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SEASONAL INTERACTIONS BETWEEN THE NORTH PACIFIC OCEAN AND THE ATMOSPHERE DURING THE 1960's

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ABSTRACT

An attempt is made to explain the large-scale seasonal ocean-atmosphere interactions that occurred from 1961 through the winter of 1967–68 and that led to a special "climatic regime" over the North Pacific and North America. This regime was characterized by anomalously warm water over the central ocean, which helped generate atmospheric circulations of a kind favoring the persistence of the warm water, especially in the nonsummer seasons. The prevailing atmospheric circulation generated by the warm water during winter consisted of strong and southward-displaced cyclogenesis that produced a standing (Rossby) long wave downstream, resulting in climatic cooling over the eastern two-thirds of the United States. A theory is advanced for the evolution of atmospheric pressure and sea-surface temperature patterns in other seasons based on theoretical and empirical considerations.

The inception of the regime came abruptly in the late summer and fall of 1961, following several years when the eastern North Pacific Ocean slowly cooled over a vast area and to great depths. This cold pool of water appears to have been responsible for strong development of the Pacific High in the fall of 1961, probably through reducing the depth and outflow in the friction layer. The strong anticyclogenesis then set up numerous processes (particularly anomalous Ekman drifts and heat exchanges), the net result of which was to replace anomalously cold surface water with warm water, especially in the central North Pacific. The newly established thermal regime in the upper layers of the sea became dominant and seemingly irreversible for several years.

If these ideas carry a germ of the truth, one should expect spells of abnormality lasting several years in both atmosphere and sea and abrupt transitions between spells.

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1. INTRODUCTION

It has been almost a half century since Helland-Hansen and Nansen (1920) carried on their pioneering work on large-scale air-sea interactions. Beset by obstacles in obtaining adequate records of sea-surface temperature and meteorological variables, by slow and cumbersome methods of data processing, and by fragmentary knowledge of the general circulation and heat budgets of both media, they were unable to bring to fruition many sound ideas. Since then the problem has been attacked by Jacobs (1951), and in the past decade by Bjerknes (1962), Rodewald, and myself in papers too numerous to cite.

Since the ultimate aim of these studies is to be able to predict long-term fluctuations, and because data have been routinely worked up since 1961, I decided to look into contemporary and lag relationships between seasons of this period. The reason for choosing seasons rather than months is that considerable month-to-month persistence is present in sea-surface temperatures (Roden, 1964; Kraus and Morrison, 1966) and also in atmospheric pressure (Namias, 1952 and 1959*b*). Since the time constant in the ocean is much larger than in the atmosphere, the response time of one medium to the other must represent a highly complex problem, and the use of large-scale seasonally averaged parameters might yield significant information as it has in the case of studies of the time-averaged centers of action in the atmosphere.

Some of the most interesting and important work on very large-scale, almost global, air-sea interactions has recently been carried on by Bjerknes (1969). Bjerknes found a link between equatorial sea-surface temperatures in the central Pacific, the extent and intensity of the subtropical anticyclones, and the extratropical westerlies. He showed that equatorial rainfall is dependent upon the underlying sea-surface temperatures and reasoned that

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the variable liberation of heat of condensation results in variations in the strength of the Hadley cell, which then transmits influences to higher latitudes through angular momentum transport. My report complements Bjerknes' in that it deals primarily with the *longitudinal* variations in extratropical pressure and sea-surface temperature distribution, rather than with the overall strength of the zonal circulations related to tropical conditions. At some future time, these two aspects of the problem will undoubtedly be fused into a more complete picture. At that time long-range forecasting of sea and atmosphere will probably become realized.

It is hoped that results of such studies as Bjerknes' and mine will assist in the formulation of more realistic numerical prediction models for use in extended and long-range forecasting.

The oceanic data used in this report were derived primarily from sea-surface temperature monthly summaries for the eastern North Pacific (east of 180°) prepared by the Bureau of Commercial Fisheries (Renner, 1961–68) from the U.S. Weather Bureau collectives, and from 10-day averages compiled and kindly furnished by the Japan Meteorological Agency (1949–1968). The meteorological data were taken directly from the files of the Extended Forecast Division of the U.S. Weather Bureau, ESSA (1949–1968). Anomalies of the sea-surface temperature are measured from a base, commencing about 1900, of roughly 40-yr average values given by the U.S. Naval Oceanographic Office (1944). The base for the meteorological anomalies is a 16-yr mean beginning in 1947. The differences in the base periods for the sea-surface temperature and for the meteorological elements constitute no major obstacle to the work presented here. It is important to bear in mind, however, that the sea-surface temperature data for a given month, or even season, are extremely "noisy" because of many sources of error, unequal distribution of observations, and (probably in some areas) appreciable natural variability in both space and time. To a considerable extent, the use of seasonal means smooths out the field, but a space-smoothing device has been used in addition to bring out the mean 7-yr average seasonal patterns. This device consisted of averaging interpolated data at the four corners of each 5° square of latitude and longitude. The meteorological data (extracted from twice-daily charts) require no smoothing. Points at each 5° of latitude and longitude were, however, used for all calculations involving correlation coefficients and the like.

2. NORMAL SEASONAL SEA-LEVEL PRESSURE AND SEA-SURFACE TEMPERATURE PATTERNS OVER THE NORTH PACIFIC

Before studying anomalies, it is obviously important to be familiar with the normal states. For this reason, we shall refer frequently to the long-period mean sea level isobars for each season and the corresponding mean

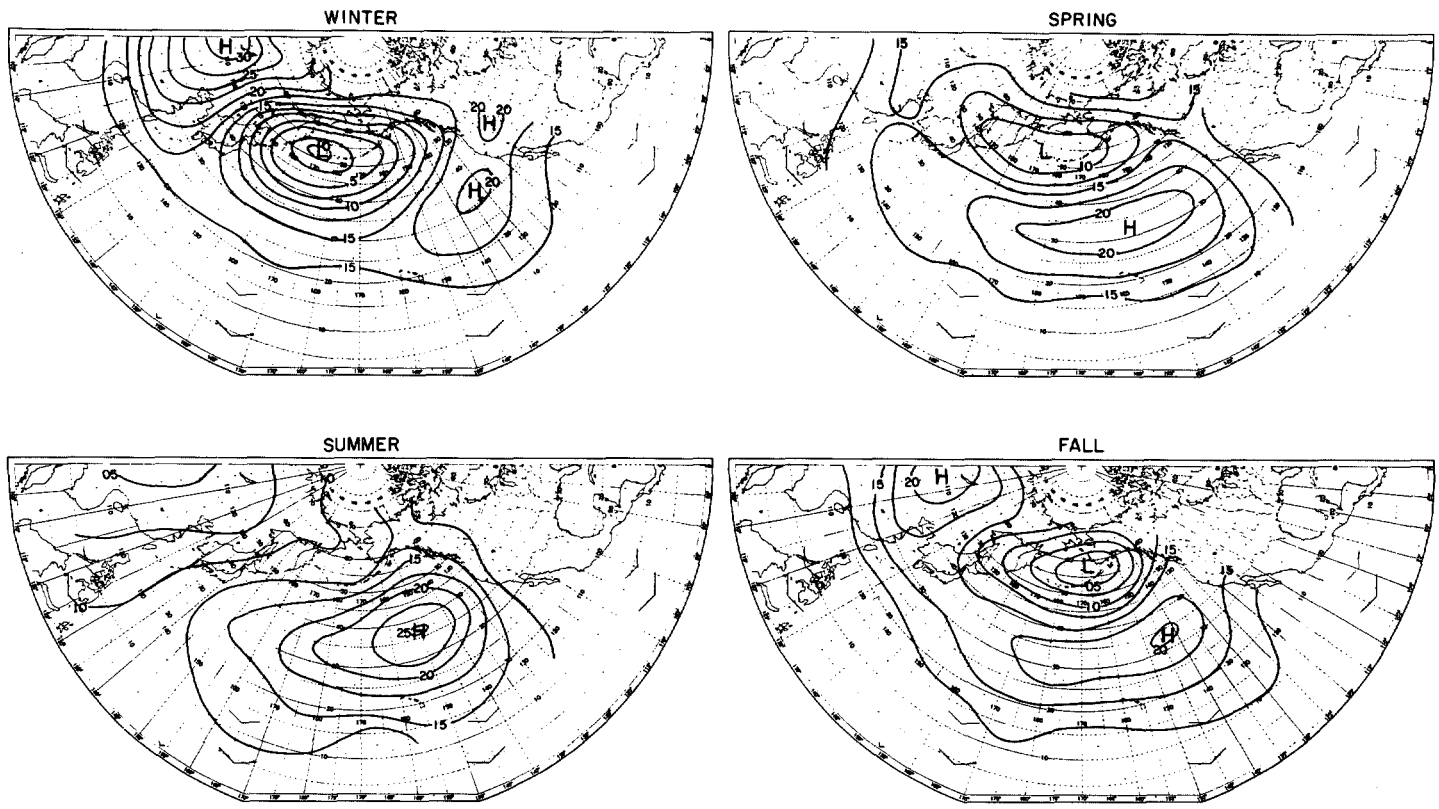

FIGURE 1.—Normal sea-level isobars for the four seasons (winter taken as December, January, and February, etc.) computed from twice-daily charts for the period 1947–63. Isobars drawn for each 2.5 mb and labeled as millibars with hundreds omitted.

sea-surface isotherms displayed in figures 1 and 2. The domination of the North Pacific by the Aleutian Low in winter and by the Pacific High in summer (fig. 1) is singled out for special attention. These two centers of action imply the principal cyclone and anticyclone tracks (Klein, 1957) as well as the prevailing broad-scale air currents. The normal sea-surface isotherm patterns (fig. 2) are sufficiently well known to require no description.

Maps of standard deviation of monthly mean sea level pressure for January, April, July, and October, worked up by H. C. Willett (1967) for the period 1899–1960, are shown in figure 3. From these charts it is clear that the North Pacific is indeed the site of a vast and changeable atmospheric center of action. The variability along the Asiatic coast is only about one-fifth that in the Aleutians. This difference in variability is one logical reason why *causes of many abnormal weather patterns should be sought in air-sea interactions over the North Pacific.* The wintertime differential variability implies that the eastern portion of the Siberian anticyclone is more or less established in the same manner from one winter to the next as is the sequence of cyclone waves off the Asiatic coast. Precisely *where* these cyclones move and intensify over the North Pacific may be determined more by anomalous sea temperatures than by variations in the strength and position of the Siberian anticyclone. Circumstantial evidence for this hypothesis shall be presented.

While similar maps of variability are available for sea-surface temperature from this 7-yr period and from Clark's work (1967) involving the 1951–58 period, only the average latitude profiles for summer (fig. 4) shall be shown because the variability patterns are mainly zonally oriented and show similar general relationships for other seasons. Plotted in figure 4 are also the normal latitudinal sea-surface temperature gradients. Perhaps it is not surprising to see that the maximum seasonal variability occurs in the area where the maximum meridional gradient exists. This would be a necessary condition if the normal gradient were more or less fixed by ocean currents and if warm and cold water advection brought about by north and south transport were an important factor in generating local anomalies. However, these areas of maximum variability are also sensitively placed with respect to the Aleutian Low and Pacific High, so that variable winds and air-mass characteristics can play a major role in determining the surface heat budget.

3. KIND OF AIR-SEA INTERACTIONS THAT MIGHT BE SOUGHT

On the basis of theory and experience, one might reasonably expect certain large-scale air-sea interactions. These expectations would necessarily vary in kind with season because of variations in areas where cyclones and anticyclones are apt to be found and because of different prevailing air-mass characteristics. Thus, in winter when

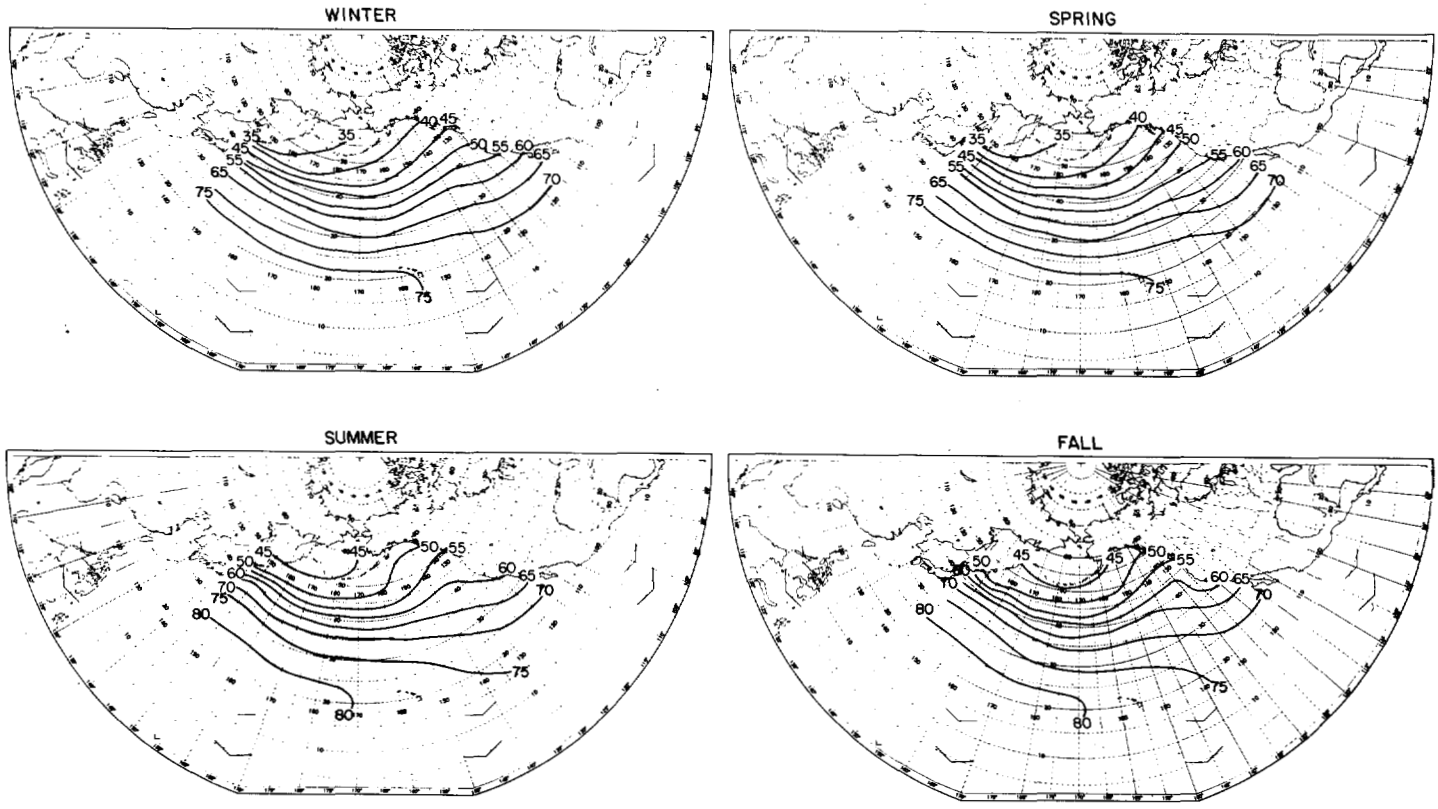

FIGURE 2.—Normal seasonal sea-surface isotherms (°F) computed from monthly values listed in H.O. Publication No. 225 (U.S. Naval Hydrographic Office, 1944).

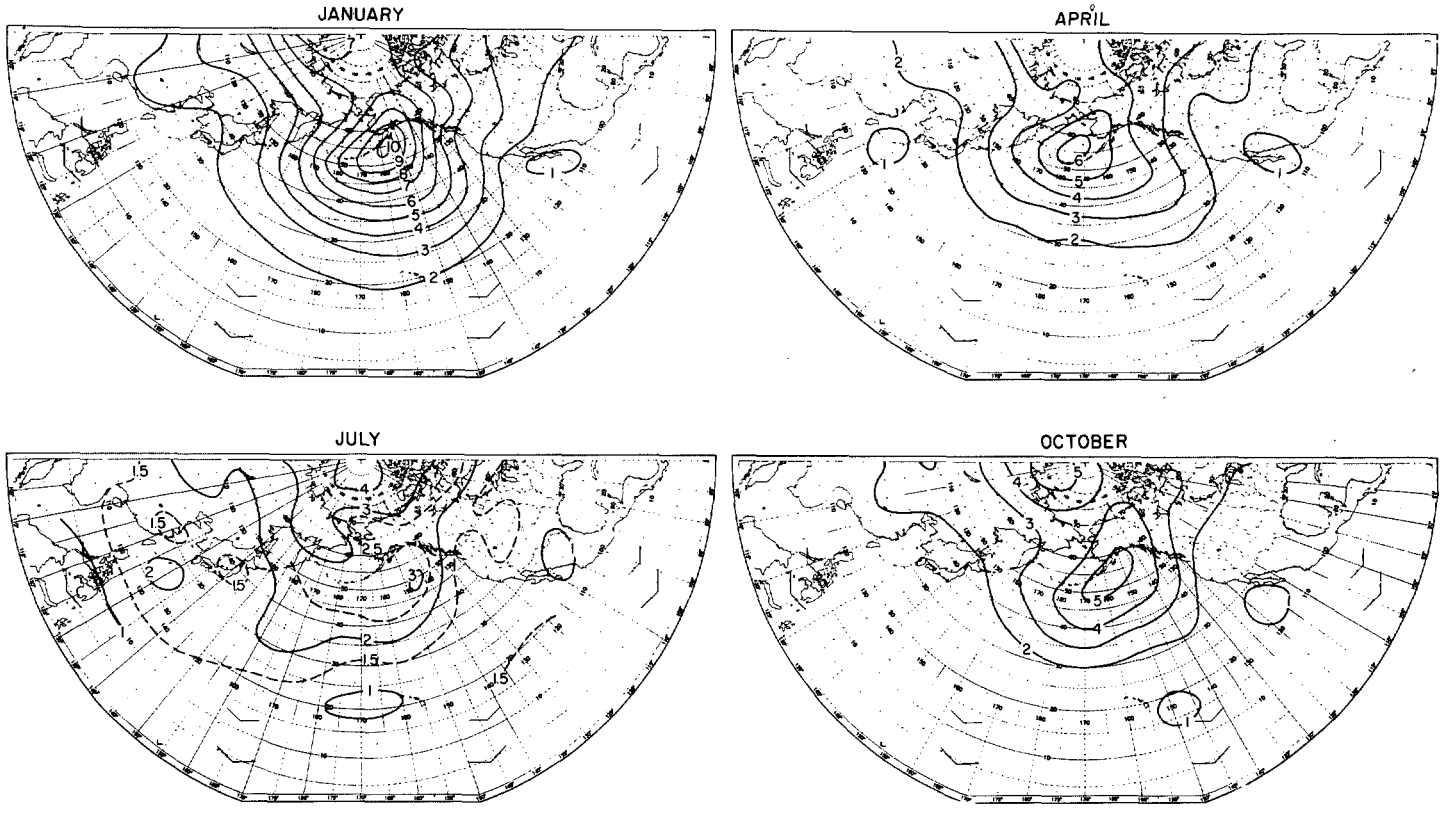

FIGURE 3.—Isopleths of standard deviation of monthly mean sea level pressure (millibars) for January, April, July, and October worked up by H. C. Willett (1967) for the period 1899–1960.

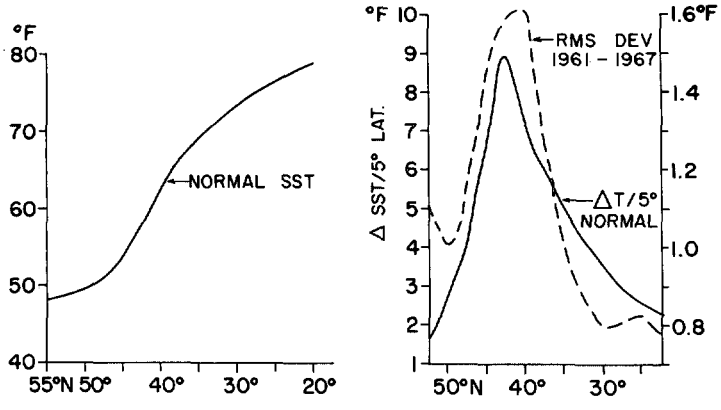

FIGURE 4.—(Left) normal meridional sea-surface temperature profile for the North Pacific in summer. (Right) normal meridional gradient (temperature change per 5° lat.) and root-mean-square deviation (°F) for the summers of 1961–67.

the Aleutian Low is maintained by rapidly deepening cyclones moving northeastward off the Asiatic coast, bringing frigid air masses from Siberia and Alaska out over the ocean, an extensive anomalously warm pool of water established in fall in the central Pacific might lead to greater-than-normal cyclonic activity in its vicinity. The factors directly responsible for the boost in cyclonic activity would be increased diabatic heating of the air masses, vapor discharge into the air leading to liberated heat of condensation, and vertical destabilization of the air. In addition, the atmospheric baroclinicity along the cyclone path would be enhanced to the west and north of the warm pool. An example of a winter (1962–63) in which this sort of interaction led to exceptionally strong cyclones far south of their normal position was given in an earlier paper by the author (Namias, 1963). Another example of a remarkably similar kind occurred during the winter of 1967–68.

It is unlikely that an anomalously warm water pool would produce comparable effects if it were close to the Asiatic or Alaskan coasts, because here the winter land-sea contrast is so great as to swamp variations of the type we have described.

During fall, when cyclones begin to become more active along the Aleutian chain and in the Gulf of Alaska, a similar stimulation of cyclonic activity may occur if the sea-surface temperature has been anomalously warm along the prevailing storm track. A special study of fall cyclogenesis (or cyclolysis) of this type was presented at the International Conference on Cloud Physics (Namias, 1968).

The Pacific anticyclone might also be expected to be influenced, either indirectly by vorticity redistribution from a "forced" anomalous cyclonic pattern over the central or western Pacific (i.e., by teleconnections) or directly by extensive underlying pools of anomalously cold (or warm) sea-surface temperature. In the latter case, air over cold water in summer and fall would be

more stable than normal, the atmospheric mixing layer shallower, and, therefore, there would be less "leakage" of air from the surface friction layer of the Pacific anticyclone. In effect, the greater stability in the boundary layer would serve as a "lubricator" for the anticyclonic flow. This principle was first pointed out by Wexler (1943) in his detailed study of anticyclogenesis along the east coast of the United States in spring. The result is a stronger than normal Pacific High if the cold water pool is situated near the normal high center. On the other hand, warm water would discourage strong anticyclone development. Statistical studies by Petterssen (1950) have also showed that bodies of water like large lakes influence cyclogenesis and anticyclogenesis.

Similar effects might operate in eastern portions of the Pacific High in nonwinter months when coastal upwelling and California Current transport are sensitive to the west-east atmospheric pressure gradient. Since this gradient is largely determined by the pressure in and to the east of the Pacific High, there would be an air-sea coupling in which the sea-surface temperatures interact with the pressure distribution in the manner described. The abnormal development of displacement of the east Pacific anticyclone would probably result in corresponding displacements of west Pacific storm tracks.

With an anomalous mean sea level pressure distribution (and it is always anomalous) it is obvious that sea-surface temperatures will also develop abnormalities. This is because the resultant winds and frequency distribution of wind directions over an anomalous period differ from normal, and thus the wind stress sets up drifts in the Ekman layer that may advect water from cold or warm sources. Besides, any variation from normal in the frequency distribution of winds carries with it variations in air-mass characteristics that enter into the air-sea heat exchange. Among the most important of these variations are temperature differences between air and sea, wind velocity, humidity, and cloudiness. Besides, the extent of coastal upwelling is frequently determined by the pressure (and hence wind) distribution. A rough method of estimating the large-scale sea-surface temperature patterns of anomaly based on some of these considerations has been described by the author (Namias, 1959*b*, 1965) and extended by Eber (1961), Arthur (1966), and Jacob (1967).

Because the scale of monthly or seasonal anomalies in sea-level pressure is usually of the order of a third to a half of the North Pacific, it is not surprising to find that coherent fields of sea-surface temperature anomaly are also of this size. Moreover, because the centers of action in the atmospheric general circulation (and their anomalies) are interdependent (Rossby and Collaborators, 1939) and determine prevailing wind and air-mass characteristics, it would be expected that interdependence would characterize large-scale anomalies of sea-surface temperature. Such spatial interdependencies in either sea or atmosphere shall be referred to as "teleconnections." Hanzawa (1958) has indeed found evidence for a major teleconnection between western and eastern Pacific sea-surface temperature anomalies.

The above considerations have been exploited in the following attempt to describe and explain the special characteristics of the 1961–67 period.

4. AVERAGE CHARACTERISTICS OF THE 1961–67 PERIOD

SEA-SURFACE TEMPERATURE ANOMALIES

The 1961–67 period averaged warmer than normal over the entire area of the North Pacific covered by our data (see fig. 5). We shall not comment now on this amazingly large and long-lasting abnormality except to say that it could be associated through complex lag effects with the climatic warming observed over many portions of the world from the turn of the century through the 1950's (Mitchell, 1963). The warmest water with respect to normal was observed in the central Pacific with maximum values of about +2°F in a 10° square centered at 35°N, 165°W.

The 7-yr averages for each of the four seasons are shown in figures 6 and 7. They have been spatially smoothed by averaging the four values at the corners of each 5° square and placing the result in the center. While each of these charts exhibits the central warm pool, it was strongest in fall (almost +3°F) and weakest in summer (+1.8°F). On the charts for spring and summer, below-normal average temperatures were observed off the west coast of the United States. A small patch of below-normal average temperatures also appeared in fall at around 40°N, 150°W.

We have already described the general features of the latitudinal distribution of root-mean-square deviations, but table 1, showing the seasonal maxima, may be of interest, since it indicates little seasonal variation and slightly higher variability in summer. Similar results were found by Clark (1967) for the 1951–58 period.

MEAN SEA LEVEL PRESSURE DISTRIBUTIONS

The mean pressure anomaly for all seasons of the 7 yr is given in figure 5, and that for the individual seasons in figures 6 and 7. The 7-yr period as a whole was characterized by generally subnormal pressures, except in the Bering Sea and Aleutians and in the extreme southeast portion of the ocean. The gradients imply less-than-normal westerly air flow in the central Pacific north of 35°N, more-than-normal northerly flow into the Gulf of Alaska, and less-than-normal northerly flow in the extreme southeast Pacific.

The seasonal pressure anomaly charts for the 7 yr (figs. 6 and 7) show the following noteworthy features:

Winter—much lower pressures than normal (−4.5 mb or about two standard deviations) in the central Pacific, associated with greatly weakened trade winds and with southward-displaced westerlies and the Aleutian Low.

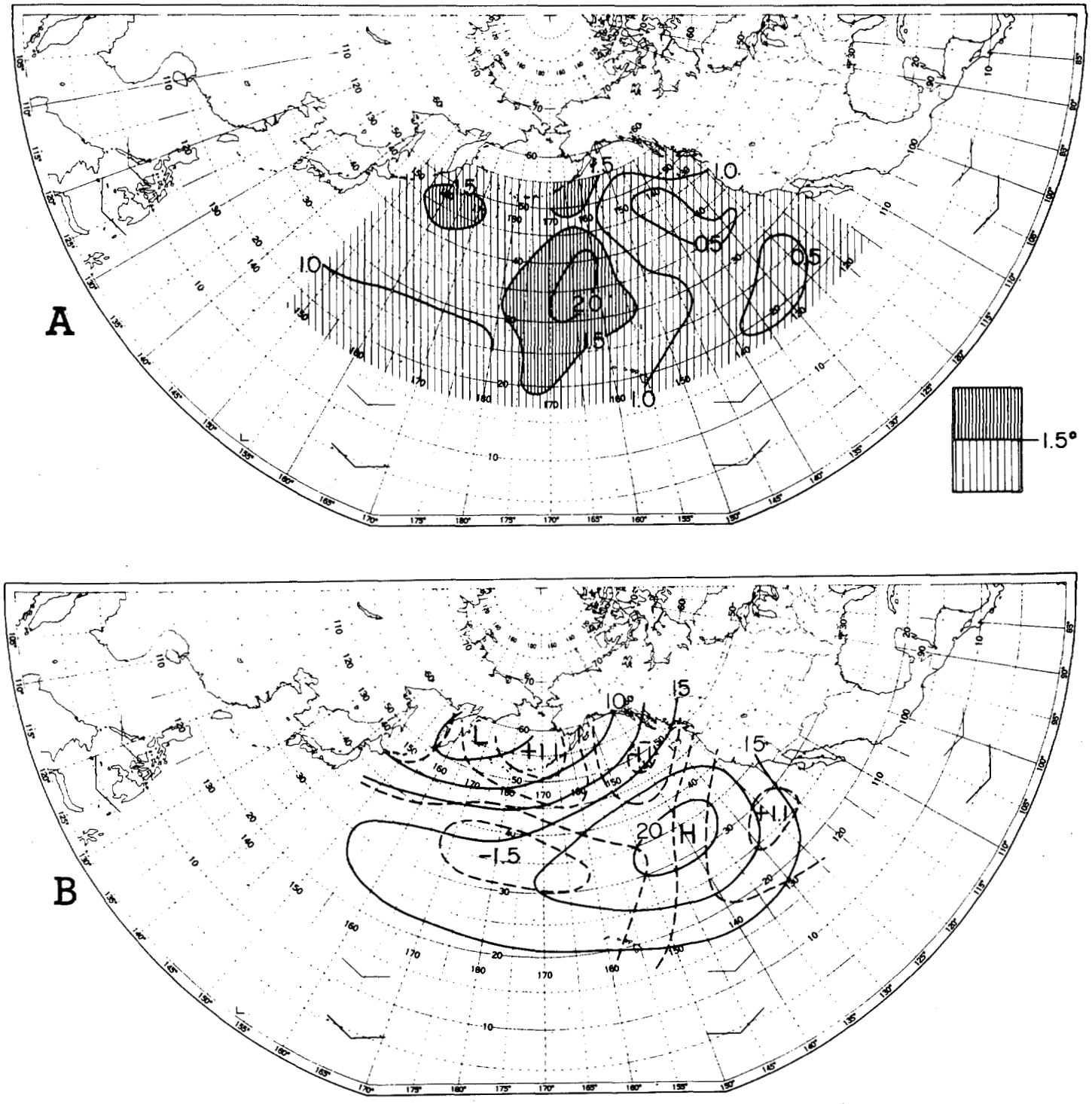

FIGURE 5.—(A) mean sea-surface temperature departures from normal (°F) for the period 1961–67. Isopleths are drawn for each 0.5°F. (B) mean sea level isobars (solid) and isopleths of anomaly (broken) for 1961–67. Isobars drawn for each 2.5 mb and isopleths of anomaly for every 0.5 mb with centers in millibars and tenths.

Spring—abnormally weak Aleutian Low and a strong Pacific High displaced northward with increased cyclonic activity at low latitudes. Note the strong anomalous pressure gradients.

Summer—Pacific High displaced east of its normal position with greater cyclonic activity than normal over central and western portions of the ocean.

Fall—Gulf of Alaska Low especially well developed while Pacific High is weak to the east but stronger than normal in the center. Note the anomalous southwest component of air flow off California.

CONTEMPORARY RELATIONSHIPS BETWEEN THE ANOMALIES OF SEA-SURFACE TEMPERATURE AND SEA-LEVEL PRESSURE

Some qualitative relationships come to light in a comparison of the anomalous patterns of sea-surface temperature and sea-level pressure. Even in the mean for the entire 7-yr period (fig. 5), the warmest water pool lay in

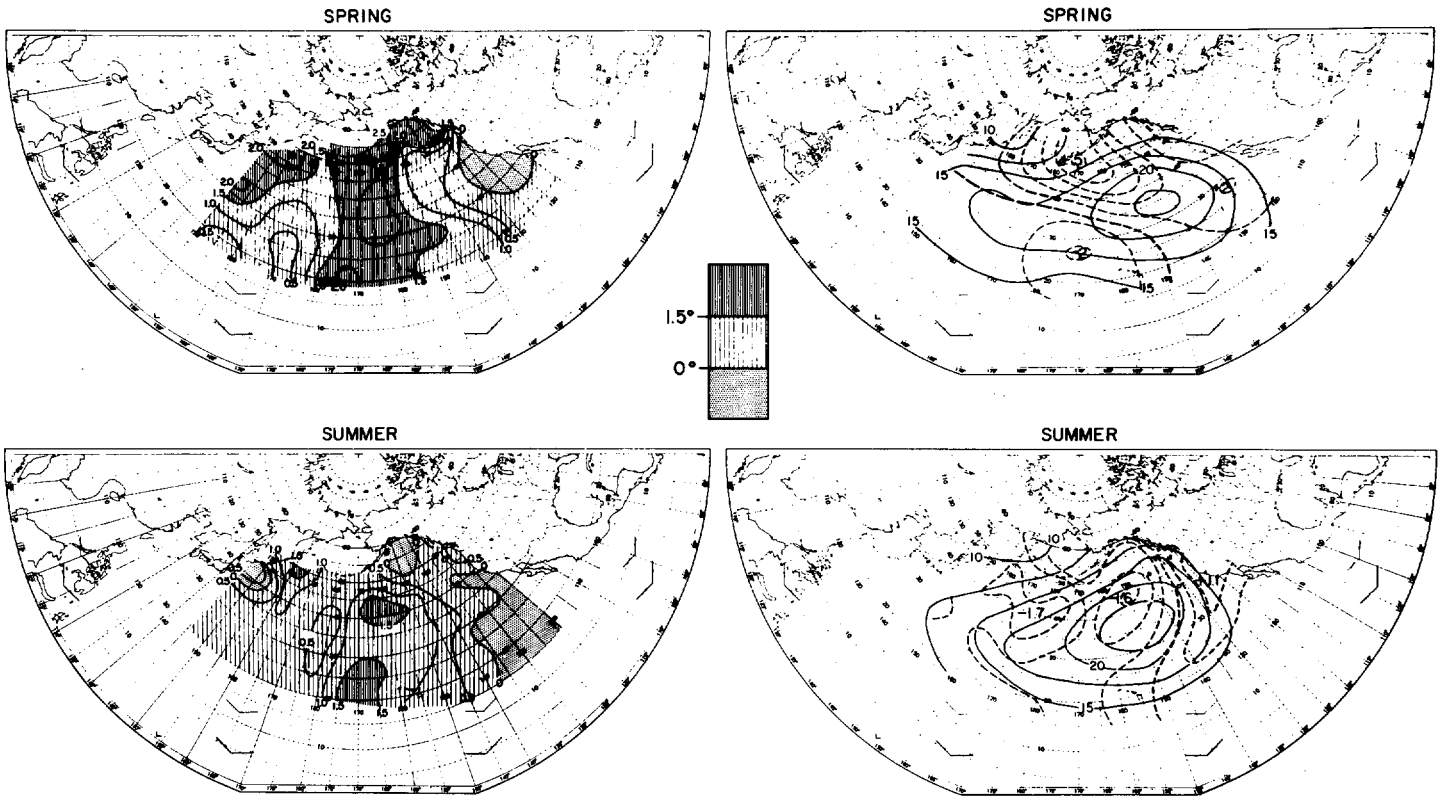

FIGURE 6.—(Left) average sea-surface temperature anomalies for the springs and for the summers of 1961–67. (Right) corresponding means of sea-level pressure and isopleths of anomaly. (Anomalous lines for spring drawn for each millibar, and for summer each 0.5 mb.)

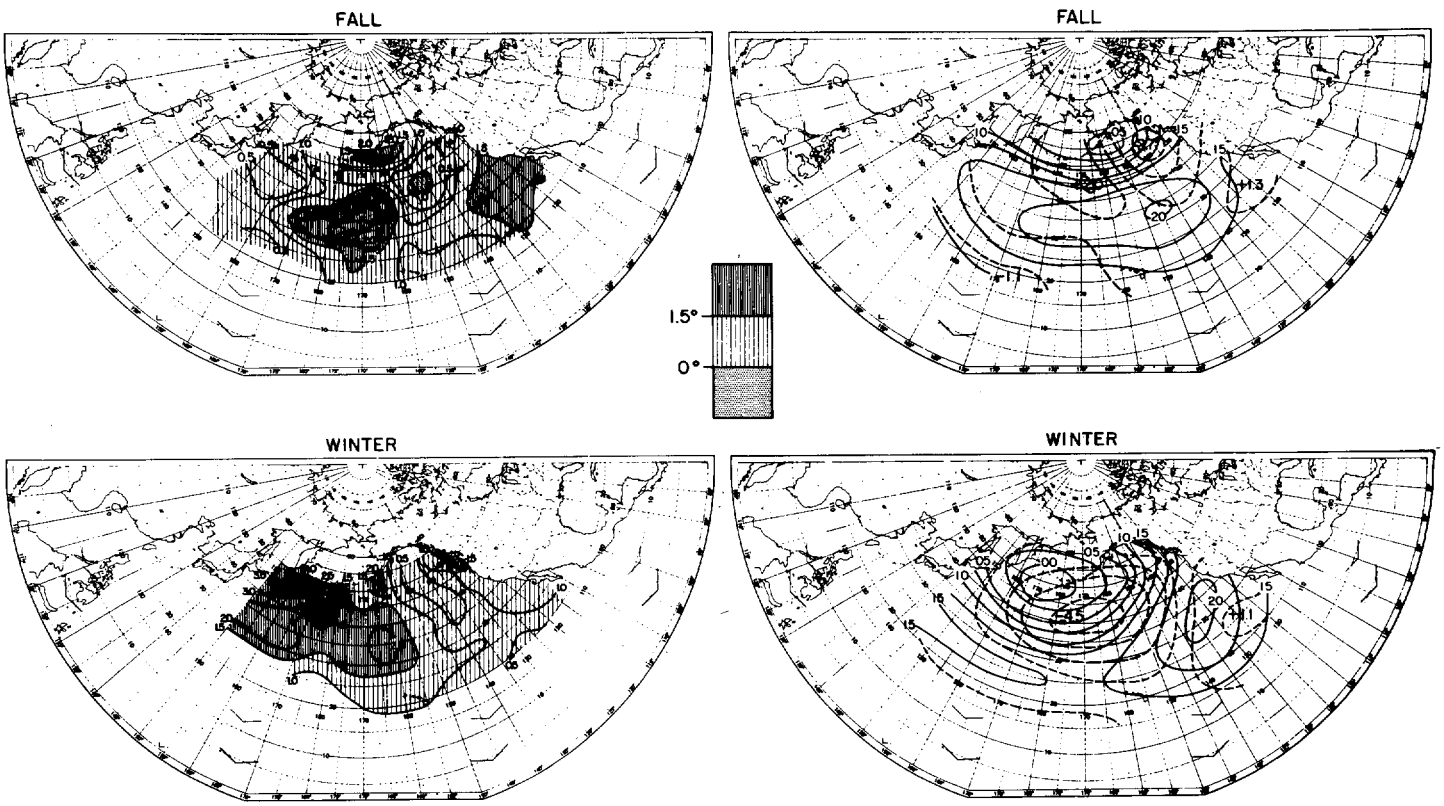

FIGURE 7.—Same as figure 6, but for the falls and winters of 1961–67 (including the winter 1967–68).

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TABLE 1.—*Latitudinal maximum seasonal root-mean-square deviations from the long-term normal of the sea-surface temperatures of 1961–67*

Winter	1.30°F	at	45°N
Spring	1.25°F	at	40°N
Summer	1.60°F	at	40°N
Fall	1.42°F	at	40°N

the vicinity of the negative pressure anomaly. Its northward extension occurred in the area where a net integrated Ekman drift[2] existed that was more northward than usual, as can be seen from the isopleths of anomalous pressure. The decline of sea-temperature anomaly east of 160°W and north of 40°N appears to be associated with the increasing influence of abnormally frequent, cold northerly air currents from Alaska. Other aspects of the sea-surface temperature pattern, particularly south of 35°N, are not easily explained. Relationships come into sharper focus if the seasonal charts are compared. Thus, in spring and fall (figs. 6 and 7), the warm pools were located in areas where the anomalous gradients of pressure suggest strongest northward water transport, where anomalously warm, humid air was transported northward, and where wind velocities were reduced with respect to normal. The decline of anomalous temperatures east of the warm pool is clearly associated with the accentuated southward air transport and associated factors leading to heat loss from the water. Note the reaction in temperatures off the California coast to differences in pressure anomaly fields.

In winter and summer, relationships between anomalous gradients of sea-level pressure and sea-surface temperature anomalies are relatively unclear. This circumstance may suggest that complex storage effects generated in the antecedent springs and falls may have been important in determining the water temperatures and that the atmosphere may interact with the ocean in quite different ways in winter and summer compared to spring and fall. That is, the stress may be on different terms in the heat exchange to the atmosphere. These matters shall be discussed in connection with seasonal lags.

Correlated point values of sea-level pressure with sea-surface temperature, using the seven pairs of values for each of the seasons in 1961–67, are shown in the charts of figure 8. While this is a very coarse procedure for bringing to light air-sea interactions, it does illuminate some, even though pressure gradients are more informative. Shaded (for positive) and dotted (for negative) areas

[2] We refer here to the water transport 90° to the right of the wind direction that takes place in the mixed layer.

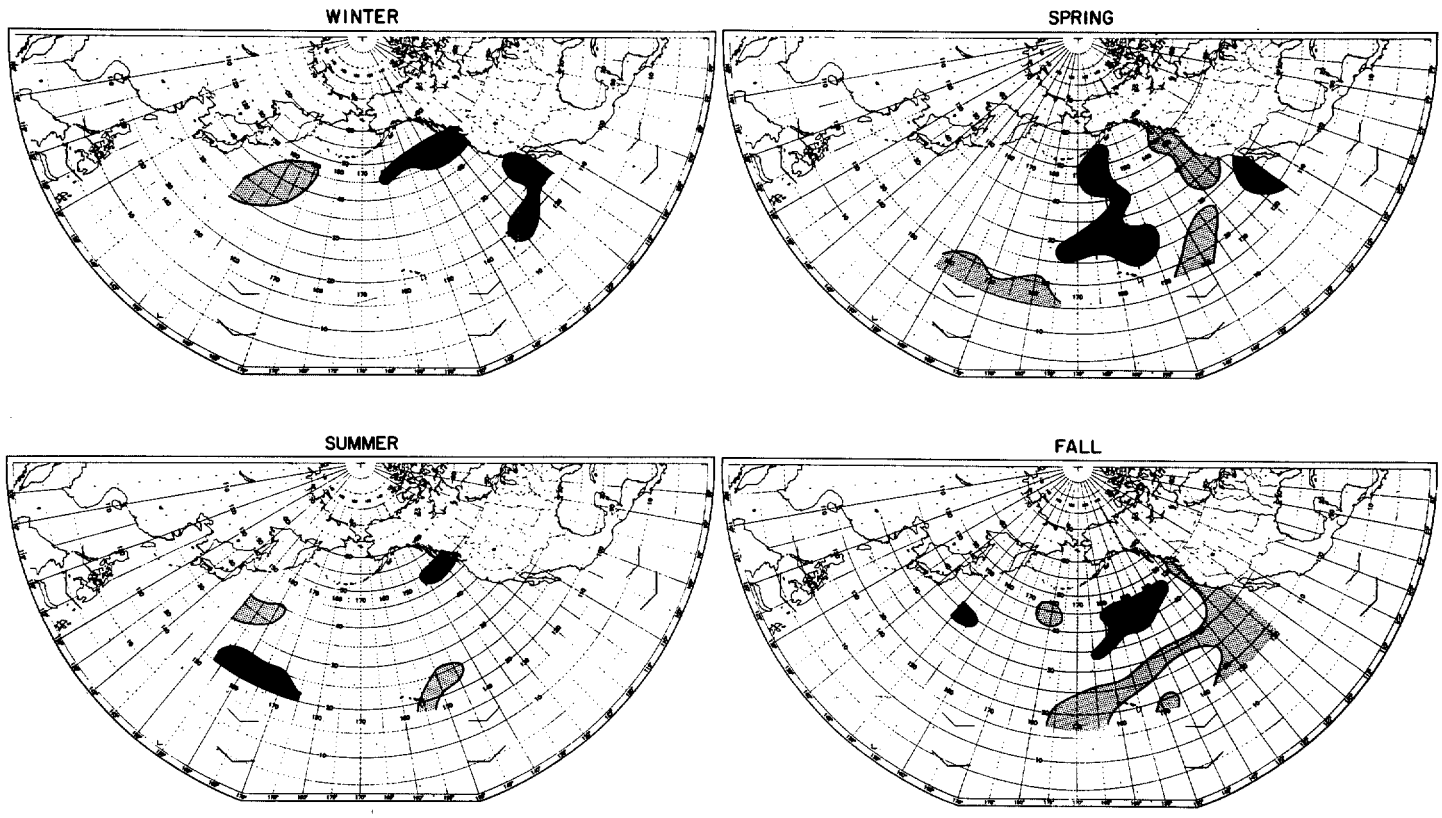

FIGURE 8.—Contemporary correlations between sea-level pressure and sea-surface temperature, 1961–67, that exceed 0.54, the 11-percent significance level (shaded areas). Heavy shading represents positive correlation, light shading negative.

embrace correlations that exceed three probable errors where

$$\text{probable error} = .6745\ \frac{1-r^2}{\sqrt{n}}.$$

The shading, denoting possible significance,[3] was desirable because of the spatial variability in correlation coefficients introduced by the "noisy" sea-surface temperature fields. A further criterion in analyzing these coherent areas of high correlation was that they must contain at least three adjacent points (in the 5° grid) of significant correlation coefficient. This analytical procedure was in fact adopted for all correlation fields displayed in this report.

Before discussing the charts in figure 8 or other correlation fields, I would like to make it clear that it is most unlikely that in all areas they represent statistically stable fields. Seven pairs of values are, at best, an inadequate statistical sample, and patterns of anomalies in the sea and in the atmosphere have climatic fluctuations of other kinds than occurred during the 1961–67 period. The principal reason for employing these correlation fields is that they frequently offer clues to physical processes and air-sea interactions. The fields presented are particularly germane to the 1961–67 seasonal interactions, although some of the features would probably show up in other decades and thus be climatologically stable.

As for the contemporary correlations between pressure and sea-surface temperature (fig. 8), only the charts for spring and fall appear to have meaningful large-scale patterns. Those for winter and summer have isolated patches covering only about the area expected by chance. It will be recalled that the spring and fall anomalous pressure gradients implied Ekman drifts and heat exchanges associated with the anomalous temperatures.

In the spring, sea-surface temperatures were positively correlated with air pressures in central Pacific longitudes but negatively correlated off the west coast of the United States and southwestward. The latter area of negative correlation indicates that when the east Pacific High was well developed or east of its normal position the pressure gradient and hence the California current is usually strengthened. This modified pressure distribution also leads to increased coastal upwelling. Besides, more heat is extracted from the water, as a result of the southward movement of abnormally cold air, of extra evaporation losses due to increased wind, and of increased turbulent vertical transport of heat in the relatively unstable air. Probably this is why similar negative correlations extended into the trades. A similar relationship held in fall. Since the 14-yr period, 1954–67, shows similar fields

[3] The precise level of significance is difficult to determine since the sample (seven pairs for each point) is so small. For large samples, a correlation three times the probable error would be significant at about the two-tailed 5-percent level; but according to Dixon and Massey (1957), with seven pairs 0.54 is significant only at the one-tailed 11-percent level. I wish to emphasize that these spatially coherent fields of higher correlation are used only as guides to the physical processes that took place during this 7-yr period, not as an exercise in the problem of statistical significance. For such an exercise, one would have to consider the nonrandomness of the spatial distribution of both elements.

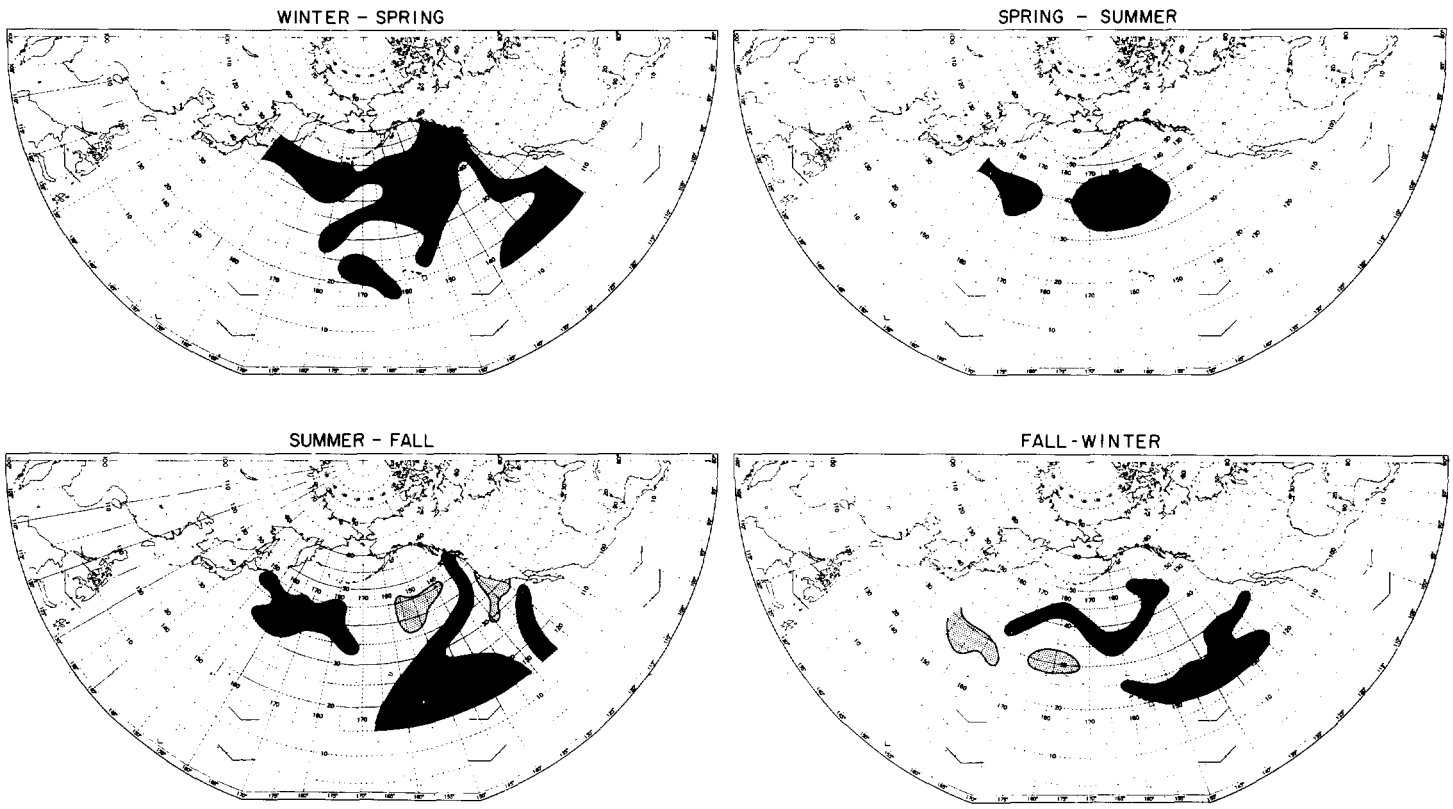

FIGURE 9.—One-season lag autocorrelations of sea-surface temperature, 1961–67. Shading as in figure 8.

of significant negative correlation (not reproduced) between pressure and sea-surface temperature off the west coast in the nonwinter months, this is probably a climatologically stable feature.

While it is tempting to accept this interaction as entirely a response of the sea to the air, it is likely that abnormal sea temperatures also produce variations in atmospheric pressure in the manner outlined earlier—that is, by altering the depth of the atmospheric friction layer and hence the "leakage" of air from the anticyclone. Also, cooling of the air column in the case of cold water adds a small increment of pressure hydrostatically, although it requires a drop of temperature of about 1°C up to 700 mb to effect a 1-mb increase of pressure.

The central area of positive correlation found on the spring and fall charts in areas of high variability in pressure (fig. 1) may indicate downwelling or relatively weak upwelling under high pressure, strong upwelling under low pressure, and variable heat losses from the water associated with high- and low-pressure systems. For example, in cyclones, more wind and more cloud (less insolation) leads to less heating, while the reverse holds in anticyclones during these seasons.

5. ONE-SEASON LAG RELATIONSHIPS

SEA-SURFACE TEMPERATURE

The one-season lag autocorrelations of sea-surface temperature are shown in figure 9. In the 1961–67 period there were large coherent areas of positive correlation during each pair of adjacent seasons. Particularly noteworthy are the sizable areas of persistence north of 35°N on the winter–spring and spring–summer charts, but not so evident on the summer–fall and fall–winter charts. This tendency for persistence from winter to spring and spring to summer north of 35°N seems to be a general relationship which holds for other decades. For example, it shows up even stronger for the 14-yr period 1954–67 than for the 7-yr period 1961–67 (fig. 10). The reason for the differing of this persistence with time of year appears to lie in the fact that the depth of the mixed layer (and hence the reservoir of anomalous heat) in winter and spring is about three times that in summer and fall. This fact is strikingly brought to light by the data on mixed layer depths presented by Giovando and Robinson (1965). A plot of their data along the strip between 140° to 145°W for 4 mo characterizing the seasons is reproduced in figure 11. Hence, abnormalities established in winter and spring are apt to penetrate to appreciable depth and thus to have greater longevity under changeable atmospheric conditions than those established in summer and fall when the mixed layer is shallow. The variable persistence indicated above shows up in table 2 where the lag correlations are shown for a 10° square believed to be representative of the northern branch of the westerlies. There can be little question of the reality of the general conclusion that persistence of sea-surface temperature in northern portions of the North Pacific is strongest from winter to apring and spring to summer. Of the differences between lsutocorrelations, only the one between the two negatives acks significance at the 10-percent level.

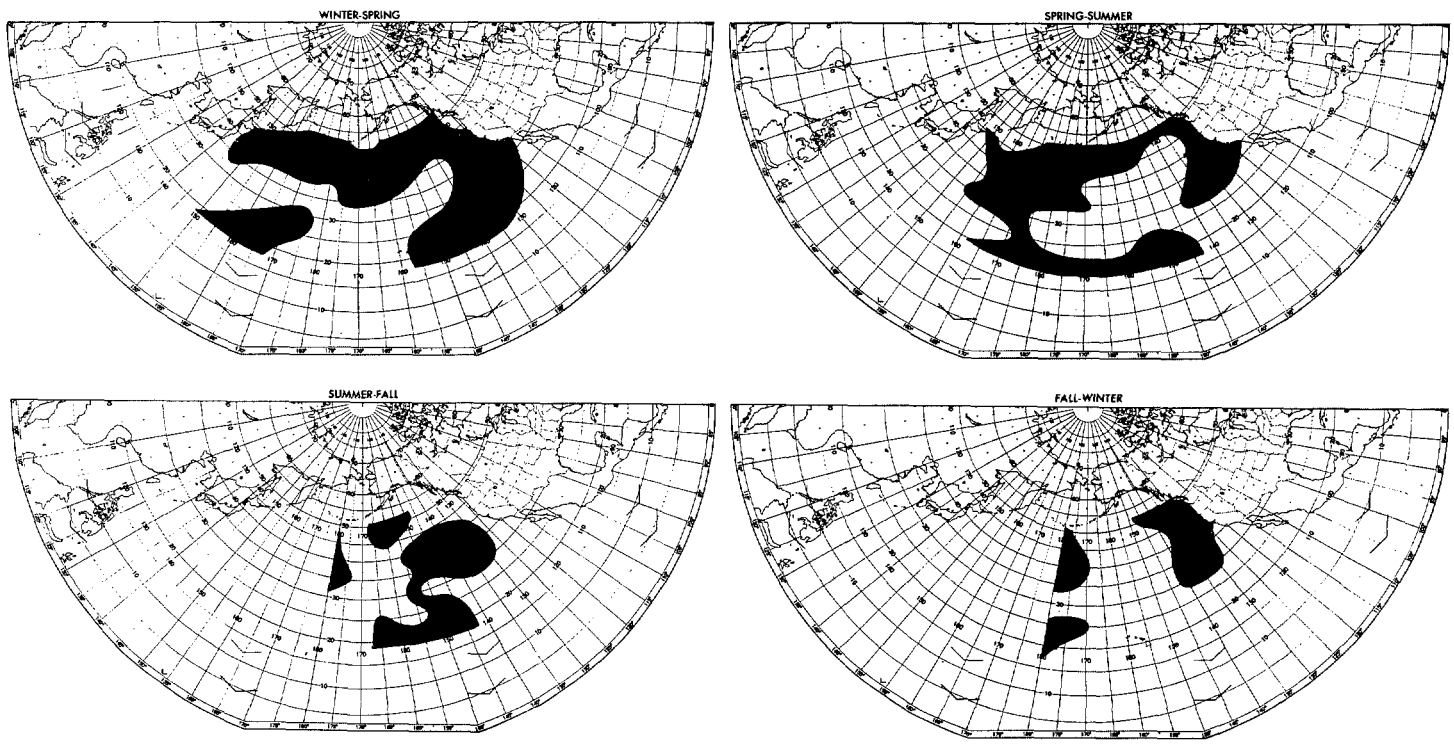

FIGURE 10.—Same as figure 9 but for 1954–67. Shaded areas embrace correlations exceeding 0.44, the 6-percent significance level.

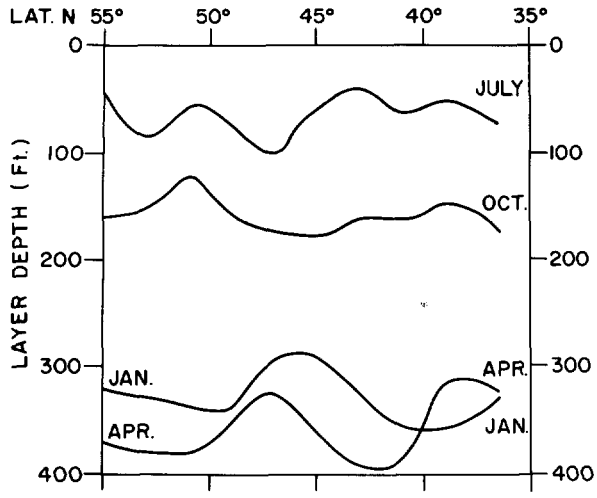

FIGURE 11.—Mean potential mixed layer depth beween 140°W and 145°W for the months of January, April, July, and October (adapted from Giovando and Robinson, 1965).

TABLE 2.—*Autocorrelations at one season's lag, 1954–1967, for sea-surface temperature anomalies in a 10° square centered at 40°N, 150°W*

	Autocorrelation
Winter-spring	0.76
Spring-summer	0.63
Summer-fall	−0.28
Fall-winter	−0.13

The sizeable areas of positive lag correlation south of 35°N are not easily explained, especially since bathythermograph data are not abundant in that area. The summer–fall and fall–winter correlations are difficult to explain, except possibly for the high persistence area in the eastern trades, which may reflect either a deep reservoir leading to persistent thermal sea abnormalities, or may reflect persistence in the air mass and wind system south of the Pacific High (persistent anomalous heat exchange).

SEA-SURFACE TEMPERATURE AND SEA-LEVEL PRESSURE

Charts showing areas of high lag correlation of sea-surface temperature with the following season's sea-level pressure are displayed in figure 12. Except for negative areas off the west coast indicating the inverse relationship treated earlier between eastern portions of the Pacific High and sea-surface temperature in winter to spring and spring to summer, these two charts show no meaningful patterns. On the other hand, those for summer to fall and fall to winter have large coherent patterns that call for explanation.

In the cases discussed below, it is assumed that some persistence of the sea-surface temperature carries over into the subsequent season because of the vast heat capacity of the water. However, the subsequent season's atmospheric developments sometimes encourage and sometimes discourage persistence of the sea-surface temperature anomaly.

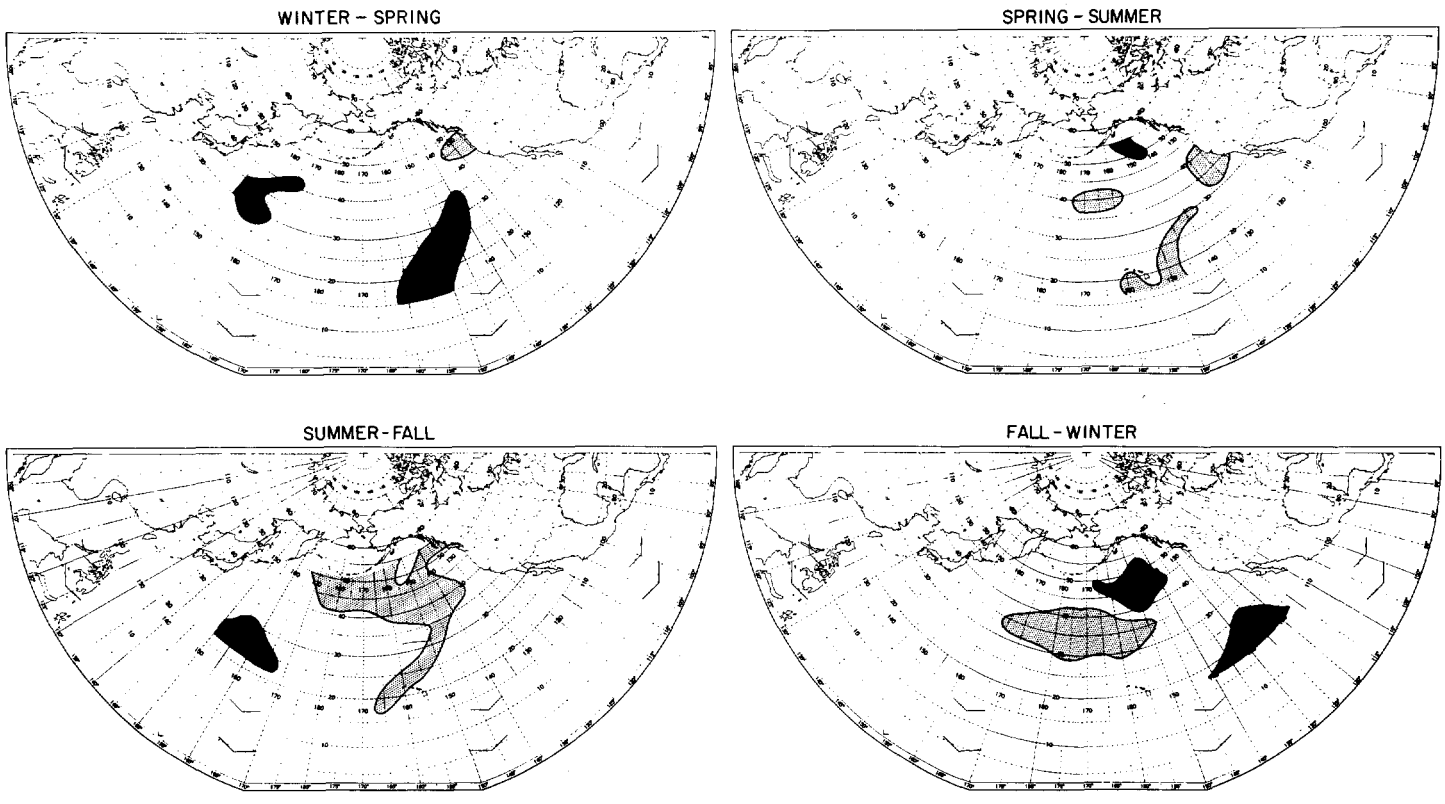

FIGURE 12.— One-season lag correlation between sea-surface temperature and subsequent sea-level pressure for the period 1961–67. See legend to figure 8 for meaning of shading.

In the summer–fall chart, the large negative area extending north of 40°N is a result of the variable cyclonic development of fall cyclones as they move over the reservoir of warm or cold water masses developed in the preceding summer, a topic discussed in more detail elsewhere (Namias, 1968). In addition, the fall variability in the intensity of the northern limb of the Pacific High appears to be associated with the antecedent water-temperature anomalies, cold water in summer favoring high pressure in the fall and warm water in summer favoring low pressure in the fall. This latter effect appears to be associated with a variation in the depth of the atmosphere's friction layer—cold water favoring greater vertical stability and a shallower atmospheric mixing layer than warm. Therefore, as Wexler (1943) pointed out, the leakage of air from the anticyclone is less in the former than in the latter case, and higher surface pressures can be maintained. It will be seen from the normal sea-level pressure charts for fall (fig. 1) that the area along 40°N lies just between the Aleutian Low and the Pacific High. Therefore, the area is especially sensitive and can become a seat of anticyclogenesis or cyclogenesis depending on the antecedent summer sea temperatures.

In winter, as the Aleutian Low spreads its influence southward (fig. 1) bringing fronts, cyclones, and cold Siberian air masses, the central portion of the Pacific becomes a place for variable cyclonic (or anticyclonic) activity influenced again by the antecedent fall's sea-surface temperatures. This relationship appears to have been strongly operative during the period 1961–67, as indicated by the large area of significant negative correlations between 30°N and 40°N over the central North Pacific. The mechanisms involved are those treated in some detail in an earlier investigation (Namias, 1963) of the highly abnormal winter of 1962–63, when the Aleutian Low was displaced far south of normal and departures from normal of sea-level pressure at 40°N, 165°W, averaged −15 mb for the 3 winter mo.

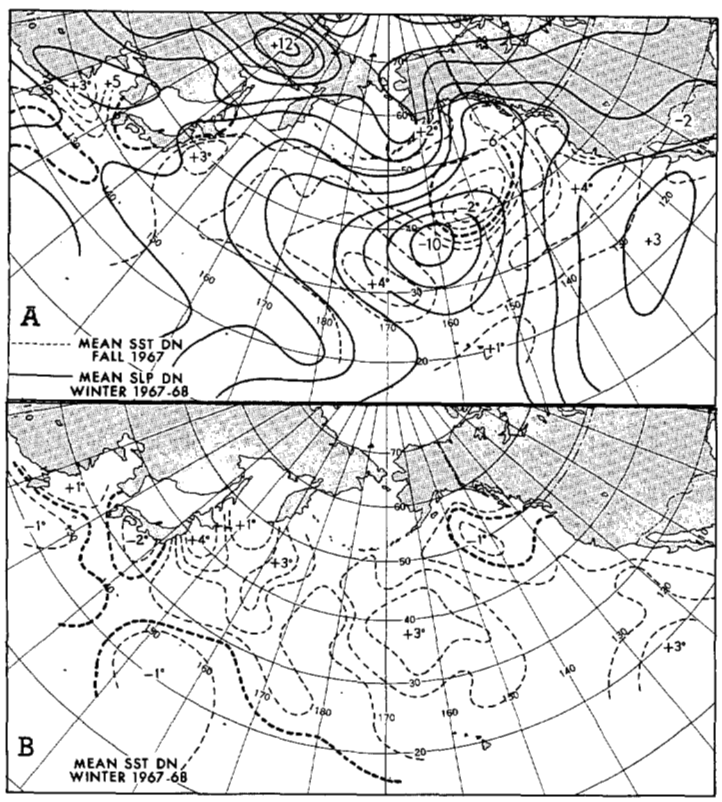

FIGURE 13.—(A) sea-surface temperature anomalies for fall 1967 (broken) and isopleths of anomaly of sea-level pressure (solid, in millibars) for winter of 1967–68. (B) sea-surface temperature anomalies for winter, 1967–68.

These mechanisms involved enhanced diabatic heating, including release of latent heat of condensation (both relative to normal), over an abnormally warm water pool. Another similar case when the Aleutian Low was depressed far south of normal occurred in the 1967–68 winter. As in 1962, the fall of 1967 was characterized by a pronounced and extensive warm pool of water at low latitudes, as shown in figure 13. The following winter's departures from normal of sea-level pressure are superimposed (2-mb isopleths). The central departure is 10 mb—a value exceeding two standard deviations. It is interesting to note the parallelism of the axis of negative pressure anomaly westward from the center and the axis of maximum autumn sea-surface temperature departure.

From the orientation of the isopleths of winter pressure anomaly, it is clear that anomalous Ekman transport and heat exchange would act to decrease surface water temperatures more rapidly than normal in the area of the warmest water at around 30°N, 170°W, but perhaps increase it farther east. These changes in sea-surface temperature anomaly were indeed observed in the chart for winter 1967–68 shown in figure 13B.

The month-to-month changes for two points are graphed in figure 14 as anomalies of sea-surface temperature (top curves, A) and as temperatures (related to means for a 1951–57 period) on the bottom curves, C. The middle curves (B) show the monthly mean atmospheric pressure anomalies and the anomalous components of resultant geostrophic wind direction. Note the anomalous easterly components associated with the rapid relative warming at 40°N, 160°W, and the westerly and northerly components associated with the rapid rate of cooling at 30°N, 170°W. The failure of temperatures to undergo their normal rate of decline from October to December at 40°N, 160°W, appears to be due to a number of factors: relative lack of vertical stirring and upwelling, diminution in evaporation and sensible heat losses associated with lighter winds than normal (normal winds here are westerly in fall), and enhanced warm water advection from the south.

SEA-LEVEL PRESSURE AND SEA-SURFACE TEMPERATURE

The charts showing one-season lag correlations between sea-level pressure and the subsequent season's sea-surface temperature are not reproduced. Except from winter to

spring, there are some large coherent areas. The mechanisms responsible for these coherent areas seem to be suggested by analysis of the earlier presented material. It is interesting to note that in all seasons, sea-surface temperature was better correlated with itself than with pressure in the preceding season.

6. SEASONAL EVOLUTION OF THE 7-YEAR MEAN PATTERNS

Because of the frequent similarity of sea-level pressure patterns between the same seasons of the years 1961–67 and the similarity of sea-surface temperature patterns,[4] it is possible to treat the evolution of the 7-yr means as though they comprised 1 yr. Therefore, in the following paragraphs, we shall be concerned largely with the mean sea-surface temperature and sea-level pressure anomalies of figures 6 and 7. The explanation of the seasonal evolution will naturally hinge on material discussed in earlier sections of this report.

The anomalous winter distribution of sea-level pressure is ascribed to the vast warm water pool generated in the central Pacific in fall. This pool inaugurated anomalous development of cyclonic activity in the area and thereby resulted in southward displacement of the Aleutian Low and the associated westerlies. Part of the increased cyclogenesis may have been due to the increased baroclinicity developed to the west and north of the warm pool. The reservoir of excess heat in the sea was not depleted during the winter, probably because of the entrapment of back radiation by increased cloud (with enhanced cyclonic activity) and the reduction in evaporation losses due to air moister than normal, resulting from the frequent rains (Namias, 1963).

[4] For example, in six of the seven winters sea-level pressures were below normal over an area extending approximately from 35°N to 50°N and from 160°E to 135°W. Over most of this area at least six out of seven winters had positive departures of sea-surface temperature.

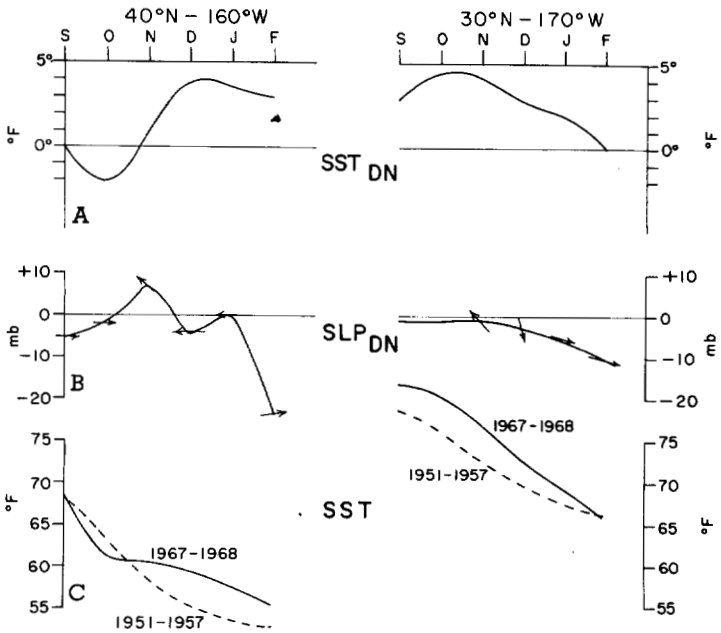

FIGURE 14.—Temporal variations of mean monthly elements from September 1967 through February 1968. (A) sea-surface temperature anomaly. (B) sea-level pressure anomaly and anomalous component of geostrophic sea-level wind (arrows). (C) sea-surface temperatures (solid) and 1951–57 means (broken). Locations of two points given at top of chart.

Pressure anomalies reversed from negative to positive from winter to spring in northern latitudes and, as a result, sea-level isobars became anticyclonically rather than cyclonically curved south of the Aleutians. This change did not appear to stem from responses (teleconnections) to changes in circulation over Asia, judging from a synoptic survey of the individual years, but appears to have been forced by air-sea interactions in the site of change. The following facts and hypotheses are offered in explanation.

Firstly, a strong anomalous gradient of sea-surface temperature east of the warm pool persisted from winter through spring. West of the warm pool, a gradient also persisted. If we consider first the area north of 40°N, it is clear that in areas east of the warm pool, the gradient of anomalous sea-surface temperature, by imparting itself to the overlying atmosphere, would result in an increase of the north-south component of the thermal wind in midtroposphere. For example, for the west-to-east thermal gradient of about 2°F per 20° longitude indicated on the spring chart of sea-surface temperature anomaly, one can compute the anomalous thermal wind component at 700 and at 500 mb assuming that this gradient persists aloft.[5] These computations come out to be about 1.9 kt at 700 mb and 3.7 kt at 500 mb—significant deviations for seasonal values. A similar computation can be made to the west of the warm pool, giving enhanced south-to-north components. The net result of these anomalous components would be to favor a high pressure ridge (or positive anomaly) roughly over the warm area, which through hydrostatic and mixing processes could work down to the surface.

Assuming that this explanation is valid, one may ask why the effect took place in spring and not in winter when heating processes over the warm pool led to low pressure. A partial answer is afforded by the normal winter and spring isobaric charts (fig. 1). From these it is clear that the vast expanse and intensity of the Aleutian Low in winter relative to spring would make the postulated "thermal wind effects" much smaller and perhaps insignificant compared to heating effects. In spring, on the other hand, the normal position of the Pacific High together with the weaker and more zonal winds might make the "thermal wind" mechanism more operative.

In the extreme eastern North Pacific south of about 40°N, another mechanism must have dominated because the positive anomalies of the Pacific High in spring were well to the east of the warm pool. The generation of cold

[5] The observed 1000–700-mb thickness at 45°N averaged 74 ft higher at 160°W than at 130°W for the springs of 1961–67. Temperatures at the 700-mb or 500-mb level are not readily available.

water off the west coast must be ascribed primarily to changes in pressure distribution leading to enhanced north-to-south air flow and all the associated cooling effects (including upwelling). This change in flow was in part a necessary consequence of a forced anomalous ridge over the central Pacific (north of 40°N), in other words, a teleconnection demonstrable theoretically (½ Rossby wave) or empirically. The resulting cold water may also have played a part in encouraging high pressure in eastern portions of the Pacific High, as described earlier in section 3. Perhaps all these considerations led to the anomalous eastward displacement of the Pacific High south of 40°N in spring.

The 7-yr change in pressure anomaly pattern from spring to summer shows another reversal over much of the North Pacific, when negative anomalies replaced positive except for the persistence under eastern portions of the Pacific High. Since the magnitude of pressure anomalies is relatively small in summer (small seasonal standard deviations), the general picture was dominated by the vast Pacific anticyclone, an overpowering seasonal "signal." Yet, small summer anomalies are frequently meaningful in terms of deviations of all the meteorological elements from normal.

In the areas characterized by negative pressure anomalies in summer, the increased cloudiness, upwelling, and wind speed associated with more than normal cyclonic activity appear to have produced anomalous cooling of the sea surface relative to spring. However, the prevalence of positive sea-surface temperature anomalies in summer indicates that the deep reservoir of warm water established in antecedent months retained some of its heat through the season over most areas (see fig. 6). Off the California coast the reservoir of cold water established in spring persisted through summer.

Two possible influences of sea on atmosphere should be considered in an attempt to explain the evolution of the summer pressure anomalies from spring. In these it is assumed that summer atmospheric anomalies are generated primarily by the abnormal sea-surface temperatures. In other words, the pressure anomalies are considered as perturbations forced by the underlying Pacific waters and are therefore not very dependent on remote continental circulations. Now the motion and intensity of the great Pacific High can influence the behavior and path of cyclones to its west and north. In the spring and summer, it has been suggested (section 5, "Sea-Level Pressure and Sea-Surface Temperature") that cold water in the eastern Pacific may have led to eastward displacement of the Pacific High in summer, and this in turn would permit a greater than normal intrusion of cyclones into the western Pacific. Secondly, these cyclones, some of which were tropical in origin, may have developed through additional heat of condensation released when their path lay over the warmer waters.

The fall 7-yr mean sea level pressure anomaly resembles the spring pattern to some extent, but one of its most distinctive features is the anomalously low pressure in the Gulf of Alaska. This latter anomaly owes its cause to the frequent cyclogenesis that took place in the falls of these years as cyclones from the west traversed warmer than normal water (Namias, 1968). The teleconnections associated with this negative anomaly in the Gulf of Alaska call for a strengthened anticyclone in the north-central Pacific, and this also favors the renewed generation of the warm water pool in the south-central regions of the North Pacific.

The coupling between air and sea in fall also suggests that some of the "thermal wind" effect, mentioned in connection with the spring anomalies, also came into play in fall.

The remarkable change in sea-surface temperatures off California from negative in summer to positive in fall was apparently due to the shift in anomalous wind component from northwest to southwest, thereby reducing the upwelling and heat exchange factors that had produced anomalously cool water there. This change in pressure anomaly pattern off California was directly related to the enhanced development of the fall Gulf of Alaska Low.

7. INITIATION OF THE 1961–67 REGIME

As mentioned in the introduction of this report, the choice of the period investigated was based on the convenient availability of oceanographic and meteorological data at the time of beginning this research. Thus, 1961 was chosen as the first year with adequate seasonal averages in both media. From the 1961–67 data, it appeared that this period possessed repetitive characteristics in different years and that we were, in fact, dealing with a special climatic "regime." The body of this report contains many such indications. To be more quantitative, I have compared the seasonal standard deviations of the pressure anomalies of this 7-yr period with estimates of the standard deviations for the seasons of the period 1899–1960. The latter estimates were based on the monthly standard deviations shown in figure 3 and computed under the assumptions that no correlation exists between months. (While this is not strictly correct, it does not affect the argument.) Maps (not shown) of the difference, 1961–67 standard deviations minus long-period normals for each season, show that the 1961–67 period was less variable than normal over most of the North Pacific.

When did this climatic regime begin? While this sort of question is usually unanswerable with meteorological sequences, there seems to be strong circumstantial evidence that in this case it was initiated in the fall of 1961.

Some evidence is contained in long-period records of the sea-surface temperatures, which, while not yet completely processed, are available from manuscript charts compiled by James Johnson (1967) of the Bureau of Commercial Fisheries. From these charts, I have computed seasonal average temperature anomalies for two 10° squares, one square centered at 35°N, 170°W (near the center of the

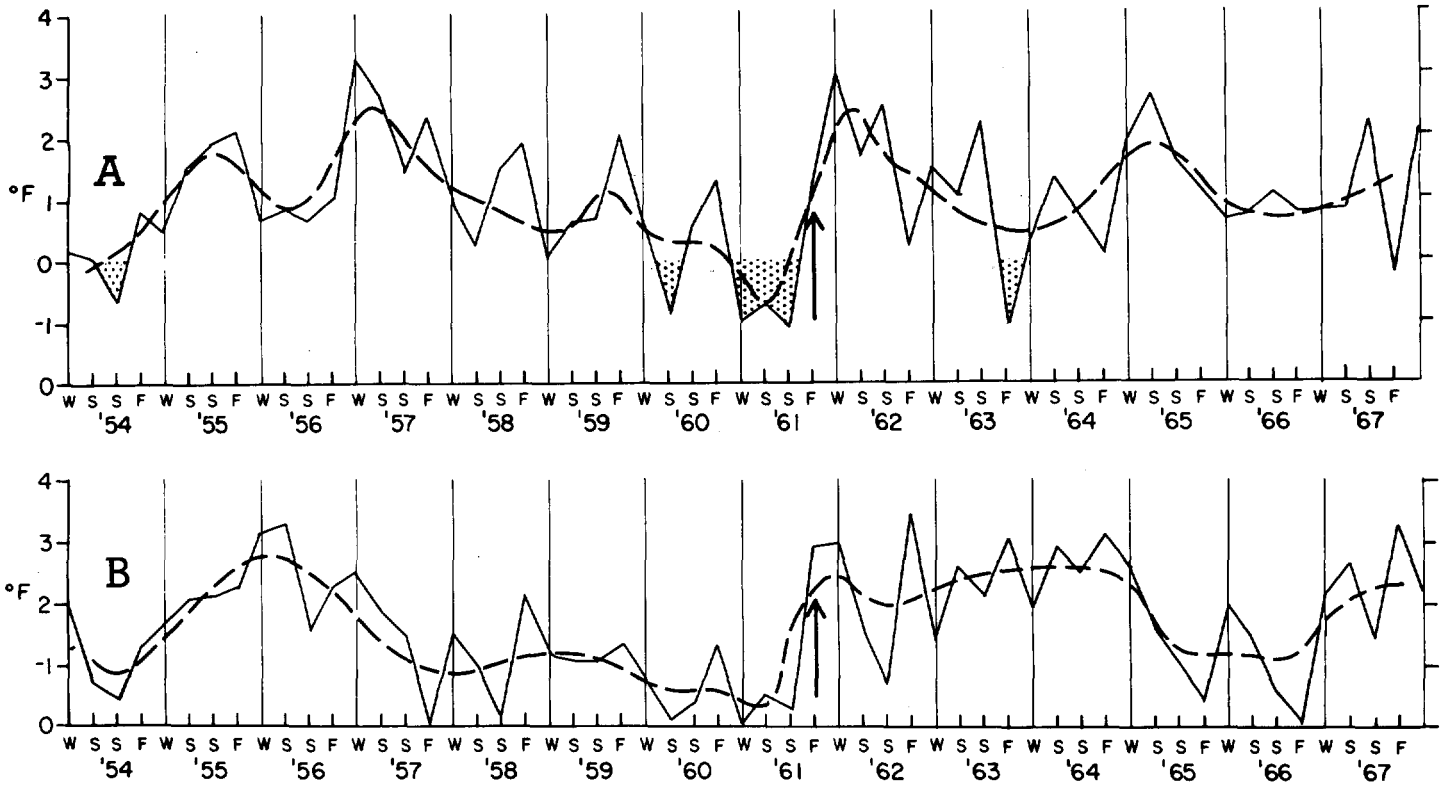

FIGURE 15.—Seasonal mean sea-surface temperature departures from normal for 10° square centered at 40°N, 150°W (A), and at 35°N, 170°W (B). Broken curves are smoothed with the help of three-season overlapping means. Shaded area in (A) denotes below-normal temperatures. Arrows denote change in climatic regime.

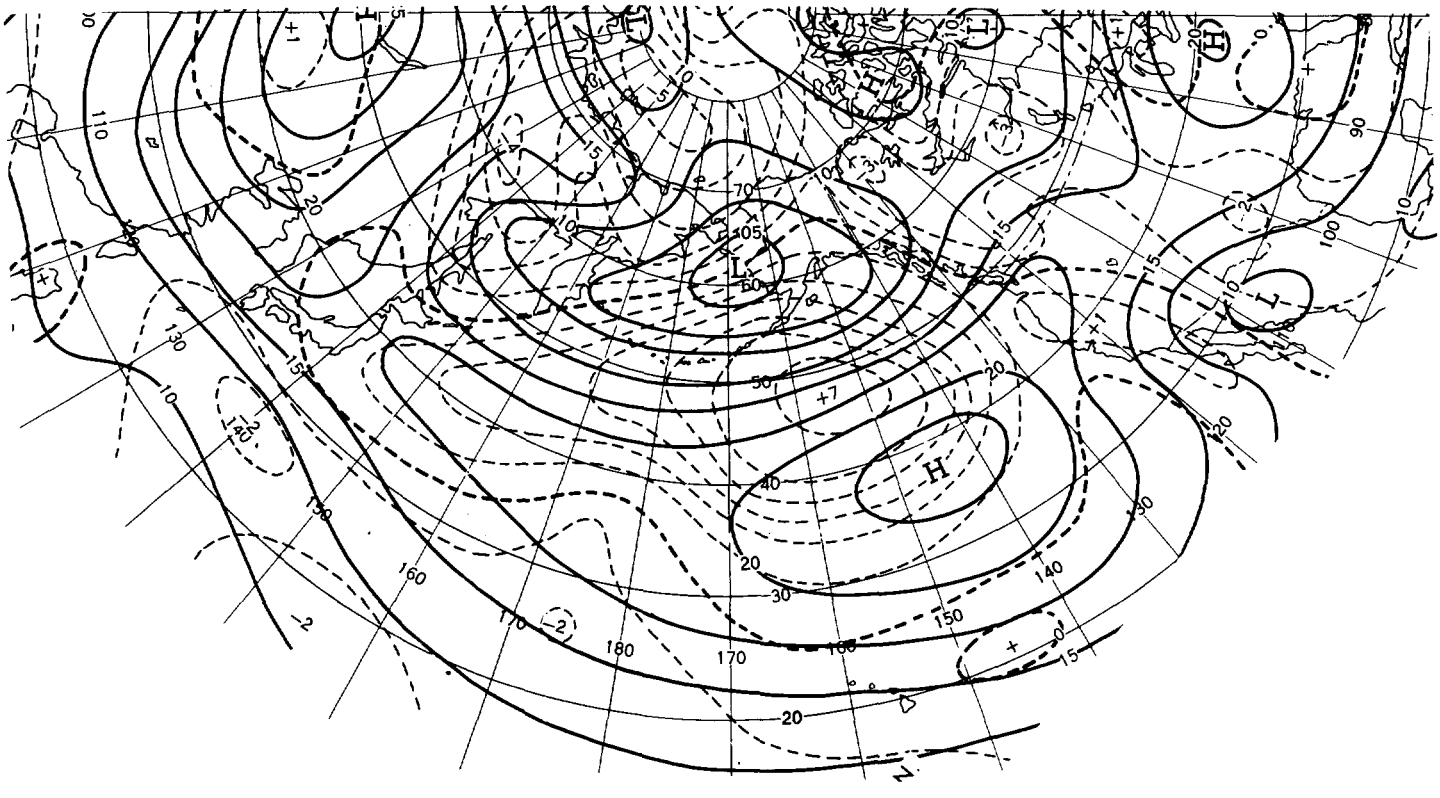

FIGURE 16.—Mean sea level isobars (solid) and isopleths of departure from normal (broken) for fall 1961.

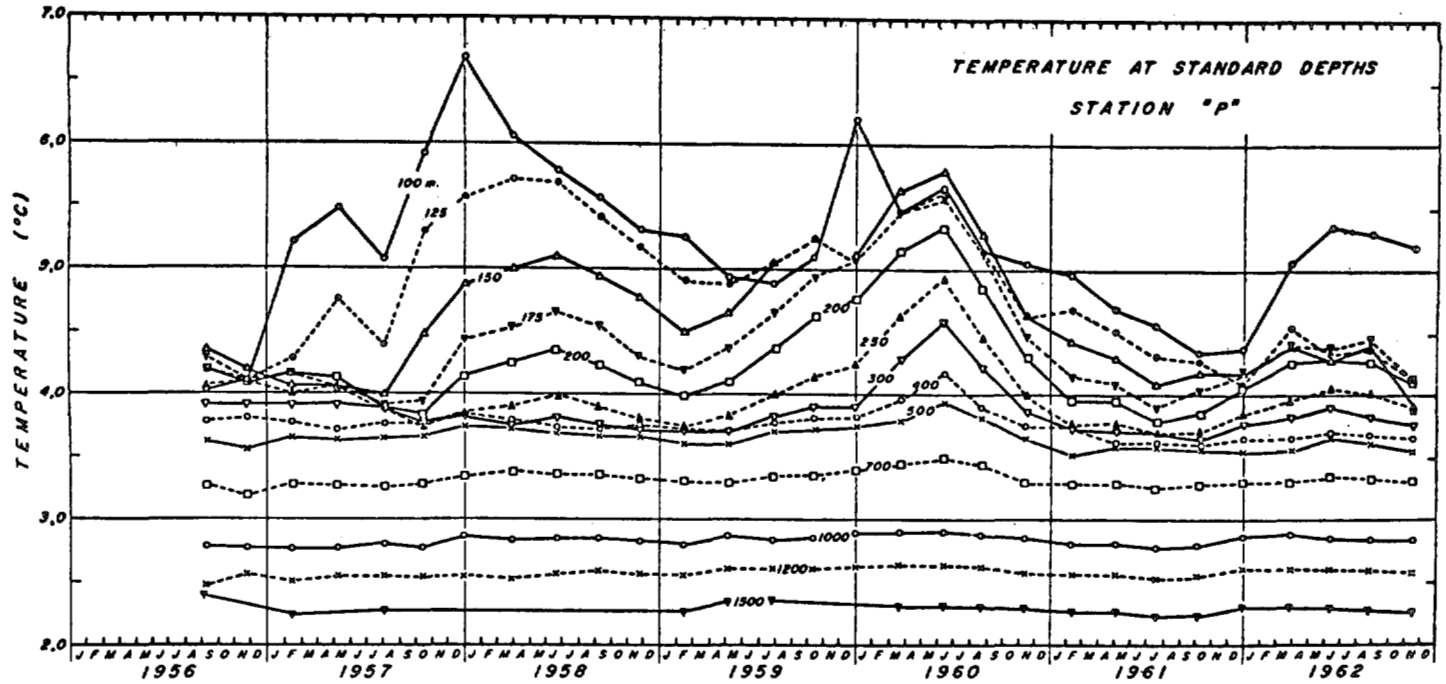

FIGURE 17.—Temporal variations of temperature (°C) at standard depths from 100 m down to 1500 m at Station "P," 50°N, 145°W (from Tabata, 1965).

predominantly warm pool), and the other centered at 40°N, 150°W, an area chosen for reasons to be given later. Time plots of these values since 1954 are presented in figure 15.

The lower graph (B, for the square centered at 35°N, 170°W) shows an abrupt increase in temperature anomaly from summer to fall in 1961, following a few years of small oscillations about a much lower mean. After the abrupt increase, the temperature deviations oscillate with small fluctuations around a much higher level.

If we examine the seasonal charts of sea-level pressure and its anomaly, it is found that an abrupt change in anomaly pattern also occurred in the fall of 1961. It took the form of an anomalously strong North Pacific High with departures of over 7 mb (2 σ's) at 45°N, 155°W (fig. 16). This pressure and anomaly pattern is immediately recognizable as being indicative of strong anomalous warming of the sea surface over large areas, particularly in the 10° square centered at 35°N, 170°W. The warming relative to normal (or lack of seasonal cooling) was the net result of several cooperating factors: Ekman layer advection of warm water masses from the south, less heat loss than normal from the water due to warm and moist air advection, and less wind stirring due to lack of cyclonic activity. The warming farther north, for example in the 10° square centered at 40°N, 150°W (fig. 15A), is also associated with these factors, but probably is due largely to lack of the vertical mixing usually common in fall, since the Aleutian Low was so far north of its normal position. Thus, if the generation of the fall, 1961, sea-level pressure pattern can be explained, we have an important lead to the cause of the central Pacific warm water pool to which we have assigned a major role in triggering off and maintaining the 1961–67 climatic regime.

To trace this chain of causality, we refer to the seasonal sea-surface temperature anomaly patterns in which the development of a very extensive cold pool over the east-central Pacific began in the winter of 1960–61 and continued uninterrupted through the summer of 1961. A graphic illustration of the development of this cold pool is furnished by the plot of sea-surface temperature anomaly for the 10° square centered at 40°N, 150°W (fig. 15A). After a few years of steadily declining anomalies, a cold pool of water persisted for the first three seasons of 1961. Because of the sustained surface coldness and the fact that convective mixing would thereby be encouraged, the inference was made that an anomalously deep reservoir of cold water must have been established by the summer of 1961. Later on, my attention was called to Tabata's exhaustive work (1965) on the records of weather station Papa (50°N, 145°W). Figure 17 reproduced from his paper (fig. 6 in his paper) shows that a marked drop in temperature beginning after the summer of 1960 took place not only at the 100-m level but down at least as far as the 500-m level. We shall not dwell on the generation of this deep cold pool, a more fitting subject for oceanographers, except to say that the sea-level pressure patterns starting in winter 1960–61 were highly indicative of pronounced surface cooling and strong upwelling. Dr. Tabata in a personal communication to me pointed out evidence for a tongue of cold deep water arriving at station Papa from the west during the summer and fall of 1961. Another interesting part of Tabata's curves is the long-period decline in sea-surface temperature beginning as early as 1957.

Whatever the cause of the development of the cold water pool, once it developed over such a large area and in such depth, it must have influenced the overlying pressure distribution. The effect on atmospheric pressure is

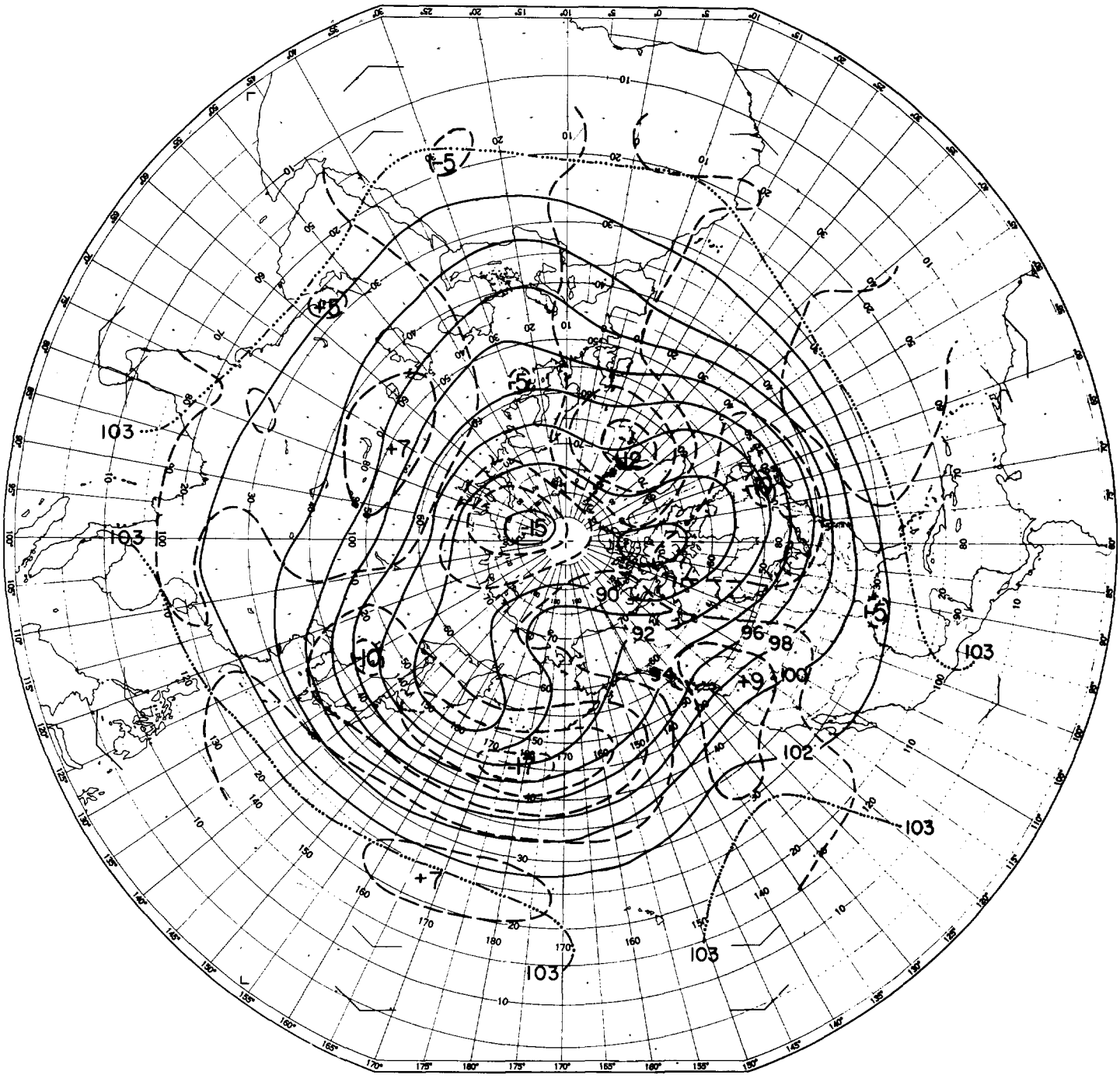

FIGURE 18.—700-mb mean contours (solid, labeled in tens of feet) and isopleths of anomaly (broken, drawn for every 50 ft) for the seven winters 1961–67.

apt to be greatest in fall when the Aleutian Low and Pacific High vie for domination in the area of the cold pool (see fig. 1). Therefore, the "shielding layer" effect proposed by Wexler (and discussed in section 3) whereby the leakage of air in the friction layer is reduced because of increased vertical atmospheric stability [6] would permit the Pacific High rather than the Aleutian Low to dominate this area. Thus, positive sea-level pressure anomalies developed over the cold pool.[7]

This strong development of the Pacific High then created the warm water pool to its southwest and may have set off the complex chain of events leading to the anomalous climatic regime of the 1960's. It must be stressed that while I have assigned the initiating role to the cold water pool, one can undoubtedly trace the large-scale air-sea interactions back further and further.

[6] This increase in static stability shows up in computations made for the point 40°N, 150°W (near the center of the Pacific High in the fall of 1961), using observed monthly mean thicknesses between 1000 and 700 mb, converting to °C for the approximate temperature at 1500 m, and using the sea-surface temperature for the base of the column. Thus, an abrupt change in lapse rate from 0.68°/100 m in August to 0.55°/100 m in September occurred. The latter value, about 0.1°C/100 m more stable than normal, persisted throughout fall 1961.

[7] A detailed study of cases of such anticyclogenesis will appear in a forthcoming issue of *Deep Sea Research* in an article, "Autumnal Variations in the North Pacific and North Atlantic Anticyclones as Manifestations of Air-Sea Interaction," written by the author (Namias, 1969).

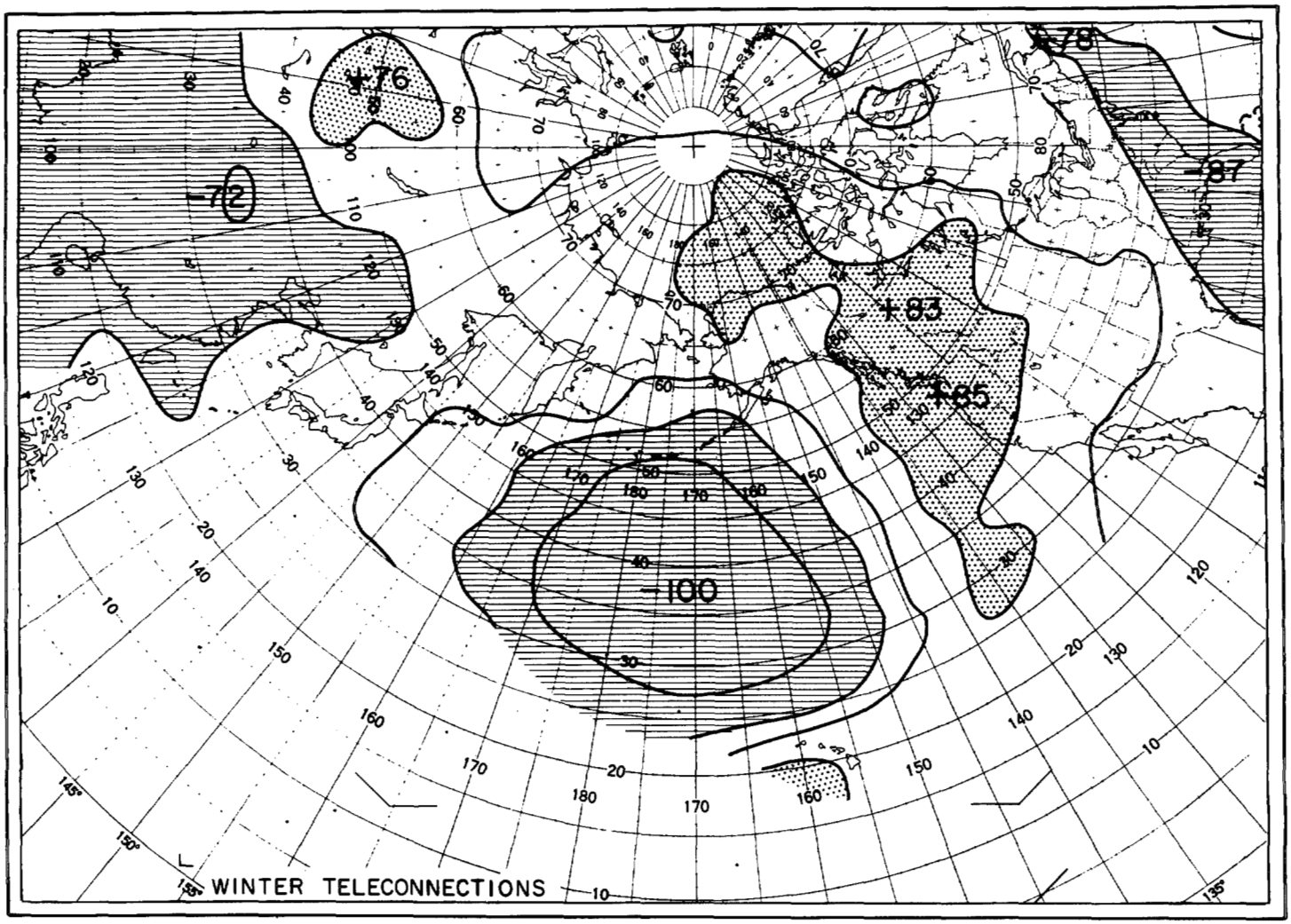

FIGURE 19.—Isopleths giving the probability of sign of anomaly when a negative center in winter dominates the area around 40°N, 170°W. Stippling represents positive anomaly; shading, negative. Isopleths are for 75-percent and 50-percent probabilities.

The starting point for discussion is therefore arbitrary. Then again, it should be emphasized that once initiated, the abnormality feeds on interactions in areas other than its site of initiation. In our case, the persistent and persistently recurring warm pool in the central Pacific seems to have taken over command while the initiating cold pool was covered over by a layer of warm water (e.g., note the increase in temperature at 100 m in 1962 in fig. 17 relative to deeper layers).

8. RESPONSE OF TEMPERATURE PATTERNS OVER THE UNITED STATES

Many years ago Rossby and Collaborators (1939) showed how perturbations in the westerlies in one area influence the flow in other remote areas through barotropic redistribution of vorticity. If for any reason one of the large centers of action in the atmosphere is forced into an abnormal location, one may therefore expect to find responses in other centers of action.

During the 1961–67 period treated in this report, the southward wintertime displacement of the Aleutian Low has been stressed (see fig. 7). The developing and occluding cyclones that made up this Low transferred their vorticity aloft, so that mean midtropospheric contour patterns of the 1961–67 winters frequently showed a strong central Pacific trough. The mean 700-mb pattern and its isopleths of anomaly for the seven winters, shown in figure 18, reflect this abnormal trough. It also shows an abnormally strong ridge along the west coast of North America and a strong trough over eastern North America. Both of these latter features were so placed as to be sympathetic responses to the central Pacific trough in accord with Rossby's longwave concepts. They are also in agreement with empirically determined teleconnections worked up by O'Connor (1969) and used in routine extended forecasting practice (fig. 19).

This amplified longwave pattern over North America, composed of a strong ridge in the west and a strong trough in the east, was associated with frequent and strong outbreaks of Arctic air into much of the United States east of the Continental Divide and with mild subsiding Pacific air west of the Divide. In fact, quantitative specification can now be made of the U.S. temperature

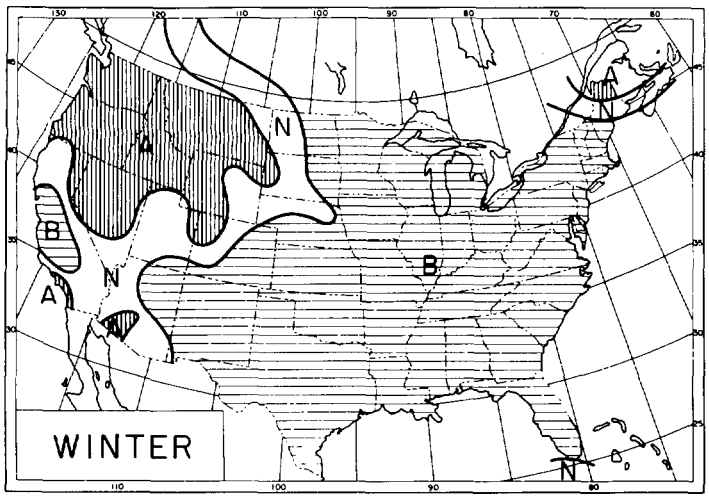

FIGURE 20.—Mean 7-yr (1961–67) temperature anomaly for winter expressed in three categories—below, near, and above normal.

anomalies to be associated with such a flow pattern by employing the methods of Klein (1965).

The observed mean temperature anomaly pattern for the seven winters, given in figure 20, agrees with that implied or specified from the 700-mb contour pattern. This temperature pattern was not only prevalent during the seven winters 1961–67 but was also observed in the winter of 1967–68.

In the winter of 1962–63, when this temperature pattern was especially pronounced and persistent, it was ascribed to a number of cooperating and thus amplifying effects, but its primary instigation was believed to be the air-sea interactions over the North Pacific (Namias, 1963). It now appears that the U.S. climatic fluctuation of the 1960's, involving reversal of the warming trend observed over preceding decades, may be a striking example of the dominant role played by North Pacific large-scale air-sea interactions.

9. SUMMARY

Seasonal mean sea-surface temperature and sea-level pressure patterns during the 7-yr period 1961–67 over the North Pacific have been studied with the aim of explaining their large-scale air-sea interactions. The essential non-seasonal variations in both media were first described with the aid of departures from long-term averages (normals) and with contemporary and lag correlation fields. The outstanding sea-surface characteristic of the 1961–67 period was the persistence and extent of warm water, particularly in south-central areas. This water, reaching maximum warmth in fall, was frequently the seat of abnormal cyclogenesis in the vicinity of the warm pool in winter. The cyclogenesis was attributed to enhanced sensible and latent heat flux, release of latent heat of condensation and baroclinicity. Because of numerous factors offsetting heat losses, particularly entrapment of back radiation and lessened evaporation associated with the persistent cloud cover and rain, the anomalous heat of the warm pool was not depleted in winter.

After winter, the anomalous thermal structure of the water, operating in conjunction with the climatologically changing springtime conditions, frequently produced an opposite pattern of pressure anomalies but again one that encouraged the warm pool to persist. The principal springtime effect appears to have been one in which the anomalous gradients of sea-surface temperature affected the thermal wind distribution in the atmosphere and thus influenced the pressure distribution.

Although cyclogenesis was slightly enhanced over the warm water in summer, perhaps associated in part with occasional tropical storms, the magnitude of the water temperature anomaly was only slightly reduced by cloud cover and exchange processes. By fall, strong development of cyclones in the Aleutians and Gulf of Alaska as they moved over warm northern waters forced the maintenance of a strong Pacific High—once again setting in operation several cooperative factors that regenerated the central Pacific warm water pool.

In the above described manner a special climatic regime took place in the 1960's. The inauguration of the regime was traced back to the abrupt generation of the warm water pool in the fall of 1961 following several years of near-normal water. This abrupt rise in sea-surface temperature was then attributed to a vast and anomalously strong Pacific High, which developed in the fall of 1961 and led to numerous cooperative mechanisms leading to warm surface-water production. Among these were strong advection from the south, diminished upwelling, and diminished sensible and latent heat exchange. The chain of events was then traced back to the formation of a persistent deep and horizontally extensive pool of *cold* water in the first 9 mo of 1961. This cold pool did not lead to anticyclogenesis until the time was ripe, namely, in fall when the Aleutian Low and Pacific High vie for domination, and when the depth of the atmosphere's mixing layer is critically important in determining the frictional leakage of air from anticyclones. Although one probably could, with extensive data and study, carry the chain of events back further in time, we have arbitrarily chosen our starting point with the development of the cold pool.

After the fall of 1961, when a layer of warm water was generated over the cold, a new climatic regime became established and the old one terminated. In other words, an irreversible change had occurred and molded the climate for several years.

Finally, downstream effects of the North Pacific air-sea interactions on atmospheric circulation were credited with producing the cold winters observed over the eastern two-thirds of the United States during the 1960's.

ACKNOWLEDGMENTS

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