SEA LEVEL DEPARTURES ON THE CALIFORNIA COAST AS RELATED TO THE DYNAMICS OF THE ATMOSPHERE OVER THE NORTH PACIFIC OCEAN

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Considerable attention is being directed at the present time toward fluctuations in sea level as related to the dynamics of the oceans and, to a lesser degree, the dynamics of the atmosphere. Most of the work along these lines, however, has been concerned with seasonal rather than non-periodic variations. Nevertheless, an analysis of sea level data compiled over a period of many years at four California tidal stations indicates that non-periodic fluctuations of considerable magnitude also occur. Since these fluctuations are probably the direct or indirect result of variations in certain meteorological elements, it becomes of interest to investigate the nature of those atmospheric changes that occur simultaneously with changes in sea level.

A preliminary examination of the problem indicated that the sea level variations might be divided into two classes; i. e., (1) local variations of short duration and (2) widespread variations of long duration. The short period variations may be limited to one or two stations on the Pacific coast and are undoubtedly due to local changes in the oceanic circulation. The second class of departures will include those variations of longer duration which appear to affect all stations on the coast. It was soon discovered that it would be impossible to isolate the meteorological factor in the short period local variations by means of the small quantity of oceanographic and meteorological data available due to the complicated pattern of the oceanic circulation in the region immediately off the coast. The widespread fluctuations, however, appear to be due to major changes in the ocean currents over the North Pacific and analyses of mean monthly or seasonal sea level and meteorological data have given positive evidence of a very close relationship between atmosphere and ocean.

Any exhaustive analysis of the relationships between ocean and atmosphere requires complete and accurate data from significant areas of the ocean surface. Unfortunately, both the oceanographic and meteorological data from the North Pacific are very meager and of doubtful accuracy,

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therefore any critical analysis of the problem in quantitative terms is impossible. By the proper selection of mean monthly data when sea level departures are significant, however, it is possible to illustrate some of the more salient features of the atmospheric-oceanic machine.

LaFond (1939) attributes practically all the variations in sea level at these same tidal stations to changes in the density of shore waters above the 500 decibar level and assumes that these changes, themselves, are brought about by alterations in the flow pattern of ocean currents along the immediate coast. Nomitsu and Okamoto (1927) similarly conclude that meteorological changes are of secondary importance when considering sea level departures on the Japanese coasts and endeavor to show that differences in the density of surface waters are primary. Montgomery (1938), working with tidal data from the western North Atlantic, assumes that the major departures in sea level along the Atlantic coast are caused by variations in ocean currents. Palmén (1932), in his study of short period sea level fluctuations in the Baltic, has assumed that the departures are largely caused by local winds (*Windstau*) and has divided these effects into two classes: the component in the direction of the wind or the pure mechanical wind effect (*Windeffekt*), and the component at right angles to the wind or stream-effect (*Strömeffekt*). The present paper is concerned primarily with the *Strömeffekt* since this process is more than purely local and should appear over large areas whereas the *Windeffekt* would probably not appear in the mean monthly sea level data available.

The very fact that sea level departures are so easily accounted for by changes in the density of surface waters would lead us to suspect that these changes are probably directly related to changes in wind currents over ocean surfaces and, as a result, any series of data which shows a relationship between density (or temperature/ or salinity) and sea level is *sui generis* including meteorological effects.

HYDROSTATIC EFFECT OF ATMOSPHERIC PRESSURE

If the sea surface is in a state of static equilibrium with respect to the atmosphere, any change in atmospheric pressure will result in a change of sea level. That is, sea level will be lower with a high barometer and higher with a low barometer. If the departures in atmospheric pressure are measured in inches or millimeters of mercury then the corresponding departures in sea level similarly expressed will bear the ratio 1 : 13.2. Practically all the values of the pressure factor assigned by various investigators approach this figure, although they may be greater or less in partially enclosed seas or bays.

Since the hydrostatic effect appears only when a pressure gradient exists, departures in pressure at any individual station can be used only in a qualitative sense but they may be valid if such departures accurately represent numerically equivalent changes in pressure gradient. All of the works examined by the writer have applied an arbitrary correction to the sea level data based upon pressure departures at some one coastal station. A consideration of pressure gradients has been neglected in all cases.

Mean sea level and mean atmospheric pressure for all months of May, 1923–36, are presented in Fig. 59. These data indicate good qualitative

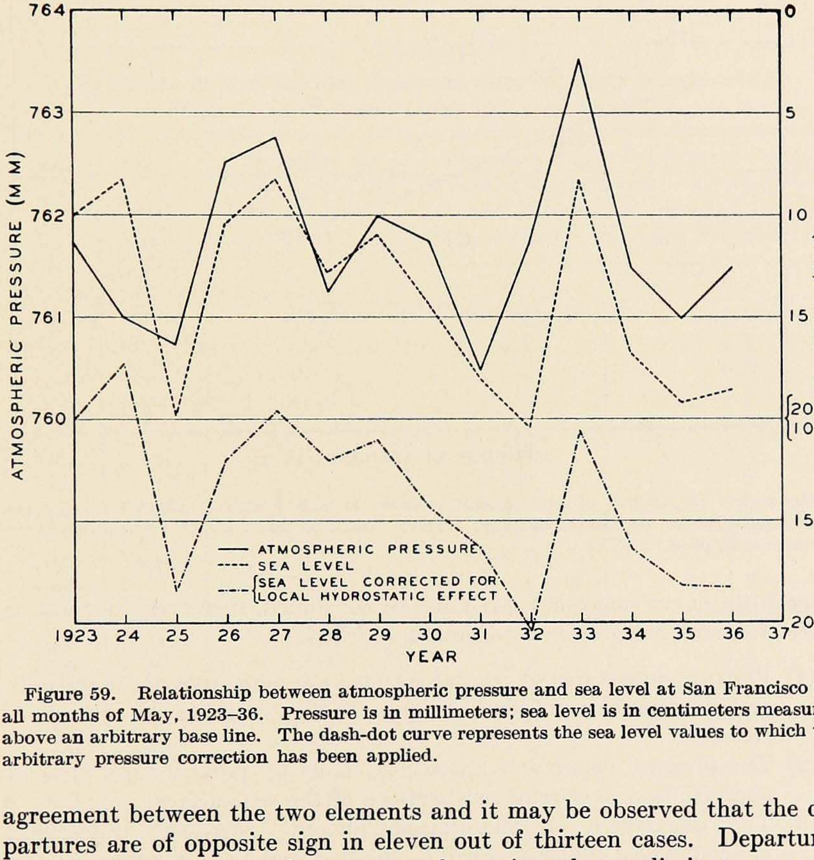

Figure 59. Relationship between atmospheric pressure and sea level at San Francisco for all months of May, 1923–36. Pressure is in millimeters; sea level is in centimeters measured above an arbitrary base line. The dash-dot curve represents the sea level values to which the arbitrary pressure correction has been applied.

agreement between the two elements and it may be observed that the departures are of opposite sign in eleven out of thirteen cases. Departures for a single month in each year were chosen in order to eliminate seasonal effects. The series illustrated was selected at random but other months show the same relationship although it is not so marked during the fall and winter months when the oceanographic and meteorological picture of the North Pacific is considerably more complicated than during the spring and summer months. As shown in Figure 60, however, the actual numerical departures are highly irregular and the sea level variations far too large to be accounted for by local hydrostatic effects alone. In fact, as illustrated in Figure 59, the sea level data show practically the same variations after the hydrostatic correction has been applied, the process merely serving to

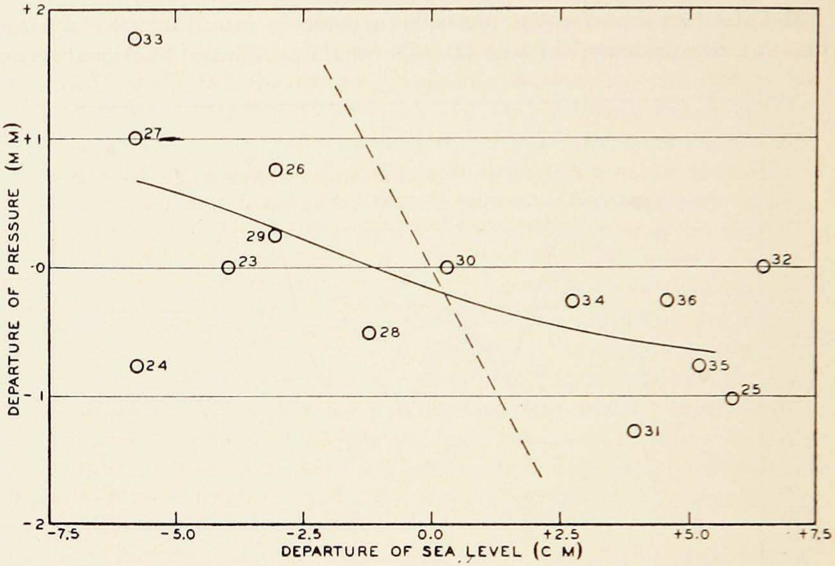

Figure 60. Departures of atmospheric pressure at San Francisco plotted against sea level departures for all months of May, 1923–36. Dashed line represents the pressure departures multiplied by 13.2.

smooth the curve somewhat. It must be concluded, therefore, that one or more of the following three conditions is satisfied:

(1) Pressure departures at coastal stations are indicative of numerically greater departures of similar sign over the sea along the immediate coast.

(2) The pressure departures are accompanied by greater departures of opposite sign over removed portions of the sea surface.

(3) The departures in atmospheric pressure represent widespread meteorological changes which, themselves, serve to alter the dynamic picture of the ocean.

First, with respect to (1). In order to study the monthly pressure departures over the eastern North Pacific, a series of maps was constructed showing mean atmospheric pressure for twenty months when sea level departures at coastal stations were significant. The data were obtained from the synoptic charts prepared twice daily at the U. S. Weather Bureau in San Diego. Analysis of these maps indicates that departures in atmospheric pressure at coastal stations are usually accompanied by greater departures of similar sign over the sea off the coast but the relationship, quantitatively, appears to be very irregular.

Data for San Francisco are presented in Table I. These figures show that departures in pressure at San Francisco were accompanied by departures of similar sign in the region off the coast to longitude 140° W. in 75% of the

TABLE I

Departure of Atmospheric Pressure from Monthly Means at San Francisco and over Pacific to Latitude 140° W.

Year	*Month*	*Departure of Pressure at San Francisco (mm)*	*Departure of Pressure Between Lat. 140° W. and Coast (mm)*	*Departure of Pressure Gradient from Normal Between Lat. 140° W. and San Francisco (mm)*
1931	Feb.	−2.3	−1.3	+2.5
1933	"	+2.8	+4.8	+3.0
1933	Apr.	−1.3	+3.0	+6.4
1934	"	−1.0	−1.5	0.0
1935	"	−2.0	−3.6	−0.8
1936	"	+0.2	−2.0	−1.5
1933	May	+1.8	+2.3	+0.5
1934	"	−0.4	−1.0	−1.8
1930	June	−0.1	+2.3	+3.8
1933	"	+0.5	+3.3	+3.0
1930	Aug.	+1.5	−0.5	−4.1
1933	"	−0.5	−0.8	−1.3
1936	"	−0.2	−0.2	−1.0
1930	Oct.	−1.0	−2.0	−2.0
1933	"	−0.8	−2.3	−1.5
1930	Nov.	−0.5	+0.8	+1.5
1933	"	+1.0	+3.6	+2.8
1930	Dec.	+1.3	+1.0	+0.2
1931	"	−2.0	−3.6	−0.5
1933	"	−0.2	−3.6	−5.3

cases examined, and in 80% of these cases the departures off the coast were numerically greater than at San Francisco. These differences are too slight, however, to account for any significant proportion of the effects illustrated in Figure 59.

With respect to (2), i. e., are pressure departures at coastal stations accompanied by significant departures of opposite sign over removed portions of the sea surface? Any departure in atmospheric pressure, of course, demands corresponding departures of opposite sign over other areas, the problem here being one of regional adjustments within areas where hydrostatic displacements of the sea surface are possible. Clayton (1938) has recently shown that regional adjustments in pressure do not follow any known set law and that the *baroplions* and *baromions*[1] over the ocean appear to be entirely independent of the intensities or locations of the centers of the pressure fields with which they are associated. Analysis of pressure data at permanent stations on the North Pacific by the writer appears to bear out this conclusion. The pressure departures at San Francisco were first compared with corresponding departures at stations on the Asiatic coast of the Pacific. Although there was slight evidence that departures in the two areas tended to be of opposite sign, the data were not conclusive. A good agreement would not be expected, however, in view of the fact that the two areas are most frequently under the influence of entirely different atmospheric-dynamic systems. Mean monthly pressures at San Francisco and Honolulu were then compared but with the same results. In the latter case the departures were of the same sign in approximately the same number of cases as of opposite sign.

A comparison of mean monthly pressures at Mazatlan, Mexico (lat. 23° N.) and Honolulu (lat. 21° N.), however, indicated somewhat better correspondence. Even though the pressure departures at these stations were usually of small magnitude, it was interesting to discover that the departures were of similar sign in only twenty out of eighty months examined. The relationship was particularly outstanding during several seasons when the pressure departures at either station were particularly significant.

None of the data examined appear particularly conclusive from either point of view and the most that can be said is that local pressure departures do not imply significant departures of opposite sign within small areas where hydrostatic adjustments in sea level are possible. This fact is of little importance, however, since the total pressure departures are invariably small and not of the proper order of magnitude to account for the departures in sea level.

The evidence so far presented appears to indicate that the hydrostatic effects of pressure are relatively non-important. It must be concluded that the sea level departures that occur simultaneously with departures of atmospheric pressure are largely manifestations of significant meteorological changes over the ocean. Since no appreciable flow of surface waters can take place due to slopes produced through the hydrostatic deformation, it must be assumed that the meteorological effects are largely those of winds on ocean currents.

[1] Areas of plus departures and minus departures, respectively.

DYNAMICS OF THE ATMOSPHERE AS RELATED TO SEA LEVEL

Mean monthly wind data for the North Pacific are not available for detailed analyses of the effects of wind on ocean currents and sea level but it is possible to compute mean wind velocities for individual months from the pressure maps previously described. Winds thus computed from the pressure gradient are more consistent, easier to handle and probably as correct as those based on Beaufort estimates. This is particularly true when a few widely separated ships are available; it is possible to accurately define a pressure system with comparatively few reports but many reports are necessary to define the wind system with the same degree of accuracy.

Since neither wind velocity nor the resulting water transport due to these winds vary linearly with respect to pressure gradients, nor to one another, any close quantitative relationship between mean monthly pressure gradients and sea level would not be expected. Nevertheless, since the twenty maps have been prepared for months when sea level departures were greatest, it would be expected that the pressure departures would be equally outstanding and would thereby serve to give a qualitative picture of the major wind effects.

A cursory examination of these maps at once shows that sea level at the four tide stations is below normal when the high pressure field over the North Pacific is best developed or displaced toward the coast, and above normal when the system is weak or displaced toward the south or west. This relationship is particularly outstanding during the spring and summer months when the Pacific high pressure system is dominant and the short-period meteorological changes of small magnitude. The relationship is not always so apparent during the fall and winter months when the atmospheric-dynamic system is considerably more complicated. Three maps prepared for December months do not show this relationship between pressure and sea level to any degree but it may be remarked that the meteorological changes during the periods under consideration were so great and so rapid that it was impossible to construct reasonable mean pressure maps for these months.

Data regarding the pressure gradients measured between longitude 140° W. and San Francisco are given in Table I. It may be noted that the sign of the departure of pressure gradient differs from the sign of the departure of mean monthly pressure over the same area in only one case of the twenty (Feb. 1931). Thus, when the mean atmospheric pressure along the coast is high, the pressure gradient is relatively large; when pressures are low, the pressure gradients off the coast are small. The good agreement between the mean pressure at San Francisco and sea level illustrated in Figure 59 is immediately explained and the suggested condition (3), (p. 184) apparently satisfied.

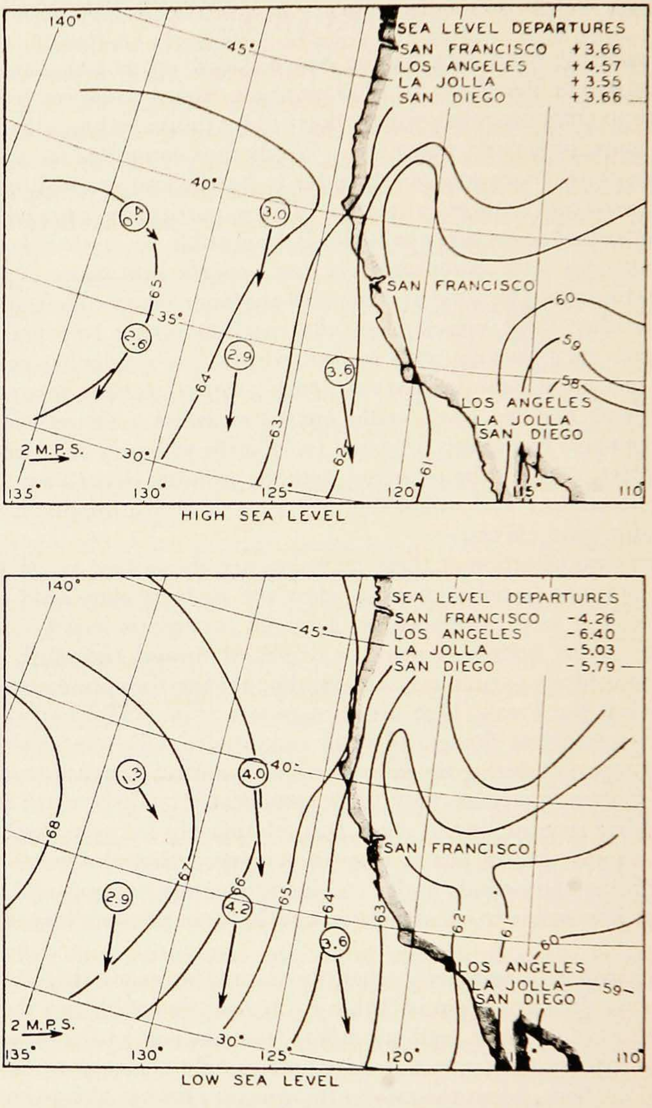

Figure 61. Composite maps of the pressure distribution over the Eastern North Pacific Ocean for periods of high sea level (above) and low sea level (below). The pressures are in millimeters; the sea level departures entered in the circles are in centimeters. The resultant northerly component of the wind in meters per second is entered in the circles on the wind arrows. Seasonal effects have been eliminated through the selection of data, i. e., an equal number of each of the calendar months appear in each of the maps.

Composite maps for all months with high and with low sea level are shown in Figure 61. Seasonal effects have been eliminated through the selection of data. These maps are typical of most of those in the series with the exceptions of the three months mentioned previously. The surface winds computed from the illustrated pressure fields parallel the coast in the cases of both maps but the map showing the lower sea level values at the four coastal stations presents the highest velocities. The surface winds computed on the basis of the pressure distribution have been multiplied by the factor 0.62 (Rossby, 1936) but this factor may be somewhat in error because

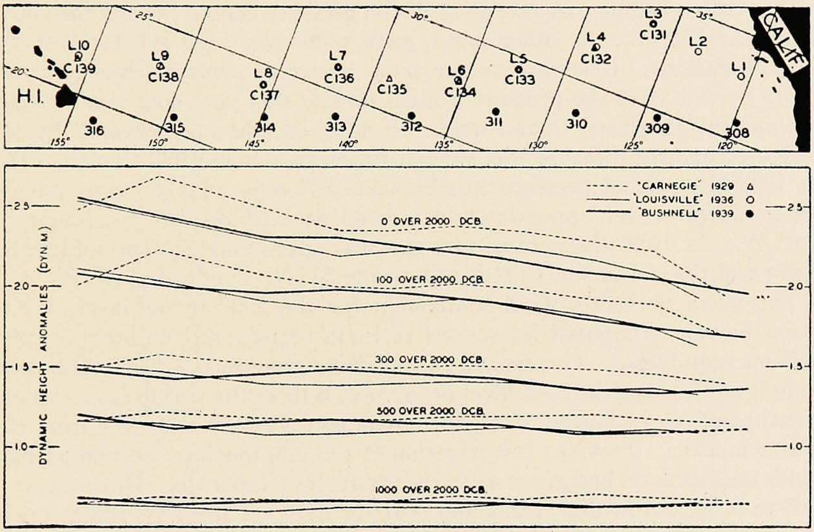

Figure 62. Dynamic heights over the Eastern North Pacific Ocean between longitude 131° W. and 139° W. computed on the basis of the *Carnegie*, *Louisville* and *Bushnell* sections.

of the great stability of the lower layers throughout nearly all months. This error will be most significant during the late spring and early summer months when the coastal inversion is best developed. However, at the present time no practical method of eliminating this difficulty is apparent.

Since the North Pacific high pressure system normally persists throughout all months, it would be expected that the sea surface would slope upward from the coast toward the center of the pressure field as a result of the *cum sole* transport of the surface waters induced by the anticyclonic wind system. The dynamic heights computed from the *Carnegie*, *Louisville* and *Bushnell* sections (Figure 62) show this to be the case, the rise of the surface being of the order of 30 cm. between 130° W. and 140° W. The short-period sea-level fluctuations on the coast are occasionally of the order of 30 cm. or more although the monthly departures seldom exceed 8–12 cm.

The longer the period under consideration the more outstanding is the relationship between the development of the pressure field and sea level. This fact is in line with the conclusions drawn regarding local and widespread variations. For example, the entire year 1933 gave unusually low sea level at all tide stations on the Pacific Coast. Reference to data concerning mean annual pressures over the eastern North Pacific compiled by the Japan Imperial Marine Observatory (1934) reveals that the Pacific high pressure system was also unusually well developed during this year with a corresponding displacement of the pressure center toward the coast. The year 1930 on the other hand, gave unusually high sea level at the coastal stations. Reference to the same source of pressure data (loc. cit. 1931) reveals that the pressure system during this year was weaker than normal and displaced to the west. In addition, the area covered by the region of highest pressure was several times greater in 1933 than in 1930. In 1933 the central pressure was between 767 mm. and 768 mm. and the geographical center approximately located at latitude 31° N., longitude 139° W. In 1930 the central pressure was approximately one millimeter lower and the center was shifted to latitude 33° N., longitude 146° W.

The mean northerly wind component for the 1000 meter level at San Francisco was computed for several series of months on the basis of pilot balloon soundings.[1] The results gave a fair agreement between the component at this level and sea level departures during the spring and summer months but, as with other data, the agreement was not as good during the winter months. Previous investigation of the relationship between surface winds and sea level had given negative results for all months. However, it is well to bring out in this connection that the data are from soundings made once daily at 2:00 a. m. (P. S. T.) and thus at a period when surface winds are not often representative of the general circulation over the ocean due to the local effects of topography and the katabatic process. Figure 63 illustrates the relationship between the northerly component at 1000 meters and sea level departures at San Francisco for all months of April, 1929–36. The agreement between the two elements indicated in the diagram is probably as good as could reasonably be expected since the increased velocities due to changes in the pressure field over the North Pacific may appear at some distance from the coast and not be apparent at the coastal stations. The existence of such a condition off the coast of Southern California is indicated in Figure 61.

It has previously been mentioned that other investigators of the problem

[1] The greater portion of the soundings were actually made at Oakland, several miles inland from San Francisco.

have found most of the sea level variations accounted for by changes in the density of surface waters, but it should be pointed out that the changes in density can only be accounted for by meteorological processes, either directly or indirectly. The transport of light surface waters away from the coast will bring sub-surface waters of greater density to the coastal regions and the isopycnal surfaces will now slope upward toward the coast. LaFond (loc. cit.) has shown that the greatest change in density off the Southern

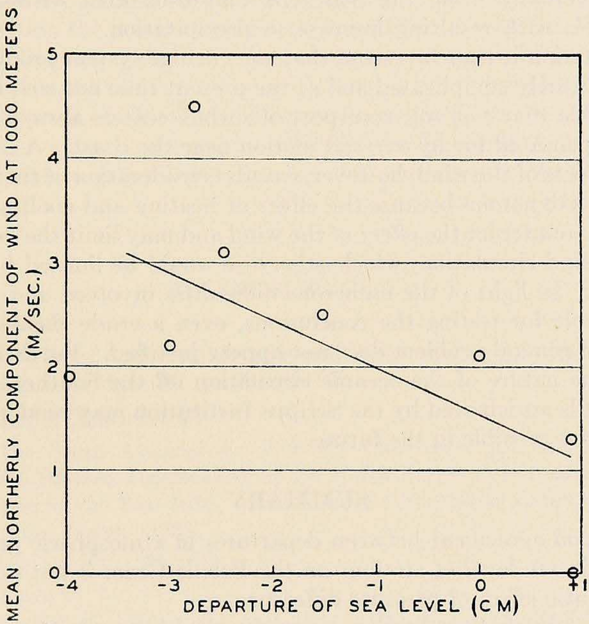

Figure 63. Relationship between sea level departures at San Francisco and the mean monthly northerly wind component at 1000 meters computed on the basis of pilot balloon soundings for all months of May, 1929–36.

California coast tends to occur in the upper 75 meters and that the changes in density below this level can account for only a fraction of the observed sea level departures. It is true that the intrusion of waters of greater density may occur as the result of subsurface currents but it may be assumed that these currents, too, are the result of the general circulation of surface waters.

Evaporation and precipitation may also alter the distribution of density, but none of these processes can directly influence sea level to any appreciable extent. Nevertheless, LaFond (loc. cit.) has shown a good agreement between the annual rainfall at La Jolla and the annual sea level departures.

It must be concluded that the meteorological processes causing precipitation in this region also produce high sea level and a consideration of the problem indicates that this is the case. Because the San Diego area is near the boundary region for winter cyclonic activity, seasons with above normal rainfall should also show a general shift of the Pacific high pressure field from the coast seaward and correspondingly, winds with a northerly component should be less frequent. A shift to the south of the high pressure field may actually bring the Southern California area within a zone of frontogenesis with resulting increase in precipitation.

In summation it may be stated that the current system produced by the wind is extremely complicated and at the present time not well understood. It is probable that *cum sole* transport of surface waters always takes place but is compensated for by vertical motion near the coast. A discussion of the total effects of the wind, however, entails consideration of thermodynamics as well as dynamics because the effect of heating and cooling of surface layers may counteract the effect of the wind and may limit the development of a pure wind circulation, which otherwise would be limited by frictional forces only. In light of the numerous difficulties involved and the meager data available for testing the conclusions, even a crude theoretical treatment of the general problem does not appear justified. Further investigation into the nature of the oceanic circulation off the Southern California coast which is anticipated by the Scripps Institution may render some such considerations possible in the future.

SUMMARY

1. The good agreement between departures in atmospheric pressure and departures in sea level at stations on the Pacific Coast is not explained by the hydrostatic effect of pressure difference.

2. It is shown that sea level averages for time intervals of one month or longer are definitely related to the development of the high pressure field over the North Pacific Ocean.

(a) Low sea level values occur when the pressure field is best developed or shifted toward the coast; high sea level is recorded when the system is weak or shifted toward the west or south.

(b) This relationship is most pronounced during the spring and summer months when the atmospheric-oceanic system is least complicated by local and short-period meteorological changes.

3. It is concluded that the effect of the pressure distribution is due to the wind system produced by the gradients established and that the total mass of water transported away from the coast varies as the wind component parallel to the coast. An agreement between the northerly component of the wind at 1000 meters and sea level is found.

4. It is suggested that the good agreement between the density of surface waters, rainfall and sea level found by various investigators may be explained on the basis of variations in the atmospheric-dynamic system over the regions under consideration.

Acknowledgements

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