957-58. We have attempted to show that one of the effects of such a shift is to alter the zooplankton community off the coast of North America for approximately 800 km from 40°N to 52°N by replacement of large copepods with small copepods. We have used hypothetical changes in feeding efficiency during the early sea life of juvenile salmonids as an example of one kind of effect that variations in ocean transport could have on a commercial fish stock. Effects of this type of environmental perturbation should increase from north to south, and should be mediated by the buffering action of nursery environments such as large bays, estuaries, and protected coastal waters. It will also vary between species and phenotypes.

The problem of linking a decline in commercial fish stocks to changes in ocean climate is difficult to resolve. Long term fluctuations in abundance of fish populations in the California Current system have been estimated from the examination of fish scales in the undisturbed sediments of the anoxic Santa Barbara

Basin (Soutar and Issacs 1974). Since these records extend back in time prior to commercial exploitation, they implicate changes in ocean climate as a cause of persistant instability. The existing data base is insufficient to provide any more conclusive analysis and we suggest a useful hypothesis relating ocean transport, prey size spectrum and biomass, and feeding success that could be field tested, considering the time and space scales identified here.

Acknowledgments

Suggestions from Drs. Kees Groot, Kim Hyatt, John Mason and Dan Ware substantially improved the manuscript. We gratefully acknowledge their helpful suggestions.

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Appendix: Summary of Unusual Sightings of Marine Species Off British Columbia During the 1982–83 El Niño

Compiled by John D. Fulton

Species	Location	Time	Source of record and remarks
1) Extensions of Northern Range			
FISH			
Synodus lucioceps (California lizard fish)	Cape Beal (Bradys Beach)	Aug. 15	Bamfield Marine Station (Bergey)
Xiphias gladius (Swordfish)	47°01.1'N, 130°24'W	Sept 20/83	PBS, caught in gill net (Sloan)
= previous record	46°01.1'N, 128°39.4'W	June 30/82	Univ. of Victoria (Tunnicliff)
Remora remora	46°42'8 N,131.25.0'W	Aug 4/83	PBS (Robinson)
PLANKTON			
(Copepod) *Acartia danae*	48°49.0'N, 128°37.4'W	Sept 20/83	IOS plankton haul (Ashton)
= previous record	46°32'N, 125°57'W	Sept 1935	Davis (1949)
2) Isolated sightings			
FISH			
Genyonemus lineatus (White croaker)	Swanson Channel	March 83	B.C. Provincial Museum (Teden)
Seriola lalandi dorsalis (Yellowtail)	47°57.0'N, 130°50.0'W	Aug 5/83	B. C. Provincial Museum (Teden)

Species	Location	Time	Source of record and remarks
Trachurus symmetricus (Jack mackerel)	47°33.0'N, 131°12.4'W	Aug 2/83	B. C. Provincial Museum (Teden)
	Barkley Sound	July 12/83	(Bauer)
Engraulis mordax mordax (Anchovy)	Quatsino Sound	Nov 18/83	B. C. Provincial Museum, young small specimens indicate spawning? (Teden)
2) Isolated sightings (cont'd)			
FISH			
Sardinops sagax (Pacific sardine)	Clayoquot Sound	Aug 83	Schooling with anchovy (Dawson)
INVERTEBRATES			
Emerita analoga (California sand crab)	Kyuquot Sound	Aug 83	Juveniles on Sand Beach (Austin)
BIRDS			
Puffinus occidentalis (Brown pelican)	Victoria	July 24/83	(Hill)
	Denman Island	July 27/83	(Sparrowhawk)
	Cape Beal	Aug & Nov 1983	Bamfield Marine Station (Bergey)
Puffinus bulleri (New Zealand shearwater)	Cape Beal	Aug-Nov/83	Bamfield Marine Station (Bergey)

Species	Location	Time	Source of Record and Remarks
Puffinus creatopus (Pink-footed shearwater)	Cape Beal	Aug-Nov/83	Bamfield Marine Station (Bergey)
Thalasseus elegans (Elegant tern)	Queen Charlotte Islands	Summer '83	(Phillips)
Sterna caspia (Caspian tern)	Queen Charlotte Islands	Summer '83	(Phillips)
Steganopus tricolor (Wilsons phalarope)	Queen Charlotte Islands	Summer '83	(Phillips)
REPTILES			
Dermochelys schlegelii (Leatherback turtle)	Off Nootka Sound	July '83	(Cary)
PLANKTON			
1) Copepods:			
Scottocalanus persecans	Queen Charlotte Sound	May '83	(Ashton)
Pleuromamma xiphias	50°43.0'N, 131°08.3'W	Aug '83	(Ashton)
2) Isolated sightings (cont'd)			
Heterostylites longicornis	54°43.0'N, 131°08.3'W	Aug '83	(Ashton)
Arietellus plumifera	50°43.0'N, 131°08.3'W	Aug '83	(Ashton)
Aegisthus macronatas	50°43.0'N, 131°08.3'W	Aug '83	(Ashton)

Species	Location	Time	Source of Record and Remarks
3) Widespread Sightings			
INVERTEBRATES			
Velella velella (By-the-Wind-Sailor)	B. C. Coast	Mar-Sept '83	Many sightings all summer on outer coast.
FISH			
Mola mola (Ocean sunfish)	B. C. Coast & Juan de Fuca Strait & Johnstone Strait	Mar-Nov '83	Numerous sightings
Scomber japonicus (Chub/Pacific Mackerel)	B. C. Coast & Strait of Georgia	June-Dec '83	Particularly abundant in Barkley Sound (486 fish in one seine set)
Sarda chiliensis (Pacific bonito)	B. C. Coast	July & Sept '83	Several sightings
Brama japonica (Pomfret)	Edge of Continental Shelf, Dixon Entrance	Aug '83	Catches on set lines
PLANKTON			
1) Copepods			
Mesocalanus tenuicornis	B. C. Coast	Spring & Summer '83	(Ashton)
Lucicutia flavicornis	" "	"	"
Ctenocalanus vanus	" "	"	"

Euchirella curticaudata	" "	" "	"
Euchirella rostrata	" "	" "	"

3) Widespread Sightings (cont'd)

PLANKTON (cont'd)

2) Molluscs:

Euclio pyramidata	B. C. Coast	Spring & Summer '83	(Ashton)

3) Salps:

Salpa fusiformis	" "	"	"

Records and Sightings of Fish and Invertebrates in the Eastern Gulf of Alaska And Oceanic Phenomena Related to the 1983 El Niño Event

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This report presents records of sightings and captures of unusual marine species from the eastern Gulf of Alaska during the 1982-83 El Nino event and, where possible, relates the occurrence of the species to anomalous oceanographic conditions. Surface water temperatures of the locations were not reported at the time of observation or capture; therefore, specific oceanographic conditions synoptic with the biological data are unavailable.

General information on surface water temperatures may indicate the relationship between the mass of anomalously warm water and the occurrence of unusual marine species in the eastern Gulf of Alaska. Anomalously warm surface water began developing in southeastern Alaska and Prince William Sound by October 1982 (Fluharty, 1984). By March 1983, all of the eastern Gulf of Alaska and the Bering Sea were unusually warm (>+0.5°C), with the warmest (+1.5°C) off southeastern Alaska. The warm water anomaly continued in the eastern Gulf of Alaska and southeastern Alaska inside waters until August (Fluharty, Fig. 2 and Table 1, 1984). By August, the warmest cell of surface water in the Gulf of Alaska had moved westward to southeast of Kodiak (56°N, 148°W). A cooling of southeastern Alaska inside waters and the far eastern Gulf of Alaska followed in September and October. The warm water anomaly reestablished in the eastern Gulf of Alaska by March 1984.

Northwest shifts of warm water marine species have been reported in previous years (Radovich, 1961). Most reports have been linked to the occurrence of strong to very strong tropical El Nino events; 1941, 1957-58, 1977, 1982-83. Northward displacement of marine species has been envisaged as coincident with the northward displacement of usual sea surface temperatures (Hamilton and Mysak, in press) and northward shifts of major oceanographic features (French et al., 1971). General warming of northern surface waters and major shifts of oceanographic features are undoubtedly causative factors involved in biological displacements, but interannual variable development of eddies in the northeast Pacific Ocean (Mysak, 1985) may be an important factor in moving southerly species well north of the usual ocean boundary features.

The Sitka Eddy (Mysak, 1985; Hamilton and Mysak, in press) is an anticyclonic (clockwise) eddy that develops intermittently at 57°N, 140°W in the eastern Gulf of Alaska. A satellite thermal image of the sea surface shows the clockwise motion of the eddy (Mysak, Fig. 6, 1985) and the mixing of cold and warm water on the eddy perimeter. This figure and others (Ron Scheidt, personal communication, 1984) show that masses of warmer water frequently break off from the eddy and are carried northeasterly by the prevailing current until they join the northwesterly flow of the Alaska current. These large warm water masses are probably carried with the Alaska current, to the vicinity of Prince William Sound and then west to Kodiak Island, and may even be incorporated into other eddies which develop in these regions (e.g., Shelikof Eddy; Mysak, 1985). Warm water fish within these warm water masses may thus be carried far north of the prominent ocean temperature boundaries.

As the Sitka Eddy develops, it has been noted to move in a northwesterly direction across the Gulf of Alaska (Mysak, 1985). This motion and the spawning of smaller warm water masses as it rotates clockwise may also move warm water species further northward.

Warm water species (i.e., bluefin tuna, blue shark, and albacore) are frequently reported from Prince William Sound and Shelikof Strait (Radovich, 1961, and this report). It is germaine to the hypothesis of eddy involvement in the movement of fish northward to point out the apparent correlation between sightings of California bluefin tuna in Shelikof Strait near Kodiak (Radovich, 1961) and the presence or absence of the Sitka Eddy (Mysak, 1985). Radovich reported northward movements of warm water species in 1957, 1958, and 1959. California bluefin tuna (Thunnus thynnus) was reported to occur in Shelikof Strait in 1958 but not in 1957 or 1959. Coincidentally, the Sitka Eddy was well developed in 1958 but not in 1957 or 1959 (Mysak, Table 1, 1985). This eddy development was associated with a very strong El Nino with an intense warming trend beginning the summer of 1957 and ending in summer 1958 (Hamilton and Mysak, in press). These eddy and fish observations may be simply coincidental or correlated; hopefully, data provided in this report will help resolve the question. Currents within the Sitka Eddy are known to extend to as deep as 1,000 m (Mysak, 1985) and therefore could affect pycnocline depth within the eddy and in nearby areas as the warm waters mix with cold waters. Changes in pycnocline depth may thus influence biological productivity of the area.

The Sitka Eddy was present in 1954, 1958, 1960, 1961, 1977, and 1983 (Mysak, 1985) and shows signs of developing in 1985 (satellite image 8 February 1985). In addition to explaining movement of warm water fish species to the northern part of the Gulf of Alaska, the Sitka Eddy may also assist in moving offshore species toward Cross Sound and inside waters of southeastern Alaska.

Methods

Records of unusual sightings or captures of marine species were collected from research vessels, fishermen, commercial fish processors, and State and Federal fisheries scientists. These groups were asked to report any unusual sightings during the 1982-83 El Nino event; therefore, the reporting may be somewhat biased over non-El Nino years. Nevertheless, we expected reports of very unusual species during all years. Rare or more common sightings may, however, go unreported during non-El Nino years. Data collected under a continuing oceanographic surveillance were summarized for this study. Daily surface water temperatures at Sitka and Auke Bay for the years 1975-1983 were summarized monthly by personnel of the Auke Bay Laboratory. Unusual oceanographic phenomena were noted during submarine diving operations off southeastern Alaska in 1983.

Responses of fish to temperature changes are reviewed and discussed in relation to temperature anomalies and pelagic fish distribution in the eastern Gulf of Alaska. Identity of fish were confirmed using Eschmeyer et al. (1983).

Results

Oceanographic phenomena. Anomalously warm surface temperatures were recorded in both the outer coastal and inside passage waters of southeastern Alaska during 1983 (Table 1). For the outer coastal waters, greatest differences from the mean surface temperatures were in June and July and followed general trends reported for the eastern Gulf of Alaska (Fluharty, 1984). Inside waters warmed rapidly in April and had higher temperatures and anomalies from the mean (May-July) than outside waters. The maximum anomaly in Auke Bay was +2.1°C. The inside waters began cooling rapidly in August, then slower by November--again showing a positive anomaly by the end of the year.

Anomalous warming of subsurface waters also occurred off southeastern Alaska in 1983 (Mysak, 1985). An observation of an anomalous subsurface layer of phytoplankton off southeastern Alaska supports the idea that changes in the pycnocline depth may influence biological productivity.

On 13 August 1983, at 35.2 km west of Klokachef Island, which is off the coast of the Khaz Peninsula on Chichagof Island, an unusually dense layer of phytoplankton was observed from a manned submersible at 9-27-m in water of 128 m depth. The presence of a phytoplankton layer deeper than 2-10 m signifies a change from usual conditions (Straty, personal observation). We did not observe this phenomena at over 40 locations off the coast of southeastern Alaska surveyed by submersible during late July and early August 1978 and 1980. Off the coast of southeastern Alaska (to 35.2 km offshore), the water generally appeared more turbid in 1983 than during the same monthly periods in 1978 and 1980.

Table 1.--Water surface temperatures representative of southeastern Alaska during 1982-83 El Nino.

	Outer coast (Sitka)				Inside passages (Auke Bay)			
Month	Mean 1975-81	1982	1983	1983 anomaly	Mean 1975-81	1982	1983	1983 anomaly
Jan	5.1	5.0	5.6	+0.5	3.6	3.7	3.6	0
Feb	4.6	4.2	5.7	+1.1	3.1	2.6	3.4	+0.3
Mar	5.0	4.8	6.1	+1.1	3.6	3.1	4.0	+0.4
Apr	6.4	5.9	7.5	+1.1	5.4	4.9	7.0	+1.6
May	9.0	7.7	9.8	+0.8	8.5	8.0	10.6	+2.1
Jun	11.4	12.2	12.9	+1.5	12.6	14.5	14.0	+1.4
Jul	13.3	12.5	14.8	+1.5	13.3	15.3	15.4	+2.1
Aug	14.4	13.4	14.9	+0.5	13.7	14.6	12.3	-1.4
Sep	12.5	12.4	12.7	+0.2	10.8	11.6	10.6	-0.2
Oct	9.9	9.5	10.3	+0.4	7.6	7.6	7.6	0
Nov	7.5	6.8	7.8	+0.3	5.7	5.3	6.0	+0.3
Dec	5.8	6.4	6.0	+0.2	4.5	4.4	5.0	+0.5

Note: Water surface temperatures are more representative of oceanic conditions at Sitka, Alaska than at Auke Bay, Alaska. Water surface temperatures of Auke Bay, Alaska, and the inside passages are strongly influenced by local weather and the warming and cooling of surrounding terrain. Beginning August 1983, dense cloud cover and high rainfall reduced incoming solar radiation and resulted in an unusually early cooling.

Occurrence of Unusual Species. As in 1941 and 1958, the 1983 El Nino event apparently caused the presence of southern or tropical species of fish and invertebrates far north of their normal range. Anomalous occurrence of five species of sharks and rays, seven species of bony fish, four invertebrates, and one reptile in Alaska waters were reported during 1982-83 (Table 2). Several of the reports for sharks and rays were unconfirmed. Specimens of most bony fish and the invertebrates were taken. The significance of southern or tropical species in Alaska waters varies with the species and can only be based on subjective opinion, because systematic sampling has not been conducted in normal versus El Nino years.

Sharks and rays, in subjective order of significance, are Pacific manta, tiger shark, white shark, blue shark, and spiny dogfish. White shark, blue shark, and spiny dogfish have been previously reported in Alaskan waters. Pacific manta and tiger shark are apparently new sighting records.

Bony fish reported, in order of significance, are black durgon (a triggerfish), Pacific bonito, California barracuda, ocean sunfish, albacore, Pacific pomfret, and American shad. All these species except the black durgon have previously been reported in eastern Gulf of Alaska. Black durgon captured in Alaska is a range extension; it has not been previously reported north of San Diego, California.

The significance of the occurrence of invertebrates is even less well known than that of fish. Collection of flying squid, market squid, a pteropod (Clio pyrimidata) and an arrow worm (Sagitta scrippsae) in Alaska are reported. The significance of these occurrences is unknown because we know little about normal distributions. All four species are associated with waters that are warmer than those usually encountered near the Alaska coast. The leatherback turtle has been previously reported in Alaska during warm-water years (data on file at Auke Bay Laboratory).

Temperature Changes and Species Distribution. Fish respond to temperature changes by behavioral and physiological adjustments (Crawshaw, 1977). "Temperatures selected by fishes very likely represent temperatures at which they have evolved to carry out physiological functions with maximum efficiency" (Crawshaw, 1977). Fishes can internally adjust (acclimate) to different thermal environments. However, once a fish is acclimated to a particular temperature for a period of time, even small changes (<1.0°C) lead to major shifts in metabolism, fluid electrolyte balance, and acid-base relationships. Temperature preference behavior, therefore, has a survival value based on physiological parameters.

Fish respond behaviorally to a range of preferred temperatures, have upper and lower avoidance temperatures and a final preferred temperature dependent upon both internal and external variables; e.g., food availability, spawning condition, physiological status, disease, etc. (Reynolds, 1977). The range of temperature between upper and lower avoidance varies <2°->10°C

Table 2.--Summary of unusual marine species--eastern Gulf of Alaska 1982-83.

Species	Location	Date	Source[1]	Comments[2]	Associated with El Nino?[3]
Lampreys					
River lamprey *Lampetea ayresi*	Doty Cove	Jul 1983	ADFG	River lamprey are known to have reproducing populations in the Taku River and other southeastern streams.	No
	Taku River	Jul 1983	ADFG		
Sharks					
White shark *Carcharodon carcharias*	Cross Sound	Summer 1983	Straty-ABL	Confirmed by specimens.	Possible
	Stephens Passage (Hobart Bay)	Aug-Sept 1983	Straty-ABL	Unconfirmed sightings (salmon sharks also seen).	Possible
	Lynn Canal	Mar 1984	Straty-ABL	Unconfirmed (reported chummed, killed but lost).	
Blue shark *Prionace glauca*	Kodiak	Oct 1983	ADFG	Confirmed by specimens.	Probable
	Southeastern AK (outer coast)	Jun-Sept 1983	ADFG	Unconfirmed sightings by reliable sources. (Previously reported as occasional in 1978; data on file at ABL.)	
Spiny dogfish *Squalus acanthias*	Cross Sound	Jun 1983	Straty-ABL	Confirmed--frequent in in trawl catches.	Possible
	Yakutat	Jun 1983	Straty-ABL	(Usually rare north of Sumner Strait.)	
Tiger shark *Galeocerdo cuvieri*	Off Columbia Glacier	Summer 1983	ADFG	Unconfirmed but reported about same time as manta rays.	Probable

Table 2.--Continued.

Species	Location	Date	Source[1]	Comments[2]	Associated with El Nino?[3]
Rays					
Pacific manta *Manta hamiltoni*	Off Columbia Glacier	Summer 1983	ADFG	Unconfirmed.	Probable
Barracudas					
California barracuda *Sphyraena argentea*	Meyers Chuck	Aug 1983	Paust-MAP	Confirmed by specimens. Also reported at Uyak Bay, N. W. Kodiak Island and unspecified southeastern Alaska location in 1983 Reported in Prince William Sound in 1958. (Data on file at ABL.)	Probable
	Clarence Strait Southeastern AK	Jul 1983	ADFG		
Clupeids					
American shad *Alosa sapidissima*	Pt. Arden-Stephens Passage	Jul 1983	ADFG	Confirmed by specimens. Taken by seiners. Reported from Cook Inlet and Taku Inlet (gill nets). Last reported in southeastern Alaska in 1969. (Data on file at ABL.)	Probable
	Taku River	Jul 1983	ADFG		
	Cross Sound	Aug 1983	Straty-ABL		
	Icy Strait	Aug 1983	Straty-ABL		
Molas					
Ocean sunfish *Mola mola*	Noyes Island	Aug 1983	ADFG	Several caught in purse seine (500-1500 lb). Last reported off outer coast about 10 years ago by salmon trollers.	Probable
	Kruzof Island	Aug 1983	ADFG		
	Western Behm Canal	Aug 1983	ADFG		

Table 2.--Continued.

Species	Location	Date	Source[1]	Comments[2]	Associated with El Nino?[3]
Pomfrets					
Pacific pomfret *Brama japonica*	Cross Sound Icy Strait	Summer 1983 Jul-Aug 1983	Straty-ABL Straty-ABL	Confirmed by specimens. Not uncommon offshore but rare in nearshore waters. Offshore abundance associated with warm waters in 1978. Taken in Icy Strait by salmon trollers.	Possible
Tunas					
Pacific bonito *Sarda chiliensis*	Upper Lynn Canal Klawock	Aug 1983 Aug 1983	Straty-ABL ADFG	Confirmed specimens from gill nets. Others seen at surface. Last previously reported in 1963 in Clarence Strait and Prince William Sound.	Probable
Albacore *Thunnus alalunga*	Prince William Sound Southeastern AK	Summer 1983 Aug-Sep 1983	Straty-ABL ADFG	Several commercial catches reported. This species is occasionally taken offshore by salmon trollers in southeastern Alaska.	Probable
Triggerfish					
Black durgon *Melichthys niger*	Metlakatla Fish trap	Summer 1983	ADFG	Confirmed by specimen. Not previously reported north of San Diego.	Probable

Table 2.--Continued.

Species	Location	Date	Source[1]	Comments[2]	Associated with El Nino?[3]
INVERTEBRATES					
Squid					
Market squid *Loligo opalescens*	Cross Sound Prince of Wales Is.	1982, 83, 84 1982	Wing-ABL Wing-ABL	1982-83 specimens were juveniles from the stomachs of troll-caught salmon. 1984 specimens were taken by RV *Chapman*. Experimental fishing efforts in 1982 yielded fair catches. Population appears to to be on the increase.	Possible but more likely result of longer term population fluctuation.
Flying squid *Ommastrephes bartramii*	Forrester Is.	Sept 1983	Wing-ABL	Taken by jigs under night lights--common. First confirmed specimens for southeastern Alaska. This species has been subject to experimental fishing off central British Columbia.	Previous collection effort too sparse for comment.
Pteropods					
Pyramid snail *Clio pyrimidata*	Yakobi Is.	Sept 1983	Wing-ABL	From coho salmon stomachs. Typically associated with warmer offshore waters. Usually seen only during strong onshore transports in our area (e.g. 1978).	Possible

Table 2.--Continued.

Species	Location	Date	Source[1]	Comments[2]	Associated with El Nino?[3]
Chaetognaths					
Arrow worms *Sagitta scrippsae*	Bartlett Cove Glacier Bay	Aug 1983	Wing-ABL	Previously unreported north of Queen Charlotte Islands. Confirmed by specimens.	Probable
REPTILES					
Leatherback turtle *Dermochelys coriacea*	Southeastern AK Off Yakutat	Aug 1983 Jul 1983	Paust-MAP AFDG	Previous reports and specimens from southeastern Alaska associated with warm water years of 1960's and 1978. Sightings not confirmed.	Probable

[1] Sources
ABL = Auke Bay Laboratory
ADFG = Alaska Department of Fish and Game
MAP = Marine Advisory Program, Petersburg office

[2] Comments
Most unconfirmed reports are sightings by fishermen.

[3] Association with El Nino?
Probable = Species found significantly north of expected range, high confidence that distribution is result of El Nino.
Possible = species not significantly north of expected range and may occur in area in non-El Nino years.

with species (Coutant, 1977). Whole-body temperature sensitivities of fishes reported are 0.1-0.03°C (Murray, 1971, in Crawshaw, 1977). Fish naturally acclimated to either very low or very high temperatures appear to respond more readily to smaller temperature changes than do fish from temperate environments (Coutant, 1977; Crawshaw, 1977).

Fish in general apparently can respond to small temperature differences. Marine and freshwater fish probably respond similarly to temperature changes. Although most of the temperature preference data compiled by Coutant (1977) are for fresh water, the ranges of preferred temperature for the marine species tested appear to be similar to those for freshwater species.

It is unclear how temperature changes and anomalies affect fish distribution during an El Nino year or, for that matter, during normal years. Several factors other than active selection of preferred temperatures may influence ultimate species distribution; e.g., feeding behavior, availability of prey, movement along water mass boundaries, and isolation within warm water masses of various sizes followed by movement of these water masses. During the 1982-83 El Nino, observed changes in fish distribution were generally a northward extension of warm water species. These changes generally correlated with those in the physical oceanography of the region. In some cases, however, the fish appeared in areas well north of the area of major warming. Warm water masses appeared to be very discontinuous and scattered over the northern Gulf of Alaska in 1983, but larger masses of warm water were also present (Mysak, 1985).

Attributing changes in the distribution of warm water species to temperature changes alone may be an oversimplification. Temperature anomalies in the Gulf of Alaska in 1982-83 were generally about +1.5°C and, in many areas, no more than +0.5°C. Although fish may respond to these small temperature changes, the other factors may be involved simultaneously. Pelagic fish sometimes concentrate along water mass boundaries because of increased prey abundance and primary production in these areas. Once encountered, such boundaries or discontinuities, if basically permanent, may eliminate random wandering and congregate species along either the cold or warm side of the discontinuity--whichever is their preference. As these boundaries shift position during warm or cold years, fish species associated with them may be moved accordingly.

Responses of fish to small temperature changes, coupled with passive movement of isolated warm water cells, may be an important mechanism for distributing warm water fish beyond their normal distribution. Once fish are isolated in cells, they may be reluctant to enter surrounding cooler water and, thus, are carried with the warm water until it dissipates or coalesces with other warm water masses.

Evidence for relatively small changes in temperature correlated with changes in distribution of warm water fish species

Table 3.--Major changes in species composition of fish caught at various temperatures. Catches are from surface drift gill nets fished at several stations at longitude 155°00'W during the third R/V *Oshoro Maru* cruise in the North Pacific in 1984. Temperature increased as more southerly stations were occupied from Seward, Alaska, to Honolulu, Hawaii. Changes in temperature and composition of catches are indicated for selected consecutive stations occupied. Catches are from the second of paired stations and code[2] indicates changes (From Dahlberg, 1984).

Paired station numbers	Latitude	Date	Surface temp. °C	ΔT°C	+Species[1]	Code[2]
8412	47°00'	7/23/84	11.1	+1.9	Saury	+
8413	45°30'	7/24/84	13.0		Blue shark	+
8413	45°30'	7/24/84	13.0	+0.9	Saury	0
8414	44°00'	7/25/84	13.9[3]		Blue shark	0
8414					Albacore	+
8415					Flying squid	+
8415	42°30'	7/26/84	15.1	+1.6	Saury	0
8416	41°00'	7/27/84	16.7		Blue shark	0
					Albacore	0
					Flying squid	0
					Ocean sunfish	+
					Yellowtail	+
8416	41°00'	7/27/84	16.7	+1.3	Saury	0
8417	39°29'	7/28/84	18.0		Blue shark	-
					Albacore	0
					Flying squid	0
					Ocean sunfish	0
					Stingray	+
					Skipjack tuna	+
					Yellowtail	0
8417	39°29'	7/28/84	18.0	+2.0	Saury	0
8418	38°00'	7/29/84	20.0		Albacore	0
					Flying squid	0
					Ocean sunfish	0
					Stingray	0
					Skipjack tuna	0
					Yellowtail	0
					Flying fish	+
					Bigeye tuna	+
					Striped marlin	+
					Frigate mackerel	+
					Pilotfish	+
					G. marlinsucker	+

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[1] See Table 4 for scientific names.

[2] Code for appearance
+ = first appearance in catches
0 = caught here and at stations north of this location
- = not caught at this station; caught at stations north of this location.

[3] All salmon species and salmon shark were absent from catches south of this station.

Table 4.--Range of surface temperatures occupied by various fish and shellfish species in the North Pacific (from third *Oshoro Maru* cruise data, Dahlberg, 1984). Time of survey, June 11-July 30, 1984.

Cold water species	Scientific name	Temperature °C
Sockeye salmon	*Oncorhynchus nerka*	10.4-12.7
Chinook salmon	*O. tschawytscha*	10.4-12.7
Chum salmon	*O. keta*	[1]8.9-13.0
Pink salmon	*O. gorbuscha*	8.9-12.7
Coho salmon	*O. kisutch*	8.9-12.7
Steelhead trout	*Salmo gairdneri*	8.9-13.0
Salmon shark	*Lamna ditropis*	11.1-13.0
Spiny dogfish	*Squalus acanthias*	10.5-12.7
Skilfish	*Erilepis zonifer*	10.4-11.9
Intermediate species		
Pacific pomfret	*Brama japonica*	8.9-20.0
Squid	*Onychoteuthis borealijaponica*	8.9-22.7
Flying squid	*Ommastrephes bartrami*	11.1-22.7
Eight-armed squid	*Gonatopsis borealis*	8.9-13.0
Lanternfish	Family *Myctophidae*	13.0
Pelagic armorhead	*Pentaceros richardsoni*	13.0
Warm water species		
Blue shark	*Prionace glauca*	13.0-16.7
Pelagic stingray	*Dasyatis violacea*	18.0-20.0
Saury	*Cololabis saira*	8.9-20.0
Albacore	*Thunnus alalunga*	13.9-20.0
Smalleye squaretail	*Tetragonurus cuvieri*	11.1-20.0
Ocean sunfish	*Mola mola*	16.7-20.0
Yellowtail	*Seriola lalandei*	16.7-20.0
Skipjack tuna	*Euthynnus pelamis*	18.0-22.7
Bigeye tuna	*Thunnus obesus*	20.0-22.7
Striped marlin	*Tetrapturus audax*	20.0-22.7
Gray marlinsucker	*Remora osteochir*	20.0-22.7
Flying fish	Family *Exocoetidae*	20.0-22.7
Frigate mackerel	*Auxis thazard*	20.0
Pilotfish	*Naucrates ductor*	20.0
Shortbilled spearfish	*Tetrapturus angustirostris*	20.0
Common dolphin	*Coryphaena hippurus*	22.7
Butterfish	*Peprilus simillimus*	22.7
Ocean puffer	*Lagocephalus lagocephalus*	22.7
Squid	*Eucleoteuthis luminosa*	20.0

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[1] 8.9 value is from station #8403, June 13, at latitude 42°00', longitude 180°00'. All stations fished in July were at locations along longitude 155°00'W from Seward, Alaska, to Honolulu, Hawaii.

in the Gulf of Alaska is apparent in catches reported by the Japanese research vessel Oshoro Maru in 1984 (Dahlberg, 1984). Considerable differences in composition of gill-net catches occurred at a series of stations fished from Seward, Alaska, to Hawaii, along longitude 155°00'W (Table 3). Temperature changes were small (1-2°C) between stations. However, as more southerly stations were fished and as temperatures increased, more warm water species occurred in catches. The ranges of temperatures occupied by various species varied considerably (Table 4). Of the warm water species, blue shark, saury, smalleye squaretail, albacore, and, to a lesser extent ocean sunfish, skipjack tuna, and yellowtail were sometimes found in relatively cool water (13 to 17°C). Pacific pomfret, lanternfish, various squid, and pelagic armorhead may be considered as intermediate species between warm and cold because of their occurrence over a wide range of temperatures and at temperatures just at the maximum for cold water species.

It appears that temperature response of fish and distribution of several physical characteristics of the pelagic ocean environment determine the distribution of pelagic species. A well developed Sitka Eddy in 1983 combined with the unusually large numbers of warm water species reported in Alaska (Kodiak, Prince William Sound, and Southeast) supports the hypothesis that strength of the Sitka Eddy development and movement of fish from offshore to onshore are connected. The Oshoro Maru data shows distribution of warm water species during a year when the Sitka Eddy was not well developed. In 1983, blue shark were reported near Kodiak, but in 1984, the Oshoro Maru data indicated the most northerly location for blue shark capture was at 45°30'N, 155°W. More detailed information on the distribution of pelagic fish, invertebrates, and physical parameters during normal, cold, and warm years is needed before we can fully understand the cause-and-effect relationship of temperature changes, eddy formation, and fish distribution in the eastern Gulf of Alaska.

Acknowledgments

We thank Captain Kiyoshi Masuda of the training ship Oshoro Maru, Faculty of Fisheries, Hokkaido University for graciously allowing us to use in this report data collected by the Oshoro Maru.

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The Dependence of Phytoplankton Nutrient Utilization on Physical Processes in The Eastern Bering Sea Area

Mechanisms for Yearly Variation

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Introduction

Oceanographic sampling in the eastern Bering Sea has not been as extensive and consistent as it has been in lower latitude, northeastern Pacific waters. This generalization is most apparent in the biological oceanography of the eastern Bering Sea area. Since the typical production regime in this area is not clearly defined, the identification of anomalous conditions is very difficult. My approach to the subject of interannual variability therefore, will be prospective rather than retrospective in nature. In this inductive approach, I will make a preliminary evaluation of how variations in physical forcing can alter the patterns and intensity of phytoplankton production in this area. Three cases will be considered in the study area; lower Shelikof Strait and the southern shelf of the Alaskan peninsula; the southeast Bering Sea; and the Bering Straight area (Figure 1).

The spatial variability or "patchiness" of chlorophyll distribution frequently coincides with physical hydrographic features in the coastal environment (e.g., Seeliger, *et al.*, 1981). In the Bering Sea this is also true in places where frontal systems may act as conduits of nutrients to the surface and are areas of active phytoplankton growth throughout the summer (Iverson *et al.*, 1979). Specific examples of physical factors in the environment that cause variation in upper trophic levels by their influence on primary production are not numerous, but have been discussed (e.g., the relationship between mixed layer depth and zooplankton growth suggested by Parsons and LeBrasseur, 1968).

A direct association between physical environmental processes and fish abundance was found in the very productive coastal area off Peru. Plankton productivity there decreases sharply during periods of warm equatorial water intrusion. This change is believed to be climatically induced, and results in a significant decrease in the commerical catch of anchovy (Cushing, 1981). Interannual variability in plankton production has also been documented in the upwelling area off the Oregon coast (Peterson and Miller, 1975). Although

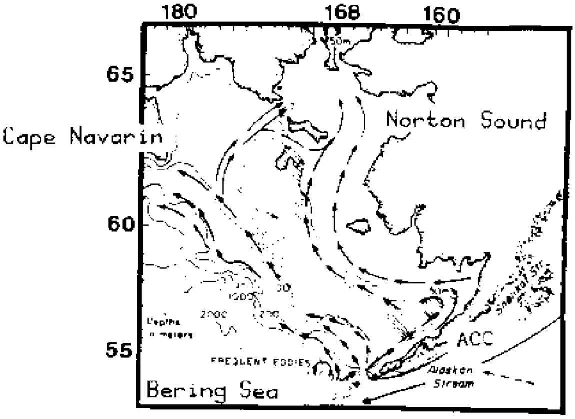

Figure 1. Map of area under discussion. ACC is the Alaskan Coastal Current, part of which is shown continuing on the north side of the Alaskan peninsula (adapted from Schumacher and Reed, 1983).

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weather patterns are recognized as important in such low frequency biological variability, the specific mechanisms by which meteorological variability affects higher trophic levels are not well understood.

A recent review of phytoplankton production on several shelf areas indicated that differences among yearly production were related to the strength and consistency of the physical mechanisms supplying nutrients during the growing season (Sambrotto, Goering, and McRoy, 1984). This trend was illustrated by computing the nutrient supply rate (NSR) for each area:

$$\mathrm{NSR} = \frac{\rho\mathrm{NO}_3^- - \text{winter NO}_3^- \text{ store}}{\text{growing season} \times (\mathrm{NO}_3^-)_{\text{bottom water}}} \qquad (1)$$

In the numerator $\rho\mathrm{NO}_3^-$ is the yearly amount of nitrate utilization (mg-at m^{-2}) and the winter store of nitrate is the amount present in the upper water at the end of winter. The difference must be supplied during the growing season. This supply is normalized to the length of the growing season (days) and the nitrate concentration of the source water (mg-at m^{-3}), to yield a supply rate (m d^{-1}). The normalization to the growing season allows the NSR from different latitudes to be compared directly.

In Figure 2, the NSR and the annual production estimated from ^{14}C measurements in several areas are compared. On this basis, it is clear that the physical oceanography controlling deep water supply also controls yearly production. In Figure 2, a cuvilinear relationship was drawn to accommodate the yearly production estimate for coastal Peru. However, excluding the Peru value, the other four

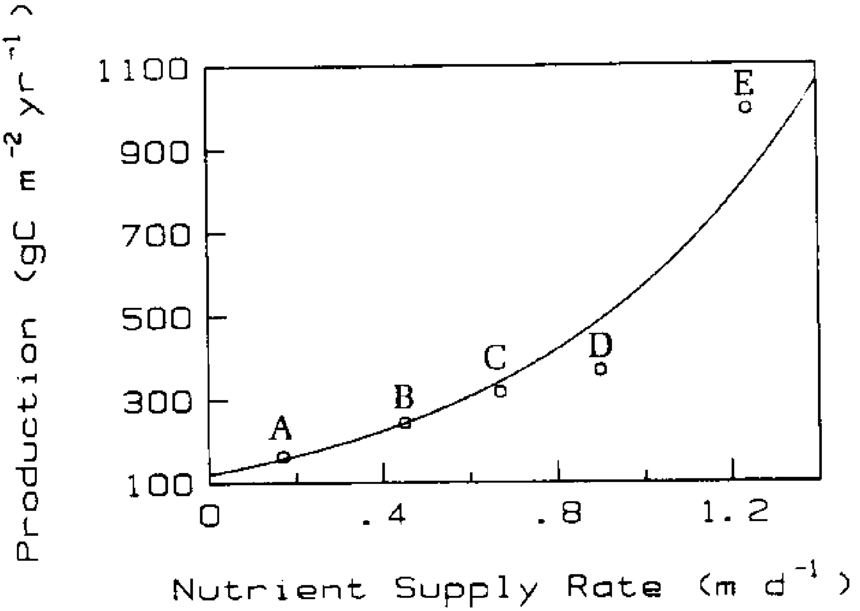

Figure 2. Relationship between yearly production from ^{14}C measurements and nutrient supply rate. Points correspond to A - Southeast Bering Sea, B - New York Bight, C - Western Bering Strait, D - Georges Bank, E - Peru. Data sources given in Sambrotto *et al.*, 1984.

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points can be fit with a straight line, suggesting the Peru value is an overestimate. If nutrient supply mechanisms are influenced by meteorological conditions, a direct link between climate variability and yearly phytoplankton production is formed. Importantly however, the NSR gives no indication of the specific mechanisms responsible for nutrient supply. Such mechanisms will be considered in more detail in three cases from the eastern Bering Sea area.

Case 1: Coastal Flow and Vertical Shear

On the continental shelf and slope of the northwest Gulf of Alaska from the Kenai Peninsula to the Shumagin Islands (Figure 1), coastal currents exist that may influence both the horizontal and vertical patterns of phytoplankton growth. Two distinct currents dominate the local flow characteristics. The Alaska Current flows counterclockwise along the shelf break in the Gulf of Alaska at velocities up to 1.5 m s^{-1} (Niebauer, Roberts, and Royer, 1981). Wind and baroclinic forcing allow some of this water to enter Shelikof Strait through its northern end (Schumacher and Reed, 1980). Additionally, the Alaska Coastal Current is a prominent feature of the entire Gulf within ca. 35 km. of the coast, reaching a velocity of >0.5 m s^{-1} and transport in excess of 1 x 10^6 m^{-3} sec^{-1} (Royer,

1981) The Alaska Coastal current is called the Kenai Current in the sea where it enters Shelikof Strait.

East of Kodiak Island, onshore winds cause convergence of offshore water into the Alaska Coastal Current. On the shelf between Kodiak and Unimak Pass however, wind stress usually promotes upwelling during summer (Ingraham, Bakun, and Favorite, 1976). The interaction of the Kenai Current and the horizontal distribution of phytoplankton was evident in a coastal zone color scanner (CZCS) image of the Shelikof Strait area. This image indicated that the down stream flow of the Kenai Current was associated with cyclonic eddy structures in both the temperature and chlorophyll distributions. This structure in the horizontal phytoplankton distribution was probably related to the baroclinic instability recognized in the flow through Shelikof Strait (Mysak, Muench, and Schumacher, 1981).

Remote sensing is spatially synoptic and can yield striking examples of the interaction between physical forcing and the spatial patterns of phytoplankton growth. The images however, do not contain any information on the vertical structure of primary production in the water column. For example, the vertical biological structure on the north Aleutian shelf is shown in Figure 3. The doming of the nitrate isopleths in Figure 3 a, coincided with a pronounced subsurface chlorophyll maximum (Figure 3 b). This subsurface chlorophyll layer also bordered the shallow near shore layer of low salinity water that forms the coastal current (Royer, 1981). The movement of this coastal, low salinity water over this area may be responsible for the shallowing of the nutrient rich water and the formation of the chlorophyll layer that persisted well into the summer.

Figure 4 is a schematic of the nutrient sources for phytoplankton growth in an area influenced by a coastal current such as the north Aleutian shelf. It depicts a hypothetical long shelf section at the edge of the coastal current. The Alaska Coastal Current (ACC) in Figure 4 is indicated entering the area from the right with some presently unknown amount of nutrients (N_{cc}). Additionally, deeper outer shelf or slope water may enter the region which could contain a large amount of nutrients (N_s). Importantly for the growth of phytoplankton in such an area, vertical mixing controls the potential supply of deep water nitrate across the pycnocline into the trophogenic zone and this exchange may be substantially aided by the vertical velocity shear created by the Alaska Coastal Current (N_v). Such a mechanism for the enhancement of vertical diffusivity in coastal areas has been suggested by Winant and Olson (1976).

This cross pycnocline flux fuels new (nitrate) productivity in subsurface chlorophyll layers associated with the shear zone and significantly influences the vertical patterns of primary production. The water stratum just above such chlorophyll layers is commonly associated with relative maxima in zooplankton abundance (Herman, 1983). Also, it has been suggested that these layers serve as important feeding environments for larval Pollock (Nishiama, Hirano, and

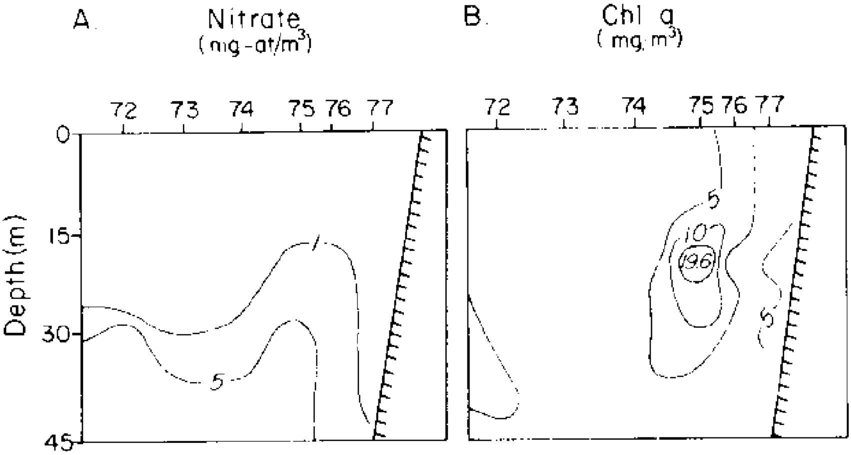

Figure 3. Section across north Aleutian Shelf in Spring, 1980 from Niebauer *et al.*, 1982. A) nitrate. B) chlorophyll.

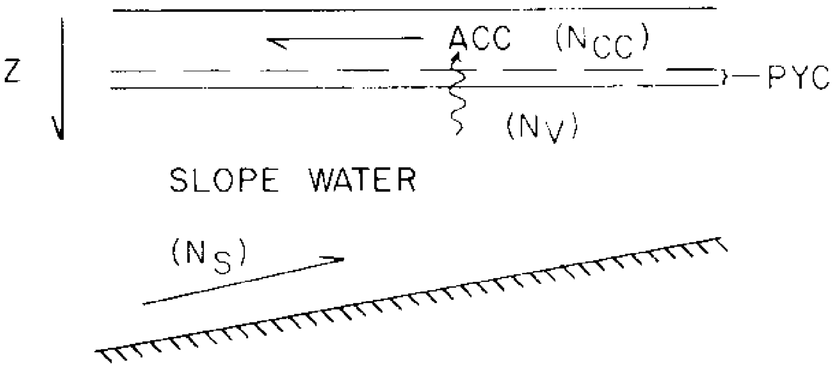

Figure 4. Schematic of nutrient supply for hypothetical long shelf section at edge of coastal jet.

Haryu, 1982). This sequence of relationships provides a mechanism by which biological processes in the coastal area could respond to variations in the transport and/or speed of the coastal current.

Case 2: Cross Shelf Diffusion and Wind Mixing

On most of the broad, high latitude southeast Bering Sea shelf, physical processes such as coastal upwelling or sharp gradients in horizontal advection are not available to supply surface nutrients for plankton growth. Long term mean currents on the shelf are small (ca. 1-2 cm/sec drift to the Northwest, Figure 1). Subtidal flow is weak (1 to 5 cm sec^{-1}) and parallel to the fronts in the vicinity of the shelf break and inner fronts, while flow in the middle domain is insignificant (Coachman, 1982). The distributions of properties are governed largely by a diffusion defined to include the tidal scales (Coachman and Charnell, 1979). Due to the lack of other mixing forces besides the predictable influence of tides over large areas of the shelf, wind mixing periodically contributes most of the water column mixing energy (Schumacher and Kinder, 1983).

Deep water nutrients therefore, are largely dependent on vertical mixing due to local wind activity to reach surface waters (Coachman and Walsh, 1981). Sambrotto, Niebauer, Goering, and Iverson (in press), show that wind induced mixing of the upper water column controls phytoplankton growth by influencing both nutrient availability and light conditions across much of this shelf. Also, yearly variations in meteorologically controlled wind mixing were associated with significant interannual variability in the total amount of production (± 50%). Perhaps of more importance to pelagic food chains in the southeast Bering Sea however, the vertical pattern of production also varied with spring atmospheric conditions.

An analysis of the observed variations in phytoplankton and zooplankton during several years of sampling in the eastern Bering Sea has been presented by Sambrotto and Goering (1983). The growth rates of large outer shelf grazers such as *Neocalanus plumchrus* varied with total areal spring production, which was less in 1981 than in 1980. The small middle shelf zooplankton such as *Pseudocalanus spp.* however, were much more abundant in the calm, relatively low production spring of 1981. Although the total spring production was less in 1981 than 1980, a more extensive subsurface chlorophyll layer was present cross shelf in late May and June of 1981. The physical mechanism responsible for the interannual difference in the vertical production regime was the amount of wind mixing occurring in May. Extensive wind mixing during May, 1980 supported intense phytoplankton growth but consumed nutrients deep into the water column as compared with the following May (Figure 5). Since the June, 1981 nitrate nutricline was higher in the euphotic zone, conditions favorable for persistent chlorophyll layers resulted.

The frequency and intensity of storms over the area in spring was largely dependent on the position and intensity of atmospheric patterns such as the Aleutian low (Sambrotto *et al.*, in press). In the case of the southeast Bering Sea therefore, as for the coastal current regime, it appears that identifiable and variable physical forces directly affect the production conditions. It should be noted however, that other factors which could influence the production regime of the southeast Bering also exhibited notable variation. For example, further data analysis indicated that the chemical characteristics of the outer shelf water (which is the source for the on shore diffusive flux of nutrients) varied significantly between 1980 and 1981.

Case 3: Bathymetric Upwelling

In addition to its large area, the eastern Bering sea is unusual among continental shelves due to a cross-shelf advection into the

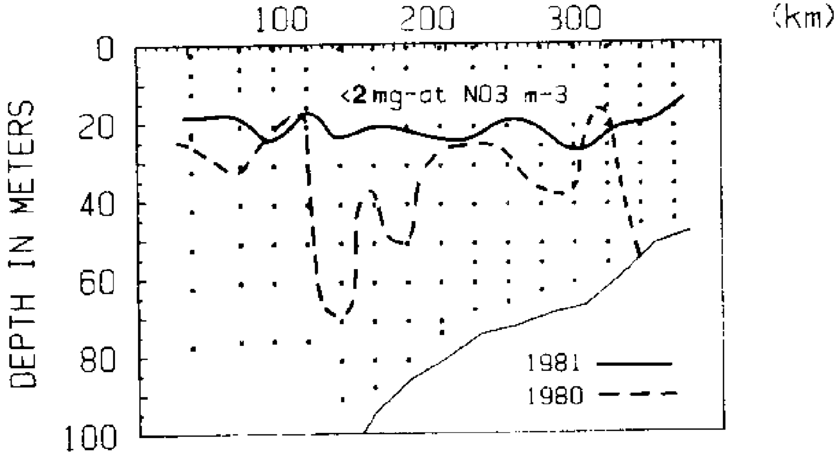

Figure 5. Comparison of cross shelf nitrate nutricline depth in the southeast Bering Sea in early June of 1980 and 1981. Section runs from Cape Newenham to the shelf break.

Arctic Ocean through Bering Strait (Figure 1). Current measurements suggest that the average flow through Bering Strait is approximately 0.8×10^6 m^3 sec^{-1} (Coachman and Aagaard, 1981). This flow is seasonal, being greater in summer due to the higher frequency of flow reversals in winter. Much of the flow appears to be a continuation of the shelf break current which turns north near Cape Navarin and will be referred to as Bering Shelf/Anadyr water (Figure 1). To a lesser extent, in the east, warmer coastal water dominated by Yukon river discharge flows out of Norton Sound. The Bering shelf/Anadyr water in the west, and the Alaskan Coastal/Yukon River in the east maintain their identity during transit through the strait.

An important characteristic of the Bering Shelf/Anadyr water is its high nutrient content (Figure 6). As this water enters the shallow Bering Strait, it continuously supplies nutrients for phytoplankton growth. This mechanism of nutrient supply is distinct from that of local upwelling since in the western Bering Strait plume a geographic separation of approximately 500 km exists between the water's source and its biological utilization. Based on measured flow rates and summer nitrate distributions, phytoplankton production in western Bering Strait was estimated at 324 g C m^{-2} yr^{-1} over 2.12×10^4 km^2 (Sambrotto *et al.*, 1984). An ice reduced growing season makes this large amount of primary production unexpected, but it is consistent with the area's large upper trophic level stocks (Johnson and Nelson, 1984).

On the scale of the northern hemisphere, the northward movement of water through Bering Strait maintains the salt balance between the Pacific and Atlantic Oceans (Stigebrandt, 1984). On more local

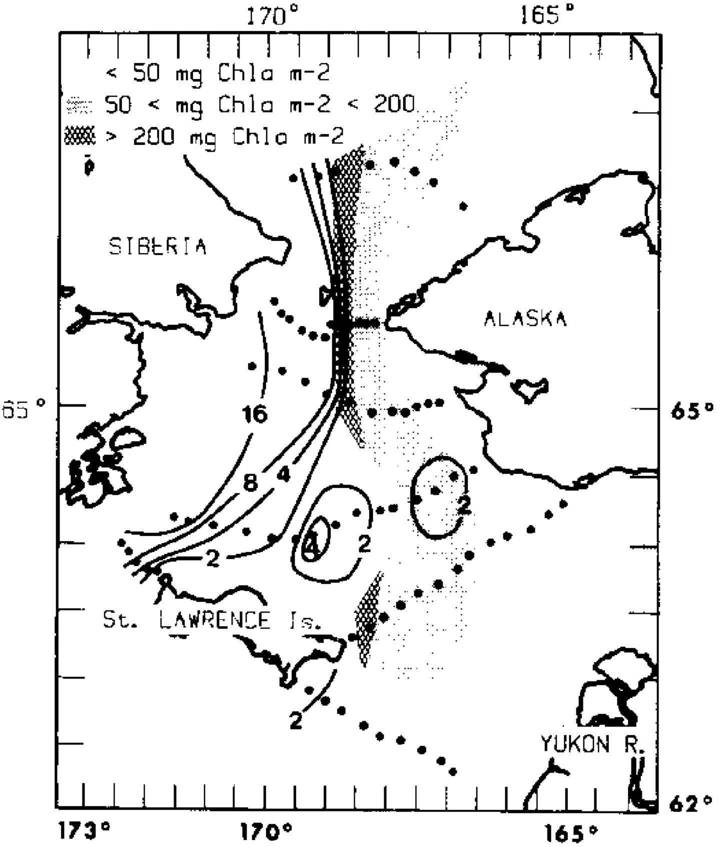

Figure 6. Average water column nitrate distribution in the Bering Strait area (labeled isopleths). Overlain is water column chlorophyll content. The chlorophyll data did not have the same coverage as the nitrate data (from Sambrotto *et al.*, 1984).

spatial scales however, atmospheric pressure patterns also influence the flow of water through the Bering Strait causing episodic flow reversals (Coachman and Aagaard, 1981). Extremely different water masses were present in a St. Lawrence Island to Alaska mainland section sampled in the summers of 1983 and 1984 (Figure 7). In 1983 low salinity Alaskan Coastal water filled most of this area (Figure 7a), while in 1984 higher salinity Gulf of Anadyr/Bering Slope water was found there (Figure 7b). The water in this area was also much colder in 1984 than in 1983 (Figures 7d and e). This suggests the cold shelf water south of St. Lawrence Island influenced this area more strongly in 1984.

These sections represent a short period of time however, and do not necessarily indicate average summer conditions. Average summer salinity in the Bering Strait area for a 25-year period was obtained

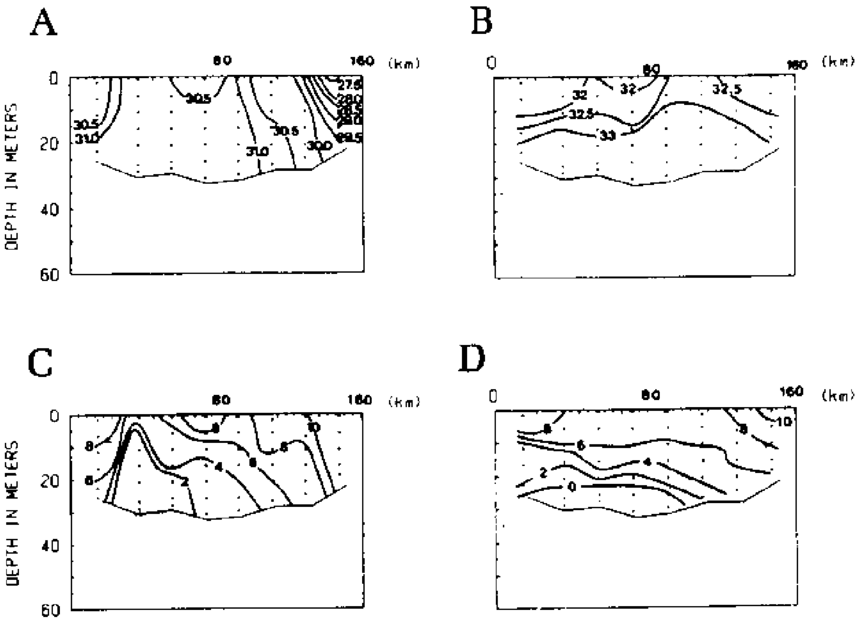

Figure 7. Comparison of salinity and temperature distributions in a section from St. Lawrence Island (on left) to near the Alaskan mainland in 1983 and 1984. A) 1983 salinity (°/oo). B) 1984 salinity (°/oo). C) 1984 temperature (°C). D) 1984 temperature (°C).

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from published data (Federova, 1968; Figure 8). In all but the two weak events, summer salinity was above the mean value of 32.10 °/oo during El Niño periods. A Chi square test therefore, indicated that there was a 64% probability that the summer salinity during El Niño years was non-randomly distributed. Although the statistical significance is not great, these data suggest that the flow of relatively high salinity Gulf of Anadyr/Slope water through the Strait may be greater during El Niño years.

This western Bering Strait flow is also cooler at the surface and more productive than the Alaska Coastal water. Interannual changes in flow characteristics therefore, may influence higher trophic levels. As an example from the pelagic food web, the reproductive success of kittiwakes varies with temperature in the Bering Strait area (Springer *et al.*, 1984). Field studies in 1984 indicated that the populations of these seabirds at the nesting colonies were in extremely poor condition (E. Murphy, pers. comm.). However, it is possible that the poor breeding success reflects environmental conditions at the winter locations of these migratory birds rather than summer Bering Strait conditions. Also, it is not clear that the 1984 Bering Strait conditions are a direct consequence of the

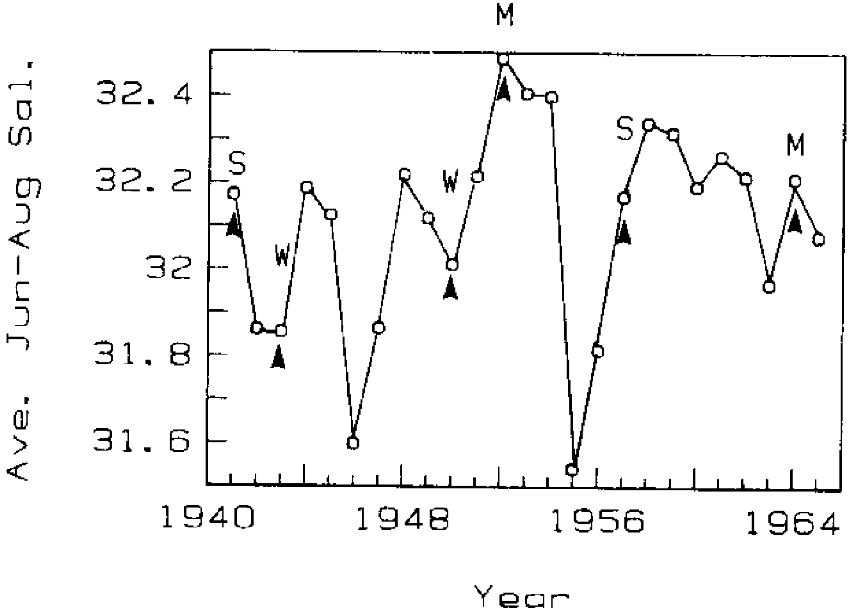

Figure 8. Average Salinity in the Bering Strait with El Niño years identified. Salinity data from Federova (1968), and El Niño years were taken from Quinn *et al.*, 1978, in which W. M. and S. stand for Weak, Moderate, and Strong events.

1982-83 El Niño event. A 16-month lag time however, was observed in the response of the winds at the Pribilof Islands to the latest El Niño event (Niebauer, this volume).

Conclusions

Temporal variations in coastal currents, wind mixing, and flow through Bering Strait can influence the spatial distributions and intensity of phytoplankton growth in coastal Alaska waters, the southeastern Bering Sea, and the western Bering Strait respectively. Much of the variation in physical forcing, in turn, may be associated with hemispheric variability in meteorological conditions. Approaching higher trophic level production from this aspect offers a means of elucidating the underlying mechanisms responsible for the observed correlation of climatic factors and variations in commercially important marine resources. Greater familiarity with the annual variations in the biological oceanography of the sub-arctic north Pacific is needed to test hypotheses regarding the temporal correspondence between annual biological variability and climatic oscillations such as El Niño.

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CONTRIBUTIONS

The Possible Relationship of El Niño/Southern Oscillation Events to Interannual Variation In *Gonyaulax* Populations as Shown by Records of Shellfish Toxicity

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Ecological studies of toxin-producing species of Gonyaulax, the dinoflagellates responsible for paralytic shellfish poisons (PSP) in shellfish, have indicated that water temperature and vertical stability of the water column are among the major factors governing development of dense populations of these species in both oceanic and enbayment environments (C.M. Yentsch, pers. comm., 1982; Nishitani and Chew, 1984 and unpublished data). The relationship between high PSP levels in shellfish (indicating unusually dense Gonyaulax sp.) and weather conditions was pointed out by Waldichuck (1958), who attributed an occurrence of unusually high toxin levels to a prolonged period of higher than usual air temperatures, much reduced wind, and sunny weather following a period of abnormally high rainfall.

During tropical El Nino/Southern Oscillation (ENSO) events of a range of intensities (i.e., both strong events when an apparent northward intrusion of warm water occurs along the western coastline of North America and weaker events when such intrusion does not occur), a ridge of high atmospheric pressure develops over western Canada (Rasmusson and Wallace, 1983). The resultant effects on hydrographic conditions and weather, e.g., sea surface temperature (SST), sunshine and winds, hence, vertical stability of the water column, might be expected to enhance growth and accumulation of toxic Gonyaulax species(1). Very limited data are available on the extent and duration of blooms of Gonyaulax spp. in the Northeast Pacific. However, there are quite extensive records of PSP in shellfish, particularly along the coasts of Washington and British Columbia, and of human illness due to PSP, which provide an indirect measure of abundance of toxic Gonyaulax spp.

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(1) Three closely related species of Gonyaulax are responsible for paralytic shellfish poisoning outbreaks along the northeast Pacific rim: G. catenella, G. acatenella, and G. tamarensis (Taylor, 1984).

We sought to determine whether occurrences of PSP in shellfish are correlated with ENSO events and, thus, whether atmospheric and oceanographic anomalies induced by ENSO events would be useful in broad-scale prediction of PSP outbreaks along the coastline of British Columbia and Washington.

Findings

As a first approach we examined the degree of coincidence between ENSO events and exceptional episodes of PSP in Washington and British Columbia (Fig. 1). For this investigation, PSP episodes considered exceptional include outbreaks in geographical areas seldom or not previously affected by PSP, outbreaks with unusually

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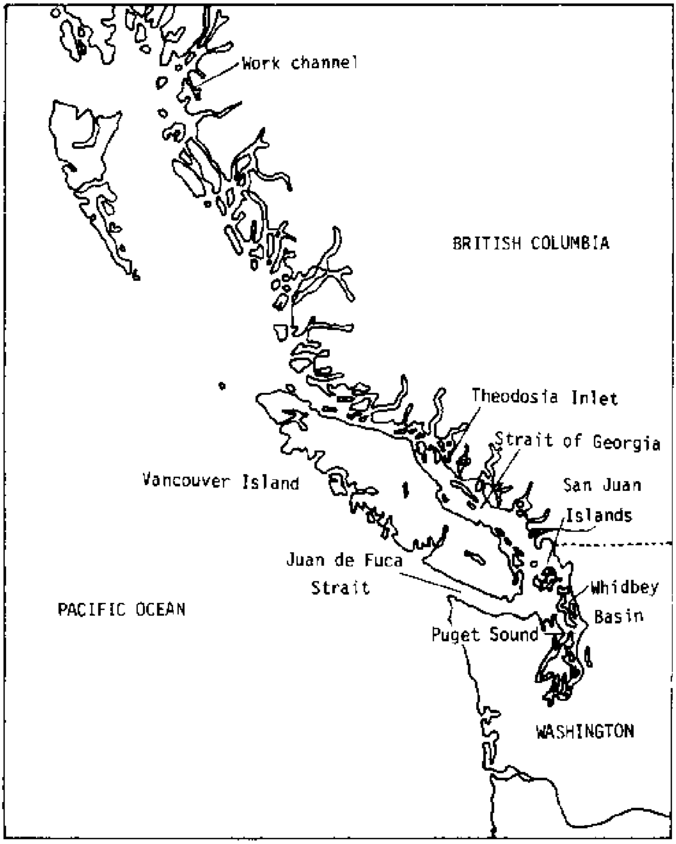

Figure 1. Coastline of British Columbia and Washington.

high PSP values for a given shellfish species (other than butter clams), and outbreaks (7 in Washington and 9 in British Columbia) in which the yearly highest level of PSP in butter clams within each jurisdiction was unusually high compared with adjacent years. (PSP data for butter clams are used because they are more complete than data for any other species.) The ENSO index, developed by Quinn, et al. (1978) to indicate intensity of events in the tropics, and occurrences of exceptional PSP episodes in Washington and British Columbia for 1942 and 1957-1984 are presented in Table 1. (Data for 1943-1956 are incomplete.)

The rationale for using exceptional PSP episodes is based on the fact that, because growth rates of Gonyaulax spp. are relatively slow, the development of a very dense population (hence, unusually high PSP in shellfish) requires that each of the many physical, chemical and biological factors governing its growth remains favorable for a prolonged period, often many weeks. Thus, occurrence of an exceptional PSP episode in a given year indicates that at one site, at least, the duration of favorable conditions was unusually prolonged.

Discussion

Exceptional PSP episodes occurred during all 9 of the ENSO events during the period of this study, i.e., in 13 of the 15 calendar years of those events. (Three of those 9 events had no second year.) Both the geographic distribution and the seasonality of occurrences of exceptional PSP during ENSO events suggest a correlation between the two kinds of events.

Exceptional PSP episodes were reported in both Washington and British Columbia in 7 of 9 ENSO events, often several hundred miles and several months apart, suggesting that conditions for growth of Gonyaulax may have been favorably affected by a widespread, long-term event. One such PSP outbreak caused deaths of humans, seabirds and perhaps fish in Washington and British Columbia in 1942 (see Table 1). A second example is the occurrence of high toxicity in butter clams, oysters and mussels in the Strait of Georgia during October, 1957 (the first such occurrence in that area), in oysters in a bay on the ocean coast of Washington in November and in razor clams on the adjacent ocean beaches the following June (the latter two episodes uncommon for that area, only 2 others having occurred in the following 26 years). When exceptional PSP occurred in years without ENSO events, it occurred in either Washington or British Columbia, not in both.

During ENSO events episodes of exceptional PSP in mussels, cockles, little neck and butter clams occurred during abnormal seasons, i.e., October-November in 4 of the 8 events with first year (EN1) data and May in 3 of 6 events with second years (EN2). (The normal growing season in inland waters in Washington is June-September.) These shifts in seasonality suggest continued growth in fall and earlier initiation of growth in spring. The latter would fit with the fact that the strongest connection between ENSO

Table 1. ENSO events and episodes of exceptional PSP levels in shellfish.

Year	ENSO Index	ENSO Year	Date	State/ Prov.	Highest PSP in butter clams (µg/100g meat)	Unusually high PSP in other species or in unusual area
1941	S	EN1			No PSP data available	
1942		(EN2)	Mar.-Apr.	BC		Massive herring kill, S.E. Vancouver Is., possibly due to PSP
			May 2	BC		Sea mussels-->human deaths, W. Vancouver Is.
			May 2	WA		Mussels, clams-->human deaths, Juan de Fuca Str.
			Early May	WA		Razor clams-->pet deaths, ocean coast (uncommon)
						Unusual number of dead seabirds, ocean coast.
1957	S	EN1	Oct. 24	BC	3174	Oysters, clams, mussels--> human illness 1st PSP reported in Strait of Georgia
			Nov. 8	WA		Oysters, bays on ocean coast (uncommon)
1958	S	EN2	Feb. 5	BC	7706	
			June 5	WA		Razor clams, ocean coast (uncommon)
1961	-	---	Aug. 3	WA	867	
1963	VW	EN1	Nov. 18	BC	1760	
1964	-	---	Aug. 26	BC	2720	
1965	M	EN1	May 31	BC		Cockles--> human death, Theodosia Inlet
			June 5	BC	8640	
			Sept. 22	WA	945	
1969	W	EN1	Aug. 11	WA	1090	
1970		(EN2)	May 4	BC	4200	
			June 24	WA		Razor clams, open coast (uncommon)
1971	-	---	July 7	BC	4200	
1972	S	EN1	Sept. 5	WA	1090	
			Nov. 21	BC		Littleneck clams - 4000µg, oysters - 1900µg, W. Vancouver Is.
1973	S	EN2				
1975	VW	EN1	June 25	BC		Mussels - 1200µg, Work Channel
1976	M	EN1	Oct. 13	WA	2220	
1977	M	EN2	May 31	BC	5100	
1978	-	---	Sept. 24	WA		Mussels - 30,000µg; 1st occurrence in Puget Sd.
1980	-	---	May 17	BC	8600	
			July 1	WA	2503	
1981	-	---	July 21	WA		Oysters - 2340µg, cockles - 1860µg, San Juan Is.
1982	S	EN1	June 1	BC		Mussels - 30,000µg, Work Channel
1983	S	EN2				
1984		(EN3)	June 18	WA		Oysters - bays on open coast (uncommon)
			June 27	WA		Razor clams - open coast (uncommon)

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2. S = strong; M = moderate; W = weak; VW = very weak (Quinn et al., 1978; Rasmusson and Wallace, 1983).
3. EN1 = first year of ENSO event; EN2 = second year of event.
4. Parentheses indicate that EN2 or EN3 year is not listed in references in 2 above.
5. Fisheries and Oceans Department, Canada, 1942-1984.
6. Washington State Public Health Laboratory, 1957-1984.
7. Quayle, 1969.
8. Herring kill (Tester, 1942) very similar to herring kills caused by Gonyaulax tamarensis toxin in New Brunswick (White, 1980).
9. McKernan and Scheffer, 1942.

events and anomalous weather, including positive air temperature anomalies, in western Canada and the northwestern United States occurs during November (EN1) to March (EN2) (Horel and Wallace, 1981).

A further suggestion that a relationship between episodes of exceptional PSP and ENSO events stems from the recurrence of relatively high levels of PSP in oysters and/or razor clams along the ocean coast of Washington during strong ENSO events in 1942, 1957, 1958 and 1984, and in only one other year, 1970, the EN2 year of a weak ENSO event. Two of these 5 coastal PSP events fit the pattern of seasonal anomalies, i.e., during November (EN1) and May (EN2). The 1984 episode occurred in June. (Along the Washington coast the positive SST anomalies associated with the 1982-83 ENSO event continued through May, 1984 [National Weather Service, 1984]).

Exceptional PSP events also occurred in 6 of the 14 years without ENSO events. During 4 of these 6 (1961, 1978, 1980 and 1981) SST's were abnormally warm throughout the region (Hollister, 1964; Mearns, in preparation; Thomson, et al., 1984). Thus, at least one factor governing growth of Gonyaulax, SST, was similar during the exceptional PSP episodes in both ENSO and non-ENSO years, although the causes of the elevated SST's differed. An additional factor in 1978 was an exceptionally deep top layer of favorable temperatures resulting from abnormally heavy river runoff in the Whidbey Basin, the area first affected by extraordinary levels of PSP in that year (Water Resources Division, 1969-1978). Conditions contributing to the exceptional PSP episodes in 1964 and 1971 are not yet known. Five of the episodes of exceptional PSP during years without ENSO events occurred in July-September, the sixth in May, 1980. (A very weak ENSO event in 1979-80 was reported in the western Pacific [Donguy, et al., 1982]).

The lack of episodes of exceptional PSP during 2 of the 17 ENSO years (1973 and 1983) does not necessarily weaken the suggestion that the two kinds of events are related. It is not to be expected that PSP events as exceptional as those discussed in this study would occur in each year of each ENSO event. The associated oceanographic and atmospheric anomalies vary in degree and duration with different ENSO events. Further, during a year in which those anomalies permit a prolonged period of hydrographic and weather conditions favorable for Gonyaulax sp. in a given area, the period of continued growth might be cut short by a localized event such as strong tidal mixing or the occurrence of a dense predator population. The lack of exceptional PSP episodes during one of the ENSO years, 1973, may be attributable, in part, to the fact that weak negative SST anomalies occurred during that year (Thomson, et al., 1984). Conditions contributing to the lack in 1983 are not known.

Conclusions

The shellfish toxicity data thus strongly support the hypothesis that ENSO events of varying intensities may promote marked increases in population densities of toxic Gonyaulax species in open coastal and inland waters along parts of the northeast Pacific Rim. Further study of SST's, and weather conditions (including atmospheric pressure, temperature, precipitation, insolation, wind direction and velocity) is being conducted to determine the strength of the correlation between anomalies in these variables, induced by ENSO events or by other factors, and high PSP levels in the shellfish.

If a strong correlation can be shown, weather conditions and SST's might be useful in broad-scale prediction of periods of dense Gonyaulax populations and high risk of hazardous PSP levels in shellfish. Two additional biological responses to ENSO events and other warm periods might be expected. The introduction of increased quantities of PSP into the food web, via a variety of filter feeders, would increase the potential for higher mortality in a great diversity of animal species, including finfish, seabirds and marine mammals. In addition, more widespread shifts from diatom to dinoflagellate dominance than indicated by PSP records could occur during ENSO events since many species of dinoflagellates grow and accumulate under physical conditions similar to those promoting blooms of Gonyaulax sp. To the extent that this shift occurs, particularly at unseasonable periods, it may be one of many factors contributing to anomalies in population densities or geographic distribution of species at all trophic levels. The extent of these two broad types of effects, whether in small bays or over a larger segment of the coastal waters, would depend on the magnitude of the oceanic and atmospheric anomalies caused by the ENSO event.

Acknowledgments

This work was supported, in part, by College of Ocean and Fishery Sciences Select Programs and Washington Sea Grant Program. We would like to thank the following people for their comments and suggestions: John Liston, Kenneth Chew, Lewis Incze, Joyce Lewin, Amy Schoener and Lee Wiegardt. Rudy Chiang and Laura Kentala kindly supplied PSP data.

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Seawater Temperature, Sea Level, and Ekman Transport along the Coast of British Columbia During the 1982–83 El Niño

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Introduction

The effects of the 1982-83 El Nino on the waters along the coast of British Columbia were manifested by the large positive anomalies in sea surface temperature, sea level and Ekman transport. These data are presented for 1982-83 and compared to those for the El Nino years of 1941 and 1958 for selected locations along the coast of British Columbia (Fig. 1). Bottom-water temperatures on the continental shelf are presented for May 1977-83.

Annual Sea Surface Temperature Anomalies

In 1983, large positive annual sea surface temperature anomalies (annual mean minus long-term annual mean) were observed at Amphitrite Point and Kains Island (Fig. 2). The anomalies were similar to those observed in 1941, but larger than observed in 1958 at these locations.

Monthly Sea Surface Temperature Anomalies

Monthly sea surface temperature anomalies (monthly mean minus long-term monthly mean) at British Columbia shore stations were generally small and variable throughout most of 1982 (Fig. 3). By December, slightly above-average sea surface temperatures prevailed; a marked increase in the anomalies occurred in January. They continued to increase and, in most cases, peaked in March-April to values as great as 2.5°C. A decrease in the monthly anomalies occurred from May to June at the stations presented except in the north at Langara Island. At those stations showing a decrease,. there was a lower-than-average increase in the monthly means from May to June. This is attributed mainly to below-average local heating in June. An increase in anomalies generally occurred from June to July, except at Cape St. James and Entrance Island. The notable exception was at Entrance Island in the Strait of Georgia where a negative anomaly was observed. After July, the anomalies decreased. During the latter part of the year, near-average temperature conditions are indicated.

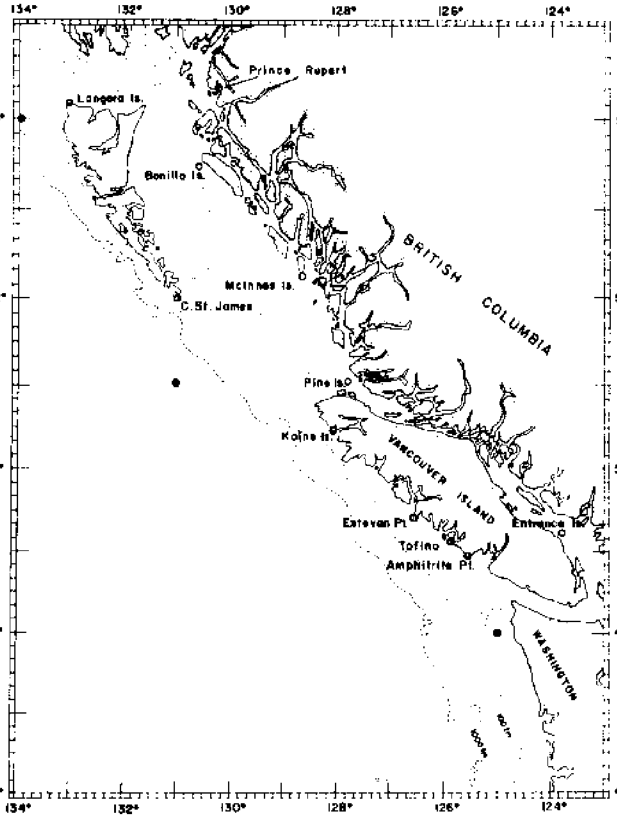

Figure 1. Map showing locations of British Columbia lightstations and sea-level recording stations (open circles) and grid points for calculations of Ekman transport (solid circles) referred to in the text.

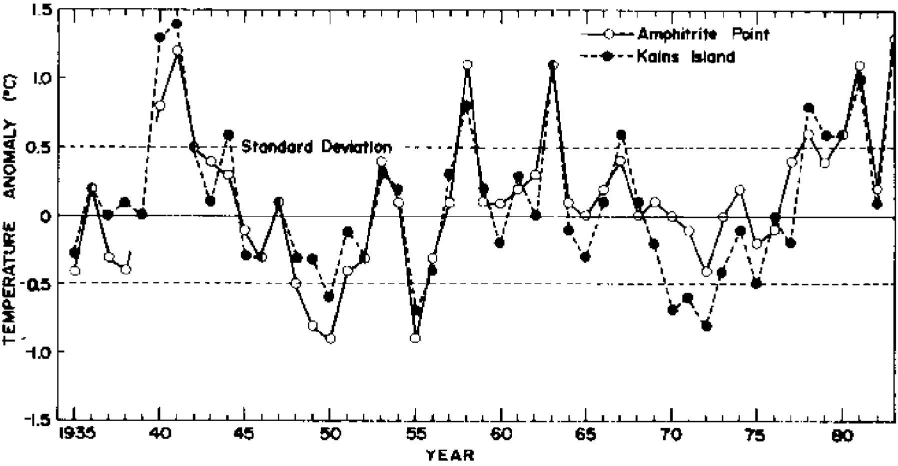

Figure 2. Annual sea surface temperature anomalies (°C) at Amphitrite Point and Kains Island, Vancouver Island, 1935-83.

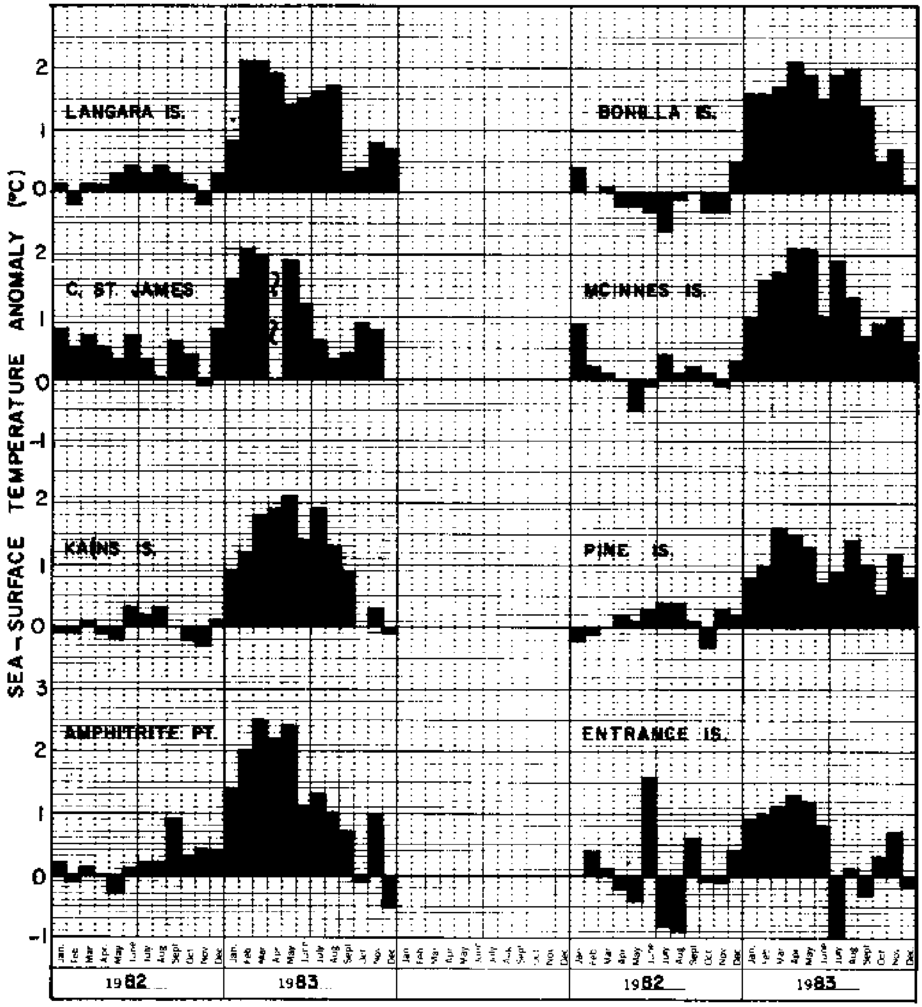

Figure 3. Monthly sea surface temperature anomalies (°C) at several British Columbia lightstations, 1982-83.

The monthly sea surface temperature anomaly patterns for 1941 and 1983 were somewhat similar in that the largest anomalies generally prevailed in late winter and spring (Fig. 4). However, in 1958, the anomalies were generally largest in spring and summer. During the last 4 months of the year, anomalies were generally larger in 1941 than in 1958. In 1958, the anomaly appeared to be earlier progressing northward. The reverse would be expected if advection was the dominant process.

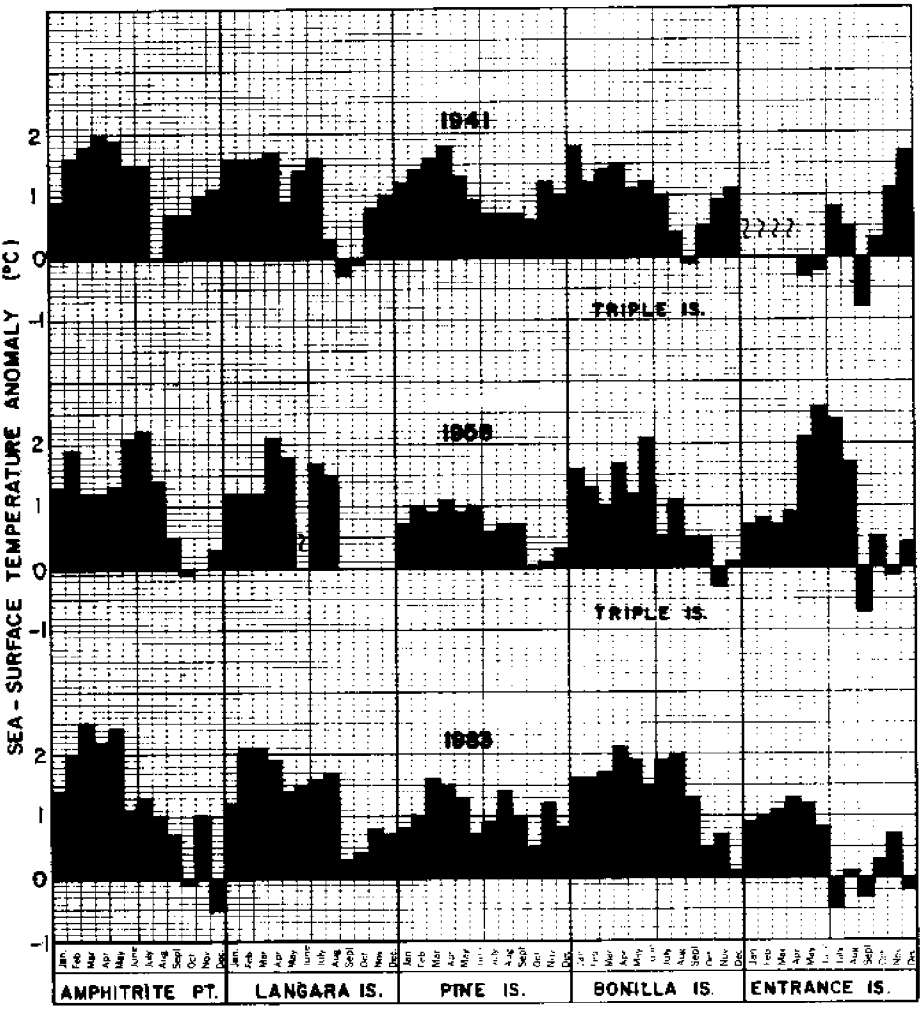

Figure 4. Monthly sea surface temperature anomalies (°C) at selected British Columbia lightstations, 1941, 1958 and 1983.

Monthly Sea Level Anomalies

Monthly mean sea level anomalies were relatively large during the latter part of 1982 at Tofino and Prince Rupert (Fig. 5). A marked increase in the sea level anomalies occurred in January, and they remained relatively large through March. The anomaly decreased markedly in April. Thereafter, the anomalies generally increased to a maximum in July, and then decreased. Anomalies at Prince Rupert were larger than those at Tofino during the spring-early autumn period.

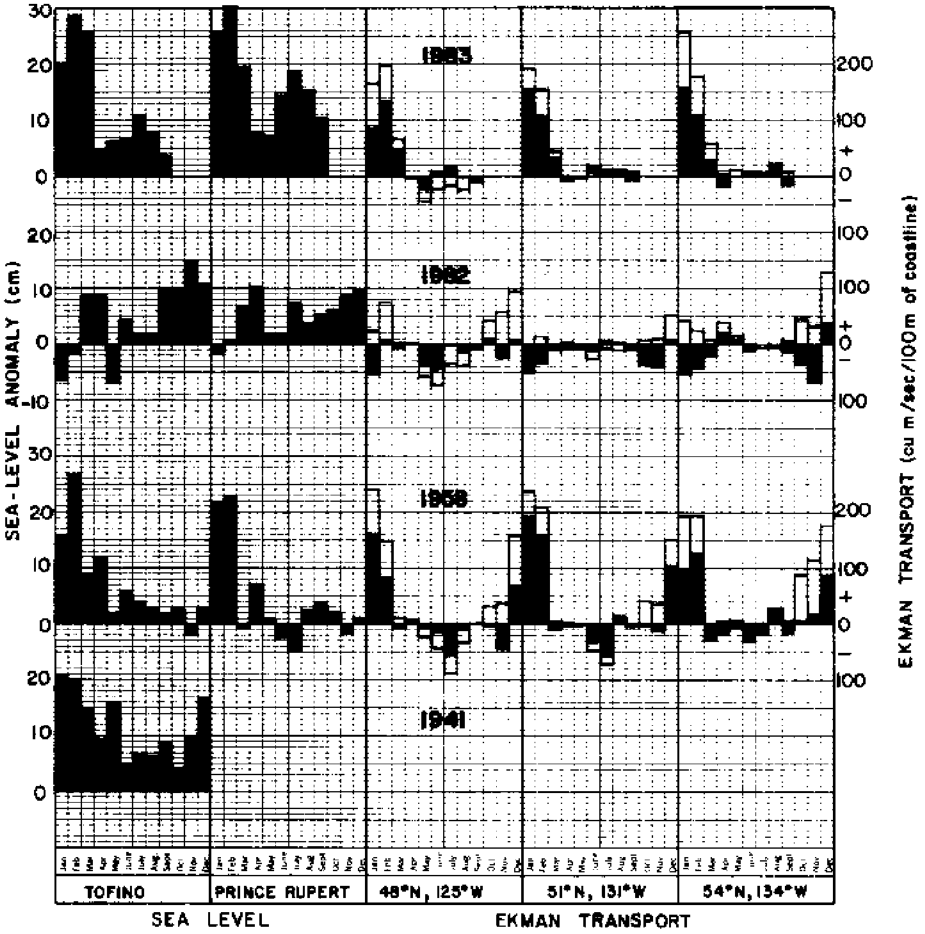

Figure 5. Monthly sea level anomalies (cm) at Tofino, B.C. and Prince Rupert, B.C. and monthly mean Ekman transport (open bars) and anomalies (solid bars) normal to the coast (cu cm/sec/100 m of coastline), 1941, 1958 and 1982-83. Sea-level anomalies were derived from unadjusted values of sea level. Transport values are from National Marine Fisheries Service, Monterey CA but the signs have been reversed; onshore transport is positive and offshore transport is negative.

Ekman Transport

Onshore-offshore transports normal to the coast indicate the relative persistence and strengths of the convergent-divergent processes. At these latitudes, the convergent condition is the strongest and more persistent of the two processes.

During October-December 1982, monthly mean anomalies indicate

Table 1. Mean bottom-water temperatures (°C) by depth interval (m) of the continental shelf waters between Amphitrite Point and Estevan Point, Vancouver Island, May 1977-83.

Depth Interval (m)	Range (°C) 1983	1983	1982	Mean (°C) 1981	1980	1979	1978	1977	Δ T* Min/Max
48-71	10.5-10.7	10.6(3)	8.7(1)	-	-	-	-	-	
72-90	9.5-10.4	10.0(4)	-	-	-	-	-	-	
91-108	8.6-8.7	8.6(2)	8.0(2)	8.0(6)	8.2(3)	7.9(7)	7.7(6)	7.3(8)	0.4/1.3
109-126	8.2-9.1	8.6(6)	7.7(6)	7.5(6)	7.8(4)	7.7(7)	7.5(14)	7.1(10)	0.8/1.5
127-145	7.8-8.4	8.1(11)	7.5(7)	7.3(5)	7.5(9)	7.4(9)	7.1(20)	7.0(7)	0.6/1.1
146-163	7.7-8.0	7.8(10)	6.9(1)	7.2(2)	7.1(3)	7.2(4)	6.9(7)	6.7(4)	0.6/1.1
164-181	-	7.8(3)	-	6.9(2)	-	7.0(2)	-	-	0.8/0.9
182-200	7.8-7.9	7.9(3)	7.3(1)	-	-	-	-	-	

Numbers in brackets indicate number of observations

* ΔT - Minimum and maximum differences between 1983 and 1977-82 values

relatively small to average onshore transport, but anomalously large onshore transport in January-March 1983 (Fig. 5). During the latter period, a strong convergent condition is indicated. Under this condition, a strong northerly flow and high sea-surface to bottom temperature over the continental shelf are indicated. In May 1983, offshore transport was relatively large at the southern grid part for this period, reflecting a relatively strong divergent condition for, at least the southern coast. In June-August, offshore transport was relatively small (June-July) to average (August), indicating a relaxation to a weak divergent condition. In contrast, offshore transport was anomalously large in July-August 1958, particularly in July. No data are available for 1941 for comparison.

Mean Bottom-water Temperatures

In May 1983, mean bottom-water temperatures on the continental shelf off central Vancouver Island were high compared to those of the six previous years (1977-82) (Table 1). Positive anomalies of between 0.4-1.5°C were observed.

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Bibliography of Niño Effects in the Eastern Subarctic Pacific

Compiled by Erik Stockdale

In bringing together the material in this volume, we ran across many publications dealing with Nino events in the eastern subarctic Pacific. They are listed here if they deal explicitly with observations or analyses associated with Nino events in the region. While the list is not comprehensive, when used with the papers in this volume, it can introduce the reader to much of the published information on the phenomenon as it appears in this region.

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APPENDIX A Program

A Meeting on Nino Effects in the Eastern Subarctic Pacific

12-13 September 1984, 0830-1630, Pacific Marine Environmental Laboratory, Sand Point, Seattle. Sponsored by International Recruitment Investigations in the Subarctic, IRIS, and supported by Northwest and Alaska Fisheries Center of NMFS.

THE PHYSICAL ENVIRONMENT. 12 September 1984.

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