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METEOROLOGICAL TREND AND THE APPARENT RISE IN SEA LEVEL ALONG THE SOUTH CAROLINA COAST

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ABSTRACT

The height of the level of the sea at any time, exclusive of the astronomical tide, is closely related to the atmospheric pressure and the prevailing wind. Where the gaging station is situated on a tidal river the precipitation over the drainage basin may also be an influence. Important secular trends of these three elements are noted during the history of the tide gage at Charleston, S. C. The progressive rise in sea level as indicated by this gage may have been influenced by these trends.

1. INTRODUCTION

In the 22-year period from 1926 through 1948, sea level has apparently increased by 0.8 foot at Charleston, S. C. If this rise were to continue for the next 30 or 40 years Charleston would have to be diked to keep the sea water out, for much of the peninsula upon which the city is built lies just at the higher high tide level. However, during the years 1949 and 1950 the computed sea level indicates an abrupt drop of almost 0.4 foot. From 1950 through 1954 there has been little change.

Much popular apprehension has resulted from this rather alarming rise. The explanations of the rise, since it is a relative question between land and sea, have resolved into two hypotheses: (a) an increased supply of water along the coast, (b) a subsidence of the land mass. These hypotheses, considered either separately or in conjunction, have not been accepted as conclusive [1].

The extensive and rapid fluctuation in the level of the sea (up 0.4 ft. and down 0.4 ft.) at Charleston during the 5-year period from 1945 to 1950 strongly suggests the weather as the cause. A substantial change in the frequency of the wind from effective directions may possibly be of importance here, as well as the underlying influence of the general trend since 1926. For it should not be ignored, in accepting a rate of rise, that measurements of sea level obtained from gages along the upper portion of the Continental Shelf are affected by important meteorological elements [2]. Yearly variations of the sea that depart from the general trend are attributed to the disturbing effects of wind and weather which are not repeated exactly [3]. In this paper it is desired to present some limited evidence that a portion of the total rise may be traced to the effects of secular trends in wind, precipitation, and pressure.

2. EFFECTS OF METEOROLOGICAL ELEMENTS

WIND

Figure 1 shows the location of the Coast and Geodetic Survey tide gage and the Weather Bureau station at Charleston, S. C., from which the data appearing herein were obtained. The tide gage is a standard automatic type furnishing a continuous trace of the water level. It

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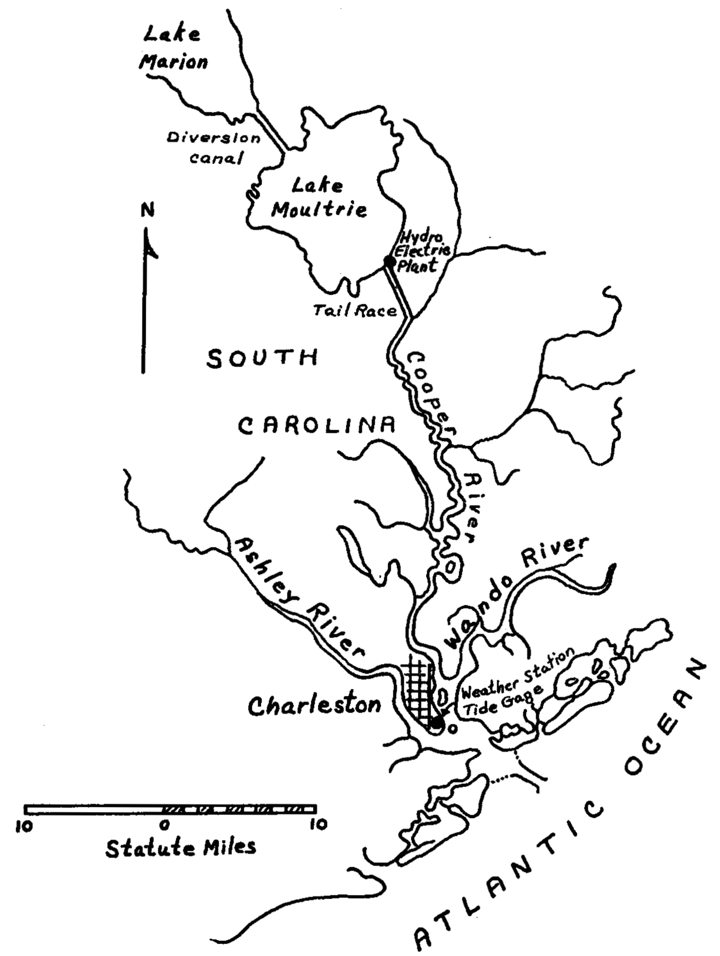

FIGURE 1.—Location of tide gage and weather station in relation to harbor at Charleston, S. C.

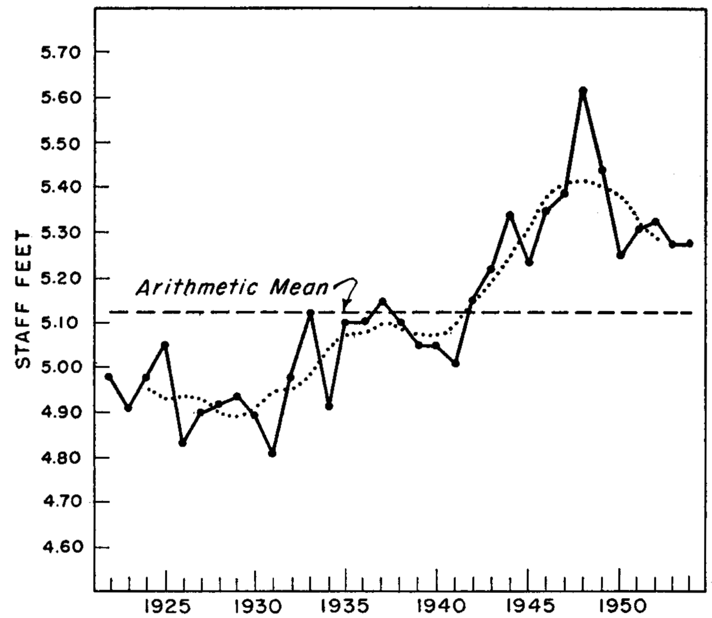

FIGURE 2.—Annual mean sea level (solid line) and moving 5-year averages (dotted line) at Charleston, S. C. over period of record. (Heights are referred to zero of the tide staff.) Note: Tide planes for Charleston are based on gage records for the 19-year period 1924–1942. Mean low water for this period corresponds to a reading of 2.3 feet on the staff of 1921. Gage heights are referred to the staff of 1921 and can therefore be referred to mean low water by subtracting 2.3 feet. The mean low water to which predicted heights refer is determined with relation to mean sea level. This relation is 2.7 feet at Charleston. Referred to a fixed datum the height of mean low water is affected by changes in sea level so that observed heights when referred to mean low water will depend on which particular years are used as a basis of mean low water determination. (This information has been kindly furnished by the Coast and Geodetic Survey, Washington, D. C.)

is situated about six miles from the open sea, on the edge of a deep channel, in a spacious harbor, into which empty three main streams: the Ashley, the Cooper, and the Wando Rivers—none of which have extensive drainage basins. In 1942 a hydroelectric plant began diverting Santee River water into the Cooper River through turbines. No bypass is released into this stream.

The weather station has been in continuous operation at this same location since 1897. The tide gage, located only a few hundred yards away, was established in 1921. The year 1922 is the first complete year of tide record. The height of the wind vane, which is 92 feet above the ground, and its location have remained unchanged since its installation. The city has had no room for expansion in the vicinity of the station, and neither tall buildings nor obstructions have interfered with the entire record. The exposure is considered excellent. The record is autographic on multiple register for wind and precipitation.

Figure 2 indicates graphically the annual mean sea level at this city. The moving 5-year averages show the general trend, eliminating the up and down changes from year to year. The significant rise from 1945 through 1948 and the abrupt fall from 1948 through 1950 are evident. This short-period fluctuation of almost 0.4 foot must be caused by wind and weather or by the operation of the hydroelectric plant. Mayport, Fla., exhibits a graph of mean sea level similar to Charleston's [1] during this period and it appears unlikely that the fluctuation can be attributed to the plant. Zetler [1] has ascribed a rise of 0.09 foot at Charleston to this diversion since 1942 and has shown the large reduction in salinity.

Any explanation of the rise involving the elements of wind and pressure should not be restricted to the harbor alone. While some minor influence must occur within its confines, the major influence is produced over the ocean and on the upper limits of the Continental Shelf. The more noticeable daily variations can be observed on the outer beaches and waterways not closely connected with the harbor.

It is commonly supposed by those who live along the coast that a wind blowing toward the shore raises the level of the sea while a wind blowing from the shore lowers it.

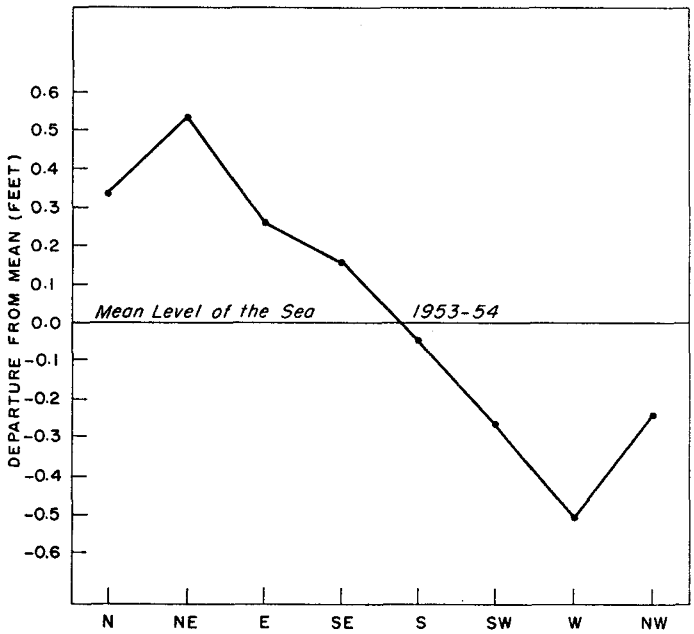

Figure 3.—Departure from the mean level of the sea, Charleston, S. C., 1953–1954, with persistent (6 hours or more) winds from the principal directions for the same period.

A more careful study will show that this is not entirely true, for the coastline from Cape Hatteras, N. C., to Savannah, Ga., extends northeast-southwest and yet a prevailing north wind at Charleston will be accompanied by considerable rise while there is little change with a south wind. To explain these effects of the wind on the water level, it may be said briefly that the wind through friction generates a current of ocean water that is forced upward on the Continental Shelf and impinges on the coastal slope [4]. These currents depend on the direction, duration, fetch, and force of the wind. The local wind may not always be representative of the condition producing the variation in the sea. In addition, the currents as a general rule move or set to the right of the wind flow. Specific measurements of wind-driven currents have been made at the lightships along the Atlantic Coast [5].

Figure 3 shows the average variations in the sea expressed as the deviation from the mean level of the sea (observed less predicted tides) that have occurred at the Charleston station during the period 1953–1954 with the wind at each of the cardinal and intercardinal points. In determining these values, only winds of persistent direction for 6 hours or more were used. At the end of at least 6 hours persistency the actual successive high and low tides were compared with the predicted tides for the same time and the differences noted. These residuals were averaged for each direction and plotted in the graph. Continuous readings of high and low water were used as long as the wind direction did not vary. It should not be assumed that the extent of the variations for every year of record would have the same values. But it can be assumed that the north, northeast, and east winds

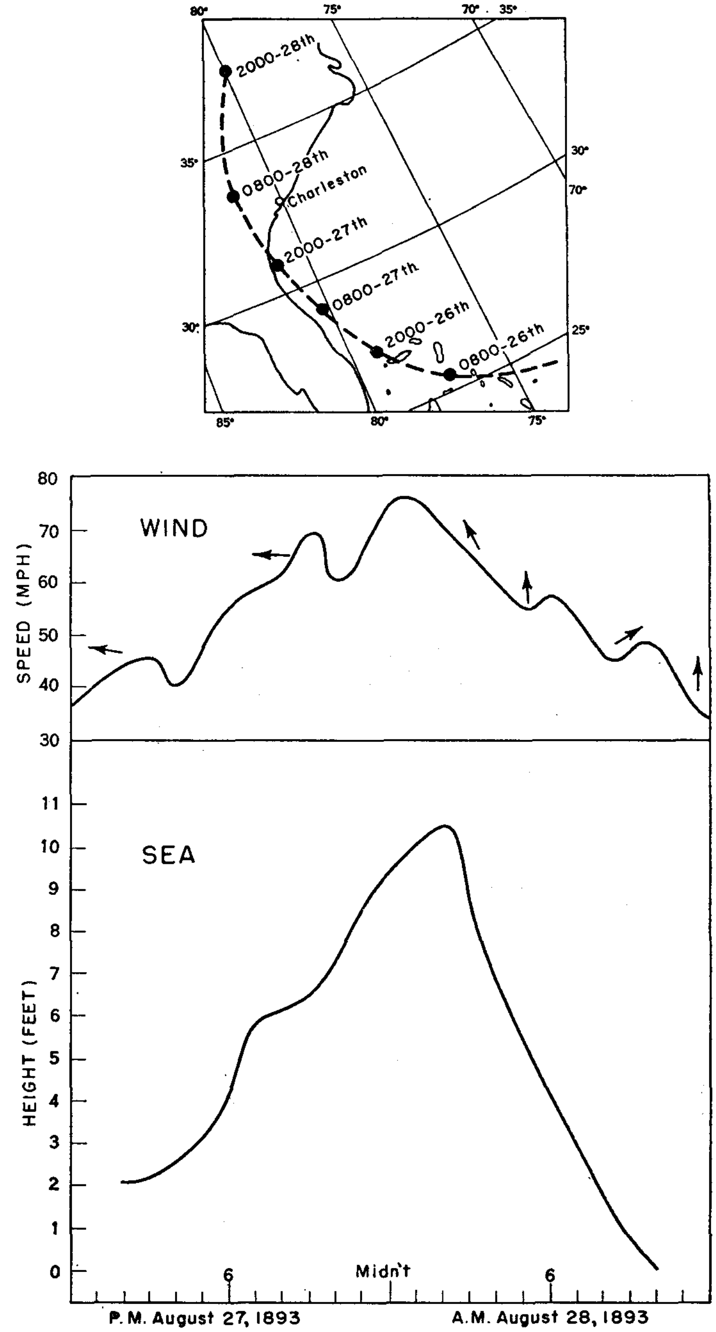

Figure 4.—Effect of hurricane of August 27–28, 1893, on the level of the sea at Charleston, S. C. The curve of sea height shows the approximate variation due to wind and pressure, the predicted tides having been removed. (Based on graph by E. P. Alexander, *Monthly Weather Review*, May 1896.) The map shows the track of the hurricane from August 26–28. (*Monthly Weather Review*, August 1893.)

produced higher water levels and that the southwest, west, and northwest winds produced lower water levels throughout the record. In this study the directions are grouped into those that produce obvious rises and those that produce obvious falls in the level of the sea: N-NE-E and SW-W-NW. The average departures accompanying

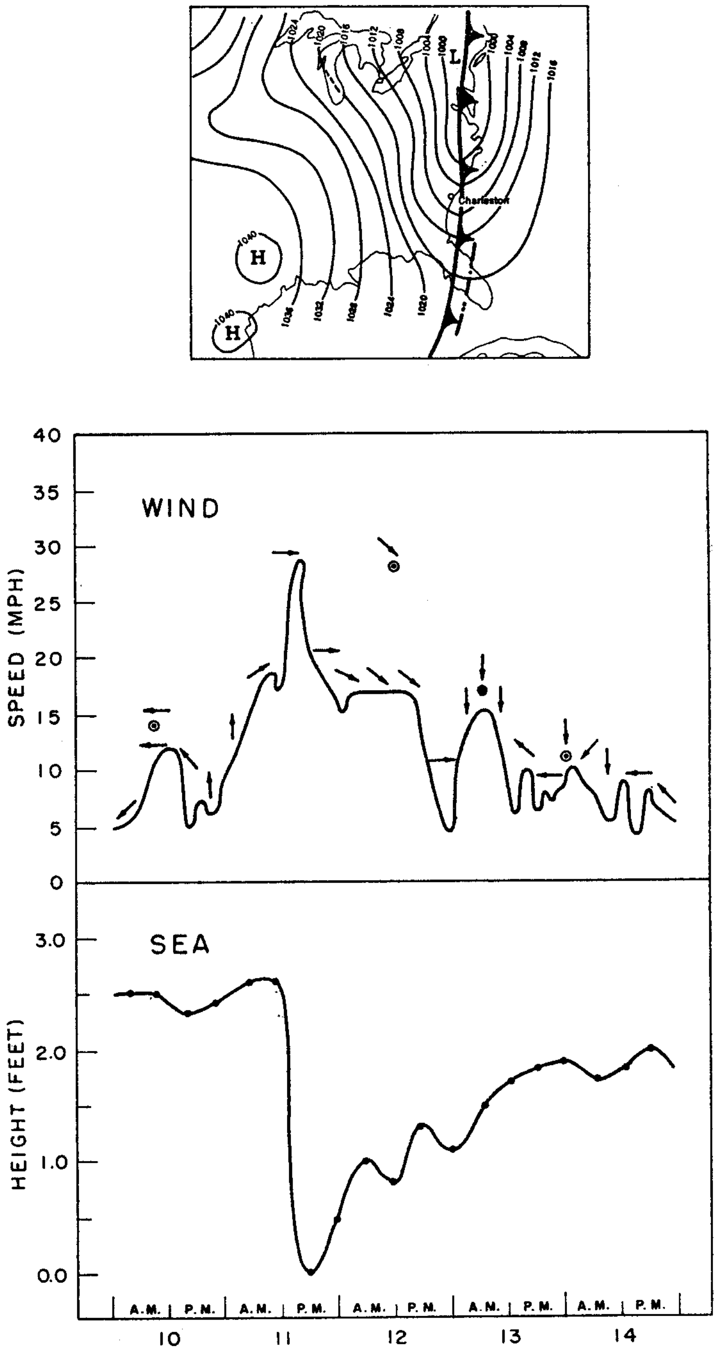

FIGURE 5.—Variation in the level of the sea (predicted tides removed) at Charleston, S. C., February 10–14, 1955, with strong westerly winds following a frontal passage. In wind graph arrows indicate direction according to the usual convention; circled dot below arrow indicates fastest full mile. Weather situation is shown by the map for 1:30 p. m. EST, February 11, 1955.

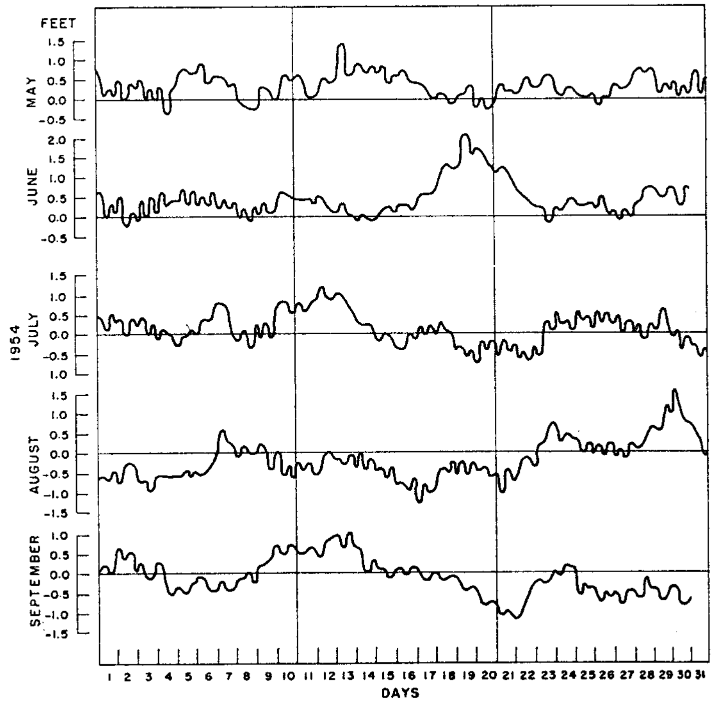

FIGURE 6.—Continuous variation in the level of the sea at Charleston, S. C., May through September 1954. Departures are based on sea level for 1954 and are the differences between the actual, and predicted tides. The departures may be attributed to disturbing meteorological effects.

the southeast and south winds are small. Consideration will not be made of these two directions in the development of the discussion.

The extent of the elevation or depression of the sea (predicted less observed tides) at Charleston may be from about 8 to 10 feet above the height of the predicted tide during the most violent hurricane to about 3 feet below with intense westerlies. An analysis of the hurricane of August 27–28, 1893, as it affected the water level at Charleston is presented in figure 4. The predicted tides occurring during the hurricane have been removed. The remaining effect may be attributed to the storm for the purpose of giving a fair idea of what the wind and pressure can do. In figure 5 the influence of some strong westerlies on the level of the sea following a frontal passage is represented.

In defining sea level, it is sufficient here to say that mean sea level is the average of the tabulated hourly heights of the tide and includes changes brought about by meteorological causes [3]. That these changes due to the weather are considerable and continuous may be noted in figure 6. In deriving the curve for this figure the actual heights at time of high and low water were compared with the predicted heights as they appear in the tide tables for this port. The predicted heights of the tide were referred to mean low water for that particular year and are based on the astronomical tides adjusted to the "normal" seasonal effects of wind and weather [2]. The difference between these two values is a reasonable estimate of the extent of the effect on the sea of the wind and weather prevailing at the time of the measurement.

In figure 7, the relative frequency in hours of the combined north, northeast, and east winds each year from 1918 through 1954 has been graphed. Records for several other stations along the Atlantic Seaboard were investi-

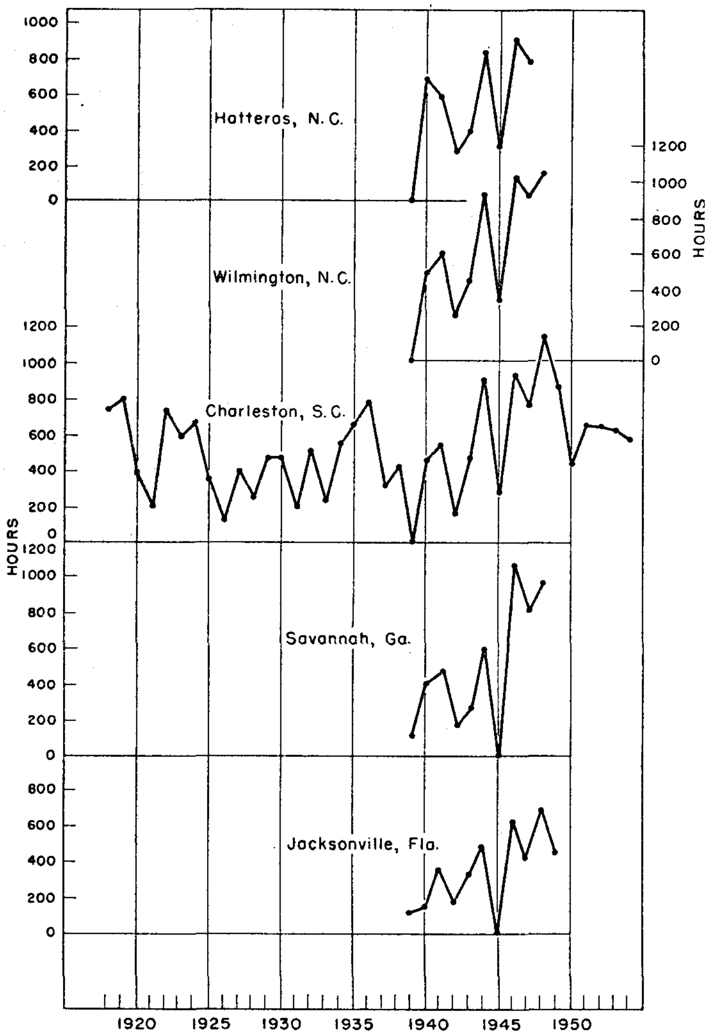

FIGURE 7.—Relative yearly frequency in hours of the combined north, northeast, and east winds at Charleston, S. C., 1918 through 1954, compared with records at other Atlantic Seaboard stations. Prepared from Station Climatological Record.

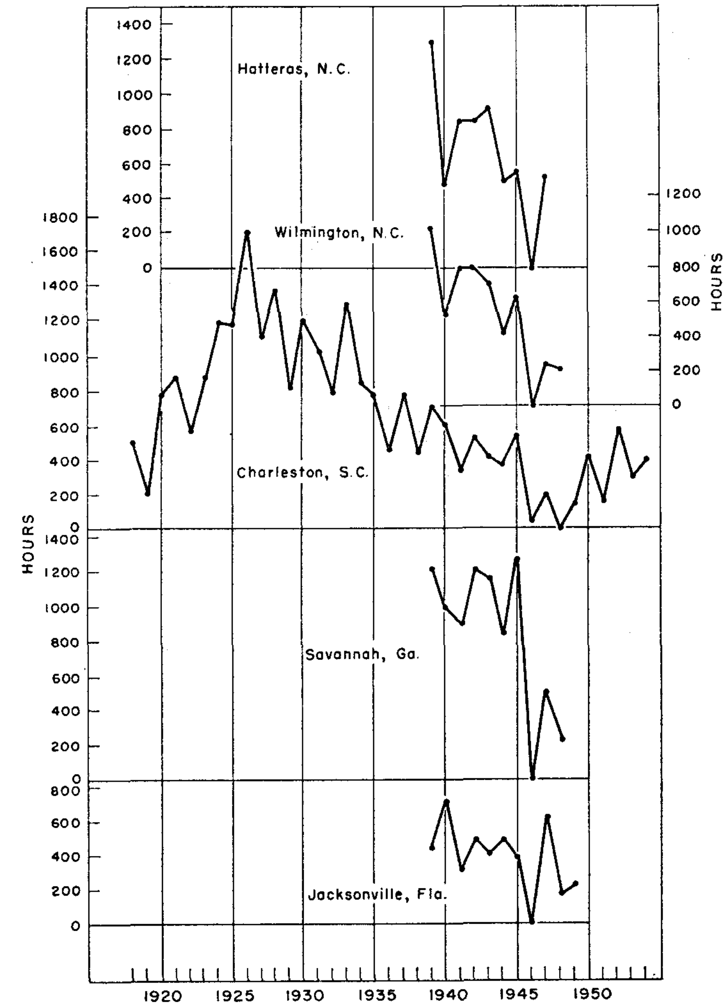

FIGURE 8.—Relative yearly frequency in hours of the combined southwest, west, and northwest winds at Charleston, S. C., 1918 through 1954, compared with records at other stations along the Atlantic Seaboard. Prepared from Station Climatological Record.

gated and also appear in the figure. The comparison appears to assure that the increase of these winds was not just a local phenomenon. The frequency of this group of combined winds for Charleston increased by almost 1200 hours from 1939 through 1948 and was still in 1954 approximately 400 hours in excess of the amount in 1926.

In figure 8, the relative frequency in hours of the combined southwest, west, and northwest winds is shown from 1918 through 1954 for Charleston and a portion of the record for the same stations as in figure 7. From 1926 through 1948 there has been a reduction of these winds of over 1600 hours at Charleston. Here too, the other stations are in general agreement. A pronounced similarity of change has occurred from Charleston northward to Hatteras, N. C. At Savannah, Ga., a sharp reduction is recorded after 1945 that is evidently caused by the station being moved to the airport.

This variation in the wind frequency is no minor change and must have significance also over the ocean adjacent to the coast where the forces are applied to the sea to pile it up or move it away. Undoubtedly this change has been a causative factor in the excessive erosion of the barrier islands along this coast in recent years [6].

If the meteorological elements that have some influence on the level of the sea were consistent, a relation between them and the rise of the sea would be remote. But it is difficult to ignore these important trends, particularly as they are related to the pattern of rise, and since they have not been repeated during the record of the gage.

In figure 9, a graph is presented to show the preponderance of these groups of combined winds (N-NE-E and SW-W-NW) as they have occurred from 1918 through 1954 at Charleston. The zero line indicates equal frequency of the two groups. That is, if the combined north, northeast, and east winds were equal to the combined southwest, west, and northwest winds for any year, the point would fall upon the zero line. That portion of the graph below the zero line indicates a preponderance, or

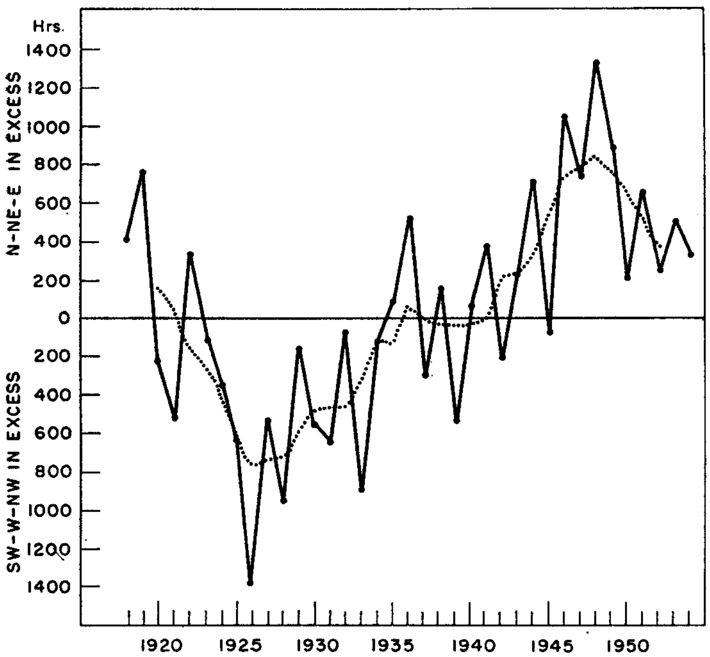

FIGURE 9.—Annual preponderance of N-NE-E or SW-W-NW wind frequencies (solid line) and the moving 5-year averages (dotted line) for Charleston, S. C., 1918–1954. The zero line indicates equal frequency of the two groups. The N-NE-E wind group lowers the level of the sea; the SW-W-NW group raises it.

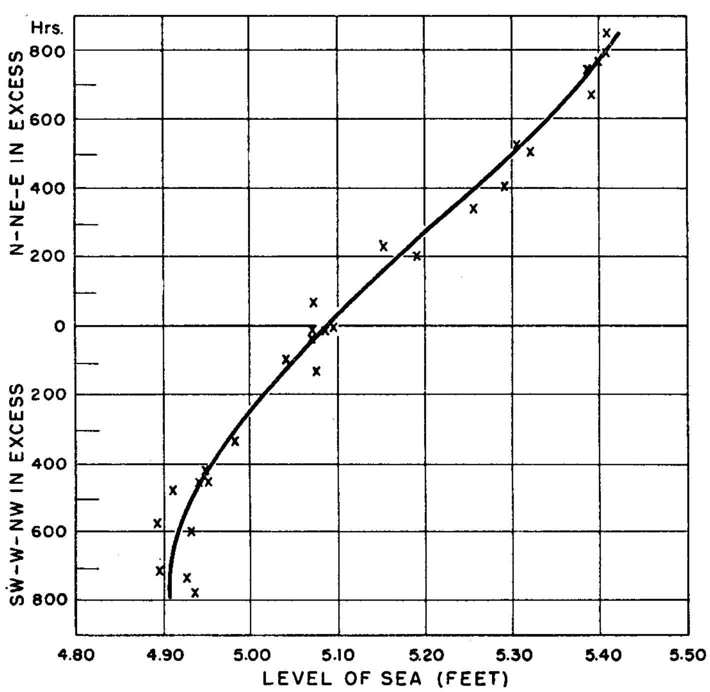

FIGURE 10.—Relationship between 5-year moving averages of wind preponderance and 5-year moving averages of level of the sea, Charleston, S. C., 1922–1954. (Heights are referred to zero of tide staff.)

excess of one group over the other, of winds that lower the sea; and that portion above, a preponderance of those winds that raise the sea. From 1926 through 1948 a progressive variation from southwest, west, northwest preponderance to north, northeast, east preponderance has taken place; a difference of almost 2800 hours. The moving 5-year averages have been computed and graphed to eliminate the sharp yearly changes.

Since it is the writer's intention to present this information in a very general manner only a brief comparison of the moving 5-year averages is made and any slight periodicity that might be introduced by this method of moving averages will not materially affect the broad conclusions intended. If the moving 5-year averages of wind preponderance are entered in a scatter diagram, figure 10, as the independent variable with the moving 5-year averages of sea level as the dependent variable, a close relationship appears to exist. Of course, there must be a limit to the effect the wind frequency can have in changing the level of the water and this may account for the shape of the line of relationship. This limitation (if the winds have been the underlying cause for the excessive rise) provides those of us who live near the sea some consolation, for it is inconceivable that all of our wind would be from the north, northeast, and east and the intensity would keep increasing. So this would leave us to contend with, what this author believes to be the case, a very small rate of rise due to geological causes.

PRECIPITATION AND PRESSURE

It is not obvious that precipitation influences the water level to any great extent within the harbor. The entrance to the open sea is wide and deep; the drainage basins of the connecting rivers are not extensive. But there is a minor effect. Fresh water, being less dense than salt water, will tend to remain in the upper layers "floating" on the more dense salt layers. The coastal plain is flat. There is not much head to the water in the upper reaches of the rivers flowing into the harbor; consequently drainage to the sea is sluggish. Figure 11 shows the yearly precipitation for Charleston and the moving 5-year averages show the trend for the period. The change has been from deficiencies during the period of low sea level to excesses during the period of high sea level. After the year 1947 rainfall began to decline but regulated operation of the hydroelectric plant has continued the flow of less dense water by the gage [1].

The average pressure distribution over the surface of the earth is not equal. Wherever contrasts of high and low pressure exist over the seas the water is depressed under the higher pressure and elevated under the lower. The extent of the movement is masked in shallow water by the effect of the wind which is a function of the pressure gradient. For a stable sea level it would be required that this normal oceanic distribution of pressure not change; or that the continuous changes fluctuate consistently. This would not be expected to occur in the change from glacial to inter-glacial periods, or in the shorter-period climatic and secular fluctuations which are characteristic of, but not as extreme in degree as, the geological [7] [8] [9].

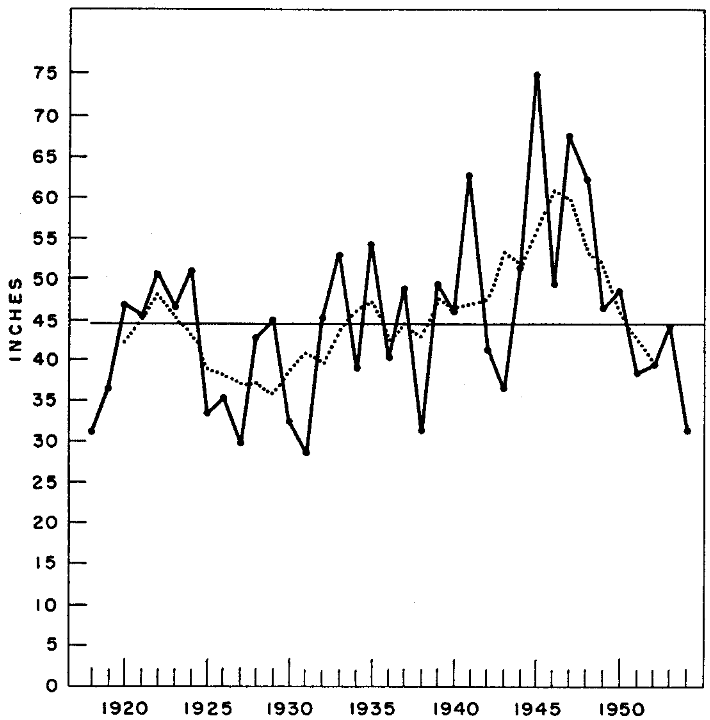

FIGURE 11.—Yearly precipitation (solid line) for Charleston, S. C., 1918–1954, and moving 5-year averages (dotted line).

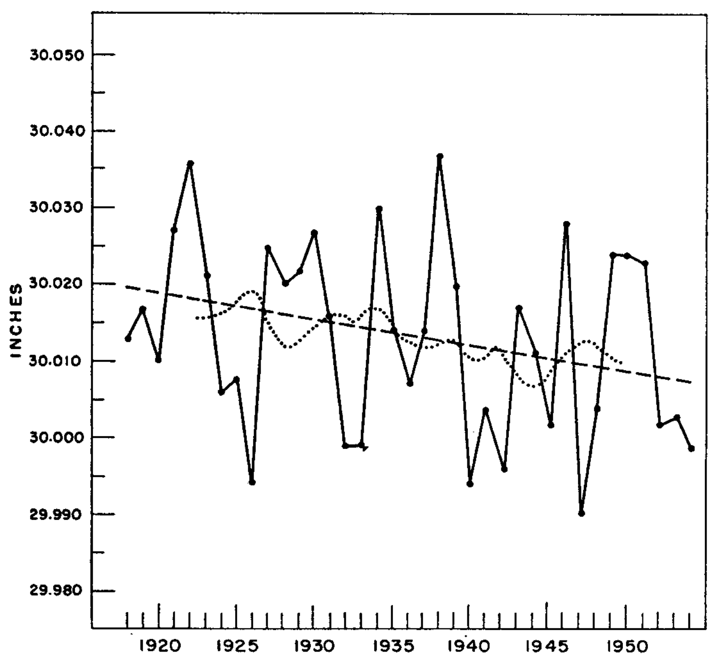

FIGURE 12.—Annual mean station pressure (solid line) at Charleston, S. C., 1918–1954, and the 10-year moving averages (dotted line). Assigned station elevation is 48 ft.

The annual mean station pressure and the moving 10-year averages at Charleston appear in figure 12. The trend has been for lower pressure since the establishment of the tide gage. The change has been very slight but possibly significant in a secular or climatic change.

To sum up the separate trends, figure 13 shows by means

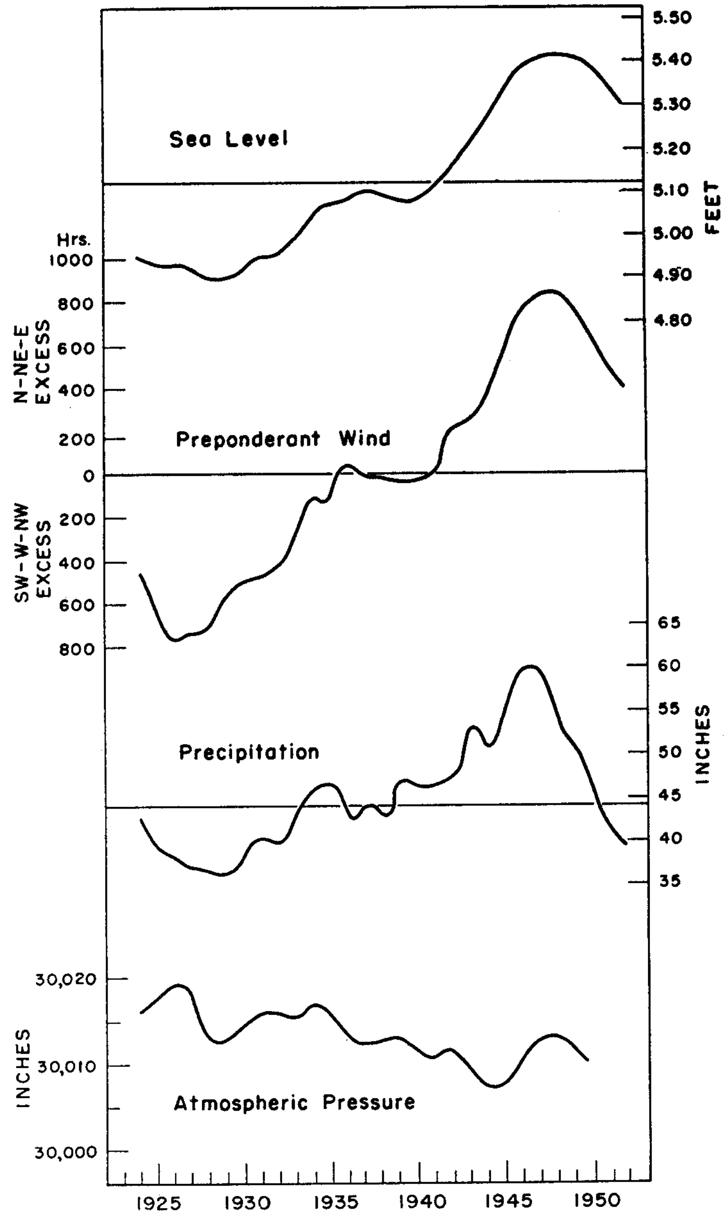

FIGURE 13.—Trend of sea level, wind preponderance, precipitation, and pressure at Charleston, S. C., 1923–1954, taken from moving averages presented in preceding graphs.

of the moving averages the sea level and the meteorological elements as presented in the previous graphs.

3. CONCLUSION

This paper is restricted to local material available to the author and is not intended as a general hypothesis based upon such limited data. There have been changes in the sea level elsewhere than the South Carolina Coast. Some Alaskan stations have recorded a fall in the sea, or a rise in the land, or just the effects of the wind and weather on the water, or perhaps all three. The sea along the Gulf Coast has shown an extensive change. No attempt has been made to apply the reasoning presented here to other sections. However, it is intended in this paper that the question be asked: has the rise in the sea level in the last 25 to 30 years been accentuated directly by a secular trend in phase with a longer climatic trend. Much emphasis has been placed on the geological reasons for the rise in the sea while the important meteorological aspects have not been completely investigated. These weather effects are so definitely related to the height of the sea for the day, week, month, and year that if they are not consistent over longer periods, a change in sea level, as sea level is computed, must occur. The fascinating explanation by Willett [7] [8] of climatic fluctuations, both long and short, may prove the key to the solution of most of the problems of variation in sea level. In any event, it would be interesting to observe the sea level in some future period if the wind, pressure, and rainfall were to return to the same values as occurred from 1926 to 1931.

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Weather Notes

TORNADOES OF BLACKWELL, OKLA.-UDALL, KANS., MAY 25, 1955

The climax of several days of tornadic and severe thunderstorm activity late in May 1955 occurred on the night of May 25. A tornado struck at Blackwell, Okla., killing 20 persons and injuring 250 with property damage in the millions.

About an hour later a tornado struck Udall, Kans., some 40 miles north-northeast of Blackwell. The tornado traveled in a general southwest to northeast direction across the center of town. Most of this south-central Kansas town of about 750 population was leveled. The death toll stands at 80 at this writing, and 250 were injured.

The purpose of this note is to present some personal observations reported to the authors by several eyewitnesses of these disasters.

Braman, Okla.—On the morning of May 25, Mr. H. M. Fox, a farmer who lives 6 miles west and 1 mile south of Braman, Okla. (see fig. 1 for locations), observed an unusual wind storm. His account follows: "The first that I noticed the storm was about 8:30 a. m., and the appearance was of a dense thunderstorm with possible hail. About 8:45 a. m. we had a very strong wind practically out of the south with a little variation to the east. I would estimate this wind at about 70 to 80 miles per hour. What struck me peculiar at the time was that there were no gusts. It was a straight and continuous wind for approximately 15 minutes. This strip of wind in width was probably 2 miles wide. It blew roofs off buildings, tore down steel buildings, TV towers and anything else that wasn't really fastened down. Immediately after the wind let up, we were out surveying the damage and we noticed that the wind would be light and variable and run from cool to hot. During the storm and immediately following, we had no hail and very little rain, probably 0.04 during the storm and afterward. Going on west from my farm, the next 2 or 3 miles had wind but no damage was noticeable. In the next 3 miles (a strip running north and south) there was also heavy damage. Then we had another strip of about 3 miles where there was no apparent damage. Right east of Caldwell, Kans., there was another strip of perhaps 2 or 3 miles that was heavily damaged. That afternoon beginning at 12 o'clock preceding the tornado at Blackwell that night, the skies were of broken clouds and the wind alternated from hot to cold for several hours."

Tonkawa, Okla.—Mrs. Robert C. Walker reported seeing the funnel of a tornado located about one mile east of Tonkawa. Mrs. Walker had a microbarograph in operation at the time. When the tornado was sighted east of town, the barogram showed a sharp fall of about 0.08 inch Hg followed by a sharp rise of about 0.10 inch Hg. (The minimum pressure was recorded at about 2055 CST, however there was no time check with which to determine the accuracy of the time element.) Shortly after 2100 CST the "worst hail in the history of our city" fell but with only light winds. Hail was heavier to the west. Some of the hail that fell in town measured almost 3 inches in diameter.

Blackwell, Okla.—The tornado struck Blackwell, Okla., about 2127 CST. It traveled from south to north with almost complete destruction over a path about two blocks wide, and considerable destruction extended 3 or 4 blocks farther on either side. Mr. Nave, who lives just south of the south city limits of Blackwell, reported a short period of wind and hail (about 2 inches in diameter). Then followed a quiet during which he went outside. Instead of the air being cool following the squall, it was "hot." Then the tornado funnel was sighted approaching from the south. It came with "the roar of forty freight trains." There was lightning all around but not in the immediate vicinity of the funnel.

Mr. B. H. Jones living on the north side of Blackwell, about 4 blocks from the damaged area, reported squally weather with wind, rain, and hail followed by a short period of quiet. He went outside, heard the "roar," and immediately sought shelter. Upon emerging, he saw the tornado funnel leaving town in a north-northeasterly direction, still in contact with the ground.

The pattern of debris at Blackwell gave the appearance of more inflow than actual rotation in the sense that trees to the west of the center of the path had been blown eastward, and those to the east had been blown westward. Debris from the buildings yielded little information because of the difficulty in being able to determine from whence it came.

Eight Miles West of Arkansas City, Kans.—Following are two eyewitness accounts from an area about 23 miles north-northeast of Blackwell close to U. S. Highway 166, about 8 miles west of Arkansas City, Kans., Mr. and Mrs. Post, who live at a farm just south of the highway, report that their power failed at 9:58 p. m. (time ascertained from a stopped electric clock) followed in about 5 minutes by hail and shortly thereafter by a terrible roar. This was followedby a quiet lull which lasted probably less than a minute. The storm struck again, blowing down several large trees. These trees lying down toward the east must have been felled by a west wind. The couple was in the house the entire time, but looked out the windows during the course of the storm. When the initial roar was heard only blackness was visible to the south. After the tornado had passed over, it was clearly visible to the north against the background of almost constant lightning farther to the north. Neither Mr. nor Mrs. Post experienced any sensation of change of pressure during the course of the storm.

(*Continued on p. 238*)