SPACE SCALES OF SEA-SURFACE TEMPERATURE PATTERNS AND THEIR CAUSES

JEROME NAMIAS[1]

ABSTRACT

The space scales of monthly mean sea-surface-temperature (SST) anomalies over the North Pacific are determined from data gathered over a 20-year period and analyzed with the help of correlation fields. The characteristic scales are ascribed to complex coupling between the atmosphere and ocean—specifically to long waves in the upper westerlies and latitudinal variations in the westerlies, both of which produce anomalous oceanic advection and heat exchange. The coherence of mid-tropospheric (700-mb) heights, the cross-correlations between these and SST values, plus atmospheric "teleconnections" (long distance relationships) implicit in these upper-level flow patterns reveal the character of coupling.

At the historic 1958 CalCOFI meetings at Rancho Santa Fe the central theme was the large-scale climatic warming of the North and equatorial Pacific which had evolved over a few years preceding the conference (Sette and Isaacs, 1960). Elton Sette, who co-chaired this meeting, stimulated much discussion of the time and space scales of this warming. In his work over subsequent years he has made numerous major contributions to the subject of large-scale oceanic temperature patterns. It is the purpose of this note to bring to light some new data and ideas relevant to these problems and thus serve both as a testimonial to Elton's work and as an expression of gratitude for his unceasing encouragement to those of us working along similar lines.

The source of data for the present work is a series of monthly mean sea-surface temperatures (SST) extending from 1947 to 1966 generated at the Scripps Institution of Oceanography from files of about 8,000,000 ship reports which were compiled by the National Marine Fisheries Service from the National Weather Service reports. Monthly averages of 2° geographic squares were computed and then further averaged around 5° intersections for areas north of lat 20°N. A 20-year average for each month was then computed. Departures of the monthly means from the 20-year averages were used in the work described below along with 700-mb heights obtained directly from the National Weather Service.

To determine the coherence of North Pacific SST patterns and possible teleconnections between them I have correlated the SST deviations from the 20-year mean at one point with deviations of the other 154 points used in the 5° oceanic grid for each of the winter months (December, January, and February) over the 20-year period making a set of 60 values for each point. Examples are shown in the middle charts of Figures 1, 2, and 3. A similar procedure was used with the atmospheric 700-mb heights as shown in the upper charts of these figures. Finally, cross-correlation fields were prepared relating SST point values to the 700 mb-height values elsewhere as shown in the lower charts. The latter two sets of charts involving atmospheric parameters were constructed to help explain the physical nature of the large-scale air-sea coupling which accounts for the observed scale of the predominant SST patterns.

Before discussing these charts, I should mention that the 700-mb level rather than sea level

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[1] Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA 92037.

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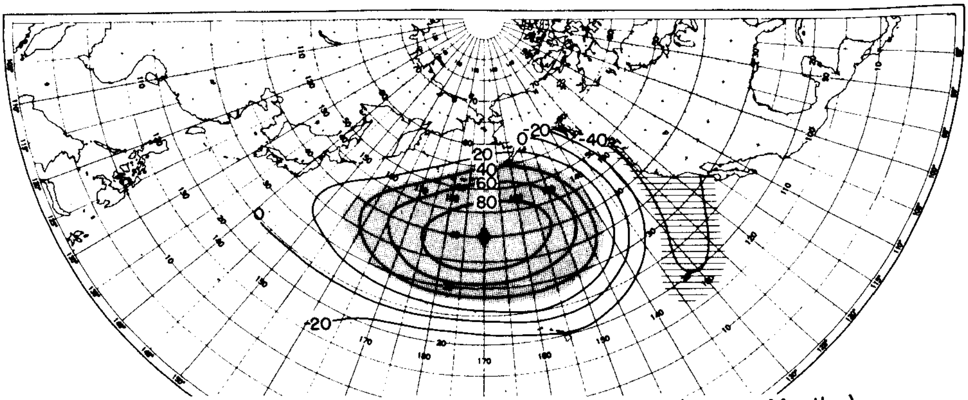
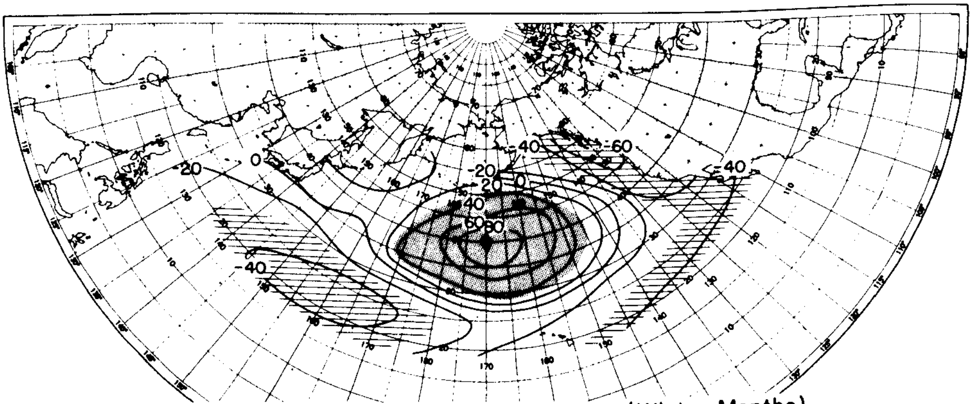


r 700 mb at diamond vs. 700 mb elsewhere (Winter Months)



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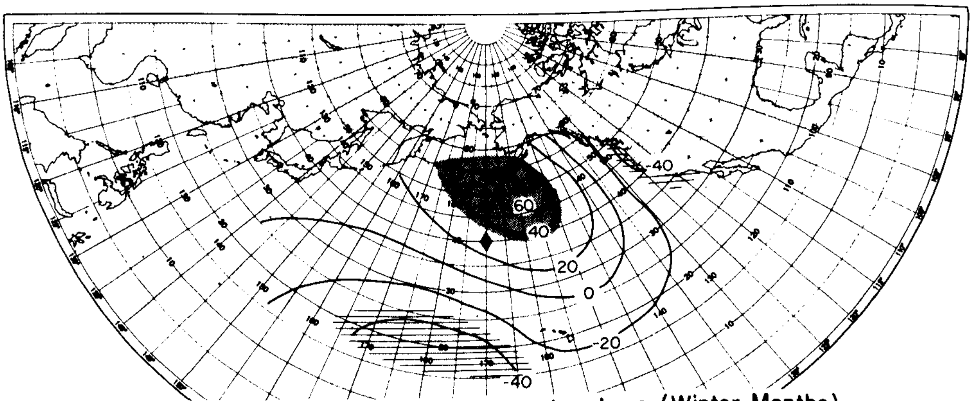
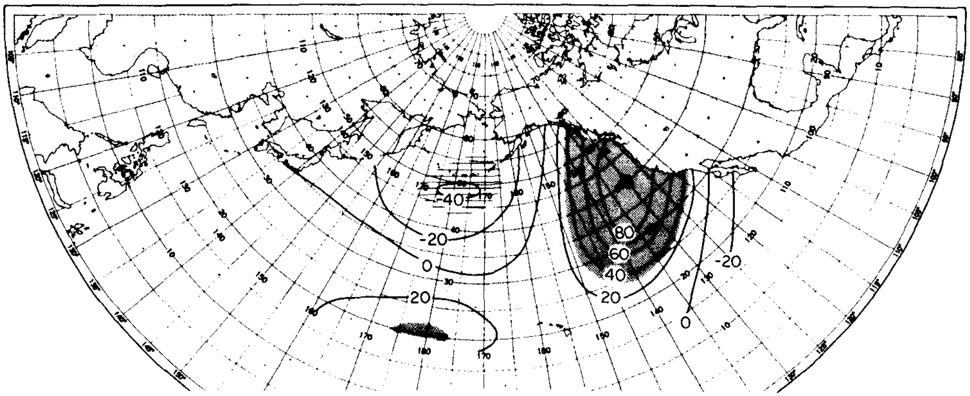


r SST at diamond vs. 700 mb elsewhere (Winter Months)

FIGURE 1.—Contemporaneous correlations between lat 40°N, long 170°W (diamond) and elsewhere for 700-mb heights (upper), sea-surface temperatures (middle), and SST vs. 700-mb (lower). Shaded areas represent correlations exceeding 1% level of significance—positive correlations stippled, negative hatched.



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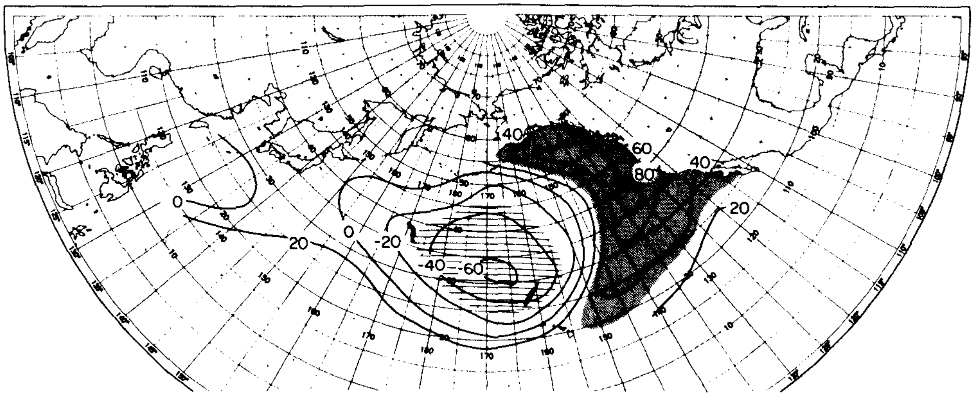

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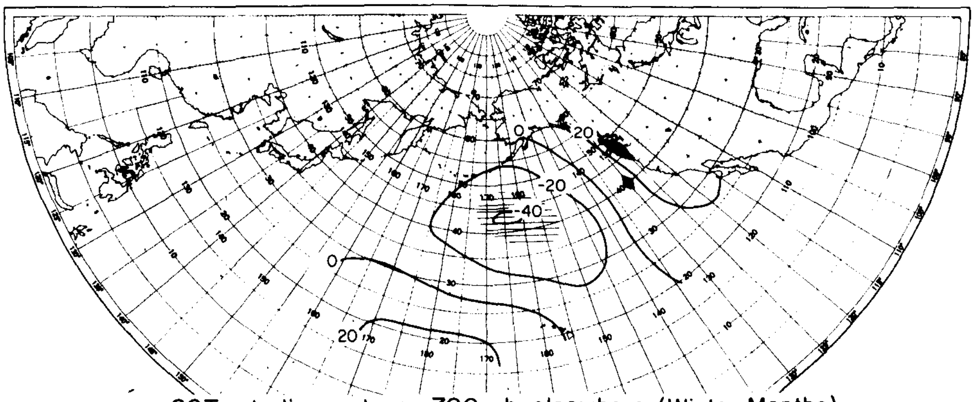
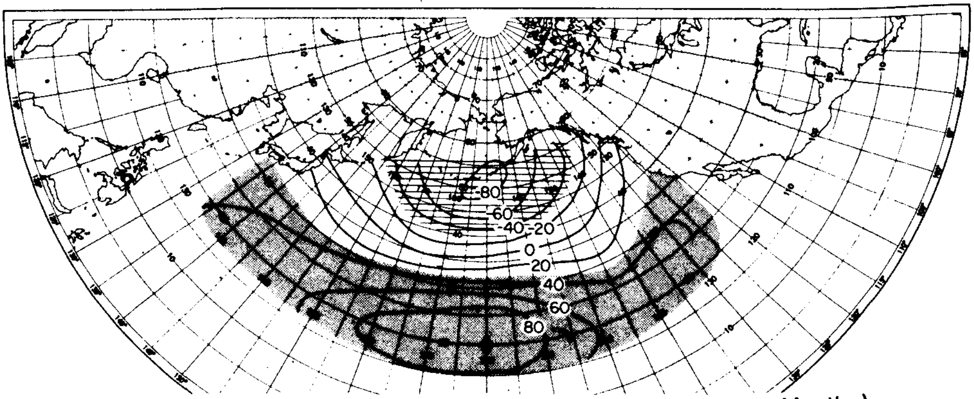


r SST at diamond vs. 700 mb elsewhere (Winter Months)

FIGURE 2.—Contemporaneous correlations between lat 40°N, long 130°W (diamond) and elsewhere for 700-mb heights (upper), sea-surface temperatures (middle), and SST vs. 700-mb (lower). Shaded areas represent correlations exceeding 1% level of significance—positive correlations stippled, negative hatched.



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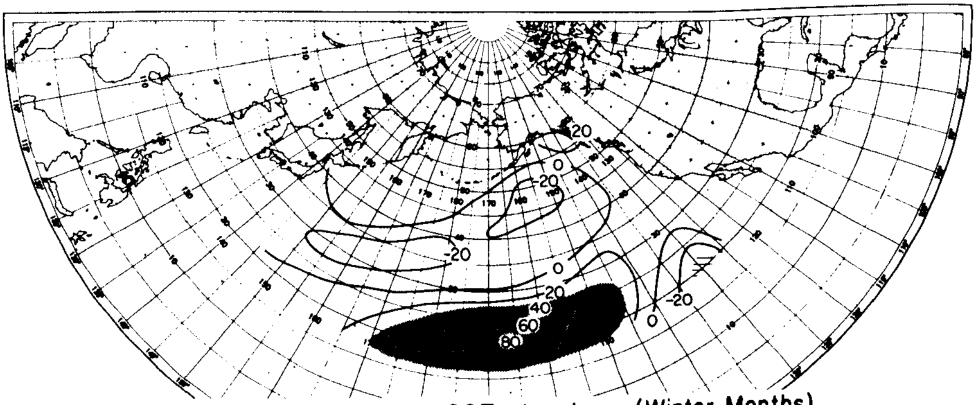
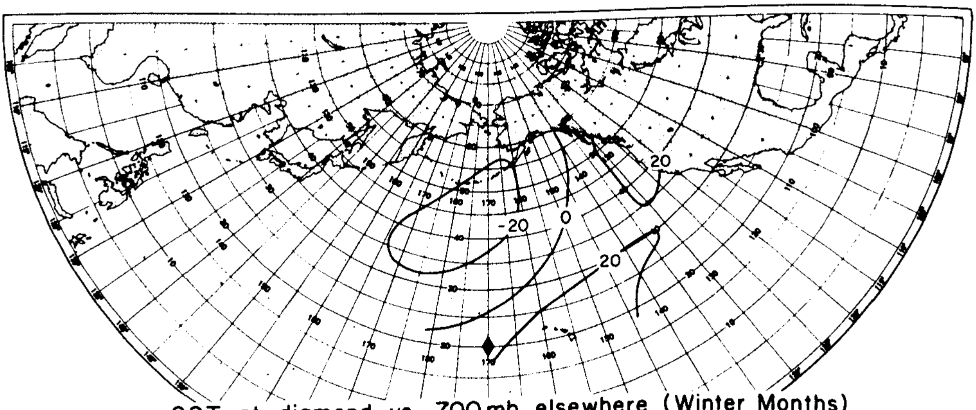


r SST at diamond vs. SST elsewhere (Winter Months)



r SST at diamond vs. 700mb elsewhere (Winter Months)

FIGURE 3.—Contemporaneous correlations between lat 20°N, long 170°W (diamond) and elsewhere for 700-mb heights (upper), sea-surface temperatures (middle), and SST vs. 700-mb (lower). Shaded areas represent correlations exceeding 1% level of significance—positive correlations stippled, negative hatched.

was chosen for the atmospheric variable because mid-tropospheric wind patterns often give a better specification of contemporaneous SST patterns than do sea-level maps. In general terms the physical reasons underlying this better specification from 700-mb rather than sea-level patterns lie in the fact that the 700-mb anomalies reflect not only the character of the anomalous sea-level pressure and wind distribution but they also contain implicitly the vertical stability of the lower troposphere. This association results from the high positive correlation between 700-mb height and mid-tropospheric temperature, and with cyclonic or anticyclonic contour curvature (Namias, 1947). The stability of the 1,000-700-mb layer to a large extent determines the vertical heat, moisture, and momentum flux from the surface—fluxes which are naturally important factors entering into the heat budget of the sea. Furthermore, since 700-mb height usually implies 700-mb temperature over ocean areas, some rough measure of back radiation is implied by the 700-mb heights.

Returning now to Figures 1-3 several points clearly emerge:

1. The space scale of coherent SST anomaly patterns is large—perhaps of the order of one-fourth to one-third of the North Pacific.

2. The SST scales are not far different from the 700-mb height scales and indeed display a remarkably similar form.

3. Strong teleconnections exist between SST anomaly fields of opposite sign over areas spanning almost one-half of the North Pacific; these teleconnections appear to be related to similar 700-mb teleconnections.

To aid the explanation of the above three empirical findings it should be remembered that time-averaged atmospheric patterns over large areas in temperate latitudes always reveal the presence of long or planetary waves whose horizontal dimensions are about 4,000 miles from crest to crest, but whose geographical positioning varies from month to month and also between the same month of different years. Thus, the atmospheric anomalies (and resultant prevailing winds and air masses) also vary. A quasi-stationary anomalous wind pattern generally creates anomalous SST patterns of a certain form. Most often cold water is advected and appreciable heat extracted in the cold dry northerly air currents behind mid-tropospheric troughs, while warmer water masses are advected and less heat extracted in the warm moist air currents ahead of troughs. Therefore, with atmospheric long-wave dimensions such as 4,000 miles (crest-to-crest) it is not surprising to find in Figure 1 that both 700-mb heights and SST anomalies are *negatively* correlated between the Central Pacific and the West Coast of the United States (one-half wave length) while both have similar coherence fields around the diamond.

Further clarification of the physical mechanism for this coupling can be obtained from the cross-correlations of SST with 700-mb height (Figure 1, lower). With anomalously warm water in the Central Pacific there are apt to be high 700-mb heights (anticyclonic ridge) in the north but low heights (cyclonic trough) in the south. Since correlation fields of the type shown in the upper and lower portions of Figures 1 and 3 may be interpreted in terms of flow (Stidd, 1954), we can approximate the resultant wind by remembering that it flows parallel to the contours with lower heights to the left. The anomalous wind component at the diamond is thus southeasterly and leads to less loss of heat by evaporation and sensible heat and greater advection of warm water from the south. Note also the contemporary reaction to *northerly* anomalous wind components in the eastern North Pacific—accounting for the colder than normal waters usually found there when the diamond area is warm. Of course, the above reasoning may also be applied (in reverse sense) when anomalously cold water exists at the diamond.

Figure 2, relating surrounding values to the diamond at lat 40°N, long 130°W, also shows the large-scale coherence and area of negative correlation one-half wave length upstream. The isopleths in the bottom figure indicate warm southerly air flow and warm sea transport accompanying positive SST values at the diamond and negative 700-mb height departures from normal in the Central Pacific. Of course, abnormally low SST values at the diamond imply anomalous cold air and sea advection from the north.

Figure 3, which relates surrounding values to the diamond at lat 20°N, long 170°W, instead of demonstrating the east-west (trough-ridge) teleconnections described in connection with Figures 1 and 2, focuses on north-south teleconnections. These relationships were first pointed out by Walker and Bliss (1930) in studies of the North Pacific Oscillation, and later expanded by Willett, Bodurtha, and staff (1949),[2] Lorenz (1951), and O'Connor (1969). The upper section of Figure 2 shows that 700-mb heights are strongly negatively correlated between lat 20°N and 50°N, implying a north-south half-wave length of some 30° latitude.

A large part of this negative correlation is associated with "blocking" situations (low zonal index patterns) wherein anticyclones are found near the Aleutians contemporaneously with cyclones near Hawaii (Kona Storms). In the reverse case, abnormally strong Aleutian Lows are usually accompanied by strong subtropic anticyclones (high zonal index patterns).

The middle portion of Figure 3, while showing large-scale coherence around the diamond, indicates that the area of negative correlation lies farther south in the SST pattern than in the 700-mb pattern, so that little correlation exists between SST anomalies at lat 50°N and lat 20°N in the central North Pacific. Probably this small degree of correlation implies a much more complex mechanism than wind-driven advection and heat exchange, or that sea-level anomalies in these situations are not well prescribed by the 700-mb anomalies. Also, the diamond lies outside the zone of major influence of the westerlies.

Although there is a strong tendency for North Pacific SST anomaly patterns to have compensating large pools of warm and cold water, it should not be assumed that the mean temperature anomaly of the entire North Pacific is zero. Figure 4 shows that the mean SST for the entire North Pacific (north of lat 20°N) varies over a range of about 2°F in extreme seasons, and as much as 1°F in extreme *years*! Assuming normal atmospheric parameters, a 1°F change would imply a difference in heat of evaporation of 47.8 × 10^{20} cal., equivalent to the evaporation of 8.14 × 10^{18} g of water or about 23.4 cm of water over the entire North Pacific. The oceanic mean SST anomalies are highly correlated with the area occupied by positive signs of the SST anomalies ($r = 0.84$). Thus, the North Pacific mean anomaly is often determined not by the domination of some extreme values but by the vast extent of major anomalous areas. For example, during the extreme negative SST anomaly of fall 1964 and extreme positive anomaly of summer 1967 (see Figure 4) 14% and 73% respectively of the North Pacific had positive signs. Large areal anomalies of this sort arise from the fact that the sea has a much greater persistence than the atmosphere (Namias and Born, 1970). Hence, large warm or cold pools in one area, such as the western Pacific, are apt to resist rapid change over a month or even a season, while the eastern Pacific may be undergoing more rapid response. This differential rate of response may be due to a more shallow thermocline in one area of the Pacific than another and/or more vigorous atmospheric circulation changes.

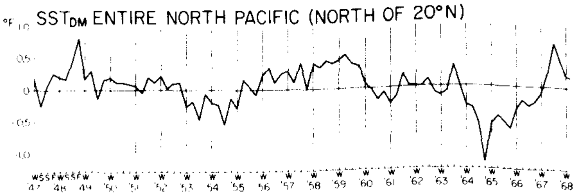


FIGURE 4.—Departures of mean sea-surface temperature (°F) from the 1947-66 averages over the entire North Pacific, north of lat 20°N.

These almost ocean-wide extremes of SST are naturally transitory, because their space scale is not compatible with modal long-wave atmospheric patterns, so that ultimately compatible patterns must be restored.

The high positive correlation between mean SST over the entire North Pacific and percent of the total area occupied by positive signs may

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[2] Willett, H. C., F. T. Bodurtha, and Staff. 1949. Final report of the Weather Bureau - M.I.T. extended forecasting project for the fiscal year July 1, 1948-June 30, 1949. Mass. Inst. Technol., Cambridge, Mass., 109 p. ("Memorandum of Understanding" with the U.S. Weather Bureau.) [Processed.]

TABLE 1.—Correlation relating mean SST over North Pacific (north of lat 20°N) and percent of positive signs of anomalies at 5° squares (based on 21 years of data), and standard deviations of these quantities.

	Correlation $\overline{SST}$ vs. % positive anomalies	σ $\overline{SST}$ (°F)	σ % of positive signs
Winter	0.83	0.28	9.77
Spring	0.71	0.25	9.20
Summer	0.87	0.37	14.18
Fall	0.86	0.40	14.21
All seasons (overall)	0.84	0.32	11.90

be found in all seasons with only small differences (see Table 1). However, the variability in percent of similar signs and mean SST seems to be seasonally dependent with summer and fall having greater variability than winter and spring, as shown by the standard deviations of SST and percent of positive signs listed in Table 1. In the warm season small changes in cloud cover and wind can produce large changes in SST since only a thin wind-mixed layer is affected. These changes often extend over vast areas because of variations in the great Pacific High and peripheral storm tracks.

ACKNOWLEDGMENTS

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