AN ABSTRACT OF THE THESIS OF

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(Name) (Degree) (Major)

Date thesis is presented 17 August 1966

Title SEA LEVEL, WINDS, AND UPWELLING ALONG THE OREGON COAST

Abstract approved Redacted for Privacy
(Major Professor)

The relationship between sea level and wind stress in a region of known upwelling was studied for an eleven-month period during 1933-34.

Sea level data, obtained from observations taken by the Coast and Geodetic Survey, were processed to remove astronomic tidal constituents and inverted barometer effect. Regression analysis was used to establish the relationship between the resultant daily mean sea levels and the north and east components of wind stress. Sea level and wind stress were significantly related. The highest correlation for sea level of a given day was with the north component of wind stress summed over the given day and the three days preceding. Sea level was next most highly correlated with the east component of wind stress summed over the given day and the two days preceding. The sea level-wind stress relationship is consistent with what is known about upwelling along the Oregon coast.

The relationship between sea level and rainfall was also examined.

Sea level and rainfall were significantly associated, but not in such a marked fashion as were sea level and wind stress. The rainfall effect may be due both to local addition of mass and to augmentation of wind stress by heavy rain.

SEA LEVEL, WINDS, AND UPWELLING ALONG THE OREGON COAST

by

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A THESIS

submitted to

OREGON STATE UNIVERSITY

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

June 1967

APPROVED: Redacted for Privacy

Professor of Oceanography
In Charge of Major

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Date thesis is presented 17 August 1966

Typed by Marcia Ten Eyck

ACKNOWLEDGEMENTS

I wish to thank Dr. Wayne Burt, Chairman of the Department of Oceanography, for his investment in the future of one who majored in history as an undergraduate. I hope that I may prove myself worthy of this opportunity for a considerable redirection of academic endeavor.

Dr. Robert Smith and Dr. June Pattullo, successively serving as my major professor, have generously shared the force and substance of their knowledge, perception, and imagination.

Dr. Roger Petersen has been immensely helpful with the statistical aspects of this study, while Mrs. Susan Borden provided valuable assistance in the tasks of data reduction and processing.

To my wife, Cynthia, I owe a special debt of thanks for her neverfailing strength, patience, good humor, and understanding.

To all those specifically mentioned, and to all with whom I have come in contact -- faculty, staff, and students, I warmly direct my appreciation for their continuing encouragement and the stimulus of association.

The study was supported by the Office of Naval Research under Contract Nonr 1286(10), Project NR 083-102.

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INTRODUCTION

The purposes of the present study are two in number. First, the study is an examination of the relation between daily mean sea level and winds along the Oregon coast for an eleven-month period (1 May 1933 to 31 March 1934). Second, the study suggests the potential usefulness of changes in sea level as an indicator of the oceanic phenomenon of upwelling.

Definitions

Sea level, as used in this paper, refers to heights measured by gauges. Of particular interest are the daily changes in the heights of sea level at a particular station. The changes in sea level are measured with respect to the average sea level over the eleven-month period of observation. These changes are designated by the symbol, Δh.

The winds of interest are the winds at the surface of the ocean over the coastal environment. The velocity of the wind is designated by the symbol, $\vec{U}$. In the study of sea level and upwelling, the important wind parameter is the stress exerted by the wind on the surface of the ocean. Wind stress is designated by the symbol, $\vec{T}$.

Upwelling is the ascending movement of subsurface water into the surface layer. Near the coast, this movement occurs in response to the offshore transport of surface water. In this paper the word, upwelling, refers to coastal upwelling as distinct from open-ocean upwelling.

The Ocean Off Oregon

Along the Oregon coast, sea level is lower than average in the summer and higher than average in the winter. The prevailing winds over the waters off Oregon come from the northwest during the summer and from the southwest during the winter. From spring to fall, upwelling is a common oceanographic feature of Oregon coastal waters.

"Coastal upwelling along the Oregon coast is clearly associated with a northerly wind stress (Smith, 1964)." The present study examines the relation between sea level and wind stress, and discusses some aspects of the relation between sea level and upwelling.

Outline of Analytical Method

Adjustment is made to the recorded sea-level heights for the effect of two of the major short-term variables (astronomic tidal constituents and atmospheric pressure). The resultant adjusted sea-level estimates are then compared with wind stress. The statistical method of multiple regression analysis is used to determine the relationship between the departures of daily mean values of adjusted sea level values (Δh) and the north and east components of wind stress ($\vec{\tau}_y$ and $\vec{\tau}_x$ respectively).

REVIEW OF SELECTED STUDIES

In this chapter I will review certain previous studies which deal with sea level, wind stress, and upwelling.

Sea Level

Cartwright (1963) has stated that the concept of sea level is a delusion; the sea surface is not level and is constantly changing.

Higgins (1965) reviewed the factors bringing about changes in sea level. Higgins showed that sea level is a function of both long-term and short-term variables, reflecting changes in the volume and mass of water in the world ocean, changes in the level of the land, and, above all, a variety of local effects. Higgins also showed that sea level is subject to worldwide changes as well as to changes of limited extent geographically.

Since the present study is concerned with daily changes in the height of sea level during an eleven-month period, such relatively long-term factors as glaciation may be disregarded. Furthermore, during 1933-34 there were no major catastrophic events in the Pacific Northwest, such as major earthquakes (Berg and Baker, 1963) or volcanic eruptions.

Thus, daily changes in sea level for the period of concern will be considered to be related to the following short term contributions:

astronomic tidal constituents, atmospheric pressure, wind stress, steric (specific volume) variations, and local addition of mass (LaFond, 1939).

Sea level undergoes regular tidal motions due to the gravitational attraction of celestial bodies. Just as harmonic analysis can be used to predict the tides (Schureman, 1940), so also, assuming a linear combination of sinusoids to represent the tides accurately, numerical filters can be designed which effectively eliminate the contribution of the major harmonic constituents to the recorded tidal heights (Doodson, 1928).

The pressure at the bottom of the ocean depends on both the overlying water column and the overlying air column. "Because the ocean behaves like an inverted barometer and adjusts its level relatively quickly to changes in the air column, the bottom pressure is a constant, other things being equal (Donn, Pattullo and Shaw, 1964)." The theoretical value of the response of sea level to changes in atmospheric pressure is 0.995 cm of water per one mb of air-pressure change, for sea water of density 1.025 gm/cm^3.

In coastal regions, the wind is one of the major factors producing variations in sea level. Winds both parallel and normal to the coastline are important. Changes in wind velocity act in such a way as to produce a surplus or deficit of water for a time, depending on the direction of the wind (Montgomery, 1938; Groves, 1957; Miller, 1957).

Steric variation is the change in height of the sea surface arising from variation in the specific volume of the water column (Pattullo, Munk, Revelle and Strong, 1955). The specific volume of sea water is a function of temperature, salinity, and pressure.

The final factor to be considered is the local addition or loss of mass. This can mean precipitation and evaporation, but is more significant in the case of river discharge (Montgomery, 1938).

Lisitzin and Pattullo (1961) have shown that in the lower latitudes in the Pacific Ocean the steric term is predominant in the seasonal variation of sea level, while in higher latitudes variation in atmospheric pressure is predominant. The latitude band of 40°-45°N approximately marks the boundary between the two zones.

Saur is one of several investigators to have studied sea level in the northeastern Pacific Ocean. Saur (1962) showed that the seasonal variability of sea level was greater with increasing latitude, and that maximum variability took place during the winter months. In addition, north of 35°N, the highest sea level was recorded in the winter, the lowest in the summer.

Wind Stress

Momentum is exchanged between the atmosphere and the ocean by means of the shearing stress of the wind. "When wind blows over the surface of the water, a shear stress exists at the interface and air drags water along (Wiegel, 1964)." The commonly accepted method for computation of wind stress on the surface of the ocean is by application of the formula adapted from Taylor (1916):

$$\vec{T} = \rho_a C_D \left|\vec{U}\right| \vec{U}$$

where:

$\vec{T}$ = wind stress on the sea surface;

ρ_a = density of air;

C_D = drag coefficient of wind on sea surface;

$\vec{U}$ = wind velocity.

Evaluation of the drag coefficient, C_D, has been particularly troublesome. C_D is a dimensionless function of other dimensionless parameters involving wind speed, roughness of the sea surface, height of wind measurement, and stability of air over the ocean (Smith, 1964). Munk (1947) showed that there exists a critical wind speed below which the sea surface is hydrodynamically smooth and above which it is hydrodynamically rough. At the critical wind speed of six to eight m/sec (measured at a height above the sea surface of ten m), "not only the rate, but the very nature of these processes seems to be altered (Munk, 1947)."

Wilson (1960) reviewed all available laboratory and field measurements of C_D, and presented average values on the basis of his investigation. Wilson's value of C_D for light winds is 0.0015 ± 0.0008

and for strong winds is 0.00024 ±0.0005; the critical wind speed is about 15 knots. The discontinuity of C_D strongly suggests that the dependence of $\vec{T}$ on $\vec{U}$ follows some other law than that of the second power (Neumann, 1956).

Wind stress is undoubtedly a function of other parameters than wind alone. For instance, Van Dorn (1953) showed that "heavy rainfall can considerably augment the stress due to the wind", through the transfer of horizontal momentum by falling raindrops to the surface of the sea.

Upwelling

Coastal upwelling is generally explained by use of what is known as Ekman's theory (Ekman, 1905). Ekman considered the influences of only friction and Coriolis effect on an ocean of infinite extent, assuming homogeneity throughout the water column and constant eddy viscosity. Ekman showed that, in the Northern Hemisphere, currents tend to flow to the right of the wind. With the wind blowing from the north along a west coast, the net transport of water in the surface layer is to the west or offshore, and water must upwell from depth to replace the water transported offshore.

McEwen (1912) applied Ekman's theory specifically to the west coast of North America. McEwen used temperature as an indicator of water movement, and showed that the transport inferred from this technique agreed satisfactorily with that predicted from Ekman's theory. More recent studies (Smith, 1964; Smith, Pattullo and Lane, 1966) have shown that upwelling observed along the coast of Oregon is also consistent with predictions based on Ekman's theory.

According to Sverdrup et al. (Sverdrup, Johnson and Fleming, 1942) and von Arx (1962), the depth of frictional influence, or lower limit of the wind-driven current, is typically on the order of 100 m in the world ocean. Off Oregon, observers have found a depth of minimum current speed somewhat deeper at about 150 m (Collins, 1964; Stevenson, 1966).

Ekman showed that winds parallel to the coast are important in the process of upwelling. Hidaka (1954) and Welander (1957) have shown theoretically that winds normal to the coast, in water shallower than the extent of the wind-driven surface layer, are also important. The circulation established is similar to that produced by the long-shore wind, but of weaker intensity and with the upwelled water coming from shallower depths. Specifically, Hidaka postulated that the most intense upwelling will occur when the wind makes an angle of 21.5° with the coastline in the offshore direction, a combination effect of longshore and offshore wind. Investigators in Nova Scotia (Longard and Banks, 1952) and Florida (Taylor and Stewart, 1959) have reported observations confirming upwelling of this type.

Upwelling, in continental-shelf waters off Oregon, can then reasonably be expected to be caused by both the longshore component (from the north) of the wind stress and the offshore component (from the east).

THE DATA

The data for this study come from the period 1 May 1933 through 31 March 1934. The data are from this restricted time period because it was during this period only that recording tide guages were in operation at several locations along the Oregon coast.

Sea Level

During 1933-34 the Coast and Geodetic Survey operated twelve tide gauges along the Oregon coast, recording sea-level heights at hourly intervals. To proceed with this study, it was practical to select a smaller number of gauges. The criteria used in selection were geographic distribution of gauges, type of estuary (if gauge was in an estuary), and distance of gauge from the ocean.

The locations of all C&GS gauges appear in Figure 1. I selected four of these gauges, Brighton, Newport, Coos Bay, and Brookings, for study. These selected stations are indicated in the figure by open circles with the names of the stations alongside. As one can see, the four stations provide nearly complete coverage of the Oregon coast, with approximate uniformity of spacing between stations.

Pritchard (1955) classified estuaries by circulation pattern and salinity distribution. His estuarine types are: highly stratified or two-layered; partly mixed; and vertically homogeneous or well-mixed.

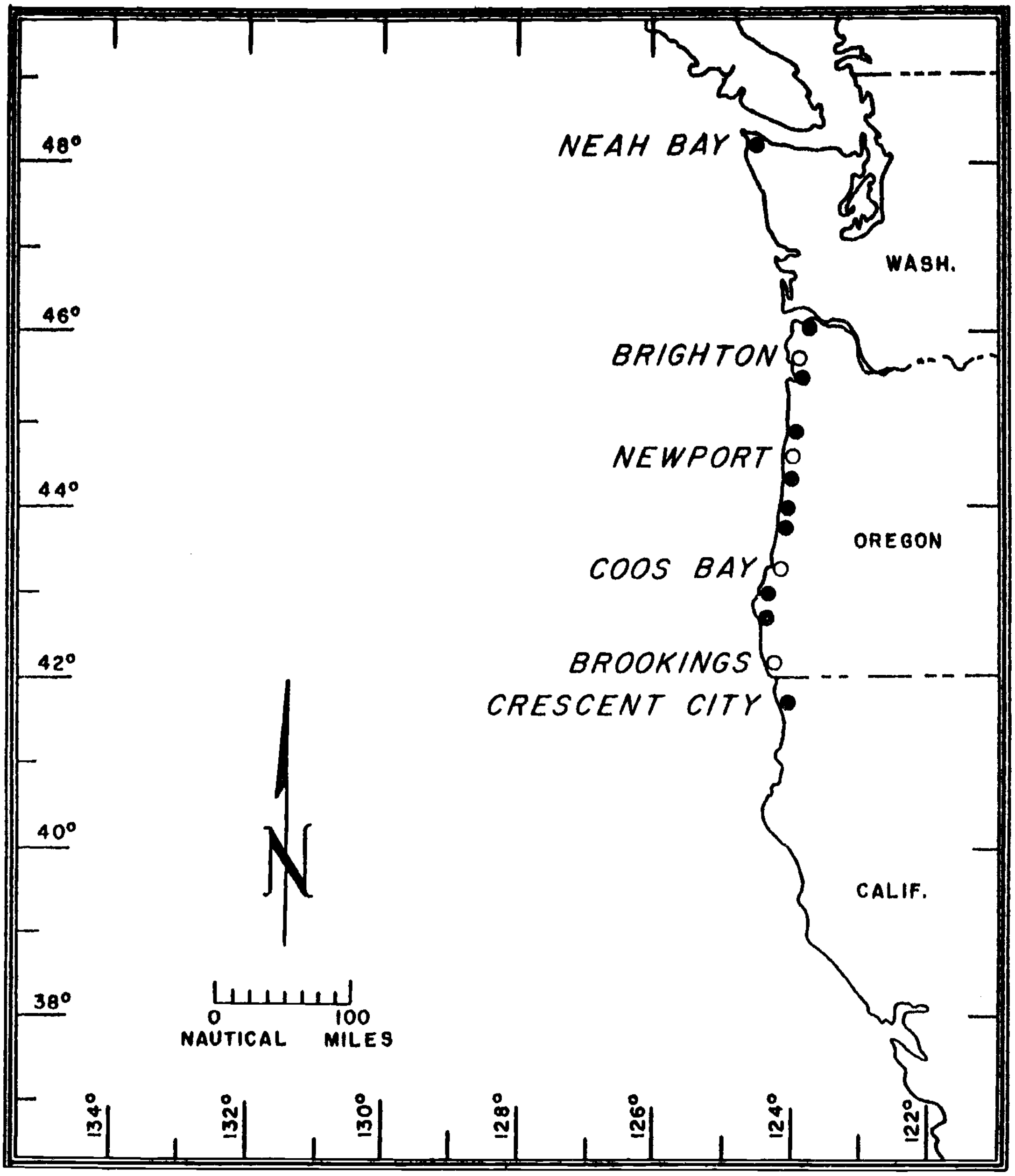

Figure 1. Locations of tide-gauge stations. Open circles show the locations of Oregon stations used in this study. Closed circles without names in Oregon show locations of the other 1933-34 C&GS stations. (Neah Bay and Crescent City are stations at which long-term records have been taken.)

Burt and McAlister (1959) investigated Oregon estuaries and classified them according to Pritchard's system. To reduce the number of variables in the study, I wanted to use gauges located on estuaries of similar type. For adequate geographical coverage, the types were vertically homogeneous or partly mixed.

The Coos Bay and Newport gauges stood within estuaries which normally are vertically homogeneous or partly mixed throughout the year. The Brighton gauge stood within an estuary which normally is partly mixed throughout the year. The gauge at Brookings was located in a cove on the open coast.

The third criterion was distance of those stations on estuaries from the mouth of the estuary. All such stations selected were less than 1 1/2 miles from the ocean: Brighton was 1.2 miles, Newport 1.0 miles, Coos Bay 1.3 miles.

Winds

Direct observations of the wind along the Oregon coast for the 1933-34 period do not exist to any useful extent. Only a few direct observations are available, and these are widely scattered both in time and location.

To compute daily values of wind stress representative of the Oregon coast, however, regular observations of winds are necessary. The only source of winds fulfilling this requirement for the present study was by computation from isobaric structure on weather maps.

Weather maps of the Northern Hemisphere are available for the period of interest in the Historical Weather Map series issued by the Weather Bureau. Accordingly, I obtained the daily weather maps for sea-level elevation from 1 May 1933 through 31 March 1934 (U. S. Weather Bureau, 1933-34) and computed the surface winds for 45°N, 125°W (see Figure 2). This location was the printed latitude-longitude intersection on the weather maps closest to the Oregon coast and I considered the winds at this location to be representative of the ocean off Oregon. There still remain major difficulties in the accurate estimation of winds from these charts.

In the first place, the projection used in the weather-map series includes all of the Northern Hemisphere on charts 15 in by 15 in; detailed interpretation of the isobaric structure was not possible. Secondly, there was only one weather map issued per day, at 1300 GMT (0500 PST); some sort of daily wind average would have been preferable. Admittedly, a great amount of averaging over time and space goes into the construction of a weather map, but only one map per day provides marginal coverage. Finally, the contouring of isobars over the ocean is of dubious quality because of the relative paucity of shipboard observations of atmospheric pressure near Oregon during 1933-34.

A further difficulty exists in the computation of winds from the

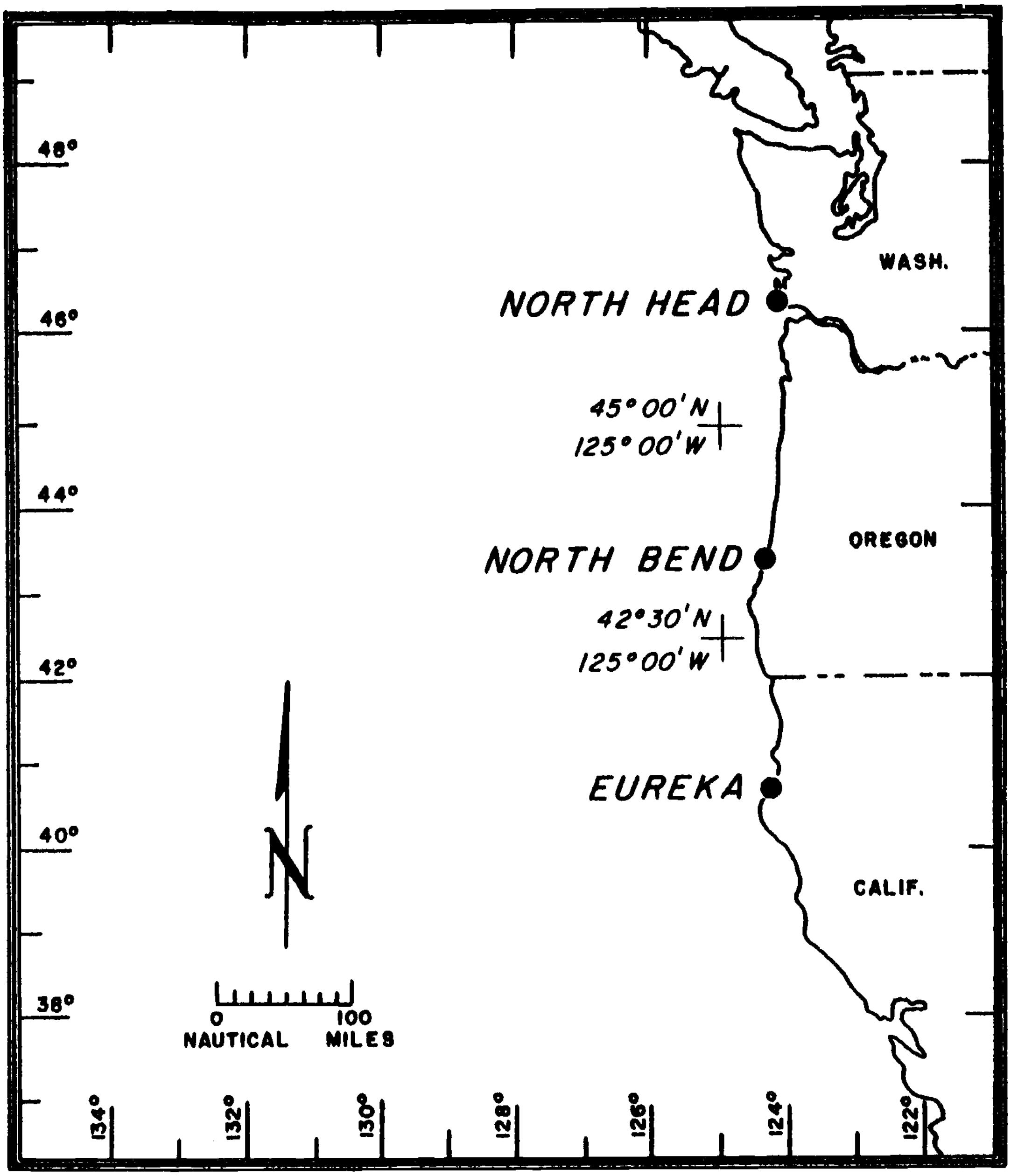

Figure 2. Locations of stations used for observations of atmospheric pressure and wind.

isobaric pattern. This difficulty centers on calculating the surface wind, knowledge of which is desired, from an estimate of the geostrophic wind, which is computed by analysis of the weather map. Numerous empirical schemes are available to aid in figuring surface wind. I selected the one presented in Techniques for Forecasting Wind Waves and Swell (U. S. Naval Oceanographic Office, 1951), a standard prediction manual.

The first step in the method is to determine the velocity of the geostrophic wind from the pattern of the isobars. The direction of the surface wind is obtained by rotating the geostrophic vector ten degrees to the left of the downwind direction. The speed of the surface wind is obtained by modifying the geostrophic speed for air-sea temperature difference (U. S. Navy, 1956), curvature of the isobars, and frictional effects. The average factor by which the geostrophic speed was multiplied to estimate the speed of the surface wind was 0. 65.

The prevailing winds for the Oregon coast come from the southwest during the winter, from the northwest during the summer, and are not well-defined in the transition periods of spring and fall. The surface winds computed for the 1933-34 period follow this pattern.

Some question remains whether computed winds provide an adequate estimate of the true wind. Since few direct observations exist for 1933-34, I turned to the summer of 1965 to investigate this matter. Appendix II describes the study made and conclusions reached.

Briefly, for the summer of 1965, greater variation existed between two different sets of direct observations, than between the computed winds and either set of direct observations. I can only conclude that, even though computed winds provide an uncertain estimate, they are still no worse an estimate of the true wind than direct observations. Bunting (1963) conducted a study of this problem and reached the same conclusion.

Atmospheric Pressure

During 1933-34 the Weather Bureau had in operation one station along the Oregon coast, a second-order Synoptic Aviation Station at North Bend. Figure 2 shows the location of the North Bend station.

The observations of atmospheric pressure taken at North Bend were adjusted by the Weather Bureau for elevation to sea level. These observations were used as representative of the ocean off Oregon. No regular observations from ships at sea were available for use in verifying this assumption.

In support of this assumption, however, pressure systems are commonly several hundreds of kilometers across. Dimensions of this sort support taking a single station as representative of the Oregon Coast. Further, in a recent study of atmospheric pressure, Roden

(1965) showed that nonseasonal pressure oscillations along the Pacific Coast of North America for a 90-year period were coherent over distances of 1200 kilometers, approximately three times the length of the Oregon Coast.

To test the 1933-34 period I used atmospheric pressure data from two additional stations on the Pacific Coast. These stations were North Head, Washington, near the mouth of the Columbia River, and Eureka, in northern California (see Figure 2). The results of regression analysis showed North Bend to be representative of North Head and Eureka ± 4 mb for a single observation. Appendix III presents the details of this test.

A variation of atmospheric pressure of ± 4 mb corresponds approximately to a variation in water level of ± 4 cm. Changes in water level of this magnitude are not insignificant, but are nonetheless minor compared to the overall range of Oregon sea level between Brighton and Brookings. Therefore, atmospheric pressure observed at North Bend is adequately representative of the coastal oceanic environment for the purposes of the present study.

ANALYSIS OF DATA

This chapter discusses the reduction of data, the monthly distributions of the data, and the method for analysis of the relationship between sea level and wind stress.

Reduction of Data

The procedure for data reduction was to check the data and remove errors, convert to cgs units, and average on a daily basis.

Atmospheric Pressure

The Weather Bureau recorded atmospheric pressure at North Bend every four hours to the closest 0.01 in of mercury. The data were checked for errors; bad values were rejected and replaced by estimates (procedure described in Appendix IV). Time-positioning of the daily average was desired as close as possible to 0500 PST, the only time of day for which wind estimates were available. The daily average of atmospheric pressure was therefore centered on 0445 PST, as follows:

$$\overline{p} = 1/6\ (1/2\ p_{1645} + p_{2045} + p_{0045} + p_{0445} + p_{0845} + p_{1245} + 1/2\ p_{1645})$$

where:

$\overline{p}$ = daily average value of atmospheric pressure;

p_{1645}, etc. = seven consecutive individual observations of atmospheric pressure, starting with 1645 of the day previous to the day on which the average is centered.

Sea Level

The Coast and Geodetic Survey recorded heights of sea level continuously at the four Oregon stations. Hourly heights were transcribed onto data sheets to the closest 0.1 ft. These data were error-checked by the same procedure used for atmospheric pressure, and then converted to cm.

The heights of sea level were next treated so as to remove the astronomic tidal constituents. The procedure employed was the X_0 numerical filter of Doodson and Warburg (1941). This filter uses a 39-hour averaging technique which applies a factor of 0, 1, or 2 to each of the hourly values, sums the resultant values, and divides by 30 (the sum of the 0's, 1's, and 2's). The end result is an average sea level, referred to in this paper as nontidal, centered on the twentieth hour. The X_0 filter reduces all major harmonic constituents of the tide with great efficiency; the largest residual amplitude is 0.007 of its unfiltered value. Of course, many filters exist which will satisfactorily accomplish the task, but the X_0 filter is relatively simple to apply and is generally regarded as superior

(Groves, 1955; Rossiter, 1960). In the present study, the twentieth hour of the daily nontidal average was centered to fall on 0500 PST.

The nontidal value of sea level for a given day was adjusted for theoretical effect of atmospheric pressure. The adjustment made had the magnitude in cm of the difference in mb between the value of atmospheric pressure for that day and the average value of atmospheric pressure over the eleven-month period. The sign of the adjustment was the same as that of the direction of departure of the daily value of atmospheric pressure from the average pressure. The value of atmospheric pressure for the same day as that of sea level was used since sea level responds to changes in atmospheric pressure essentially instantaneously for the purposes of this study (Groves, 1957; Roden, 1960). Values of sea level, from which the contributions of astronomic constituents and atmospheric pressure have been removed, are referred to in this paper as adjusted sea level.

Since the average atmospheric pressure over all oceans varies with time during the year by at least 2 mb (Pattullo et al., 1955), a more appropriate reference value for atmospheric pressure would be the monthly mean pressure over all oceans. I was unable to find in the literature a value for 1933-34. In any event, the error introduced by this omission is small since the range of Oregon sea level is of the order of tens of centimeters, and should not materially affect the results.

Heights of sea level at each gauge are measured with respect to a datum unique to that gauge. In this study, departures of adjusted sea level for a given gauge from the average at that gauge over the eleven-month period are used rather than the absolute heights themselves. This technique allows one to disregard the differences in datum among stations for purposes of comparison.

<u>Wind Stress</u>

The surface wind was estimated at 45°N, 125°W once a day at 0500 PST, and was not error-checked. Wind stress was calculated from the surface wind by the formula:

$$\vec{\tau} = C_D \, \rho_a \, |\vec{U}| \, \vec{U}$$

where:

$C_D = 1.5 \times 10^{-3}$ for $U \leq 15$ kts, 2.4×10^{-3} for $U > 15$ kts;

$\rho_a = 1.22 \times 10^{-3}$ gm/cm^3 (Froese, 1963);

$\vec{U}$ = wind velocity, in cm/sec.

The result of the calculation was $\vec{\tau}$ in dynes/cm^2 in the same direction as $\vec{U}$. $\vec{\tau}$ was considered a daily average value of wind stress for the Oregon coast, just as $\vec{U}$ was considered a daily average value of wind velocity.

$\vec{\tau}$ was resolved into components τ_y and τ_x. The Oregon coast may be described adequately as tending north-south. Thus,

τ_y was taken as the component of $\vec{\tau}$ parallel to the coast and τ_x as the component normal to the coast. The sign convention is positive towards the north and east. A south wind gives a τ_y which is positive, a west wind a τ_x which is positive.

Monthly Distributions

The purpose of this section is to provide a climatological background against which the data may be compared. Monthly means of the atmospheric-pressure, sea-level, and wind-stress data for 1933-34 are presented together with monthly distributions from long-term records of these parameters. All distributions start with May and end with March.

Atmospheric Pressure

The distribution of monthly means of atmospheric pressure at North Bend through the period of observation is presented in Figure 3. For comparison, I consulted Normal Weather Charts for the Northern Hemisphere (U.S. Weather Bureau, 1952), a statistical summary of atmospheric pressure compiled by month from weather maps over a 20-year period. The long-term monthly means for $42^{\circ}30'$N, 125°W appear in Figure 3 (the location of this point is shown in Figure 2). As one might expect, the two records are similar, with that from 1933-34 displaying greater variability by contrast with the 20-year average.

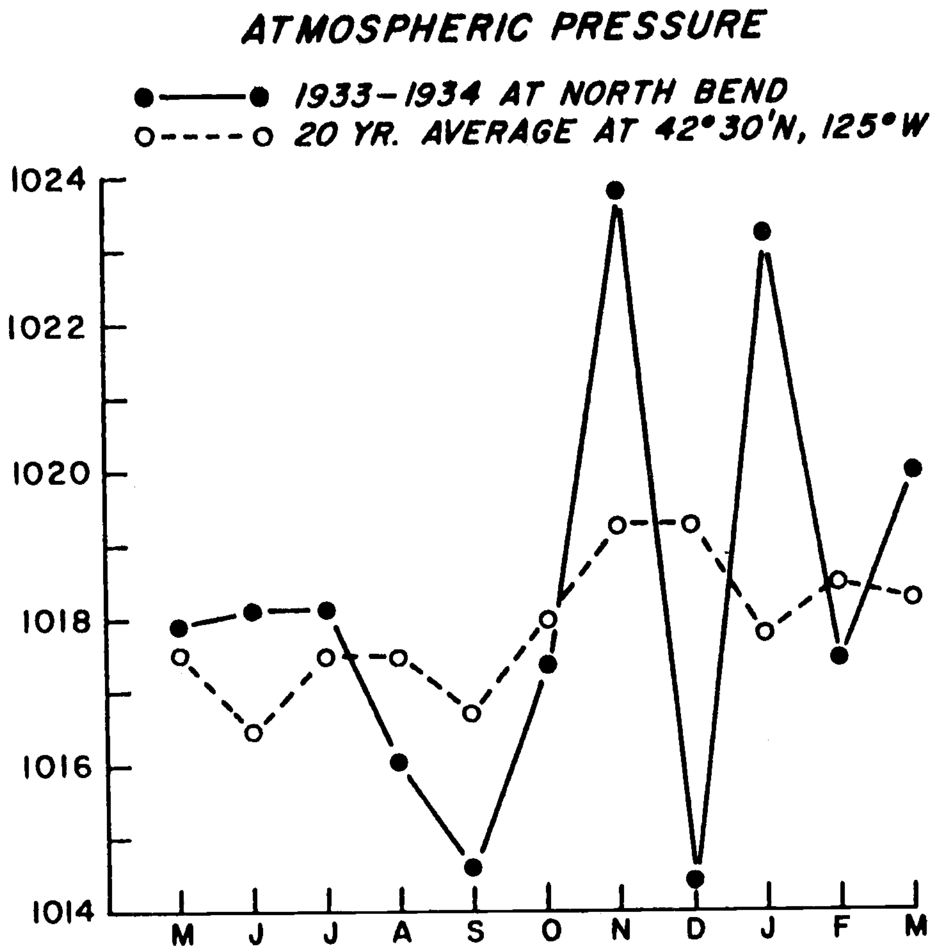

Figure 3. Monthly means of atmospheric pressure (mb). Note that the graph starts with May and stops with March.

Sea Level

Figure 4 presents the monthly mean sea levels for the four Oregon stations, referred in each case to the overall mean for the period of observation.

For comparison with the 1933-34 stations, I sought long-term tidal records from nearby coastal stations. No long-term records exist for the Oregon coast. Long-term tidal records, however, have been taken at Crescent City, California, to the south and at Neah Bay, Washington, to the north (see Figure 1 for location). Monthly means from Crescent City and Neah Bay (Pattullo et al., 1955), referred to the long-term mean in each case, are also presented in Figure 4.

The general similarity of the six records in Figure 4 is striking. All stations show a winter high and a summer low in sea level. The summer low is of longer duration than the winter high. The observations at the Oregon stations are consistent with the results of previous investigations of sea level along the west coast of North America (Pattullo et al., 1955; Saur, 1962).

Along the Oregon coast, the range of sea level during 1933-34 is largest at Brighton to the north, smallest at Brookings to the south, with an orderly transition in between. The extremes of the positive departures at all stations are approximately twice the extremes of the negative departures.

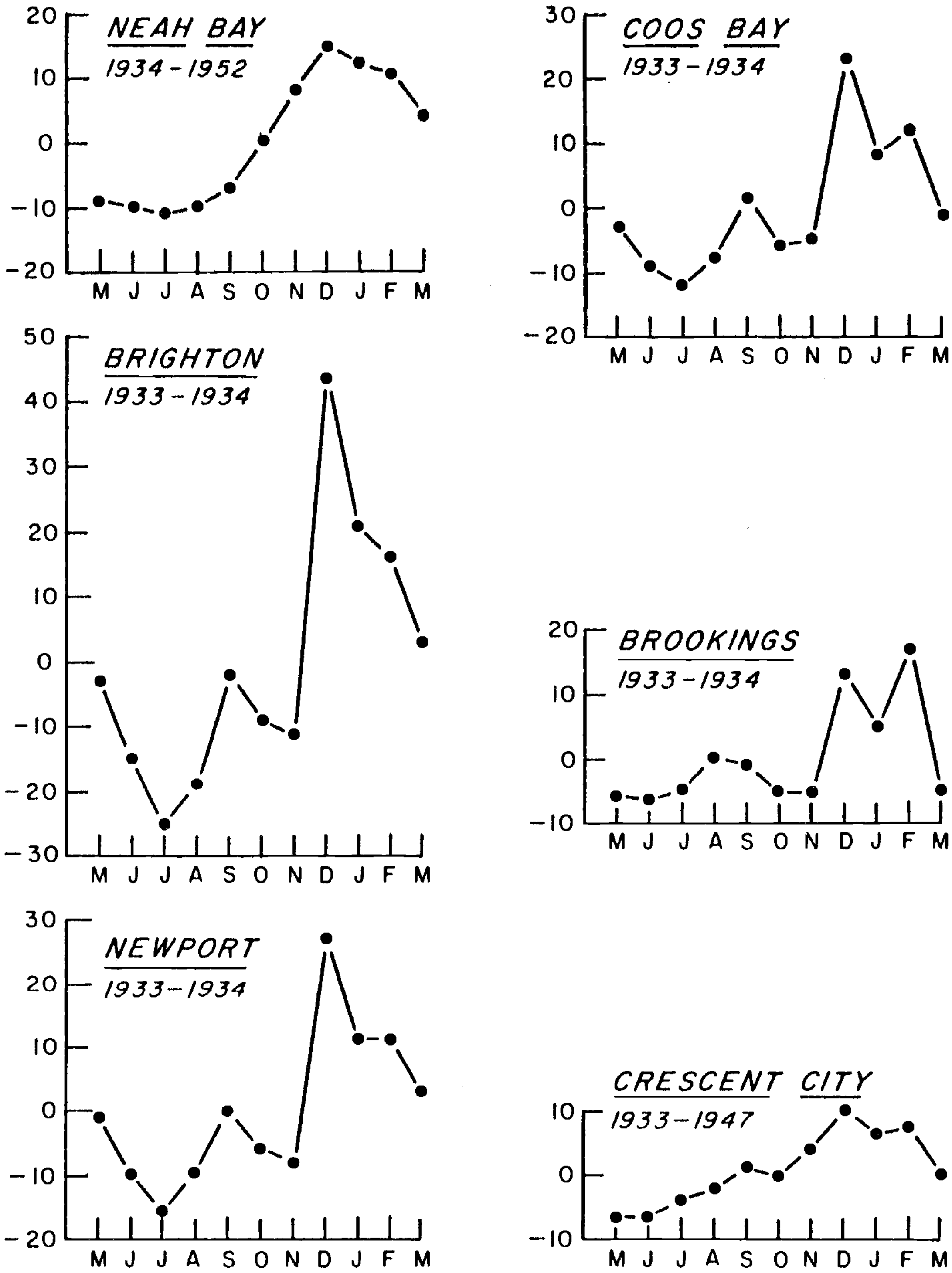

Figure 4. Monthly means of sea level (cm). Sea-level heights are with respect to means over the indicated periods of observations. All presentations start with May and stop with March.

Wind Stress

τ_y is considered to be the more important component of wind stress in upwelling. The monthly mean values of τ_y are presented in Figure 5. For comparison, the long-term monthly mean values of τ_y, taken from twenty-year normal weather maps assembled by the Weather Bureau (1952), also appear in Figure 5. As with the previous comparisons, the distributions of the two records are similar.

Regression Analysis

The multiple regression analysis of Δh, τ_y, and τ_x was performed using a digital computer (model IBM 1410).

The dependent variable was Δh, the departure of adjusted sea level for a particular day from the average sea level over the period of observation for that station. Fourteen independent variables were made up from various combinations of τ_y and τ_x, namely:

τ_y for d = 0, d = -1, d = -2, and d = -3 (individual daily observations of τ_y, where d stands for day and 0 for the same day as the day for the value of Δh under consideration, with -1, -2, and -3 respectively denoting in order each of the three days immediately preceding d = 0);

τ_x for d = 0, d = -1, d = -2, and d = -3 (similarly);

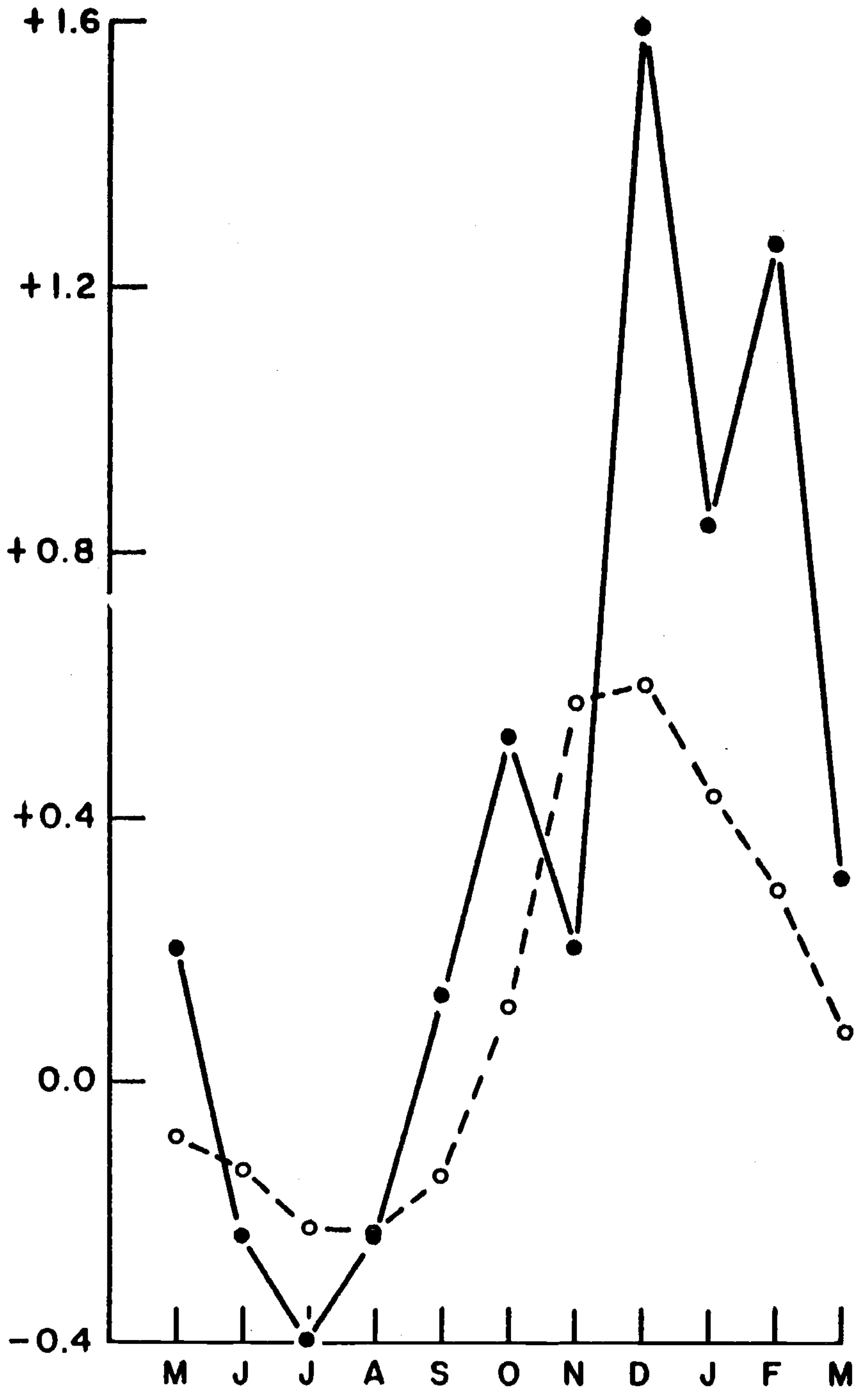

Figure 5. Monthly means of τ_y (dynes/ cm^2) at 45°N, 125°W. The solid line is τ_y for 1933-34, the dashed line the monthly mean τ_y over a 20-yr. period. A positive value of τ_y represents a wind from the south. The monthly means start with May and stop with March.

$\sum_{d=-1}^{0} \tau_y$, $\sum_{d=-2}^{0} \tau_y$, and $\sum_{d=-3}^{0} \tau_y$ (respectively representing simple sums over two, three and four days, thereby weighting the wind-stress contribution of each day in a sum equally, the last day in all cases being d= 0);

$\sum_{d=1}^{0} \tau_x$, $\sum_{d=2}^{0} \tau_x$, and $\sum_{d=3}^{0} \tau_x$ (similarly).

Values of τ_y and τ_x over a four-day period were used because of practical considerations and the desirability to keep the model to manageable dimensions. This restriction on wind-stress values considered seems reasonable oceanographically as most observations of upwelling off Oregon have shown a recognizable onset within three days after a shift of wind to a favorable direction (Pattullo, personal communication). In addition, statistical evidence supports the restriction; h was most highly correlated with sums of τ_y's and τ_x's over three or four days, with indication of lower correlation for sums over periods of time both shorter and longer.

The particular multiple regression analysis program used was a stepwise solution which adds one independent variable at a time to the solution (Efroymsen, 1960; Dixon, 1965). The independent variable (that is, value of wind stress) added at each step is the one which makes the greatest improvement in goodness of fit of the equation to the combinations of values of independent and dependent variables already considered. The equation obtained represents minimization of the error sum of squares so far as possible. Each intermediate solution yields the coefficients for the independent variables included in the equation at that point. In addition, statistical values are computed at each step so that one may determine when the addition of further independent variables produces no improvement in solution.

The initial computation conducted allowed strictly a linear fit to the points for each of the four sea-level stations, so that general relationships might be seen. Accordingly, the independent variables considered were first-order terms exclusively: individual daily values of τ_y and τ_x and various simple sums of each (as defined above). On the basis of the initial computation, the values of wind stress providing the best solutions for each sea-level station were selected.

The final computation conducted allowed the opportunity for curvilinear solutions by providing second-order terms in the independent variables and an interaction term (product of a τ_y by a τ_x), as well as first-order terms. (The physical significance of interaction, however, is not obvious.)

The results of these computations are presented in the next chapter.

RESULTS AND DISCUSSION

This chapter discusses the results of the regression analysis and the contribution of errors.

Results and Discussion of Regression Analysis

Two computations of regression analysis were made. The purpose of the initial computation was to establish the approximate relationship between the departure of adjusted sea level, Δh, and the components of wind stress, τ_y and τ_x, and to determine correlation coefficients. The purpose of the second computation was to refine the equation.

In the initial computation, fourteen independent variables were made available for the stepwise procedure, values both for individual days and for various sums of days, as detailed in the previous chapter. The data from each of the four sea-level stations were handled separately.

The results of the initial computation were generally consistent for all four stations. In each case, a sum of τ_y's was most highly correlated with Δh, and a sum of τ_x's was next most highly correlated. At this point in the stepwise procedure, all solutions were significant at the 0.1% level. All wind-stress sums were more highly correlated with Δh than were any of the wind-stress values for individual days alone. The general form of the initial equation is:

$$\Delta h = b_0 + b_1 \Sigma \tau_y + b_2 \Sigma \tau_x$$

Table I summarizes the results of the initial computation.

Table I. Summary of Multiple Regression Analyses, Initial Computation.

	b_0 (cm)	b_1	$\Sigma \tau_y$	b_2	$\Sigma \tau_x$	R^2	s. e. (cm)
Brighton	-9.0	3.5	$\sum_{d=-3}^{0}$	3.6	$\sum_{d=-2}^{0}$	0.69	0.71
Newport	-4.6	2.1	$\sum_{d=-3}^{0}$	2.5	$\sum_{d=-1}^{0}$	0.59	0.49
Coos Bay	-3.2	1.8	$\sum_{d=-3}^{0}$	1.3	$\sum_{d=-1}^{0}$	0.52	0.43
Brookings	-0.6	1.4	$\sum_{d=-3}^{0}$	-0.5	$\sum_{d=-3}^{0}$	0.28	0.39

The solution for Brookings, however, was markedly different from those for the other three stations ($R^2 = 0.28$ as opposed to R^2 of 0.52 to 0.69 for the other three). This different situation at Brookings is not surprising. The ocean seems to change character south of Cape Blanco (about midway between Coos Bay and Brookings). The boundary between the predominance of the steric contribution to the seasonal variation of sea level and the predominance of the inverted-barometer effect runs in the latitude band 40°-45°N (Lisitzin and Pattullo, 1961). Further, upwelling off Oregon typically occurs within a frontal system which hooks back to the coast south of Cape Blanco and does not include Brookings (Wyatt and Kujala, 1962). Pattullo and Denner (1965) have shown that upwelling occurred only 2% of the time at Brookings over a two-year period. It is also quite possible that winds computed for 45°N, 125°W are not representative of the ocean south of Cape Blanco. Additional investigation of the sea level-wind stress relationship at Brookings did not appear encouraging. Therefore, no further computations were conducted on the Brookings data in the present study.

Additional computations were performed for the data from the other three stations. It was practical to select a smaller set of independent variables common to the remaining stations. In the initial computations, the sum of τ_y's selected in all cases was $\sum_{d=-3}^{0} \tau_y$. The state of affairs with the sum of τ_x's selected was not so clear-cut: $\sum_{d=-2}^{0} \tau_x$ for Brighton, $\sum_{d=-1}^{0} \tau_x$ for Newport and Coos Bay. Even though $\sum_{d=-1}^{0} \tau_x$ was selected for Newport and Coos Bay, the difference in the value of the square of the correlation coefficient between $\sum_{d=-1}^{0} \tau_x$ and $\sum_{d=-2}^{0} \tau_x$ for each of these two stations was only 0.02.

Thus, the two basic independent variables chosen for the final computation were $\sum_{d=-3}^{0} \tau_y$ and $\sum_{d=-2}^{0} \tau_x$. The other independent variables made available were two second-order terms, $(\sum_{d=-3}^{0} \tau_y)^2$, and $(\sum_{d=-2}^{0} \tau_x)^2$, and an interaction term, $[(\sum_{d=-3}^{0} \tau_y)(\sum_{d=-2}^{0} \tau_x)]$.

The results of the final computation were highly consistent among stations. In each case, the order of entry of independent variables into the solution was the same: $\sum_{d=-3}^{0} \tau_y$, $\sum_{d=-2}^{0} \tau_x$, $[(\sum_{d=-3}^{0} \tau_y)(\sum_{d=-2}^{0} \tau_x)]$, $(\sum_{d=-2}^{0} \tau_x)^2$, and $(\sum_{d=-3}^{0} \tau_y)^2$. All solutions were significant at the 0.1% level at the point in the stepwise procedure where the two simple sums and the interaction term had been considered.

In the resultant equations of sea level as a function of wind stress, normalized values of wind stress are used. Normalizing was performed by dividing a wind-stress sum by the number of days over which it was summed, so that all wind-stress values appear in the final equation as average daily values. The general form of the final equation is:

$$\Delta h = b_0 + b_1 \frac{\sum_{d=-3}^{0} \tau_y}{4} + b_2 \frac{\sum_{d=-2}^{0} \tau_x}{3} + b_3 \frac{[(\sum_{d=-3}^{0} \tau_y)(\sum_{d=-2}^{0} \tau_x)]}{12}.$$

The results of the final computation are summarized in Table II.

Table II. Summary of Multiple Regression Analyses, Final Computation.

	b_0 (cm)	b_1	b_2	b_3	R^2	s. e. (cm)
Brighton	-9.6	16.0	13.4	-2.1	0.70	0.69
Newport	-5.3	10.3	7.7	-2.0	0.61	0.47
Coos Bay	-3.8	9.0	5.0	-1.9	0.56	0.41

The three solutions are generally similar. In each solution, the magnitude of b_1 is greater than that of b_2, and the magnitude of b_2 is greater than that of b_3. All solutions indicate highly significant associations between wind stress and sea level, with uniformly small standard errors.

The magnitude of each coefficient for the Brighton equation is greater without exception than that of each corresponding coefficient for Newport. The magnitude of each coefficient for the Newport equation is greater without exception than that of each corresponding coefficient for Coos Bay.

Further, $\sum_{d=-3}^{0} \tau_y$ (when compared with $\sum_{d=-2}^{0} \tau_x$) enters with proportionately greater weight for Coos Bay than for Newport than for Brighton. In addition, the interaction term enters with greater relative weight for Coos Bay than for Newport than for Brighton.

Even though all three solutions have basic similarities, the solutions obviously also have their differences. To the extent that the wind used in the calculations is representative of the ocean off Oregon, the wind stress-sea level relationship changes to some degree with travel along the Oregon coast.

A graphical representation of the equation for Newport, intermediate geographically of the three stations, is presented in Figure 6. The surface of sea level as a function of wind stress is most interesting. Once having fixed either the τ_y's or the τ_x's, the resultant family of solutions is linear. Any one family of solutions is linear, but the surface described by all solutions is nonlinear due to interaction. The surface is warped, cutting through the horizontal plane of $\Delta h=0$ (and all horizontal planes) in a curve at a varying oblique angle. For a given wind stress, sea level is highest in the presence of winds from the southwest, an observation previously made for Newport by Swanson (1965). For the same given wind stress, sea level is lowest in the presence of winds from the northeast.

The change in sea level could reflect at least two factors, one isostatic and the other nonisostatic. The isostatic term reflects steric variation due to changes in density of the water column with the onset and cessation of upwelling. The nonisostatic term reflects a true change in water mass due to variations in wind velocity. In the absence of hydrographic data for 1933-34, these speculations cannot be checked for the period of interest. Calculations from more recent years indicate that the magnitude of the observed changes in

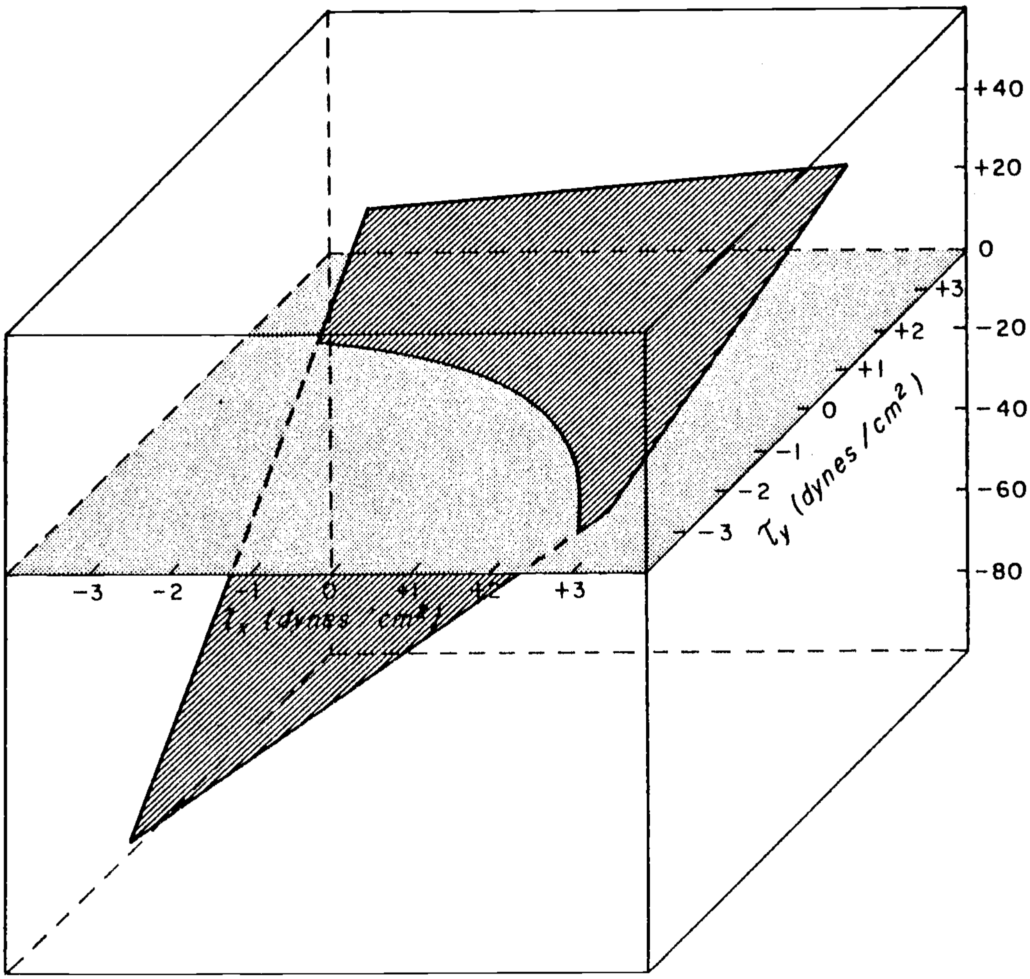

Figure 6. Graph of adjusted sea level during 1933-34 at Newport as a function of wind stress.

adjusted sea level can reasonably be explained by a combination of steric variation and changes in wind velocity.

The wind stress-sea level relationship which has been determined for 1933-34 is believed representative of the Oregon coast during other years. In addition, the relationship is consistent with the general long-term situation along the west coast of North America. Figure 7 presents a graphical comparison between long-term values of monthly mean sea level (Pattullo et al., 1955) and monthly mean longshore components of wind stress (U. S. Weather Bureau, 1952). As one can see, from Oregon north, sea level and the longshore component of wind stress are in good agreement. (To consider the 1933-34 Oregon relationships in similar context, compare Figures 4 and 5). Sea level and wind stress are not in such good agreement at Crescent City and San Francisco, coinciding with the findings at Brookings in the present study. Further, this situation at Brookings, Crescent City, and San Francisco lends support for the view of a different oceanic regime south of Cape Blanco.

Discussion of Errors

The inaccuracies of the solution of the relationship between wind stress and sea level may be due both to errors of measurement in basic quantities used and to other variables not considered.

The measured quantities used in the present study were sea

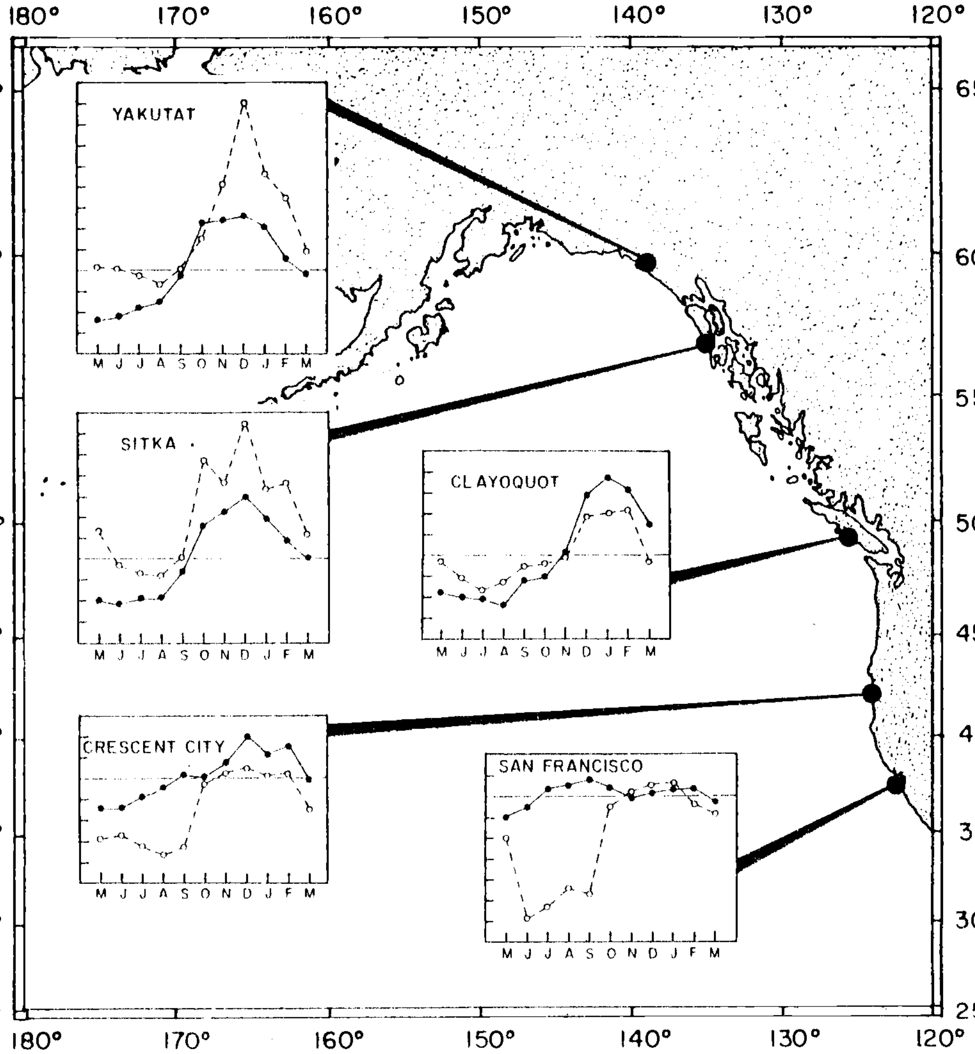

Figure 7. Distributions of monthly departures of sea level and longshore components of wind stress for selected stations along the west coast of North America. Solid lines are departures of sea level (cm); each vertical tick represents 5 cm. Broken lines are longshore components of wind stress (dynes/cm^2); each vertical tick represents 0.1 dyne/cm^2. Horizontal scale in each block represents time in months from the beginning of May to the end of March.

level, wind velocity, and atmospheric pressure.

Of the data used, the atmospheric-pressure data were of high quality. These data were recorded to the closest 0.01 in of mercury, corresponding to about 0.3 mb. The instrument used for taking the pressure observations was the cistern barometer, which is accurate for a single reading to 0.3 mb (Middleton, 1942). Daily averages taken over six observations reduce the random error to about 0.1 mb. The tides in the atmosphere are chiefly solar and small, with the maximum amplitude for the largest constituent of about 0.5 mb (Cole, 1892). Averaging over a 24-hour period effectively filters out the tidal constituents of atmospheric pressure.

The sea-level data were also of good quality. These data were recorded to the closest 0.1 ft, corresponding to about 3 cm. The instrument used for taking the observations was a standard automatic tide gauge, accurate to 3 cm (Symons, personal communications). Averaging the sea-level values over 30 points in the filtering process reduces the random error to about 0.5 cm. Many sources of error remain. Tidal constituents of long period (that is, fortnightly, monthly, and semi-annually) are not removed by the X_0 filter, but are small in any event. The elevations of reference tide staffs were observed to change during the period of observation by as little as 0.6 cm at Brookings up to 4.2 cm at Brighton; corrections were made to the records to compensate for the staff shifts

(Symons, personal communications). Upon consideration of all sources of error, a daily value of sea level is believed accurate to 1 cm.

The poorest quality data used were the wind observations. The uncertainty in a single calculation of wind velocity is of the order of $\pm 20^{\circ}$ in direction and $\pm 20\%$ in speed (Bunting, 1963). The isobaric contours on weather maps over the ocean are highly uncertain due to the relative paucity of observations. The technique by which surface winds are calculated is empirical and a fairly crude approximation at best. The wind-stress equation introduced further error. C_D is not well known. Wind stress may well be a function of higher-order wind velocity terms than second, and of other variables such as rainfall. The impact of all these error contributions to the final value of wind stress is considerable. A particular value of wind stress in the present study can be good to little better than 1 dyne/cm^2.

While large, the errors discussed are probably randomly distributed. There was no detectable bias to the distribution of these errors. Upon examination of the distribution of the signed differences between the estimated daily value of sea level from the final equations and the values of adjusted sea level, however, a bias by month was noted, an error of a different kind than those just discussed. At all stations, the adjusted values were lower than the estimated values significantly more than half the time at the 5%

level for June, July, and August. At all stations, the adjusted values were higher significantly more than half the time at the 5% level for December and January.

If the only contribution to the inaccuracy of the final solution were the errors discussed in this section, one would expect a random distribution of the differences by month. Since this situation does not exist, adjusted sea level is likely a function of other variables than wind stress alone (or of higher-order terms or of terms of different form than those considered). A prime candidate as a variable of consequence in changes of sea level is rainfall, particularly along the Oregon coast. Therefore, the relationship of sea level and rainfall was examined. The results of this examination are presented in the next chapter.

EFFECT OF RAINFALL ON SEA LEVEL

In this chapter the relationship between rainfall and sea level is examined.

During 1933-34, rainfall was recorded daily at North Bend, adjacent to Coos Bay, and at Tillamook, adjacent to Brighton, by the Weather Bureau (1933 and 1934). Daily rainfall was not recorded at or near Newport during 1933-34.

December 1933 and January 1934 were unusually rainy months. At Tillamook, 35. 78 in of rain fell during December and 17. 11 in during January.

A graphical test of the relationship between rainfall and sea level was conducted. The particular test used was the medial or quadrant test (Quenouille, 1952). In this test rainfall was plotted against sea level. The graph was first divided into two equal parts by a line perpendicular to the x-axis. A medial line perpendicular to the y-axis was then drawn which divided the graph into four quadrants. The number of points in one of the quadrants was counted. If the number was too few or too many, a statistically significant association between the two variables may be inferred.

The medial test was conducted for December 1933 and January 1934 for the North Bend-Coos Bay and Tillamook-Brighton pairs of stations. The three-day sum of rainfall, with the third day of the sum the day of interest, was plotted against the departure of adjusted sea level, Δh, for the given day. It was considered that rainfall would affect sea level both directly at or near the tide gauge and indirectly by runoff from the drainage basin of the estuary. A three-day sum was used because the majority of the rainfall effect is expressed at the mouth of the estuary within three days after falling. In typical Oregon estuaries, with soil saturated in the drainage basin, the river will crest within 24 hours after a heavy rainfall and the majority of the runoff will take place within 48-60 hours (Kulm, 1965; Sparks, personal communications).

The graph of rainfall versus sea level for December 1933 at the Tillamook-Brighton pair of stations is presented as Figure 8. For this month, rainfall and sea level are significantly associated at the 1% level. Significant associations at the 1% level also existed for January 1934 at Tillamook-Brighton and for December 1933 at North Bend-Coos Bay. Rainfall and sea level were significantly associated at the 5% level for January 1934 at North Bend-Coos Bay.

Thus, along the Oregon Coast, heavy rainfall does have an appreciable effect on sea level. The nature of this effect is visualized as two-fold. The first factor is the local addition of mass, both by the amount of rain falling at or near the tide gauge and by runoff from the drainage basin of the estuary (Montgomery, 1938). This factor is likely to be of consequence only in the presence of unusually

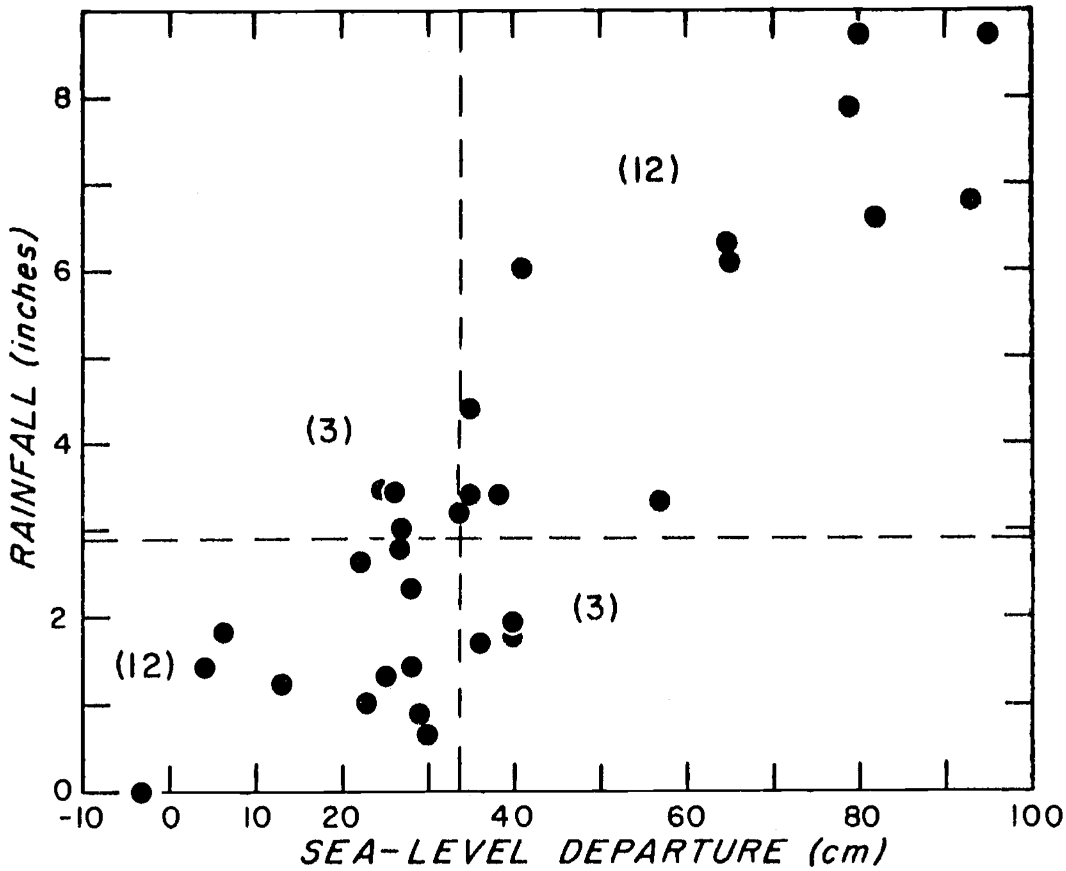

Figure 8. Medial test of relationship between rainfall and sea level at Tillamook-Brighton for December 1933. Rainfall is three-day sum (in), the third day in the sum being the day of interest. Sea level is the departure of adjusted sea level (cm) for the given day. In this example, rainfall and sea level are significantly associated at the 1% level.

heavy rainfall with the soil saturated throughout the drainage basin. It is important during the winter months off Oregon and raises sea level above the level to be expected from wind stress alone.

The second factor is the augmentation of wind stress by heavy rainfall (Van Dorn, 1953). This factor would effectively increase the wind stress on the day of the rainfall but would likely have little persistence beyond the end of the rain. It is important any time during the year when a high rate of rainfall occurs, and can be expected either to raise or lower sea level depending on the direction of the wind.

In order to examine the two probable contributing factors to the rainfall effect in greater detail, further analysis was conducted. I attempted to find correlation between rainfall and the differences between adjusted sea level and estimated sea level as a function of wind stress alone.

Local Addition of Mass

Essentially the same graphical test as described above was conducted between the three-day sum of rainfall and the signed difference between adjusted and estimated sea level. The relationship between the two variables was far less significant than in the test described above. For December 1933 at Tillamook-Brighton the association was significant at the 10% level. For the other tests, the association was not significant.

The poorer correlation can be at least partially explained by the noisiness of the signed differences. The signal-to-noise ratio for the signed differences is markedly lower than for values of Δh themselves.

Augmented Wind Stress

In this phase of the analysis, days of heavy rainfall were sought throughout the eleven-month period of observation. A day for which 0.75 in or more of rain was recorded was arbitrarily considered to be a day of heavy rainfall. At Tillamook there were 47 such days and at North Bend there were 19 such days. For each of these days, the wind stress was examined to see if an augmented wind stress would be consistent with helping to explain the sense of the signed difference between adjusted and estimated sea level.

For the Tillamook-Brighton combination, an augmented wind stress was consistent with the sense of the signed differences of sea level 65% of the time, a significantly high association at the 1% level. For the North Bend-Coos Bay combination, an augmented wind stress was consistent with the sense of the signed differences 80% of the time, a significantly high association at the 1% level.

While more encouraging than the results obtained from the analysis concerning local addition of mass, the situation involving augmentation of wind stress is still not altogether satisfying. If a real effect, the days of agreement between an augmented wind stress and the difference of sea level should have been proportionately distributed throughout the year. There were far fewer rainy days in the summer than in the winter, but even so, agreement was obtained for relatively fewer of the summer rainy days than for winter rainy days. Further, rainfall was recorded for a 24-hour period, which provides a measure of quantity and not of hourly rate of rainfall. In the study Van Dorn (1953) conducted of the augmentation of wind stress by heavy rainfall, it was hourly rate of rainfall which was critical.

Overall Effect of Rainfall

A final consideration is that rainfall and wind are highly correlated along the Oregon coast. Heavy rain is commonly accompanied by winds from the southwest. Thus, regression analysis of the relationship between wind stress and sea level automatically considers a good deal of the effect of rainfall on sea level.

The difficulties of analysis and rainfall measurement notwithstanding, rainfall explains much of the difference between sea level estimated as a function of wind stress alone and adjusted sea level. With improved measurement techniques for rainfall and wind, even more of the rainfall-sea level relationship hopefully can be resolved.

SUGGESTIONS FOR FURTHER INVESTIGATION

The present study can be regarded as yielding preliminary results only. More questions have been raised than have been answered. Many items warranting further investigation have emerged, both regarding additional processing of present data and the future collection of oceanographic data.

Present Data

The regression analysis should be expanded to include sums of τ_y's and τ_x's over periods of time up to eight days, both simple sums and weighted averages, instead of the present four days. The correlation coefficients seen to peak at $\sum_{d=-3}^{0} \tau_y$ and $\sum_{d=-2}^{0} \tau_x$, and experience in statistical work indicates that selection of these values of wind stress as those most highly correlated with sea level is valid (Peterson, personal communcation). To be absolutely certain of the validity of this selection, however, independent variables with greater lags need to be considered.

Stepwise solutions should be obtained at least on a quarterly basis, if not on a monthly basis. All solutions computed in the present study are over the entire eleven-month period. As can be observed from the distribution of the differences with time of year between adjusted sea level and estimated sea level as figured from the final equations, a single simple solution for the whole period does not seem entirely adequate.

Since all data used in this study are of a time-series nature (observations taken at equal intervals of time), spectral analysis could well be a powerful statistical tool in examining the relationship between sea level and wind stress (Hamon and Hannan, 1963). A spectral-method calculation for the data of one station could demonstrate if consideration of the frequency distribution of energy in the sea-level record yields any additional information about the regression relations.

As a corollary to additional calculations with the data presently in hand, computations should be conducted on more recent data to see if they fit the model. A tide gauge is installed at the Marine Science Center of Oregon State University in Newport and has been operating intermittently since May 1964. Part of the record has been reduced, and these data could be tested against the equation obtained for the Newport station from the 1933-34 data.

Future Work

In order to learn more about the details of the relationship between sea level and wind stress, higher quality data and hydrographic observations close in time and space to the sea level observations are necessary.

In the present study, the poorest quality data by far have been the wind observations. Wind measurement seems to be a perennial plaguing problem for which no ideal solution has yet been found. Certainly, improvements can be obtained over the 1933-34 situation. Weather maps are now contoured more accurately over ocean areas, and are available four times a day. The preferable alternative would be some sort of direct and frequent wind observation in the coastal oceanic environment from a buoy, barge, or tower.

Tide gauges need to be installed along the Oregon coast in exposed locations. In addition, offshore tide gauges near the edge of the continental shelf need to be installed so that the slope of the sea surface can be calculated and the nonisostatic contribution of wind velocity due to changes in wind velocity separated from the steric contribution.

Supporting hydrographic observations of temperature and salinity are necessary. Hydrographic observations would provide the required information so that computations of steric variation can be made.

A fringe benefit of a coastal network of tide gauges in Oregon would be to make possible examination of the nature of the latitudinal boundary between the predominance of the steric contribution to the seasonal variation of sea level and the predominance of the inverted-barometer effect. Other expected benefits would include opportunities to learn more about continental shelf waves, planetary waves, and tsunamis.

SUMMARY AND CONCLUSIONS

In the present study the relationship between wind stress and sea level has been examined for a zone of known upwelling.

Sea level was highly correlated with wind stress during the 1933-34 period of observation along the Oregon coast. The wind stress-sea level relationship for 1933-34 is believed representative of the Oregon coast during other years and is consistent with the general long-term situation along the west coast of North America.

From Oregon north, sea level and the longshore component of wind stress are in good agreement. The relationships at Crescent City and San Francisco are not in such good agreement. This situation coincides with the findings at Brookings in the present study and with the view of a different oceanic regime south of Cape Blanco.

Along the Oregon coast, sea level was most highly correlated with the north component of wind stress summed over a four-day period. Sea level was next most highly correlated with the east component of wind stress summed over a three-day period. The sense of the correlation was such that a southwest wind was associated with raising of sea level and a northeast wind with lowering of sea level.

The wind stress-sea level relationship is consistent with what is known of upwelling occurring off Oregon within the oceanic frontal system. The changes in sea level are believed related to the isostatic effect of steric variation and to the nonisostatic effect due to changes in wind velocity.

The relationship between rainfall and sea level was also examined. This relationship was not so clearcut as the effect of wind stress on sea level. Nonetheless, rainfall contributes to changes in sea level both through local addition of mass and through augmented wind stress.

Finally, much additional work remains to be done before powerful answers can be reached on the details of the relationship between sea level, winds, and upwelling off Oregon. It is hoped that this study has placed the problem in clearer focus, posed a few of the cogent questions involved, and laid some of the groundwork for profitable future investigations. Work in the years to come may well demonstrate conclusively that sea level can be used as a valid, sensitive, and convenient indicator of upwelling and other oceanic motions, and to assist in the measurement of effective wind-stress relations.

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APPENDICES

APPENDIX I

List of Symbols

cw	Clockwise rotation
ccw	Counterclockwise rotation
d	Day with respect to day of adjusted sea level under consideration
Δh	Departure of adjusted sea level for a particular day from average sea level over period of observation for that station
p	Value of individual observation of atmospheric pressure
$\overline{p}$	Daily average value of atmospheric pressure
r	Coefficient of linear correlation
s. e.	Standard error
$x(t)$	Observed value for point under consideration
$x^*(t)$	Estimated value for point under consideration
$x(t+1)$	Observed value for point one observation interval following point under consideration
C_D	Drag coefficient of wind on sea surface
R^2	Square of multiple correlation coefficient
$\vec{U}$	Wind velocity
ρ_a	Density of air
$\vec{\tau}$	Wind stress on sea surface
τ_x	East component of wind stress
τ_y	North component of wind stress

APPENDIX II
Comparison Between Computed and Observed Winds

The only available source of information on surface winds in the area off Oregon during 1933-34 was daily pressure maps. To investigate the agreement of such wind estimates with direct observations, it was necessary to make a comparison for a different period of time.

Accordingly, I acquired three different sets of wind observations for the purpose of comparison from a 35-day period during the summer of 1965. Surface winds were computed from sea-level weather charts compiled by Adair Air Force Station, Corvallis, Oregon. Direct observations of wind taken at a height above water of ten m came from the YAQUINA, research vessel of the Department of Oceanography, and the oil-drilling barge, WODECO III. Figure 9 shows the respective locations of YAQUINA and WODECO III during this period and the point for which winds were computed.

Comparisons were conducted between the computed winds and the direct observations taken aboard YAQUINA and WODECO III for those times when observations coincided. Table III presents the results of these comparisons.

The results show that the computed winds and the observations taken aboard YAQUINA are in basic agreement. Regrettably, however, observations from WODECO III do not seem reliable, on the basis of comparison with the other two sets of data. A further

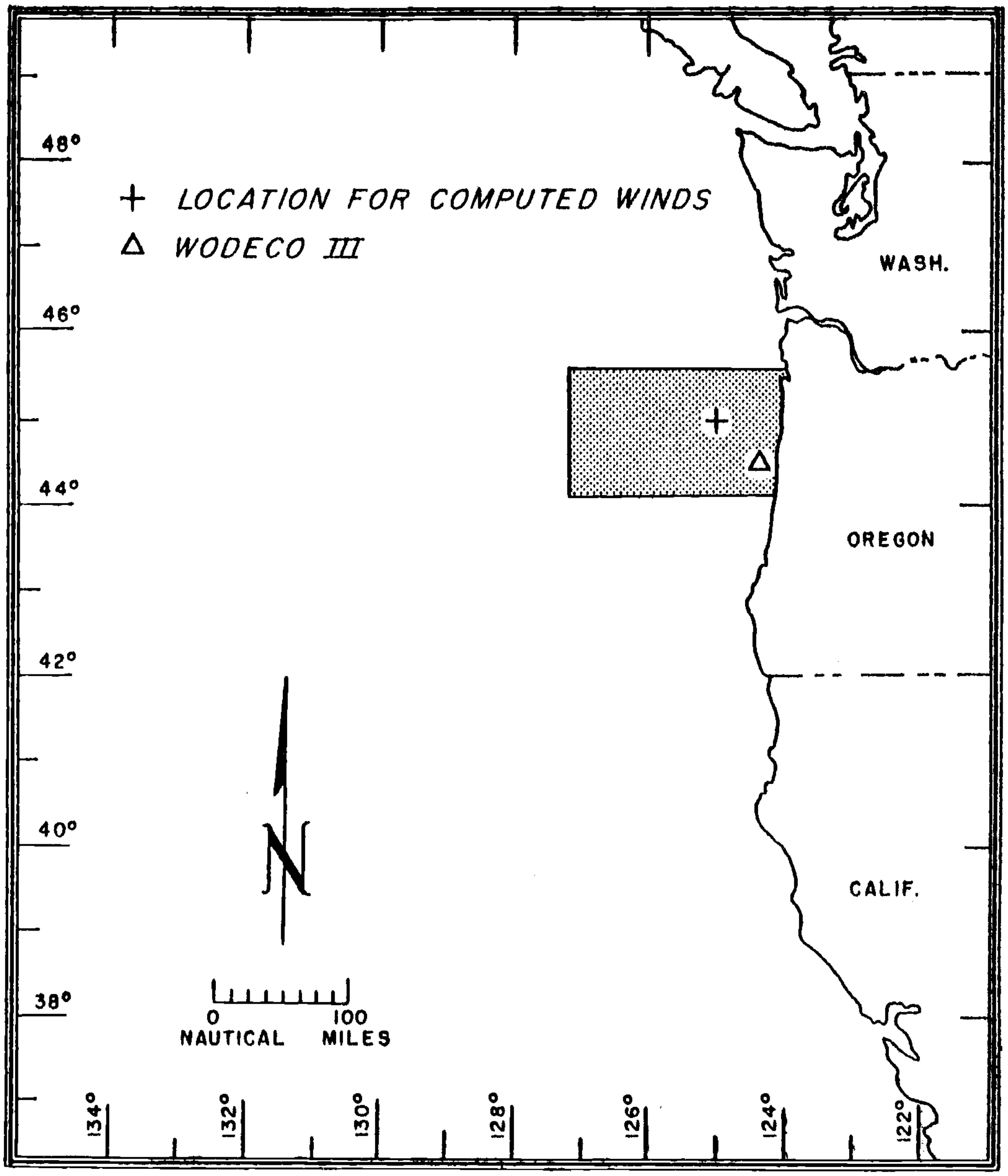


Figure 9. Locations of wind observations, 16 August-19 September 1965. Shaded area shows general area of operations of R/V YAQUINA during this time.

Table III. Comparison Between Observed and Computed Winds.

A. Average Unsigned Differences

	Direction (°)	Speed (kts)
Computed vs. barge	50	6
Computed vs. ship	20	7
Ship vs. barge	35	8

B. Distribution of Signed Differences

	With Respect To	Direction*	Speed
Computed	barge	81% cw 14% ccw 5% no diff.	64% higher 29% lower 7% no diff.
Computed	ship	64% cw 9% ccw 27% no diff.	14% higher 79% lower 7% no diff.
Ship	barge	63% cw 25% ccw 12% no diff.	100% higher 0% lower 0% no diff.

*cw means clockwise rotation; ccw means counterclockwise rotation.

comparison conducted between ship and barge (results not included in Table III), for a period of time when the ship was operating in close proximity to the barge, confirm the lack of agreement.

A possible partial explanation for the difference between the computed winds and YAQUINA observations may lie in the procedure used to estimate the surface wind from the geostrophic wind. Other investigators (Smith et al., 1966) have estimated the surface wind by rotating the geostrophic wind vector 15° to the left of the downwind direction and multiplying the geostrophic wind speed by 0.70, whereas I used 10° and 0.65. If I had used the procedure of Smith and others, the difference between the computed winds and YAQUINA observations would have been reduced.

APPENDIX III

Spatial Correlation of Atmospheric Pressure

Observations of atmospheric pressure from North Bend were used as representative of the Oregon coast. To test the validity of this assumption, I obtained data for 1933-34 from North Head, Washington, and Eureka, California, and computed linear regression of North Head on North Bend, and of Eureka on North Bend.

At each station, six observations per day were available. For the test I used the first twenty-days of May, August, and November 1933, and of February 1934. I computed linear regression separately by month for the two groups of two stations, eight tests in all.

The results of the linear regressions are summarized in Table IV. In all tests there is a consistently high coefficient of linear correlation, significant in all cases at the 1% level, and a consistently small standard error. One notes that on the average the North Head-North Bend set has somewhat higher correlation coefficients, but also larger standard errors, when compared with the Eureka-North Bend set.

Table IV. Results of Calculations of Linear Regressions for Atmospheric Pressure Comparisons.

	North Head-North Bend		Eureka-North Bend	
	r	s. e., mb	r	s. e., mb
1-20 May 1933	+0.97	1.5	+0.88	1.7
1-20 Aug 1933	+0.71	1.3	+0.58	2.2
1-20 Nov 1933	+0.72	3.0	+0.67	1.7
1-20 Feb 1934	+0.95	1.9	+0.96	1.2

Throughout the 1933-34 period of observation, atmospheric pressure was highly correlated for that portion of the Pacific coast of North America bounded by North Head to the north and by Eureka to the south, a distance half again as great as the separation between the northernmost and southernmost of the Oregon sea-level stations used. By averaging over the eight individual tests, the 5% confidence level for a single observation is placed at $\pm$ 4 mb. Therefore, one may conclude that observations of atmospheric pressure from North Bend are adequately representative of the Oregon coast for 1933-34.

APPENDIX IV

Error Detection and Correction

Data need to be checked for gross errors. These errors may be either from mechanical sources (e. g., equipment malfunction) or, as is more likely, from human sources (e. g., mistakes in reading, transcribing, and key-punching).

A simple method of error detection for time-series data is to test each value against the linear estimate between the values of the point immediately preceding and the point immediately following the point under consideration. This method, however, is crude and inaccurate. For data like sea level and atmospheric pressure, with relatively high noise and involved oscillations, the linear-estimate method of error detection is inadequate.

Mr. David Cartwright of the National Institute of Oceanography, Wormley, Surrey, England, suggested a more satisfactory procedure for the present study (personal communications). This procedure is based on a low-pass filter, which has the desirable characteristic of passing the low-frequency energy typical of the harmonic oscillations of the tides and of pinpointing the high-frequency energy typical of most errors. The filter approximates a value for a particular point by estimating the effect of low-frequency sinusoids from the values of the three points immediately preceding and of the three points immediately following the point. The interpolation formula, in reduced form, for this procedure is:

$$x^*(t) = 0.75[x(t-1) + x(t+1)] - 0.30[x(t-2)+x(t+2)] + 0.05[x(t-3)+x(t+3)]$$

where:

$x^*(t)$ = estimated value for point under consideration;

$x(t-1)$, $x(t+1)$ = observed values for points one observation interval preceding and following, respectively, the point under consideration;

$x(t-2)$, $x(t+2)$ = observed values for points two observation intervals preceding and following, respectively, the point under consideration;

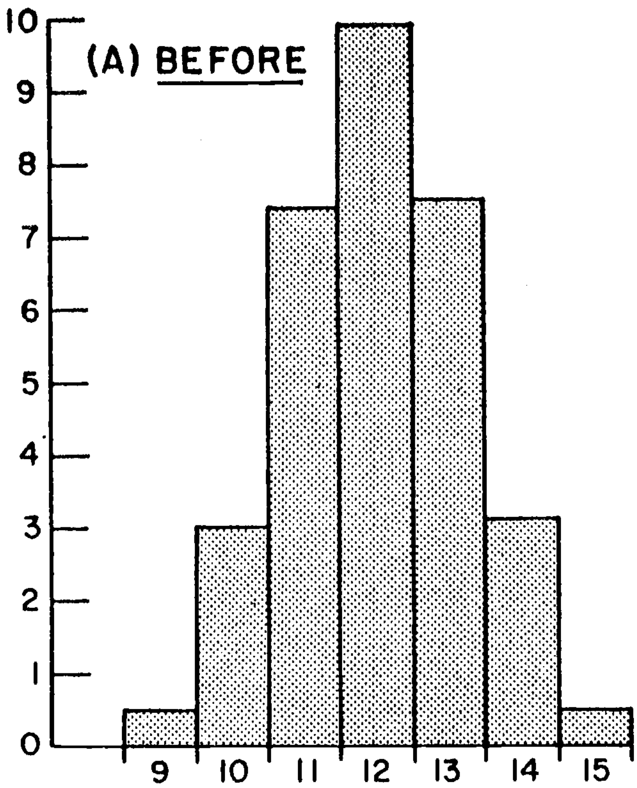
$x(t-3)$, $x(t+3)$ = observed values for points three observation intervals preceding and following, respectively, the point under consideration.

The observed values for the point under consideration, $x(t)$, is compared with $x^*(t)$. When $|x(t) - x^*(t)| \geqslant k$, where k = some specified value, then that $x(t)$ is considered as possibly erroneous. In the event of a serious error, there will be a symmetrical cluster of apparent errors, with the actual error central in the cluster. The larger the magnitude of the error, the larger will be the cluster. Those values judged to be real errors are discarded, and are replaced by the estimate, or by the proper value if upon inspection the error is obvious.

Figure 10 illustrates this procedure. For the sea-level data from Coos Bay for the hours 0900-1500 on 23 August 1933, a cluster of apparent errors appears in the upper portion of the figure, with 1200 central and an absolute difference between the recorded and estimated value of 9.9 ft. For 1200, $x = 19.0$ ft and $x^* = 9.1$ ft. In this instance the error seemed obvious, and 9.0 ft was substituted for x rather than the value of x^*. The lower portion of the figure shows the effect of this single substitution. All absolute differences are reduced to an acceptable level and no apparent error remains.

A computer program was written to implement this error-detection procedure. The program was used on raw data for observations both of tidal heights and atmospheric pressure. After rejecting values considered to be faulty and supplying replacements, the data were run through the program again. This rerun ensured that all values were now satisfactory (i. e., varying smoothly with time within a desired tolerance), all errors having been detected and corrected.

For observations of tidal heights, a rejection level of 0.3 ft was used. This was the level which preliminary computations suggested. A total of 32,133 data points for tidal heights were examined, with the result that 292 points, or 0.91%, appeared as



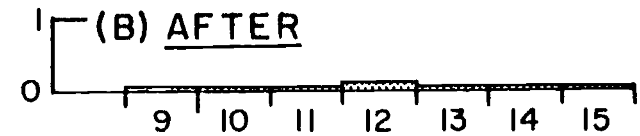


Figure 10. Illustration of error-detection and -replacement procedure. This example presents hours 0900-1500 for 23 August 1933 at Coos Bay. The graphs show the absolute difference between the recorded value and the estimated value of sea level, $x(t) - x^*(t)$, hour by hour (ft). (A) shows the situation before rejection and replacement of the value for 1200, and (B) the situation after.

possible errors. Of these 292 points, 118 points, or 0.37%, were rejected and replaced.

For observations of atmospheric pressure, a rejection level of 0.06 in of mercury was used. This was the level which appeared appropriate on the basis of preliminary computations. A total of 2,010 data points for atmospheric pressure were examined, with the result that 33 points, or 1.65%, appeared as possible errors. Of these 33 points, 15 points, or 0.75%, were rejected and replaced.