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The North Pacific Study

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Preparations are underway to investigate the nature of large-scale fluctuations of sea-surface temperatures using a buoy array extending 2000 miles across the North Pacific. These fluctuations appear to be of common occurrence and interrelated with anomalous weather conditions and changes in the distribution of rainfall, marine productivity, and marine organisms. Although monthly mean sea-surface temperatures are available from ships' data, very little is known of the associated events below the sea surface, or what oceanographic and meteorological processes are involved in the onset, development, and decay of the anomalies. A pilot study of the sea-surface temperature data is providing some hints of the nature of the events. The buoys to be used have been under development at Scripps for many years. They are simple taut-moored catamaran buoys recording meteorological parameters and water temperatures to 500 meters. One or two Convair Monster buoys will be used, as well as a few Scripps current-meter buoys. Present Scripps' buoys have survived winds in excess of 95 knots while moored in water over 3000 fathoms in depth, and have yielded the first very long continuous records of temperatures in the open sea.

Introduction

OUR studies of the variability in the Pacific will be discussed in this paper. In the following, I will briefly reiterate the general matter of variability in the ocean and trace some of our information on post-pleistocene variations in the North Pacific. I will refer to the information contained in such diverse sources as the logs of whalers and Spanish galleons, the middens of Pacific Coast Indians, and old mission records. I will dwell in some detail on the remarkable chronology displayed by the varved sediments in certain rare basins, scan through a recent conspicuous case history of ocean change, discuss Scripps' present program for the study of variability in the North Pacific, show some results of a pilot study, and outline our future plans. Since the development of competent instrumentation is a basic requirement to this study, I will also trace the development of the supporting instrument program, including the deep-moored instrument stations on which our field program will be based. Finally, I wish to suggest the range of required philosophical approaches to the problems of understanding fluctuations and offer the opinion that, in the geosciences at least, we may need to develop the pragmatic descriptive approaches in a more confident manner.

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The fluctuation of the conditions of the ocean and atmosphere of this earth clearly cover broad spatial and temporal scales, ranging from local changes over minutes to changes that involve the entire earth and persist for millenia. Between the dimensions and the time scale of the conditions that we refer to as "weather" and those that we call "climate" are substantial fluctuations of the ocean and atmosphere that involve time periods of months to decades and affect large parts of the earth's surface. It is this interval, intermediate between weather and climate, to which I will principally address myself, and the changes therein, particularly those evinced by the North Pacific.

Not only do fluctuations of this range of persistency and dimension constitute a particularly intriguing scientific problem, and probably a series of unique entrees into air-sea interaction, but this range also challenges man with environmental changes of particular importance, for the duration of these changes are significant fractions of the human life span, and even larger fractions of his span of memory. Whereas the man is adjusted to his day-to-day and seasonal changes in conditions, and whereas he accommodates also to the long-term secular changes in climate by slow modification of his behavior and habits, his resources and habits are frequently incapable of accommodating to the intensity and duration of fluctuations of this intermediate time scale.

Agriculture and fisheries, for example, cannot survive several successive years of drought or dearth, nor can the food reserves of many societies be stretched across such periods. The biblical prediction of Joseph's seven fat and seven lean years emphasizes the vital nature of this time scale, as did the United States drought of the 1930's. Today on the Pacific Coast of North America the effects of variations are conspicuous in several forms and guises; verdant forests of

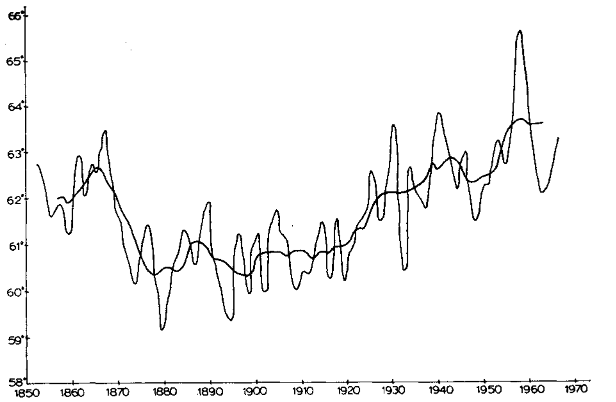

Fig. 1 Mean annual air temperatures—2-yr and 10-yr means—San Diego.

eucalyptus planted at the 1913 outset of a wet period, abandoned remains of large agricultural colonies in Baja, California stimulated by similar periods, and, of course, the new housing developments in the southwest canyons and arroyos in these past two dry decades, during which the civic conscience of bank-to-bank floods has not been exercised, although such floods occurred once in a decade in the first half of this century. Variations of conditions are experienced throughout the entire Pacific Basin. The notorious El Niño of Peru is a spasmotic and severe surge of warm water into the area normally washed by the cold Peru Current. The trade winds in Hawaii appear to be subject to quasi-cyclic alternations, and recently a fluctuating tongue of warm water in the equatorial current system has been implicated in rainfall variations at Canton Island.[1] Studies of changes in the position of the Kuroshio Current off Japan and other variations about the Pacific are also a matter of record[7] and I will refer to some of these later.

However, I will concentrate on the variations in conditions of the North Pacific. In these vast ocean reaches much of the features of North American weather receive their final identity.

Even a cursory inspection of the simplest of Pacific Coast weather records reveals almost continuous fluctuations since their inception. Figure 1, for example, is a century-long record of mean annual air temperatures at San Diego, California, compiled from U. S. Weather Bureau data.

The mean air temperatures and mean sea temperatures at such marine stations are very closely related except for the effects of recent urbanization. We can thus view this record as a mean ocean-surface temperature record. Shown are 2-yr and 10-yr running means. The 2-yr means display strong fluctuations with a 4- or 5-yr duration. In the 10-yr means, these are greatly repressed, and the 50-yr interval of

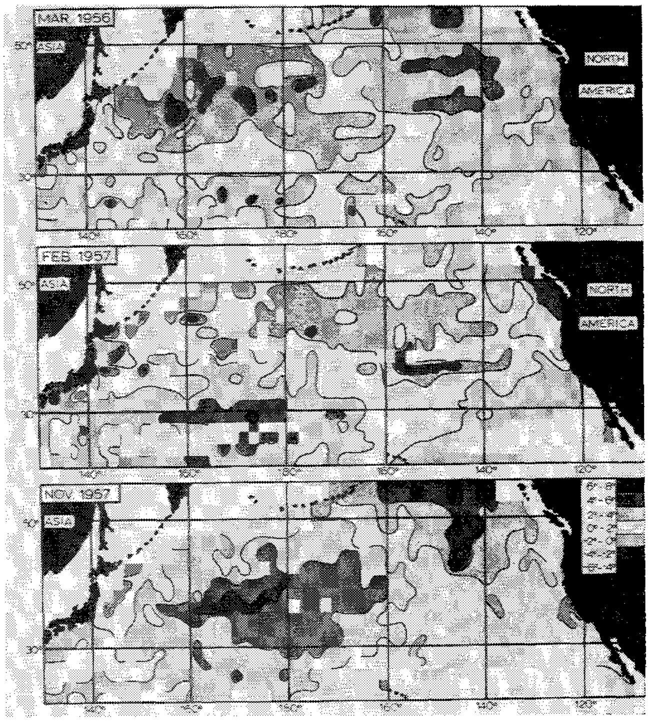

Fig. 3 Deviation of sea-surface temperature (°F) from 1947–58 mean.

low temperatures remains the dominant feature. I will refer to both of these features later and also show you another record, derived from the sediments, that extends these longer-period fluctuations back for over 2000 yr with a similar time resolution. Variations in the temperatures at such coastal stations were long thought to be very local effects, but in the last decade or so they have been shown to be correlated over dimensions of 1000 km or more, by Roden and Reid[14] and others.

Further, some years ago it was noted that the more extreme departures from the mean ocean temperatures were roughly synchronous at such widely separated regions as Peru, Japan, and California. These extreme fluctuations were sometimes in the same sense and sometimes in the inverse sense; that is, the intensity was correlated, but not the phase. Considered as a correlation of widely separated local changes, these were

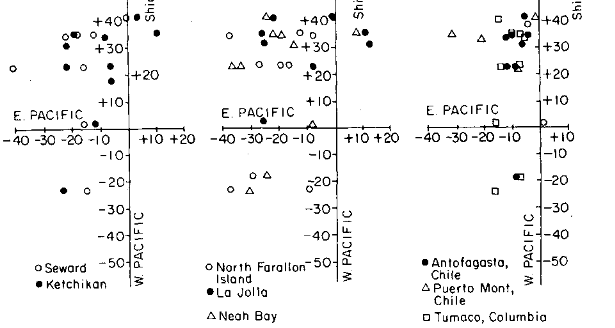

Fig. 2 Mean monthly coastal water temperature anomaly (°F) of eastern Pacific stations related to a western Pacific base station—1955 (adapted from Ref. 18).

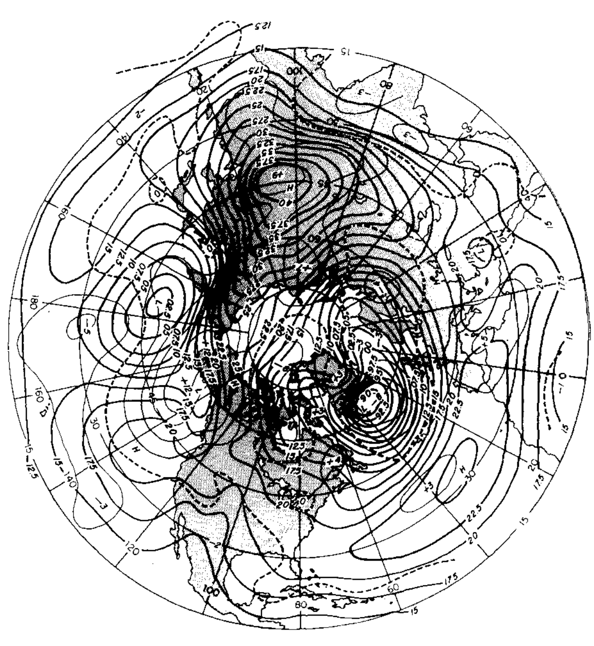

Fig. 4 Sea-level barometric pressure—winter 1956–57.[10]

thought to be cases of teleconnection. However, it now appears that these correlations are very often simply an expression of the great spatial extent of the ocean-atmosphere variations. Figure 2 is an example of such correlation, adapted from Takenouti[18] and showing the inverse correlation between temperature anomalies at a Japanese shore station (on the ordinate) and a Chilean and southern Californian station (on the abscissa) for the year 1955. Weak, inverse correlations between North American Atlantic and Pacific coastal temperature anomalies also have been indicated.

Perhaps a brief review of the case history of a well-studied variation in the Pacific will bring some of these matters into focus. The mean sea-surface temperature over the North Pacific during the years 1955 to 1958 underwent an intense change. Figure 3 traces the events from March 1956 to November 1957 from the data of the Bureau of Commercial Fisheries.[14]

During this period a great warm anomaly appeared to progress across the Pacific from Japan to the west coast of North America. This was associated with at least two periods of highly anomalous surface-wind patterns. In the winter seasons of 1956–57 and 1957–58, anomalous low-pressure areas were centered roughly over the warm surface waters. Figure 4 shows the conditions in winter 1956–57, when strong anomalous southerly winds occurred in the central North Pacific.

Qualitatively this should have had the effect of propagating and intensifying the warm anomaly toward north and east, by advection and simple thermal exchange, at least. The 1957–58 winter season was typified by an intense development of a low-pressure area over the eastern North Pacific, as seen in Fig. 5. The result of these anomalous southerly winds off the Pacific coast were marked. The southerly directed California Current weakened and swung offshore, warm subtropical water invaded the coast as far as British Columbia, and Central Pacific water moved strongly to the east.

Figure 6 is a simplified track chart of drift bottles carried from southern California to the northern coast by the strong countercurrent in that winter. Figure 7 exemplifies the displacement of marine organisms. Like the drift bottles and many of their planktonic associates, this subtropical euphausiid was displaced a thousand miles north of its usual habitat.

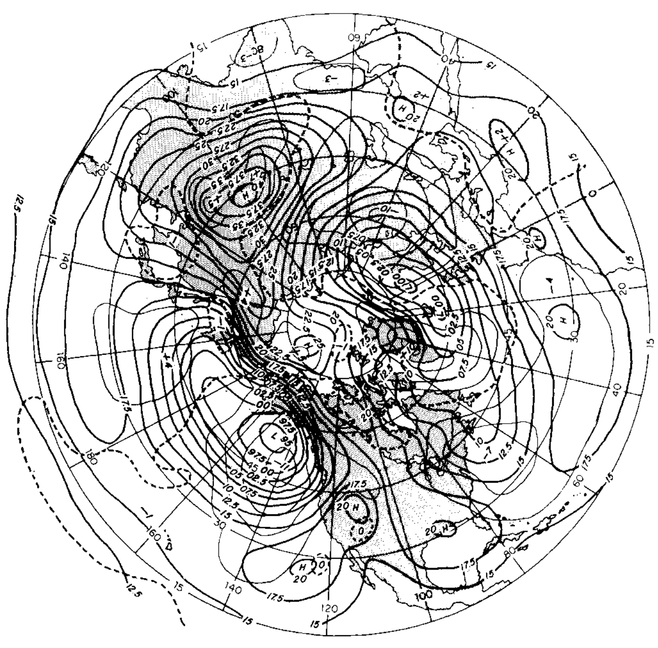

Fig. 5 Sea-level barometric pressure—winter 1957–58.[10]

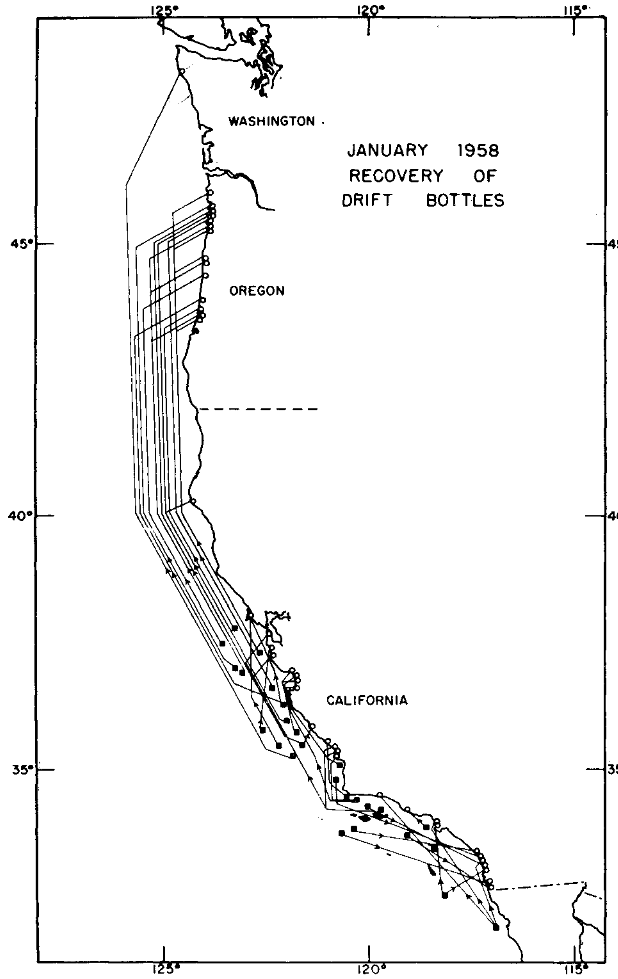

Fig. 6 Returns from drift bottles released in January 1958.[13]

I have implicated abnormal advection from abnormal winds in this change. Indeed, it appears that simple advection is partially successful in explaining these events, and several workers have developed and tested a series of increasingly sophisticated models.[16,5,9]

Namias[9] has considered the abnormal advection and the feedback to the weather system with significant success. In Fig. 8 is a comparison of Namias' hindcast sea-surface temperature anomaly for July 1958 with the anomaly observed in that month.[11]

I have here used the more recent data rather than the 9-day period employed by Namias in his 1965 paper. The comparison is considerably improved by the use of the later data. It is probable that the less satisfactory prediction of the warm anomalies in the coastal portion of the area is due to the inadequacy of the advective computation to take account of the strengthening and shallowing of the submerged coastal countercurrent as the California Current weakens.

Jacobs[5] has included additional terms in his model, such as the normal advective transport of the previous anomaly and thermal exchange terms. The prediction of sea-surface temperature anomalies is somewhat improved by these additions, with the anomalies in the coastal areas again not as well predicted as those of the open sea.

Among these various attempts at prediction, Namias[12] has described and elucidated the feedback mechanisms between the atmosphere and ocean on the gross phenomenological scale. Understanding of these processes clearly will be essential in developing insight into the origin, stabilization, intensification, or decay of these air-sea anomalies, and their relationships to weather fluctuations and climatic change.

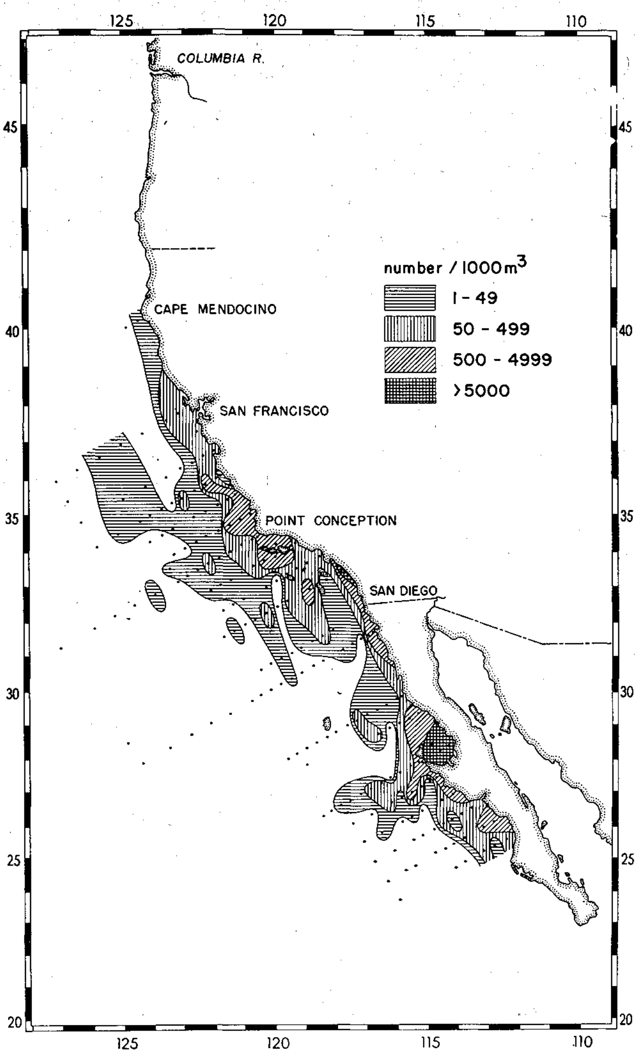

Fig. 7 Distribution of *Nyctiphanes simplex*—April 1958.[2]

I will now pass on to two aspects of my subject—first, to a brief sketch of the post-Pleistocene historical data on the Pacific Coast, and then to some of the statistical peculiarities of the sea-surface temperature anomalies of the North Pacific and the processes of which they hint.

At Scripps we are slowly accumulating much of the continuous and fragmentary data on Pacific Coast conditions. The Spanish mission rainfall data are, of course, well known.[6] Other data and observations are contained in whalers' logs, logs of Spanish galleons, letters of pioneers, etc. Data such as the years in which snow fell on the sourthern Californian and Mexican offshore islands, years of floods and of displacement of tropical or northern fauna may eventually be fitted into a more thorough knowledge of the variations in the Pacific and their etiology. We have discovered a trove of data from some little-known expeditions to the Pacific. The logs of Malaspina's expedition of 1789–1794 have long languished in the archives of the Spanish Navy in Madrid. These remarkable documents, which contain some hundreds of excellent large color drawings of marine and terrestrial animals and plants, are being investigated by Dr. Alvariño, who located them. Figure 9 is of a medusa often common in the California Current and immediately recognizable from the paintings of the Malaspina expedition. More ancient data also exist. Hubbs some years ago, studying the kitchen middens of coastal Indians, showed that the winds and currents must, in general, now be of the same nature as for the last four or more millenia.[4]

We also are developing another and inexhaustible source of data on past variations in the Pacific. These are the rare and curiously varved sediments laid down in certain coastal basins extending from British Columbia to Peru. First described by Emory[3] in the Santa Barbara Basin, these sediments are deposited at depths under water that is essentially devoid of oxygen. The sediments thus are not reworked by either currents or benthic organisms, and are preserved as layers representing the annual fall of detritus from the overlying waters. I have already shown a case where organisms have been greatly displaced by changes in ocean circulation. There are, of course, many organisms inhabiting the same and different water masses. We therefore believe that these sediments are virtually annual pages of the history books of the ocean-atmosphere system, which provide an extremely valuable entree into an understanding of the nature of oceanic fluctuations of the past, their frequency, the nature of the changing circulation, the relationships with rainfall, and the synchrony between widely separated areas. To decipher the messages we must know of the range of distribution of the organisms whose remains contribute to these sediments.

For example, Fig. 10 from McGowan[8] shows the present distribution of the microscopic shelled pelagic mollusc, *Limacina helicina*, a pteropod. Its presence in the sediments of the Santa Barbara Basin must be a measure of the strength of the California Current.

Figure 11 shows the frequency of the shells of this organism in these sediments from ongoing work of a graduate student at

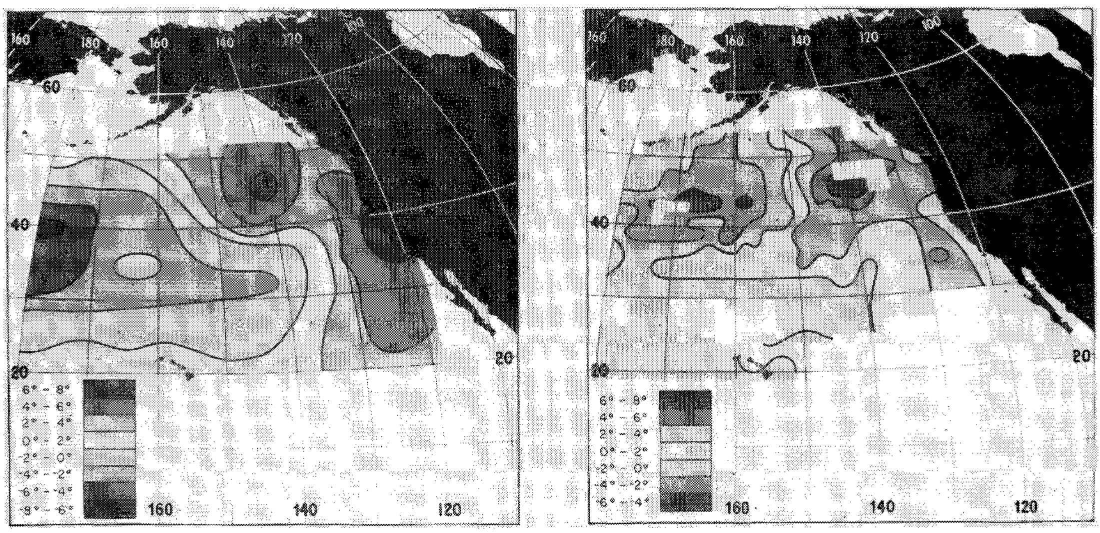

Fig. 8 Computed (left) and observed (right) sea-surface temperature anomalies—July 1958.

Scripps.[17] The figure shows an extract of a longer record and covers the millenium from about 850 to 1840 A.D. in 10-yr discrete means. For comparison is also plotted a century of air temperatures at San Diego, also in 10-yr discrete means. You will see that the characters of the fluctuations are not dissimilar, with sudden discontinuous increases and decreases.

Within the next year, the most recent century of sediments will be analyzed in 2- or 3-yr increments. We can then carry out a highly resolved comparison of this "Rosetta Stone" with the historical record. This most recent sedimentary record is not yet available. The upper sediments are not consolidated and Soutar has managed to sample them undisturbed only by the most laborious methods. They are thus too valuable to analyze in 10-yr intervals, and the analysis is not yet complete.

Diatoms and foraminifera are also being tabulated. These results should give us great insight into the history and conditions of short- and long-term fluctuations in the Pacific, extending through the historical period for several thousand years B.P. with a high time resolution.

We will attempt correlations between these data, and those from other basins, and also with data from glaciers, tree rings, the historical record, and from other sources. Just the qualitative correlations of these pteropod data with known climatic change is intriguing. For example, periods of glacial advance in British Columbia appear to be associated with rapidly increasing numbers of *Limacina*, and presumably with an increase in the strength of the California Current.

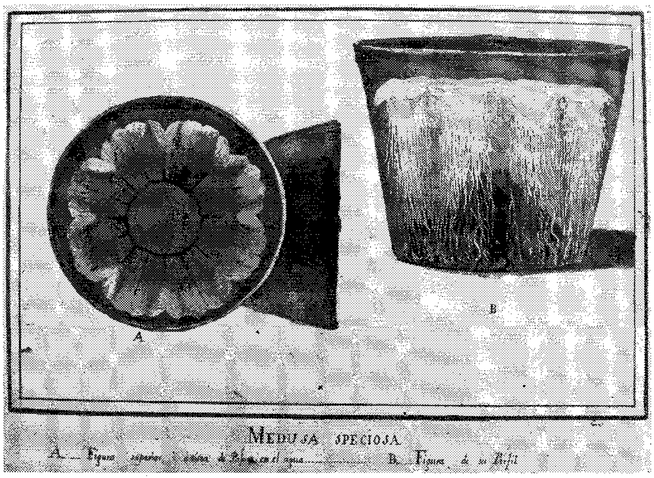

Fig. 9 Watercolor of *Desmonema rosea* from Malaspina Expedition, ca. 1790.

I have so far in this discussion pointed out some of the history of variations in the Pacific, some of the aspects of sea-surface temperature anomalies, and some of the attempts to explain atmospheric interaction of these features.

Last winter during an official weather forecast of "50% chance of showers" I washed broadside down a street in a Los Angeles taxi during one of the greatest recorded rainfalls in that area. The simple North Pacific disturbance that pro-

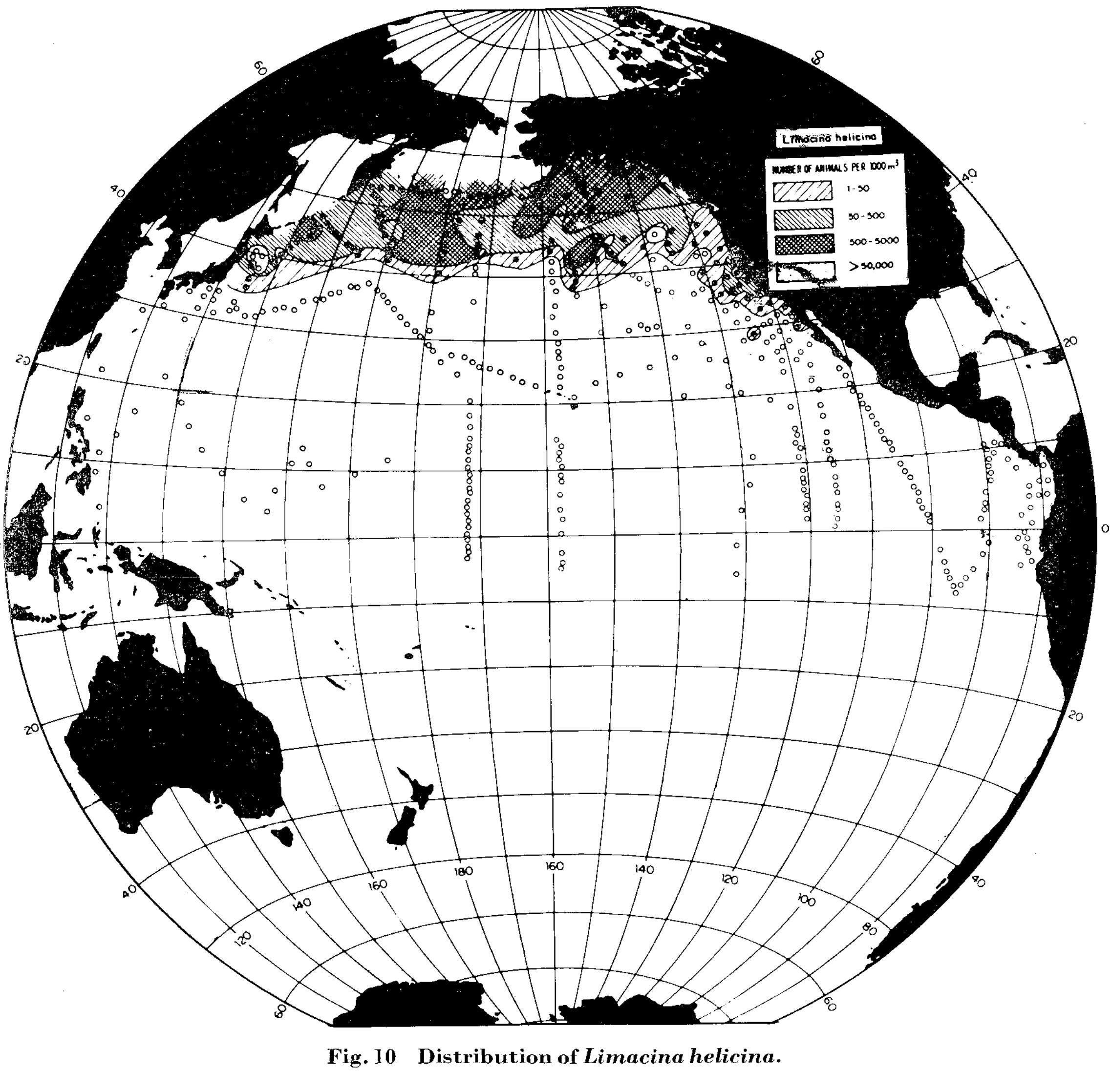

Fig. 10 Distribution of *Limacina helicina*.

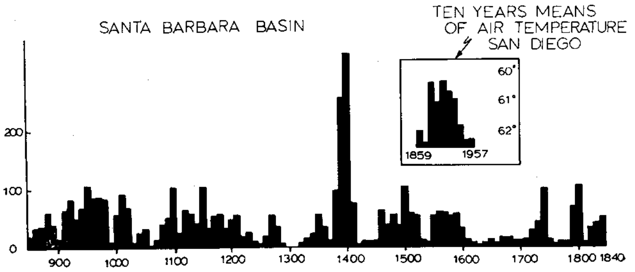

Fig. 11 Sediment record of *Limacina helicina* (shells in 10-yr intervals of sediment) with air temperature record at San Diego.

duced this deluge had moved across abnormally warm water, and it is almost impossible to avoid associating this extremely poor record of short-range forecasting in southern California this last fall and winter with inattention to the ocean conditions and their interaction with the atmosphere. Attention to and understanding of ocean conditions certainly must be involved in any highly successful model of weather and climate.

At this time the only synoptic information on ocean temperature conditions is of the surface temperatures. We need to know much more than this. We need to know what is

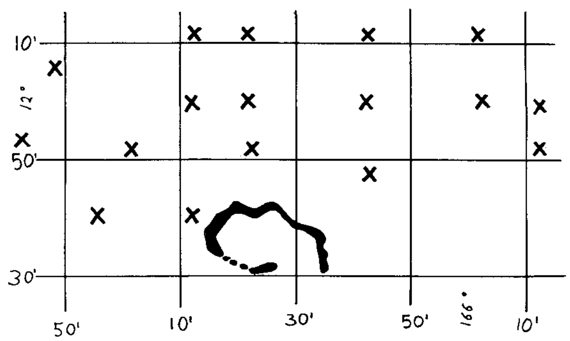

Fig. 12 SKIFF distribution of moorings for TEWA, Bikini test, 1956; 17 stations activated and recovered

transpiring below the surface of the sea during these fluctuations, so that we can determine such critical matters as the fluctuation in heat content, the relationships of the large-scale changes and high-frequency events, the nature of diurnal heating and cooling, etc. We also need to have better quantification of the insolation, wind drag, humidity, and other atmospheric conditions associated with large-scale sea-surface temperature fluctuations.

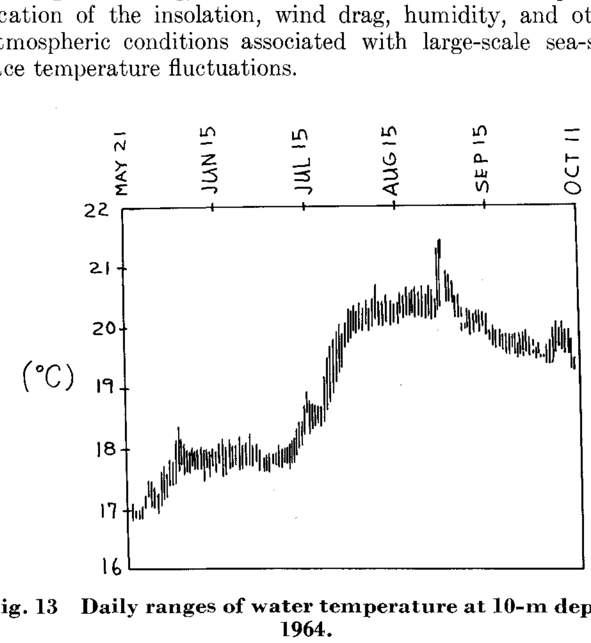

Fig. 13 Daily ranges of water temperature at 10-m depth, 1964.

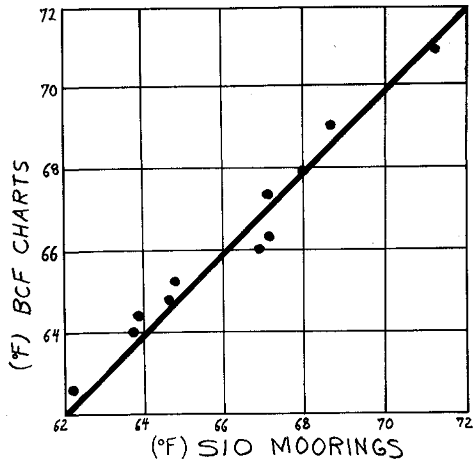

Fig. 14 Correlation diagram of two kinds of sea-surface temperatures.

At Scripps we are now getting underway on a program of measurement from widely deployed deep-moored unmanned instrument stations in the North Pacific, and I will briefly discuss the nature of these developments and plans.

Scripps' first major experience in development and employment of deep-moored unmanned instrument stations dates from the nuclear detonations of the last decade. Unmanned deep-moored stations were employed for measuring various detonation effects, including water wave and fallout. Figure 12 shows the distribution of these simple stations for one event, where 17 stations, moored in depths from 700 to 3200 fathoms, were distributed over almost 6000 square miles. These stations performed very well and most survived for 6 months or more in the tradewind seas. Since then we have continuously improved these stations, so that we now believe that a large-scale attack on the temperature anomaly problem has become feasible.

We have reason to believe that the data so obtained will be of critical significance. For example, Fig. 13 shows the daily temperature extremes from hourly measurements for a 5-months record taken by such a station moored in 2400 fathoms, halfway between California and Hawaii. In the usual installation, about 10 sensors are distributed from the surface through the mixed layer to 300 or 500 meters, depending on the location. This particular record is from near-surface temperature sensors. In this record the high-frequency temperature variations by no means obfuscate the low-frequency events. Thus, rather simple records will be adequate for studying slowly varying temperatures. This record is from one station of four, which remained installed in the east Central Pacific for 6–23 months.

It is also important to determine if the data from moorings agree with the charts of monthly temperatures emerging from the Bureau of Commercial Fisheries (BCF) merchant ship temperatures. Figure 14 is a comparison between the results from these quite different sources. On the abscissa are

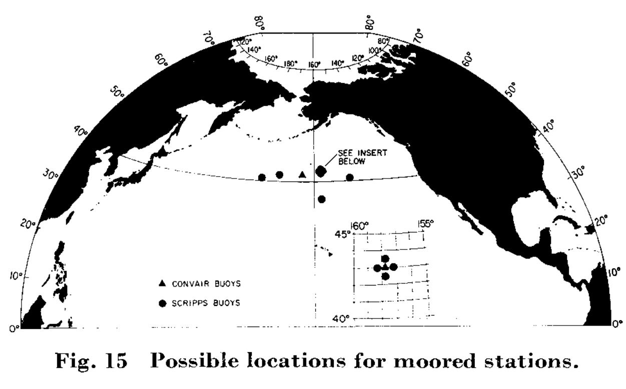

Fig. 15 Possible locations for moored stations.

plotted the monthly mean surface temperatures from hourly readings from the moorings, and on the ordinate are plotted the interpolated monthly mean temperatures taken from the published contour charts of the BCF.[14] The correspondence between the results of these quite different approaches is surprisingly high. That the BCF data should be so irreproachable is perhaps the most surprising, as they are taken, of course, from random merchant ship data. In any event, it is clear that the surface temperatures from the moorings reflect the same monthly mean temperatures as the temperature anomaly charts, and hence, the subsurface data will add greatly to an understanding of the phenomenology.

We are thus planning an initial sparse installation of about 10 of these stations, deployed roughly as shown in Fig. 15, by next fall. Two of the Convair monster buoys will be deployed along with them. Moreover, several Scripps current meters will be moored in the mixed layer. We will, of course, also employ data from aircraft, satellite, X-BT, conventional hydrographic casts, and from other sources.

One of our newest catamarans of the covered wagon design is shown here (Fig. 16) moored in 3280 fathoms in the typhoon region 600 miles north of Wake Island, at Ocean Station Victor. We have received a report from the Coast Guard that this station has now gone through 95-knot winds and 45-ft seas, in a 3-knot current, with "very superior performance." We thus can have confidence that our stations can survive and yield data during the critical North Pacific winter storms.

In preparation for this program, we have been carrying out a number of studies of the sea-surface temperatures of the North Pacific. Many of these results are quite intriguing and provide strong hints of the nature of the North Pacific temperature fluctuations, and I will show you some samples of these findings.

For these studies we have taken all published and unpublished surface temperature data at two geographical degree intervals for the entire North Pacific for a 14-yr period, 1947–1960. The data have been reduced to cards and subjected to error-eliminating programs. Mean monthly and long-term monthly mean temperatures and time and space gradients have been determined. These studies have revealed some interesting features of the long-term mean temperature fluctuations. Three of these findings are shown in Fig. 17.

About 140,000 data points are included in these diagrams. All curves are repeated for three annual cycles. The upper curve represents the mean long-term monthly temperatures. The cycloidal character of the curve is probably the result of anisotropic heat flow due to the changing depth of the exchanging layer, that is, from the differences between the processes of shallow heating (ie. the production of a shallow stable layer) and deep cooling (with instability and mixing).

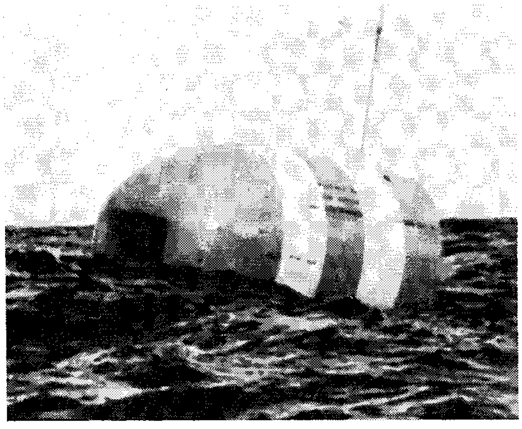

Fig. 16 'Scripps' Bumblebee catamaran buoy (covered wagon design).

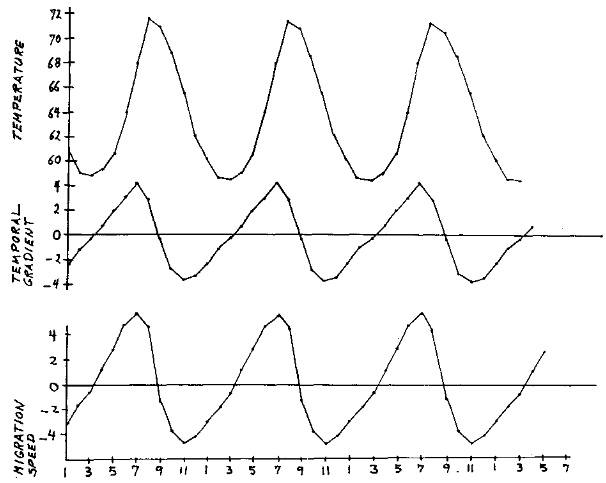

Fig. 17 Mean monthly temperature fluctuations, 1947 to 1966 (repeated $2\frac{1}{2}$ times), based on 2° squares.

The second curve is the mean monthly rate of temperature change. Peak rate of heating is greater than peak rate of cooling, as is apparent in the skew of the temperature curve. The rather remarkable linear aspect of the ascending and descending parts of the curve seem peculiar and notable, but I have no immediate explanation for this characteristic.

In the lower curve is shown the mean monthly change in position of the thermal structure calculated as if all of the annual temperature cycle were generated by moving the isotherms. The scale is in 1 geographical degrees per month. Maximum rates are about 5°/month and the total migration is of the order of 22° in 6 months or about half the monthly change in location of the zenith sun. The mean monthly temperature pattern of the North Pacific thus is roughly constant in a coordinate system midway between a terrestrial and solar coordinate system!

More immediately pertinent to my subject, however, is our similar work on the anomalous temperature features. This has shown a number of interesting characteristics. The mean dimension of a temperature anomaly, as it results from the BCF data, is about 19 geographical degrees or $\frac{1}{5}$ of the width of the North Pacific. The larger anomalies frequently occupy $\frac{1}{3}$ to $\frac{1}{2}$ or more of the North Pacific. Successive features of this size impinging on the California Current would produce fluctuations of 2- or 3-yr duration. Since *these* successive features are often of opposite sense, it may be that the approximate 5-yr quasi-periodic character of temperature fluctuation on the Pacific Coast may be due to the terminal ballistics of these anomalous temperature features.

In the foregoing, I have said something about the history of temperature fluctuations in the surface waters of the North Pacific, and discussed an entree into this history and the conditions associated with changes contained in special sediments. I have told you of our plans to study these variations, and I have shown you some of the surprising results of a pilot study of the nature of these sea-surface temperature fluctuations.

I believe that within the next few years we will know much more about the genesis, birth, adolescence, maturity, senescence, and demise of these tantalizing and important features of oceans, and their interrelationship with the atmosphere. We will also know much more about the efficacy of unmanned deep-moored stations in the study of these large-scale anomalies.

Our approach is an interdisciplinary one. Much of the critical evidence comes through the marine organisms, and much of the importance of fluctuation derives from the complex air-sea-biological interaction. The challenge is to put this broad spectrum of interaction together.

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Suspended Rigid Underwater Arrays

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The potential uses of large underwater arrays, supported in the sound channel without near field obstructions, have been of recurrent interest. This paper treats two proposed suspended array configurations designed to maintain a two- or three-dimensional matrix of transducers within given dimensional tolerances under normal environmental conditions. These tolerances result from a statistical analysis of array performance in response to structural deformations and random perturbations of the medium. One structure involves prestressing a network of suspension wires that hold the hydrophones in position; and the other uses an inflated envelope to protect the hydrophone array against the environment. The performance of critical components of each configuration is examined under static and dynamic loads. The behavior of each structure as a rigid body, held by its mooring lines, is investigated in some detail, including translational movement and attitude changes in response to steady and transient loads. For structures with a protective envelope, an acoustic analysis is required to assure tolerable effects at the hydrophones.

Nomenclature

a = membrane radius
c = speed of sound (in water)
k = wave number
$\bar{n}$ = direction of planar acoustic wave
$\bar{n}_0$ = steering vector of array
p_b = bouyancy force of flotation chambers; per unit area of membrane above mooring ring
p_γ = weight (in water) per unit area of membrane
p_i = internal pressurization of membrane
P_m = mooring force from anchor lines per unit length of mooring ring; assumed uniformly distributed
r = radial coordinate
u = transverse deflection of plane array
t = membrane thickness or time
E = Young's modulus
N = number of hydrophones
Ox_1, x_2, x_3 = rectangular Cartesian system
R = radius of spherical membrane
V = ambient current velocity
W_B = bouyancy force
$\Delta X_{\mu j}$ = differential position vector
α_i = amplitude parameter
β = angle between x_2 axis and incoming wave
γ = membrane density
$\delta\varphi_\mu$ = phase change of μth hydrophone response
λ = direction of ambient current in horizontal plane, or wavelength (evident from context)
σ = standard deviation
φ_e = external velocity potential
φ_i = internal velocity potential
ρ = density of water
Ω = characteristic frequency of a structure

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