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LONG-RANGE FORECASTING OF THE ATMOSPHERE AND ITS OCEANIC BOUNDARY—AN INTERDISCIPLINARY PROBLEM

by
JEROME NAMIAS
U.S. Weather Bureau, ESSA

INTRODUCTION

The physical sciences of the atmosphere and of the ocean are each extremely complex; the physical sciences of the combined atmosphere-ocean system is more than twice as complex. It is becoming increasingly apparent, however, that we cannot separate these two systems because of their continual interaction, seemingly on all time and space scales.

The oceanographic and air-sea interaction problems thus far treated at great length and with great care have involved phenomena of two principal space and time scales:

1. Microscale and short-period phenomena, which often occupy the efforts of an oceanographic cruise lasting a few weeks; and
2. The large-scale fields of some oceanographic element or perhaps ocean-atmosphere exchange parameter averaged by tens of years to obtain climatological averages.

Indeed, studies such as these have laid the foundation of modern oceanography and will continue to be of major importance in its development. Between these two ends of the spectrum there is a large range of scales of motion and interaction which have up to now received comparatively little attention, and whose discovery, description, and explanation await systematic research.

The importance of attacking these intermediate-scale problems arises not only intrinsically, but especially because many other scales of activity, large and small, short- and long-lasting, may be influenced—or in Stommel's (1963) words—"contaminated," so that their neglect can render ineffective otherwise well-designed observational programs.

Meteorology offers a good analogy. Not so long ago (some thirty years), many meteorologists thought that the largest-scale systems with which they need be concerned for prediction purposes were the extratropical cyclones and anticyclones—until the abundance of surface and upper-air data over the Northern Hemisphere illuminated the fact that these elements were often responsive to planetary waves 3 to 4 times their size. Moreover, these planetary waves in turn were found to be interactive not only with the cyclones but with each other and thus with the entire hemisphere's general circulation. Some work currently proceeding in extended forecasting suggests that even crossequatorial interactions are likely.

I shall describe in this paper a few suggestive studies whose results point to the need for greatly expanded work in both oceanography and meteorology in quest of knowledge of ocean-atmosphere interactions on a hemispheric space scale and on time scales of months, seasons, and years. It is only when solutions to such problems are obtained that meteorologists and oceanographers will be able to aim at validating and applying their research by making more accurate predictions of events on these scales.

THE EFFECT OF ANOMALOUS ATMOSPHERIC SYSTEMS ON SEA-SURFACE TEMPERATURES

In view of the heterogeneous nature of this audience, I shall first describe—as background—the relationship frequently found on daily weather maps between cyclones and anticyclones (and their associated fronts) and the larger scale pressure and wind patterns. Figure 1 shows a schematic diagram on which the cyclones are represented as waves along the Polar front, moving from southwest to northeast and developing and occluding as they progress. These waves are embedded in a broad low pressure trough between two extensive high-pressure areas—one to the northwest composed of cold air masses and the other to the southeast composed of warm air masses. Associated with this group of short wave disturbances is a long (or "planetary") wave in the westerly winds aloft which has a length of the order of four times that of the cyclone waves. There may be about 4 to 6 of these waves present around the hemisphere on any one day's map for the 500-mb level. The long waves and the cyclone waves provide the atmosphere's mechanism for exchange of heat, momentum, and water vapor between the tropics and polar regions. Long waves provide a means for deploying cold and warm air masses into the temperate latitudes where cyclones and anticyclones are generated. It must be constantly borne in mind that both systems, the long waves and the short waves (the cyclones) are interactive so that they cannot be treated independently.

Even if one averages the upper-level or sea-level pressure and wind distributions over periods of weeks, months, or seasons, the long waves do not disappear. They assume positions and amplitudes which vary from one period to another, and thus the prevailing air masses, storm tracks, and associated weather conditions may be inferred from the mean configuration of the long waves. We stress the latter point because most of the charts shown in this article refer to the observed mean upper-level flow patterns.

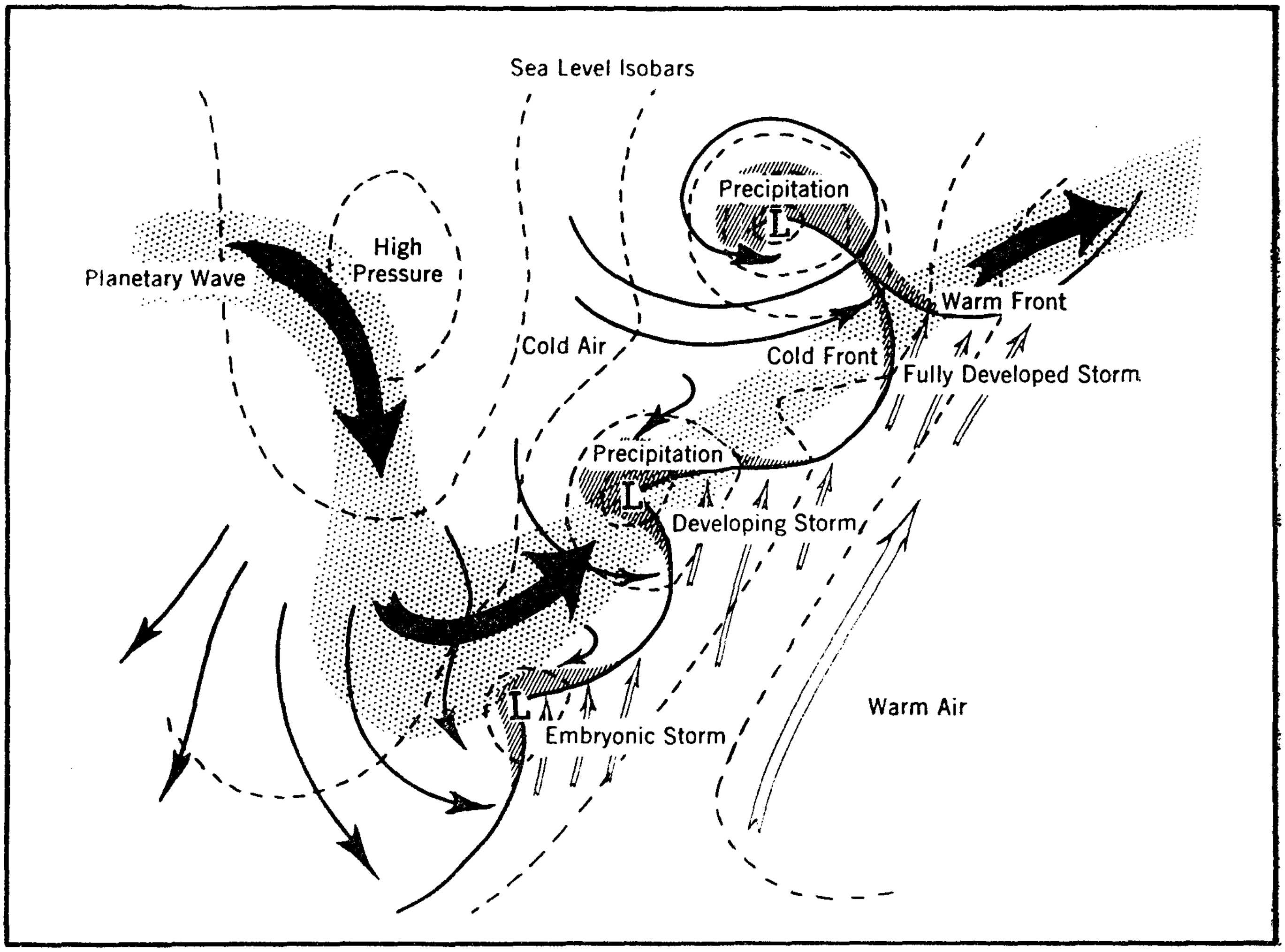

Figure 1. Schematic illustration of the relationship between planetary waves in the middle and upper troposphere and air masses, fronts, cyclones, and anticyclones customarily seen on daily weather maps. Note that the wavelength of the planetary wave is several times the size of cyclone waves along the surface polar front.

The mean pressure distribution—let us say at sea level—gives a very good approximation of the resultant wind streams for the period. Furthermore, the mean wind can be considered as being composed of a normal component and an anomalous component. The latter component may be determined by subtracting from the observed mean pressure distribution the long-term normal, thereby obtaining a field of isopleths of anomaly. Such a map for July 1958 is shown in the upper left corner of Figure 2. For the shaded area the frequency of daily observed and normal wind directions during June and July 1958 is shown in the upper right-hand part of the figure. It is clear that whereas the normal prevailing wind over the shaded area is from the west, in July 1958 it was mostly from the south and southwest, in agreement with inferences from the isopleths of anomaly. These anomalous components of the wind represent an anomalous drag on the surface water and force an anomalous Ekman drift. The southerly components in July 1958 also imply warm air transport and less than normal latent and sensible heat transfer from the underlying water. It is not surprising, therefore, to see that in the observed sea-surface temperature distributions, warmer-than-normal surface water is found in the eastern part of the Gulf of Alaska and colder-than-normal water in the western. The colder-than-normal water must also be associated in part with the upwelling near the center of the negative anomaly, where strong horizontal divergence of surface water takes place—as pointed out by Bjerknes (1962). The preceding concepts have been incorporated into a methodology for estimating numerically what the sea-surface temperature distribution is likely to be with a given mean pressure distribution whose effects are superimposed upon an initially abnormal sea-surface temperature pattern. This method has been described by the author (Namias, 1965). An example of such a computation for July 1958 is given in the lower lefthand portion of Figure 2 and for October 1963 in Figs. 4 and 5. It is interesting to note that the large anomalous drop in sea-surface temperatures in the area south of the Gulf of Alaska between September 1963 (Fig. 3) and October 1963

(Fig. 5) was associated with a very strong development of Gulf of Alaska cyclones. This can be seen from Figure 6 where the pressure distribution for October and the change from September are shown. From this figure it is clear that cooling of the surface water was induced (a) by greatly increased losses of latent and sensible heat from the surface water as windy Arctic air masses entered the Gulf from Alaska and the Bering Sea; (b) by especially pronounced vertical destabilization and stirring of the lower layers of the atmosphere, which removed heat and water vapor rapidly aloft; (c) by strong upwelling and water mixing produced by the Gulf of Alaska cyclone. James Johnson (pers. comm.) of the Bureau of Commercial Fisheries has made some calculations for this case and finds that about two-

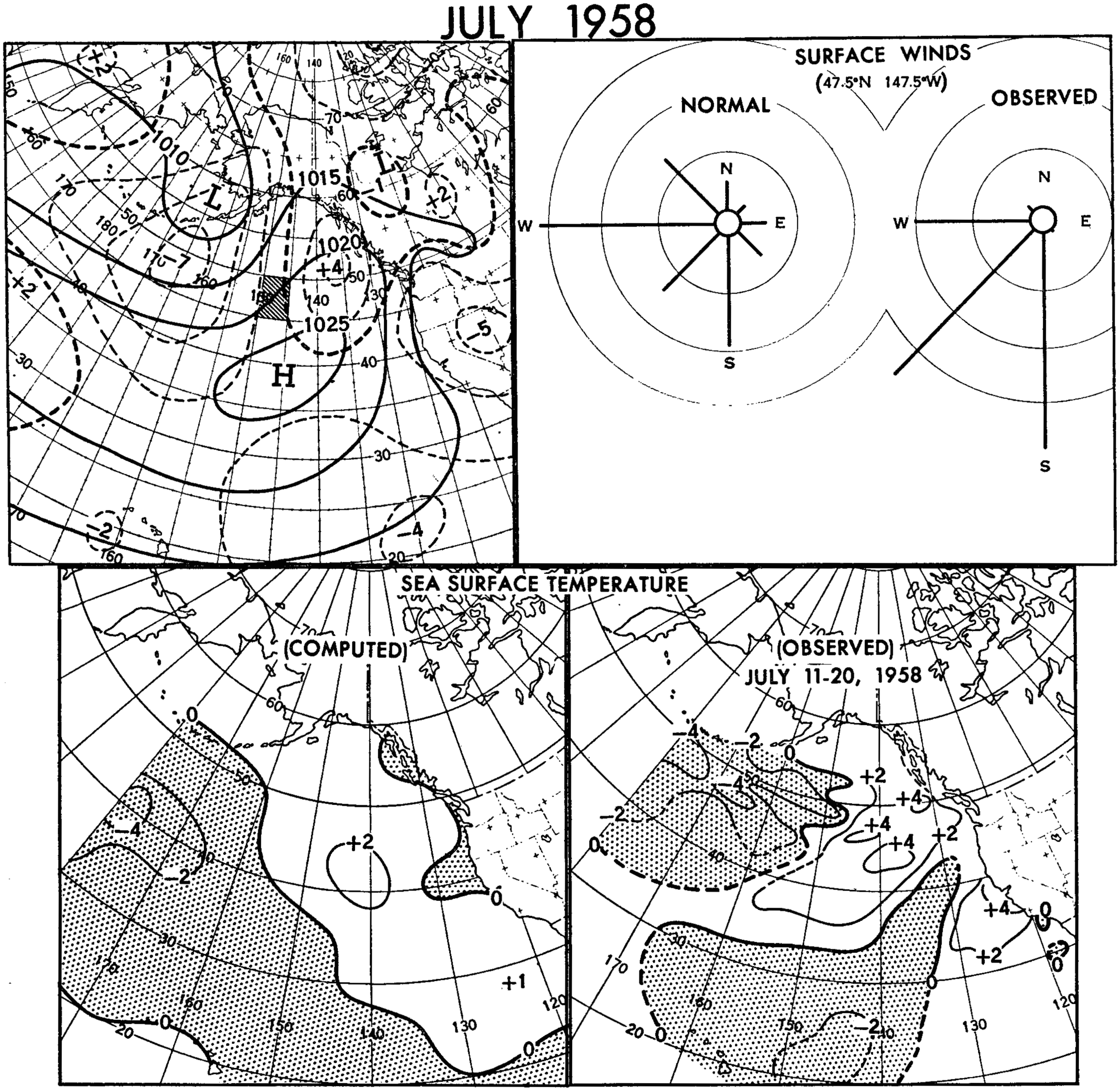

Figure 2. *Upper left:* Sea-level mean isobars (solid) and isopleths of departure from normal (dashed) for July 1958.
Upper right: Normal surface wind rose for July and that for July 1958 as computed from surface weather map analyses for the hatched 5° square shown in chart in upper left. Length of bars indicates relative frequency of winds for indicated direction.
Lower left: Computed sea-surface temperature anomalies using advection in the Ekman layer for July 1958 (°F).
Lower right: Observed sea-surface temperature anomalies for July 11–20, 1958 (°F).

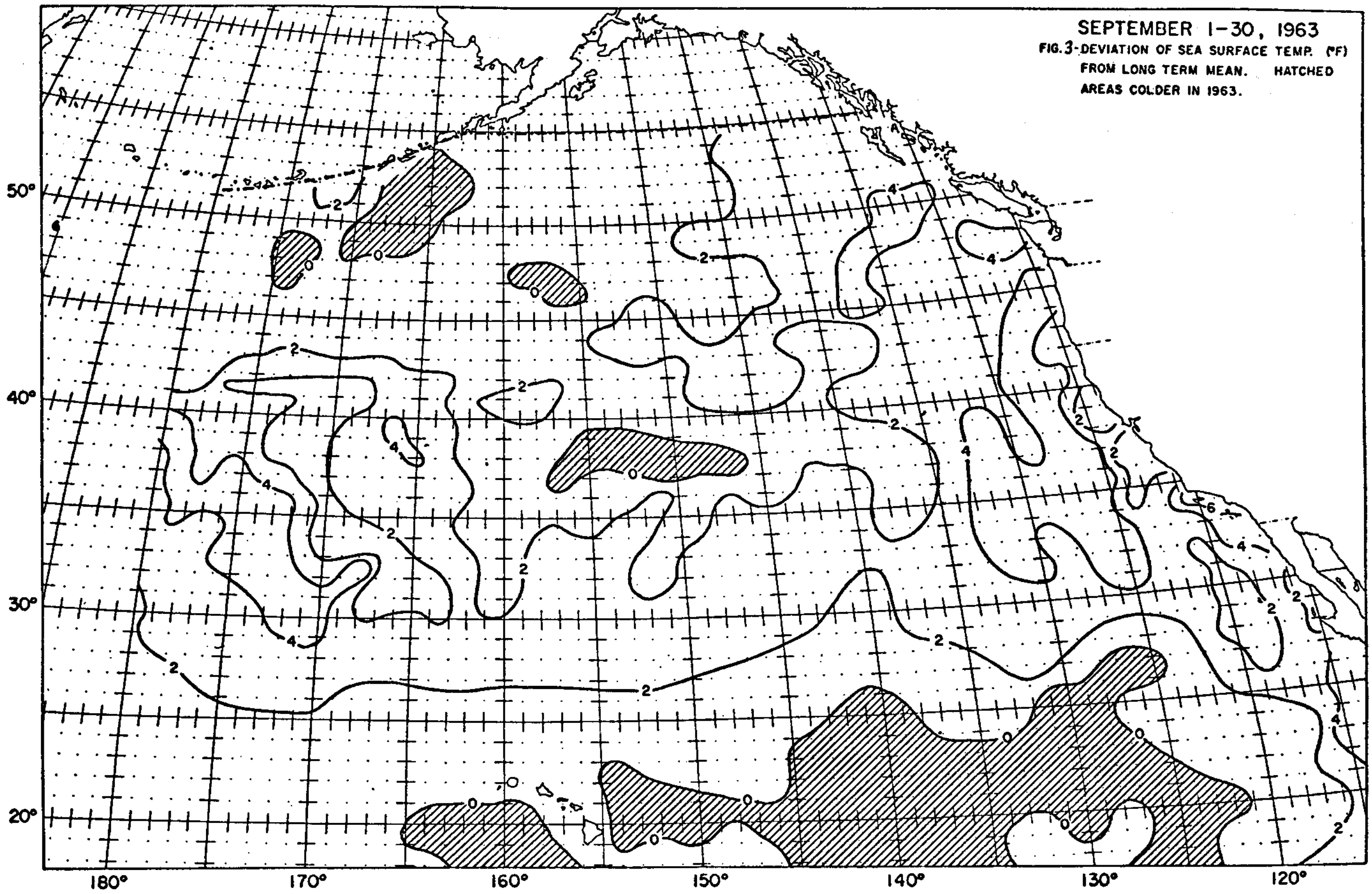

Figure 3. September 1963 departure from normal of sea-surface temperature (°F) from long-term mean. Hatched areas colder-than-normal (from Bureau of Commercial Fisheries).

thirds of the cooling was due to the increased latent and sensible heat exchange, while about one-third was due to upwelling and mixing.

The continuation and extension of abnormal warmth to the west is associated with the positive change in pressure distribution found there and particularly with the suggestion of horizontally converging surface water and resultant lack of upwelling.

Of course, it is desirable to be able to *predict* the sea-surface temperature distribution a month or so ahead. With the help of the concepts described above some first approximations are now being made by using *predicted* mean sea-level pressure distributions. Naturally, these sea-surface temperature predictions leave much to be desired because their accuracy depends not only upon the accuracy of the atmospheric pressure prediction, but also upon the complex physical problems associated with air-sea interaction and the response time of water masses to wind drag and other factors. The first trial estimate of sea-surface temperatures, made for March 1965, is given in Figure 7, together with the corresponding observed state. Considering the fact that the initial sea-surface temperature data were the means for February 1965 (although atmospheric data up to March 14 were used), this prediction was reasonably successful. Tests are proceeding on additional cases and attempts are being made to improve the method by incorporation of terms not previously considered. Professor Robert Arthur has been especially helpful in making suggestions along these lines.

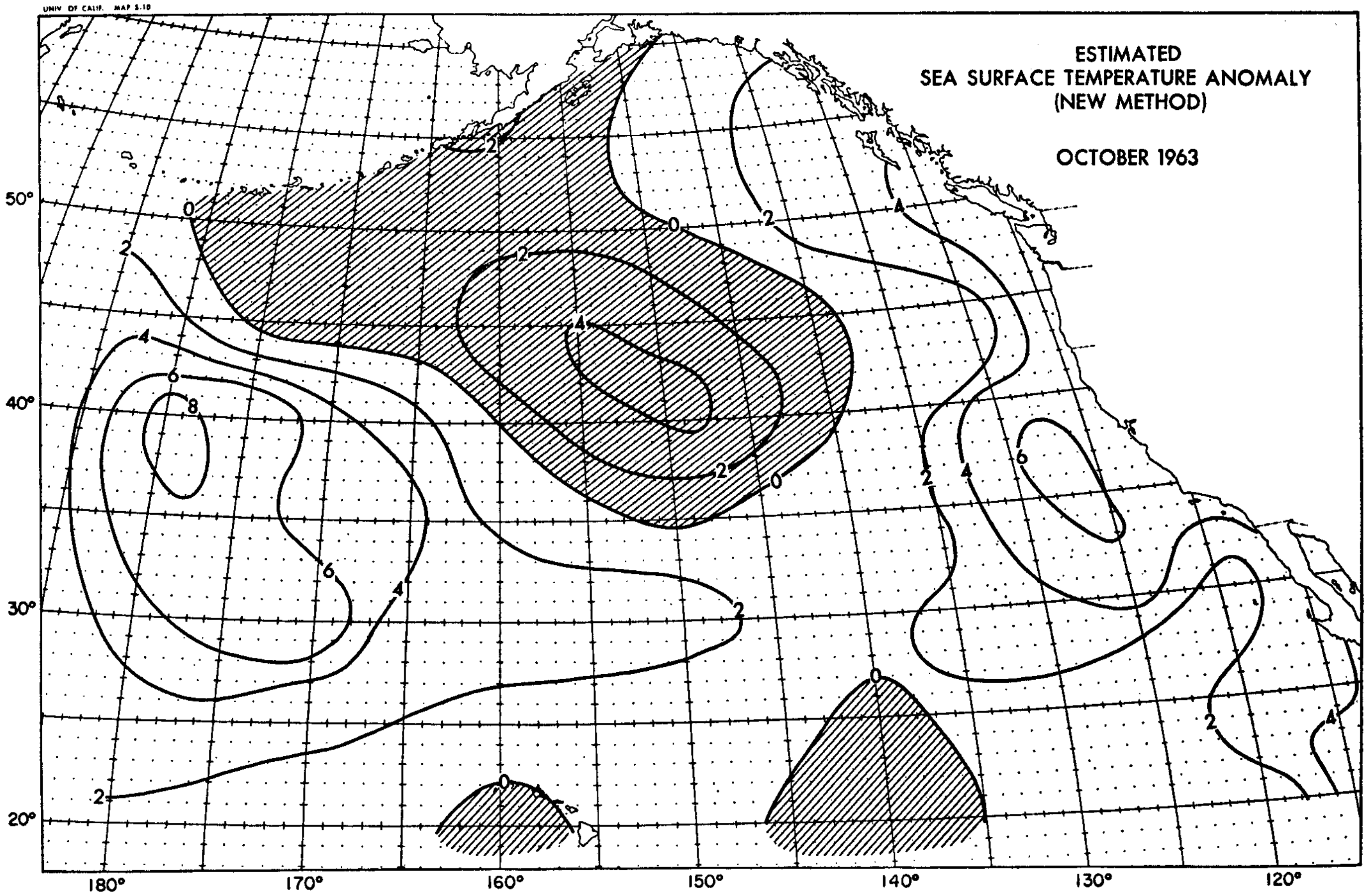

Figure 4. Estimated sea-surface temperature departures (°F) for October 1963 (see text).

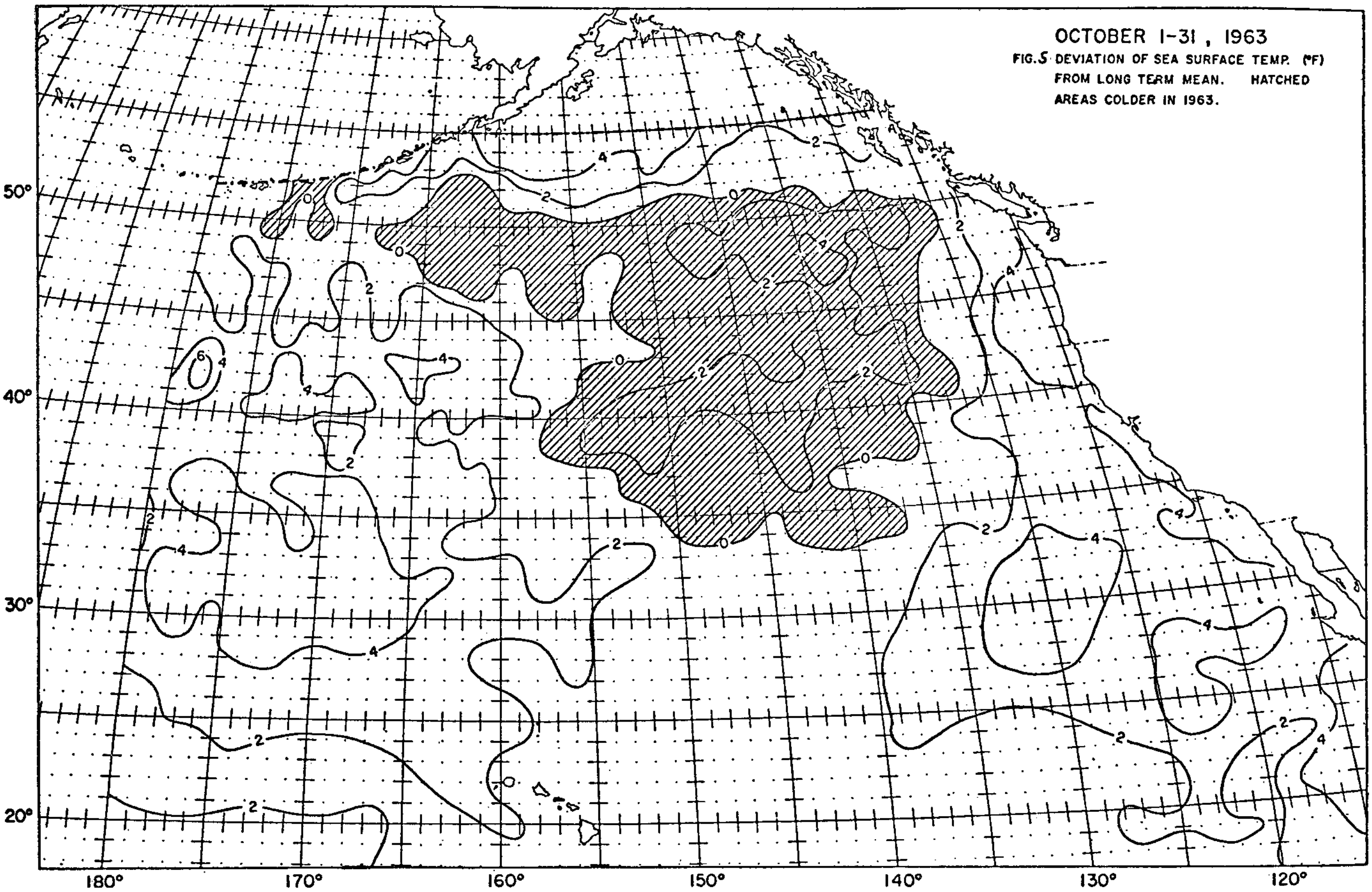

Figure 5. October 1963 departure from normal of sea-surface temperature (°F) from long-term mean hatched areas greater-than-normal (from Bureau of Commercial Fisheries).

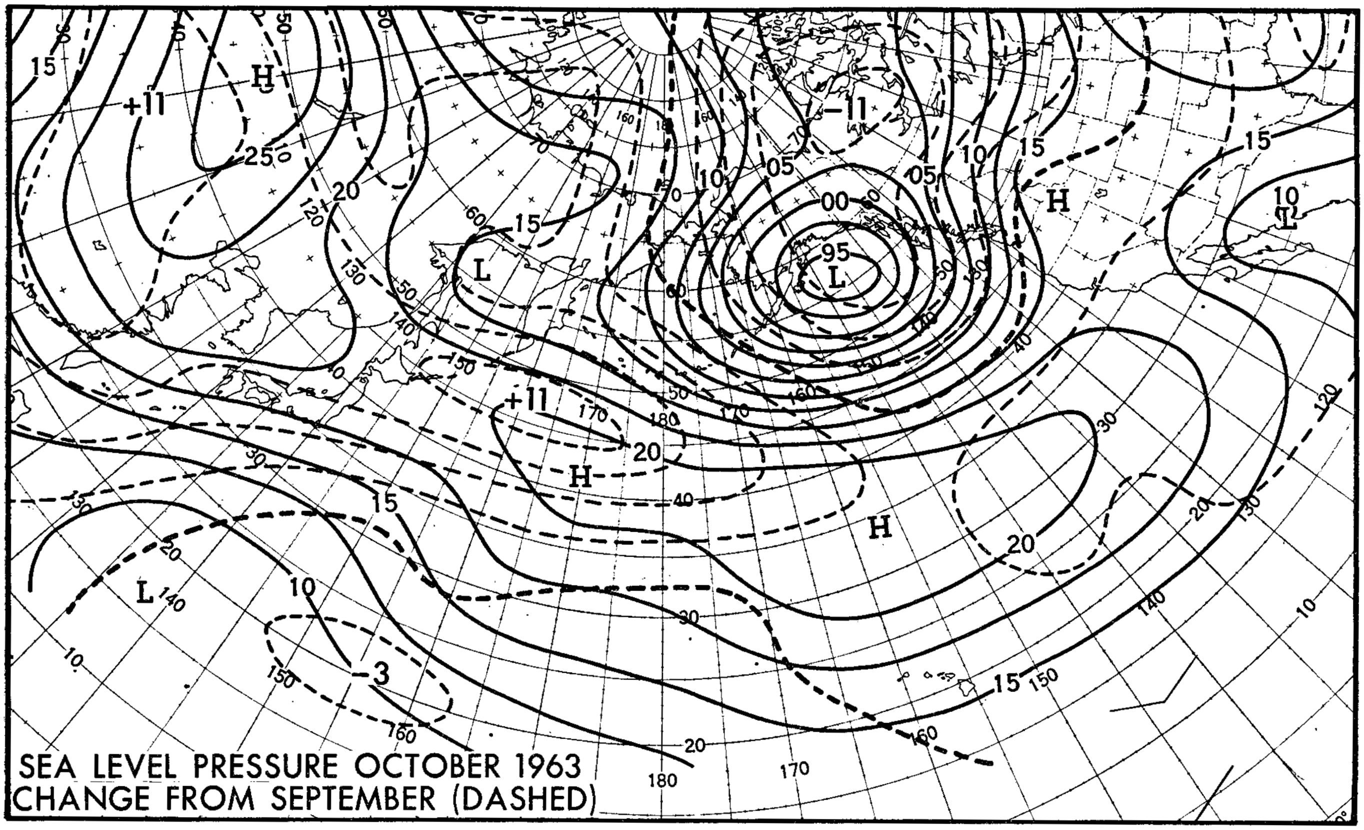

Figure 6. Mean sea-level isobars for October 1963 (solid) and changes in sea-level pressure from September 1963 to October 1963 (changes indicated by broken lines drawn for every two mbs pressure change with centers of maximum change indicated numerically).

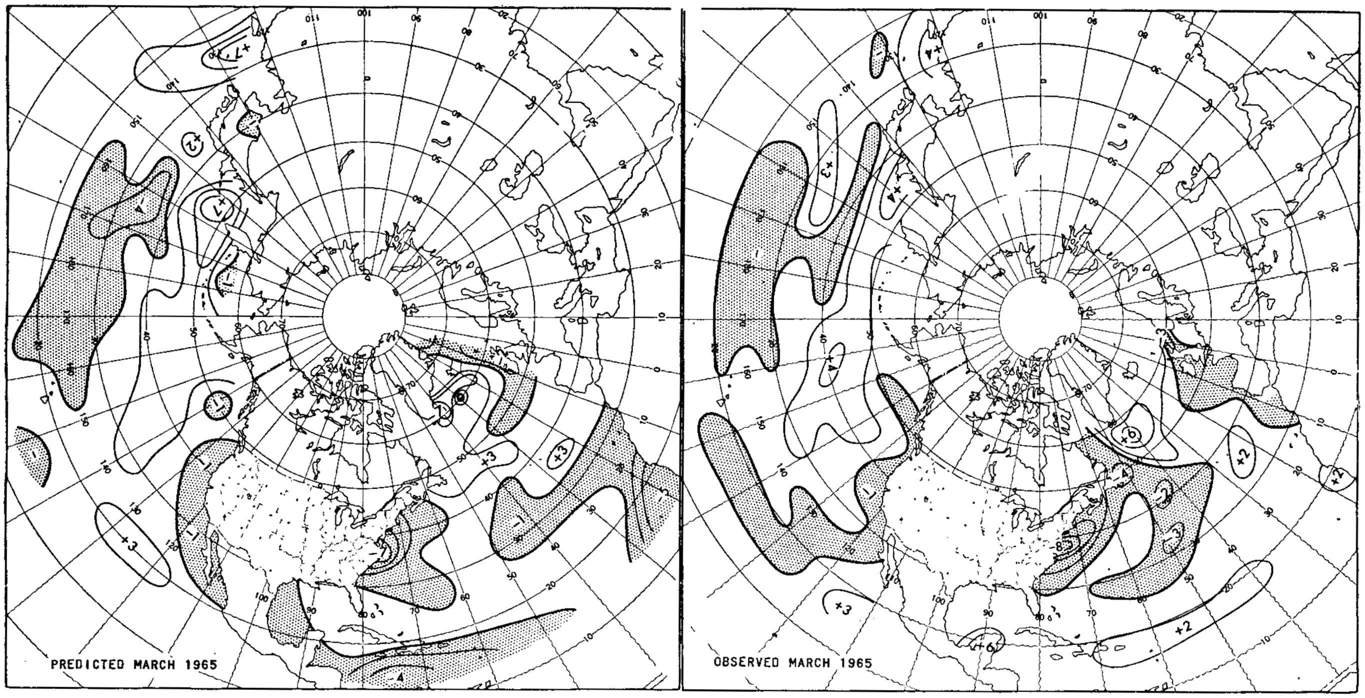

Figure 7. *A.* Predicted sea-surface temperature anomaly (°F) for March 1965. *B.* Observed sea-surface temperature anomaly (°F) March 1965.

THE COUPLED AIR-SEA SYSTEM VIEWED ON A MONTHLY AND SEASONAL SCALE

In an earlier paper (Namias, 1965) I described a slowly migrating upper-level trough which came to light on seasonal mean charts and which could be followed as it moved eastward from the west-central Pacific in summer to near the West Coast in the subsequent spring. A theory was proposed to explain how this slow motion may have come about as a result of climatological effects and wide-scale air-sea interaction. Since 1958 other cases of eastward motion of Pacific troughs from summer to fall and winter have been observed on mean maps. We shall treat below one of the most spectacular of these, which led to the unprecedented rainy period in southern California in November and December of this year, as well as to a protracted heat wave there in October and successive cool spells in September.

The upper-level charts for each month from July through November 1965 are reproduced in Figures 8-12. Superimposed upon the mean contours (solid lines) are the contemporaneous mean sea-surface tem-

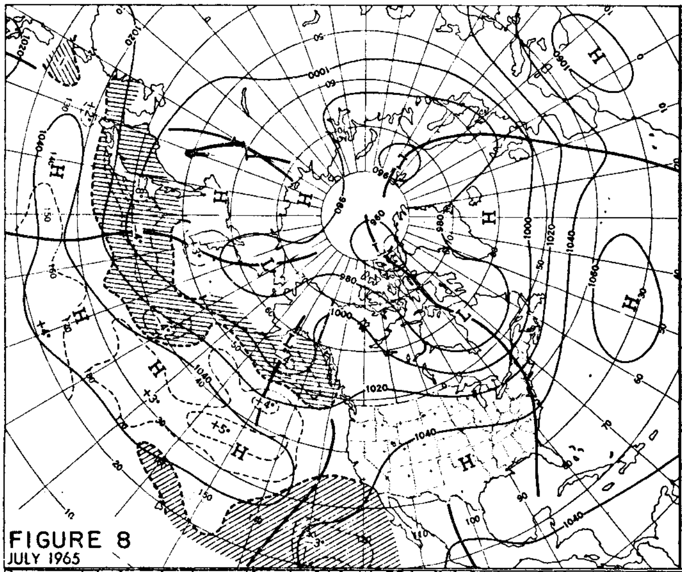
FIGURE 8
JULY 1965

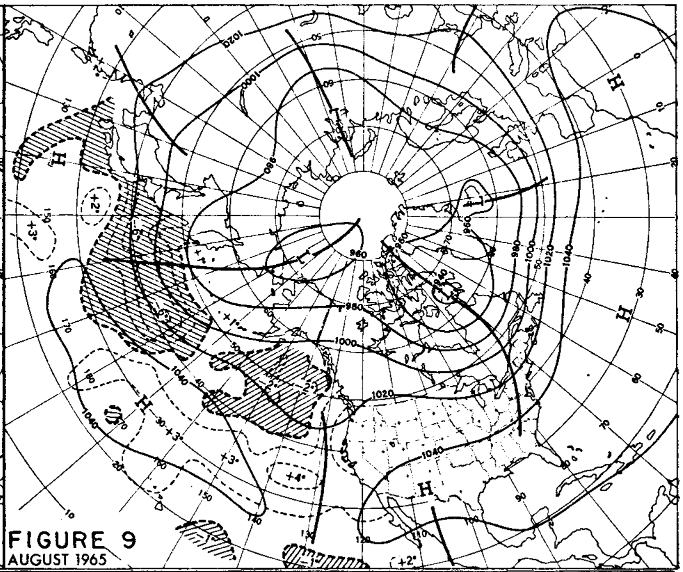
FIGURE 9
AUGUST 1965

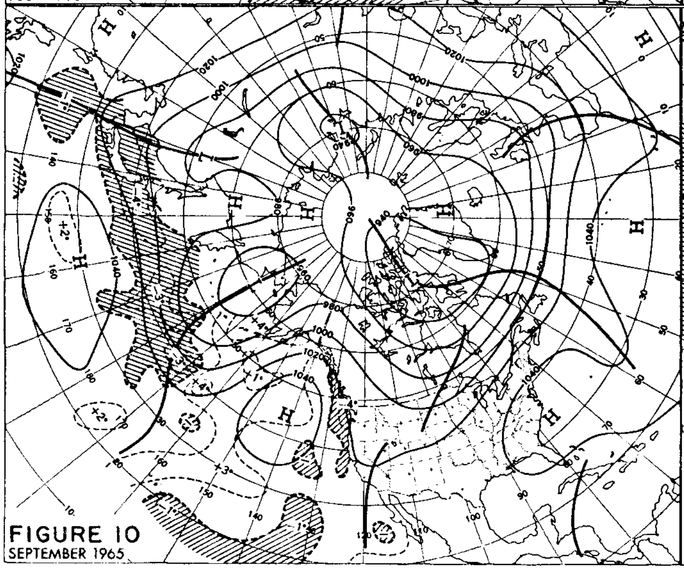
FIGURE 10
SEPTEMBER 1965

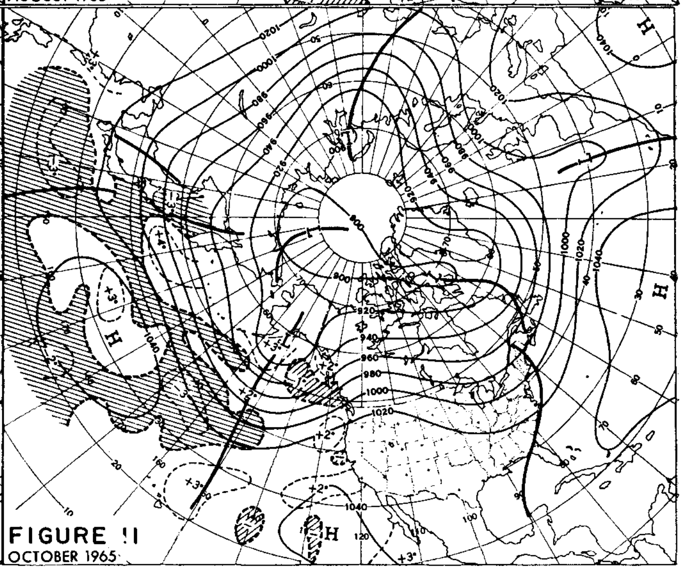
FIGURE 11
OCTOBER 1965

Figure 8. Mean 700-mb contours for July 1965. Heavy lines running roughly North-South are major trough positions. Broken lines are isopleths of sea-surface temperature departure from normal drawn for each 2°F.

Figure 9. Same as figure 8 but for August 1965.

Figure 10. Same as figure 8 but for September 1965.

Figure 11. Same as figure 8 but for October 1965.

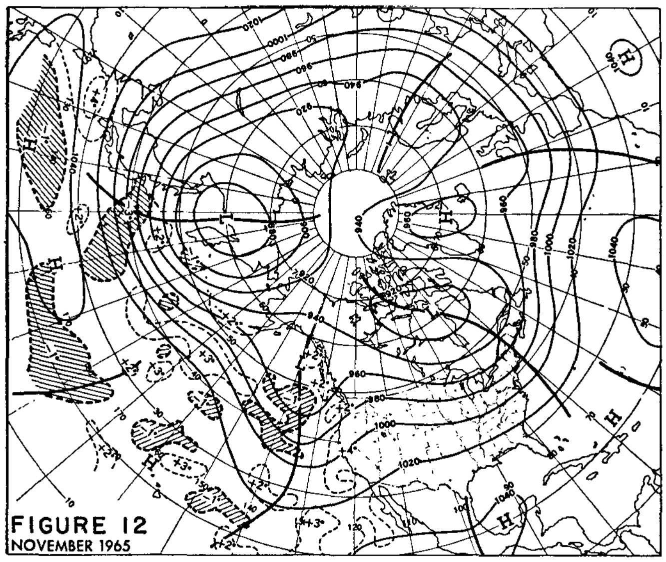

Figure 12. Same as figure 8 but for November 1965.

perature deviations from normal.* At first let us consider only the evolution of the contour field over the North Pacific and adjacent continental areas.

In July a trough (solid heavy line) extended southward from Kamchatka, roughly along longitude 155° East. In the subsequent months up to November, this trough advanced slowly eastward so as to have arrived near the West Coast in November. In addition to advancing eastward some 70° of longitude, the trough increased in amplitude, most abruptly between August and September. Associated with the moving trough are families of cyclones (not shown) more or less like these in the schematic diagram shown in Figure 1. The cyclones, generated in and to the east of the trough, are the principal mechanisms for release of precipitation—such as that falling on southern California in November.

The question arises as to how such regular trough motion might be accounted for, and here we will briefly restate the theory proposed in the 1958 report (Namias, 1959). With seasonal progression from July into late summer, fall, and early winter, there are two climatologically probable and in fact dependable, changes in the general circulation in the vicinity of Asia and over the western Pacific. As the Asiatic monsoon anticyclone develops over the continent and the contrast between air coming from this anticyclone and air overlying the warm water strengthens, a series of cyclones of increasing frequency and intensity move along and off the Asiatic Coast and an associated upper-level trough "locks-in" somewhere in the vicinity of the Asiatic coastal region, within a narrow range of longitudes (perhaps 20 degrees). As the cyclones move northeastward and intensify they carry momentum into the prevailing westerlies, and the strength of the westerlies is thereby increased over the western Pacific. Now it is well known from the early work of Rossby (1939) that the stationary wavelength between troughs is proportional to the square root of the zonal wind velocity flowing between them. Therefore, as the Asiatic trough locked in somewhere along the Asiatic Coast in 1965 and the westerlies increased, stationary wavelength considerations demanded that the trough to its east move progressively eastward. Support for the above-described mechanism is shown in Figure 13, where the square root of the zonal velocity between the two troughs is plotted against the observed wavelength for each month from July through November 1965. From this figure it is seen that the wavelength increase (at 45°N) was from 30° in July to about 80° in November while the zonal velocity increased from about 4 meters per second in July to 13 meters per second in November.

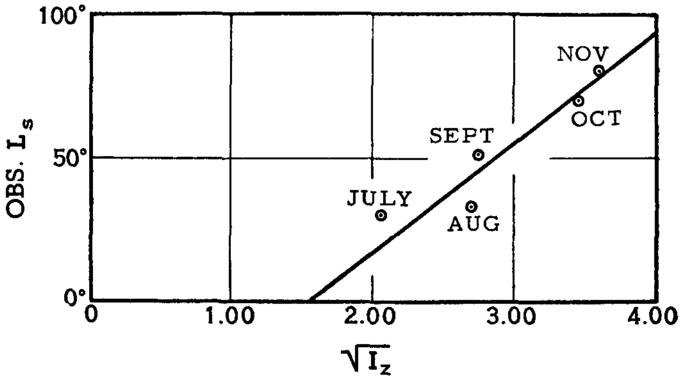

Figure 13. Relation between square root of zonal velocity between Asiatic coastal trough and next downstream trough and wavelength between troughs for months of July through November 1965. Zonal index is measured between latitudes 35° and 55°N and wavelength between troughs is measured at 45°N.

From Figures 8 to 12 and 13 it will be noted that while the distance between the Asiatic Coast trough and the Pacific trough increased some 50°, the latter trough actually moved 70° from the initial position south of Kamchatka in July. The additional 20 degrees was associated with eastward migration of the Asiatic coastal trough. This is also a climatologically frequent event associated with development of the Asiatic High. The eastward motion of families of cyclonic storms was sufficiently pronounced during this 5-month period that the mean Aleutian Low at sea level could be followed from off Kamchatka in August to off Vancouver in November, as indicated by the inset diagram in Figure 14.

The question next arises as to why a migrating trough of this kind possessed such longevity and why its abnormally large amplitude continued from September on. In the following discussion one must always bear in mind the fact that air-sea interactions vary with season and geographical location.

We cannot attempt to explain why a trough appeared south of Kamchatka in July without treating events both in the sea and the atmosphere leading up to July. It is conceivable, however, that the cold water off Japan and south of Kamchatka in July and

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*The eastern Pacific sea-surface temperature departures have been taken from the maps of the Bureau of Commercial Fisheries, while those over the western Pacific are from the Japanese Meteorological Agency.

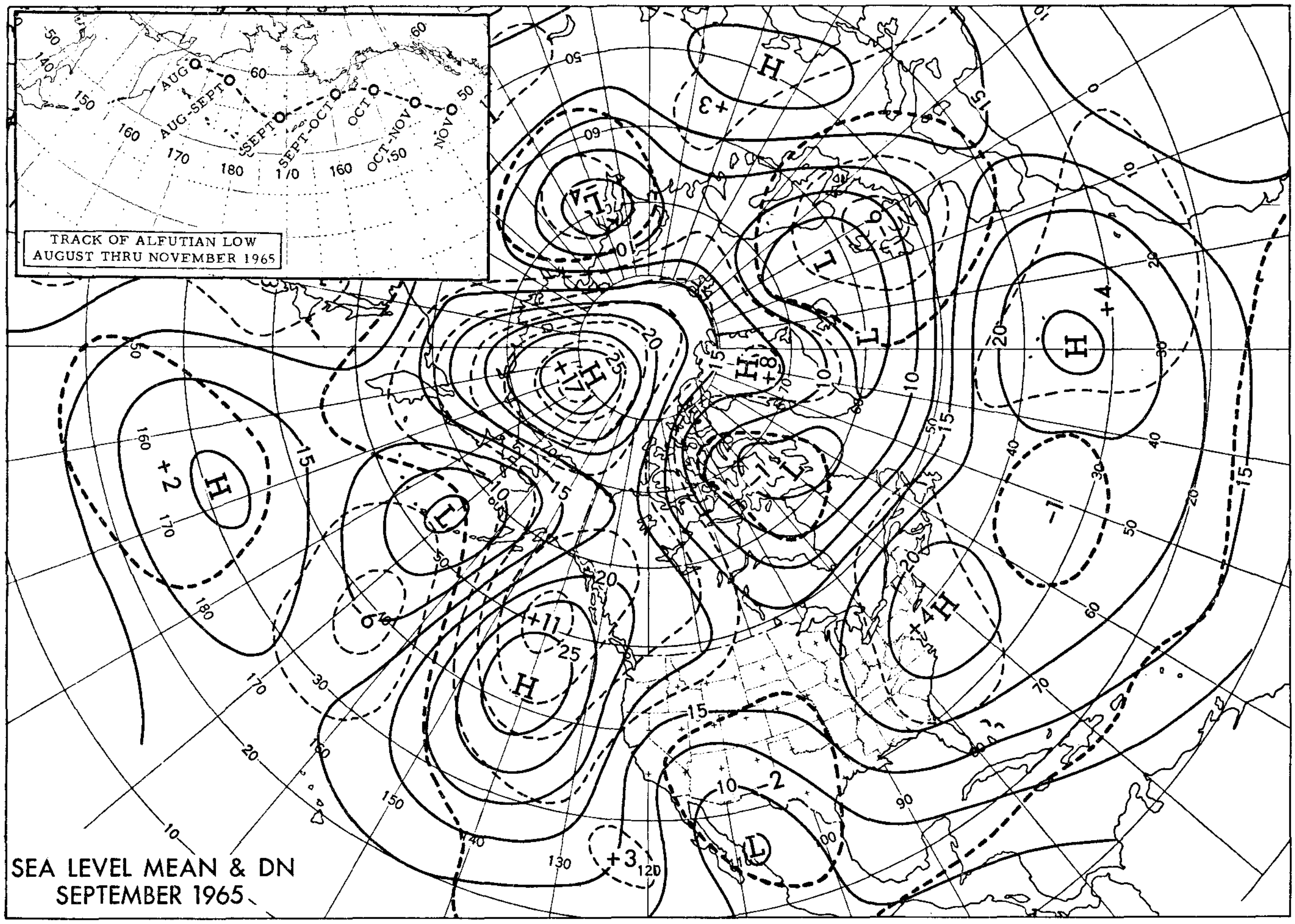

Figure 14. Mean sea-level isobars for September 1965 and isopleths of anomaly (broken) for September 1965. Numbers represent centers of maximum positive and negative departures from normal. Isopleth for zero departure is indicated as heavy broken line.
Inset: Track of Aleutian Low center for 30-day periods from August through November 1965.

August (Figs. 8 and 9) had something to do with generating this trough, because during mid-summer the East coast of the Asiatic continent is appreciably warmer than the sea and colder-than-normal water would tend to create an accentuated thermal gradient in the atmosphere favoring upper-air troughs in this area. Frequent cyclones were steered into this trough area (charts not reproduced) and, because of the associated increased cloudiness, upwelling and water stirring would maintain the cold water mass. Note that in August a strong temperature contrast existed between this cold pool and warmer-than-normal water in the central Pacific. As the locus of the mean trough changed so as to appear over this area of contrasting water temperature, its intensity was sharply increased as shown by the increased cyclonic curvature of the contours and also increased amplitude. This increase was probably associated with the increased vigor of cyclonic activity introduced by contrasting air masses in the vicinity of the trough, for these air masses receive a large share of their heat from the surface water. The increase in intensity in the ridge to the east (along 140° West) from August to September (Figure 10) is largely an inertial (barotropic) response to the central Pacific trough, as is the trough over the western United States. The latter trough-ridge complex resulted in the deployment of very cold air masses into the far west in September.

Note the change of water temperature in the Gulf of Alaska from below normal in August to above normal in September. This anomalous warming appears to be a result of advection of warm water from more southerly latitudes, less sensible and latent heat extraction from the water as prevailing winds shifted and brought warmer southerly air currents over the Gulf, and less upwelling associated with the anticyclogenesis. Note also the generation of a pool of cooler-than-normal water just off the west coast with greater upwelling engendered by increased northerly flow. The above-described wind regime in September is perhaps more clearly illustrated with the help of sea-level pressure distribution and its anomalies for September as shown in Figure 14.

By October, when the trough moved eastward to 150°W, cold water was formed just to the west of the trough and the sharp change in prevailing winds off the West Coast resulted in a dramatic warming of the surface water with respect to normal (Figure 11). As the western ridge moved into the plateau, foehn winds (Santa Anas) along the West Coast led to a protracted heat wave. With further eastward motion of the trough to an area just off the West Coast in November (Figure 12), the stage was set for the heavy rains in California, which continued into the first half of December. Since most people in this audience experienced these rains and have probably read many newspaper accounts, I need not bore you with the rainfall statistics.

Thus, the abnormal weather in California, the associated appearance and disappearance of the Pacific anticyclone, and many other phenomena relating to North Pacific ocean weather in the last half of 1965 appear to have their instigation in the coupled ocean-atmosphere continent system and the forcing influence imposed by changes in the radiation balance associated with change of season.

FALL WATER TEMPERATURES AS A POSSIBLE CAUSE OF WINTER ABNORMALITIES

Because of the vast reservoir of heat which may be established in the ocean during summer and fall, it is possible for the overlying atmospheric circulation to become greatly affected in the subsequent winter. This may arise because the climatologically determined position of the prevailing westerlies and storm tracks change materially between summer and winter. Thus, over the North Pacific, the great Pacific anticyclone dominates much of the area during summer, and cyclonic activity is usually restricted to areas off Kamchatka and north of the Aleutians. In the winter, on the other hand, as the Asiatic monsoon anticylcone develops, cyclones form and intensify as they move northeastward off the Asiatic Coast, and as the westerlies progress southward, various air mass and frontal interactions occur over the central and North Pacific which are weak or often absent during summer. The normal condition during winter is one in which cold air masses over the Asiatic Continent contribute to cyclonic intensification over the open warm ocean to the east. Diabatic heating of these air masses usually contributes to the growth rate of cyclones over the open sea. If, therefore, a large pool of warmer-than-normal water has developed in the path of the migratory fronts and cyclones, it is likely that cyclonic growth will be more rapid than normal. Furthermore, the greater-than-normal rate of growth of the cyclones may provide a further means of inducing more cold air from the north and from Asia, thereby reintensifying the cyclogenetic process. While the above ideas require much more research to prove and implement, some preliminary empirical-synoptic studies have indicated that they do have substance.

Thus, in the summer and fall of 1962 a vast pool of warm water was generated in the central Pacific, particularly between latitudes 30° and 40°N as indicated by the hatched areas in Figure 15. It appears that this warm pool developed in the preceding summer and fall because of greater-than-normal anticyclonic domination over the area, leading to lighter-than-normal winds, less-than-normal cloudiness, and more-than-normal horizontal convergence of surface water. These factors led to less transfer of latent and

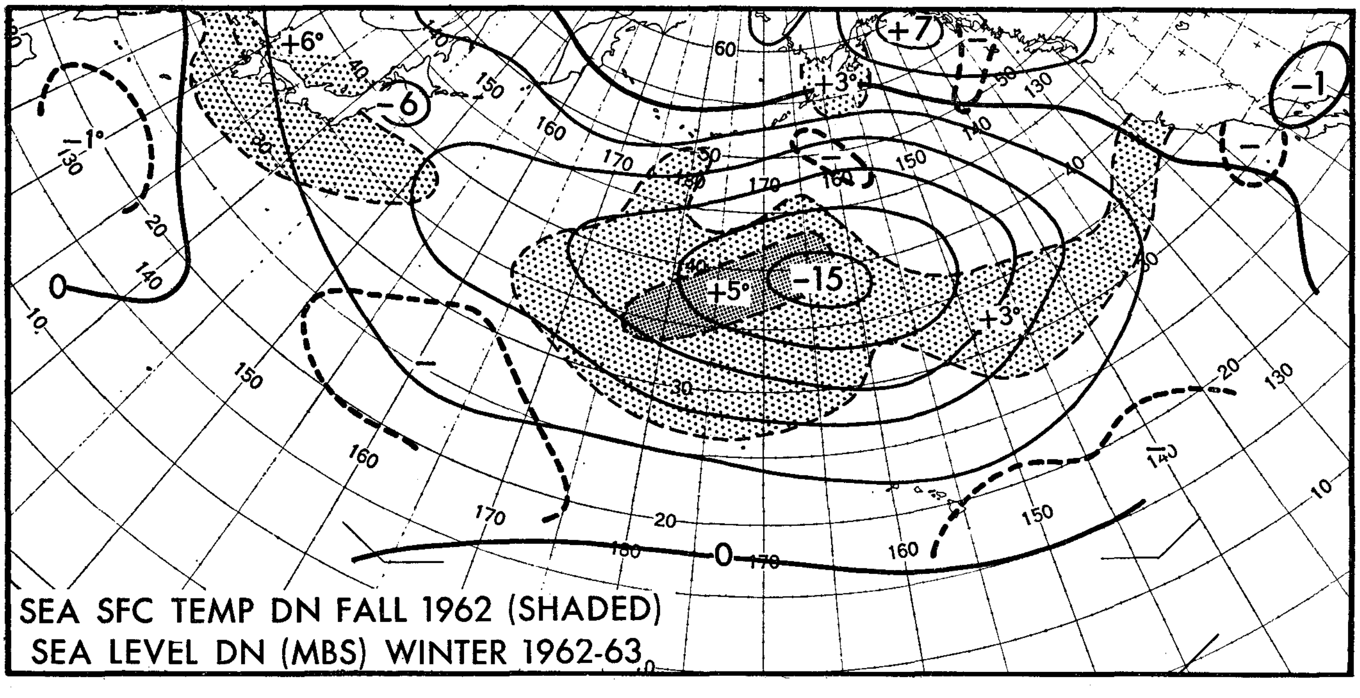

Figure 15. Warm pool of surface water observed during fall (September, October, November) 1962. Stippling indicates areas greater than 2°F above normal while heavy hatched areas indicate temperatures greater than 4°F above normal. Solid lines are isopeths of sea-level pressure from normal drawn for each 2 mbs; —15 at center indicates departure of 15 mbs below normal wintertime value.

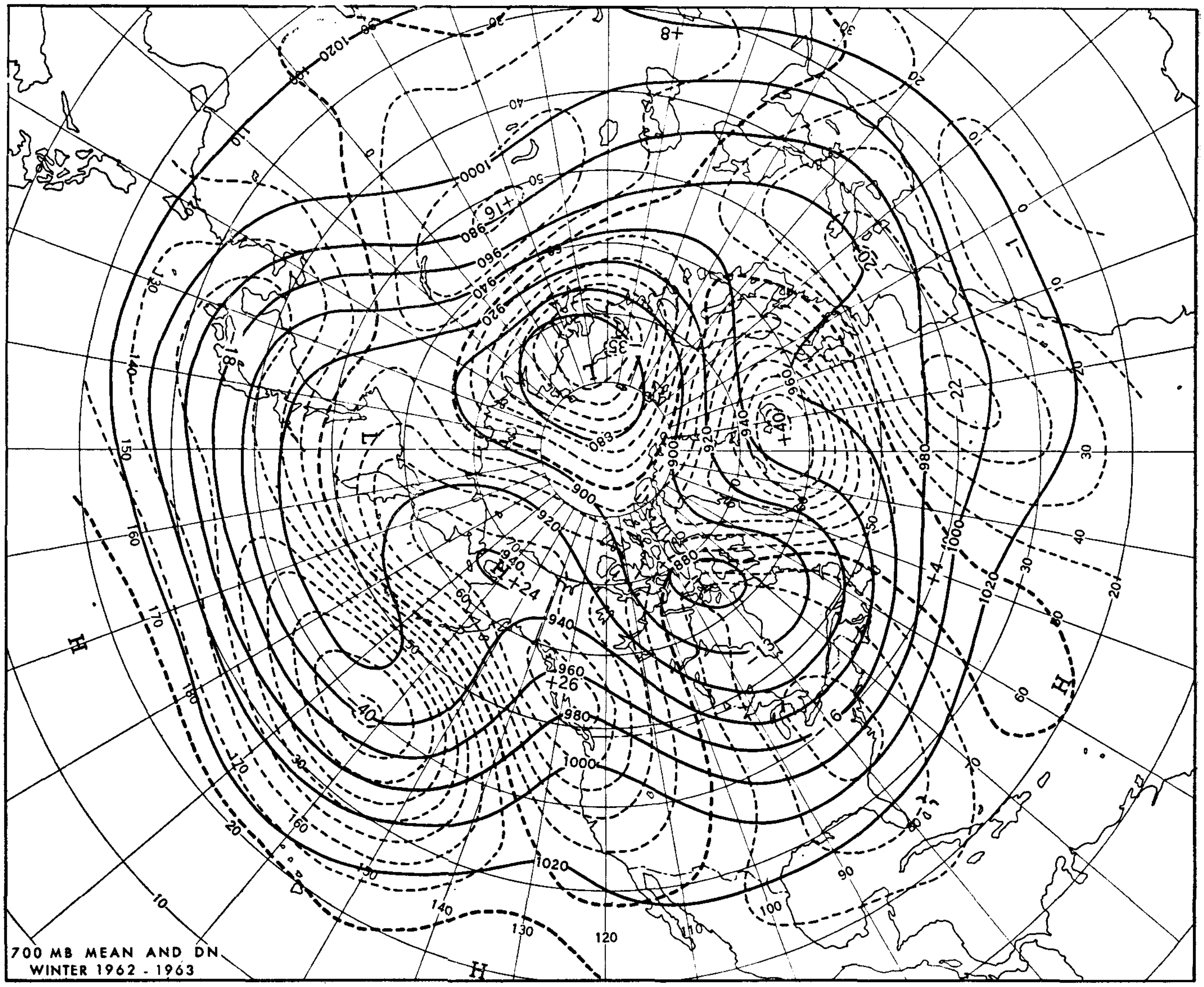

Figure 16. Mean 700-mb contours (solid) and isopleths of anomaly (broken) (both in tens of feet) for winter (December, January, February) 1962–1963.

sensible heat to the air, to diminished upwelling and to the development of a warm surface mass. As cyclones developed off Japan and the cold air masses behind them swept eastward, this warm pool seems to have been responsible for intensifying these storms materially and therefore forcing the Aleutian Low much farther south than normal. The winter departures from normal of sea level pressure shown in Figure 15 up to —15 mbs, appear to be situated near the fall warm pool and oriented like it. In Figure 16 is reproduced a map of the upper-level contours and isopleths of anomaly for the winter of 1962–63. This is taken from a paper (Namias, 1963) which treats the 1962–63 winter and the wide-scale air-sea interaction in some detail. The departures from normal over the eastern Pacific (—15 mbs at sea level and —400 ft. at 700 mbs) are almost 3 times the standard deviation of seasonal values of winters in the historical record. The negative anomalies associated with the strong cyclonic curvature aloft shown in Figure 16 undoubtedly played an important part in amplifying the ridge along the west coast of North America and into Alaska. This reaction is an inertial effect caused by redistribution of the vorticity generated by the strong trough in mid-Pacific. In turn, the strong western North American ridge repeatedly deployed cold Arctic air masses into the eastern two-thirds of the United States and also, through redistribution of vorticity, helped create the trough observed in the eastern United States during winter. This trough, however, was so placed as to generate a strong air temperature contrast between the eastern half of the United States and the adjacent waters of the Gulf of Mexico and western Atlantic. The cyclonic wave disturbances generated along the polar front separating these contrasting air masses then were afforded a favorable environment for abnormally fast growth. Firstly, they were situated in an area associated with an upper-level trough, and secondly, they could draw upon the potential energy provided by the enhanced horizontal temperature contrast. In addition, the contrast between the coastal area and the off-shore waters was further aggravated by frequent snows (rather than rains) along the Atlantic seaboard, since Arctic air infiltrated the cyclones. It is quite possible that the fast-occluding disturbances along the eastern seaboard during this winter set up conditions favoring a blocking mechanism in the eastern Atlantic—that is, relatively high pressure near Iceland and low pressure in the Azores and Mediterranean. This latter condition was associated with one of the most severe winters ever recorded over much of Europe. It is interesting to note that this prevailing wind distribution over Europe led to the westward penetration of cold continental air masses from Siberia, and consequently an unusual snow blanket was provided for much of Western Europe. By increasing the surface albedo, the snow acted to refrigerate the cold air. When this very cold air was fed into Mediterranean storms, an additional stimulus was provided to the usual atmospheric heating over the warm sea. The extra storm intensification resulted in further westward transport of the cold air to the north, and heavier snow.

Thus, during the abnormal winter of 1962–63 a remarkably steady and highly abnormal circulation and weather pattern dominated the Northern Hemisphere. Perhaps the warm pool in the North Pacific played a vital role in instigating this pattern, although it is clear that developments in other areas must have cooperated and thus reinforced the instigated pattern; that is, positive feedback loops may have been generated to provide sustained weather abnormalities. Another example illustrating the probable effect of a warm pool of water in the Pacific in displacing the Aleutian Low southward came to light during the winter of 1964–65, although the displacement was not nearly as pronounced as during the winter of 1962–63.

NUMERICAL PHYSICAL OBJECTIVES

The above treatment, admittedly sketchy, is designed to suggest causal factors which may help to explain short-period climatic fluctuations of the order of months, seasons, and up to a few years. The evidence for these factors up to now has been more or less circumstantial, and quantitative procedures must be devised to test and expand upon these ideas. Therefore, it is especially important that theoreticians in both oceanography and meteorology work closely with empiricists. If collaboration does not take place, it is difficult to see how either group can succeed in unraveling the tangled skeins of such interdisciplinary problems.

The first dynamic and thermodynamic studies of this kind have involved simplified numerical models, the aims of which have been to answer the question of how solar energy is ultimately utilized and how the atmosphere and ocean respond in order to transfer heat most efficiently. A great deal of reasonably successful work has been completed within the U.S. Weather Bureau (Smogorinsky et al., 1965; Manabe et al., 1965; Adem, 1964) and by some of the meteorological research organizations in this country. This research has thrown light on the primary mechanisms in the atmosphere which give it its characteristic time and space scales and also on the variability of these scales.

The next question to be answered involves the details of the atmospheric and oceanic evolutions, details involving such matters as variations in the location and intensity of storm tracks, the regional variations in heat supplied to and taken from the water, variations in the snow and ice cover over the continents and northern oceans, and the like. Unfortunately, these "details" may require something approaching exact knowledge of such elusive physical processes as release of latent heat, momentum and water vapor exchange, internal turbulent exchange, radiative transfers, and in fact the entire gamut of meteorological processes—to say nothing of complex oceanic processes. It is possible that some of these air and sea processes can be omitted or perhaps greatly simplified for certain predictions. On the other hand, there is no guarantee that a completely physical solution will be found, and for this reason alone the empirical approach must proceed. Besides, it appears likely that as with short-range numerical forecasts, empirical knowledge will be necessary in making optimum practical use of any physically-based long-range forecasting model.

In recent years, attempts have been made in the Extended Forecast Division of the Weather Bureau, particularly by Adem (1964) to formulate a numerical prediction model for periods of a month or a season. The basic equations used are those of conservation of thermal energy at the surface of the earth and in the mid-troposphere. The model predicts the anomalies of temperature of the underlying surface and in the mid-troposphere. Besides radiation, other forms of heating are generated within the model. This is done by expressing such heating as a linear function of variables predicted in the model.

The anomalies directly incorporated are those in the storage of thermal energy, which are introduced by using the previous month's temperature of the surface water in the ocean and the temperature of the mid-troposphere, and by calculating from the observed albedo (snow cover) at the end of that month, the anomalies in the short-wave radiation absorbed by the surface.

The numerical experiments show that important anomalies of evaporation at the surface, vertical turbulent transport of sensible heat from the surface, condensation of water vapor in the clouds and cloudiness are implied by anomalies of the computed temperature fields. Furthermore, these induced anomalies of the heating function and of the cloudiness in turn imply changes in the anomalies of the computed temperature fields.

Numerical experiments are also carried out to test the possibility of using satellite data in this model.

Despite the frightening complexity of such a program, there are reasons for optimism at this point. In the first place, there are now greater and improved sources of data in the world (including satellite measurements) and steps are being taken to press forward with a still greater implementation of data collection through establishment of the World Weather Watch. Secondly, fast and economical methods for processing these data and doing statistical and physical computations are now at hand. Thirdly, there is now better understanding of the dynamics of the general circulations of the atmosphere and the oceans. Finally, there is a new generation of young meteorologists and oceanographers well versed in physics, mathematics, and electronic computing. One of the tasks of the more senior meteorologists and oceanographers is to acquaint these young men with the real problems of long-period atmospheric and oceanic behavior in the hope that they may be able to apply their talents and achieve greater successes with long-period air and sea prediction than earlier generations could.

DISCUSSION

Schaefer: The recent 1965 meteorological and surface-temperature regime is possibly similar to that in 1957, and also the sea temperature off Peru seems to be following a similar development. It is possible, therefore, that we have an "El Niño" developing similar to 1957–59, and we would hope this time to get a better understanding, through the series of oceanographic sections which are being taken every three months along the coast from Panama to central Peru. We would also hope that we would all follow the development in the North and South Pacific, and, if we get an abnormal year, bend every effort to studying it in more detail than previously.

With limited time series, one can always find empirical correlation which may not reflect real relationships, if enough things are tried. The more complex the set of observations, the greater the chance of the computer, told only to try empirically to find relationships that explain the observed data, coming up with apparently higher significant, but actually spurious correlations. (The test is, of course, how well the prediction works for additional future observations.) The fisheries people have fallen into this trap a number of times.

Laevastu: Most properties of ocean surface layers, including sea-surface temperature anomalies, can be computed from meteorological analyses. In fact such quantitative computations of interactions form the bases of synoptic oceanographic analyses/forecasts at FNWF. However, the influence of sea-surface temperature anomalies on the atmosphere is very difficult to assess quantitatively. A moderate anomaly of sea-surface temperature would have the effect of small North-South displacement of sea-surface isotherms or be the equivalent of a slight difference of actual direction of surface wind with reference to the direction of sea-surface isotherm. The latter condition is one of the important factors determining the energy exchange, but changes rapidly on synoptic scale, thus diminishing the possible effects of sea-surface temperature anomalies.

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