COASTAL WATER TEMPERATURE AND SEA LEVEL—CALIFORNIA TO ALASKA

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My attendance at these meetings came up only recently, so the data I brought were quickly grabbed from the files plus a bit we did work up specifically for this meeting. As you know, the Coast and Geodetic Survey for years has been collecting tidal data along the coasts of the United States. The files are full of answers. The problem is now to find the questions for which we have the answers. This question is one to which we may hope to contribute at least part of the answer. Inquiries have for the last several months been coming to the Coast Survey as to why these West Coast temperatures are higher than normal, so we got interested in the story too. First we looked to see if they were warmer; then we looked at sea level, about which we also had had inquiries.

In brief, I will try to summarize the results of studies in which we took the fifteen months prior to April of 1958 and worked out monthly sea level values and monthly temperature values. We picked out ten tide stations that are the most exposed, from La Jolla, California, to Ketchikan, Alaska. The seawater temperature data here are monthly means calculated from daily observations. They are made once each weekday by bucket thermometer at our tide stations. We feel that over a period of time the tidal influence on temperatures is ruled out. These daily values are averaged to give us a monthly mean temperature at each tide station. To obtain monthly sea level value, we use a mean of hourly tidal heights during that month. This is the standard procedure for all these stations. If you look at the charts (Figs. 90-99), the data have been plotted as temperature and sea level anomalies at each of these stations. The anomaly is considered as this: temperature anomaly is the mean temperature during each month, January 1957 through March of 1958, compared with the mean of that month for the period of record. February 1958, for example, is compared with all the Februarys on record. The sea level anomaly is the sea level for the month we are considering compared to the nineteen year mean for that month, usually 1938-1956. For each month we are dealing only with the anomaly; we are not dealing with the monthly values themselves. Essentially we have cleared out the seasonal cycle by using this method.

On this coast during the period averaged, the highest sea level we have is February 1958 at Crescent City at .85 ft. above the long-term mean for that month. The observed tide ran about a foot above the predicted. These values on the graphs are not compared with the predicted but with the mean of the long-term observed data. When the anomalies for all the stations were averaged, we got a picture of the coast as a whole (Fig. 100). The upper graph is the temperature anomaly. The lower one is a sea level anomaly. In summarizing these two curves, one is struck by the parallelism between the temperature and the sea level anomalies. For the first four months of 1957, both the sea water temperature anomaly and the sea level anomaly were generally below normal. Both started to rise in May; were high during June, July, and August. Both dropped off during September, but were still well above normal. They then started to rise in October and November. Both reached the highest of the year in December. January and February of 1958 were both spectacularly high. The average water temperature anomaly in February was plus 3.5°F. The sea level anomaly in the same month averaged about half a foot—a little bit above half a foot actually above the long-term value. The peak for both was in February. Again, this is an average of the ten stations along the length of the coast. The coastal average is made up of data from La Jolla, Los Angeles, Santa Monica, Port Hueneme, Avila, San Francisco, Crescent City, Neah Bay, Ketchikan, and Sitka.

The anomalies I have been discussing have all been listed in tabular form. Some hypothesizing has been done and this is published as a Coast Survey Technical Bulletin. It covers the period from January of 1957 through March 1958. Water temperature and sea level data for these ten stations along the coast together with the anomalies and the long-period means are given in graphical form (Figs. 90-101). One particularly interesting thing that shows up in the average of all stations is a parallelism between the temperature anomaly and the sea level anomaly. You will note on the plots of the individual stations that the correspondence between temperature anomaly and sea level anomaly becomes poorer as we go father north. We automatically looked to the winds, knowing this to be a coast where upwelling existed. We got from Jerome Namias the monthly sea level pressure charts and worked out the geostrophic winds for three positions off the coast, at 35°N, 45°N, and 55°N. I will not go over what the wind pattern shows, as Mr. Namias discussed that in detail yesterday. In working with these geostrophic winds, we found the same thing that he found, that January and February of 1958 were indeed anomalous months. The correspondence of the temperature and sea level anomalies with the winds seems to be pretty good. However, the thing that interested us, was the increasingly poor correspondence between temperature and sea level anomalies as we went farther north. One reason for this undoubtedly is the variation in the wind pattern during January and February 1958 that Namias talked about before. Another reason is that from south to north, there is normally a decrease of the surface

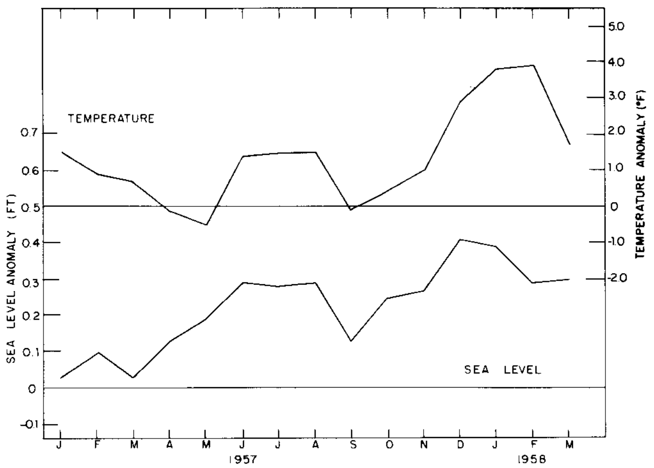

FIGURE 90. La Jolla, California, sea water temperatures and sea level anomalies, January 1957-March 1958.

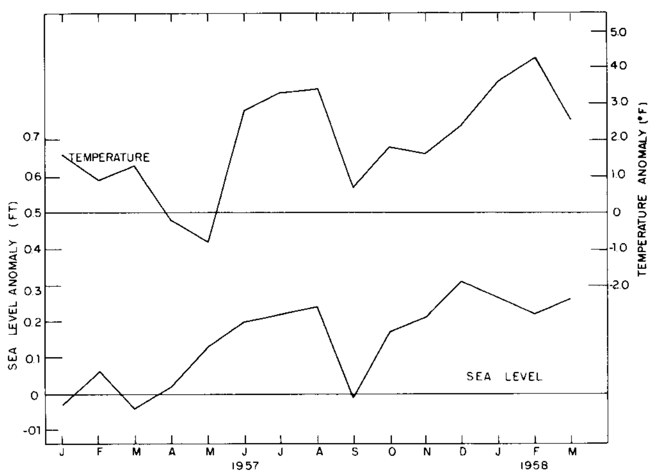

FIGURE 91. Los Angeles, California, sea water temperatures and sea level anomalies, January 1957-March 1958.

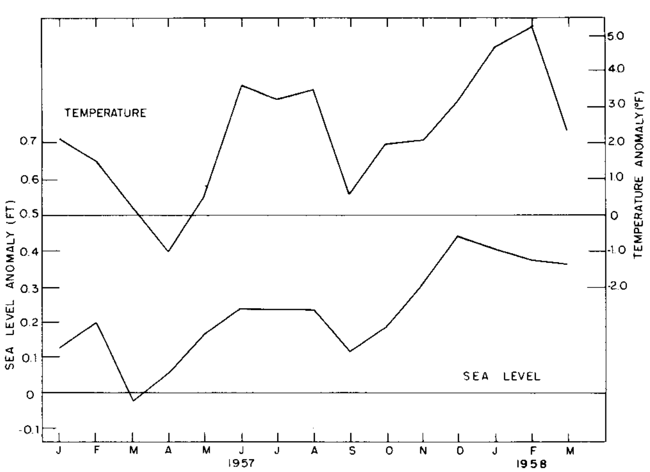

FIGURE 92. Santa Monica, California, sea water temperatures and sea level anomalies, January 1957-March 1958.

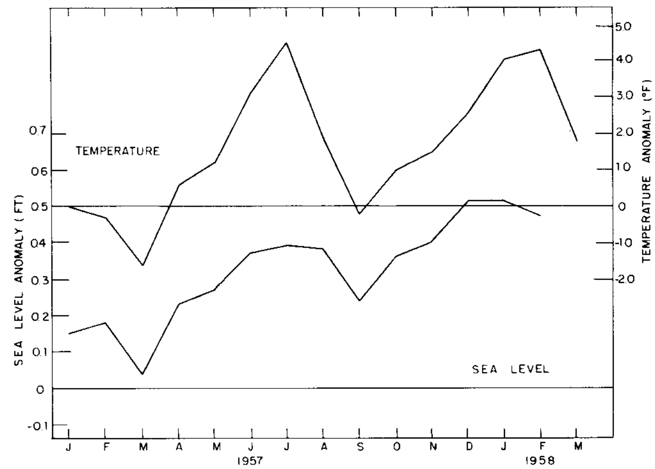

FIGURE 93. Port Hueneme, California, sea water temperatures and sea level anomalies, January 1957-March 1958.

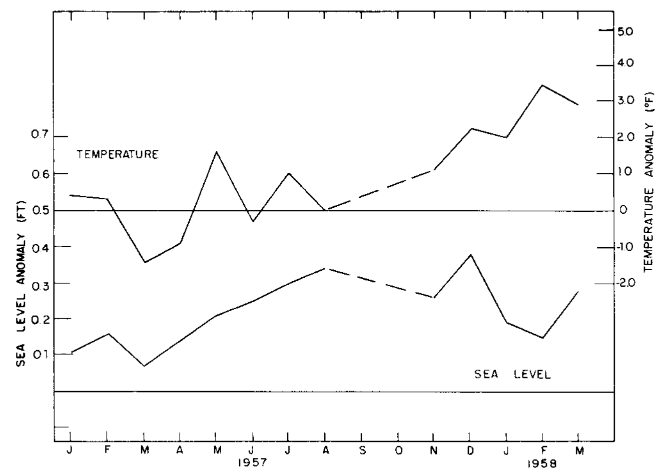

FIGURE 94. Avila Beach, California, sea water temperatures and sea level anomalies, January 1957-March 1958.

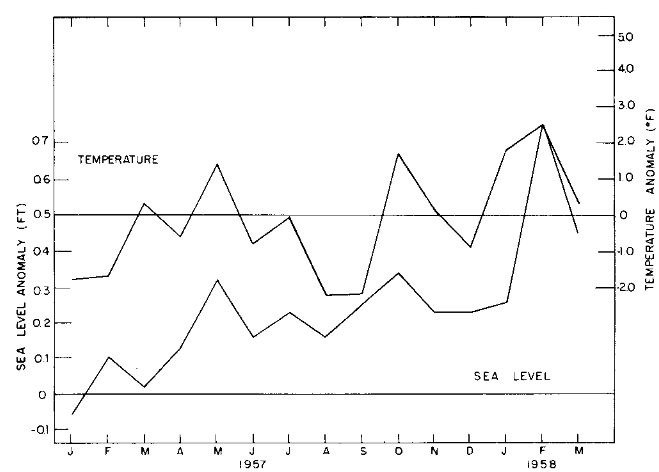

FIGURE 95. San Francisco, California, sea water temperatures and sea level anomalies, January 1957-March 1958.

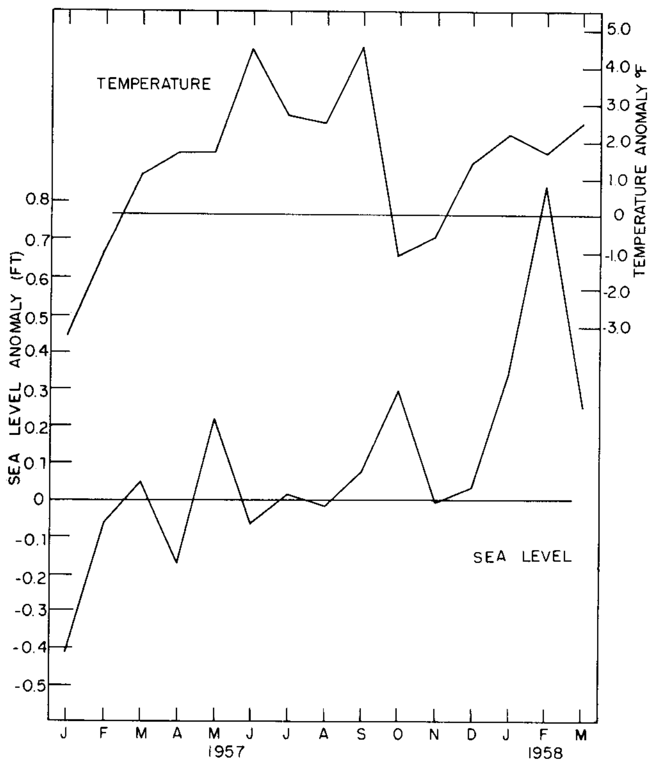

FIGURE 96. Crescent City, California, sea water temperatures and sea level anomalies, January 1957-March 1958.

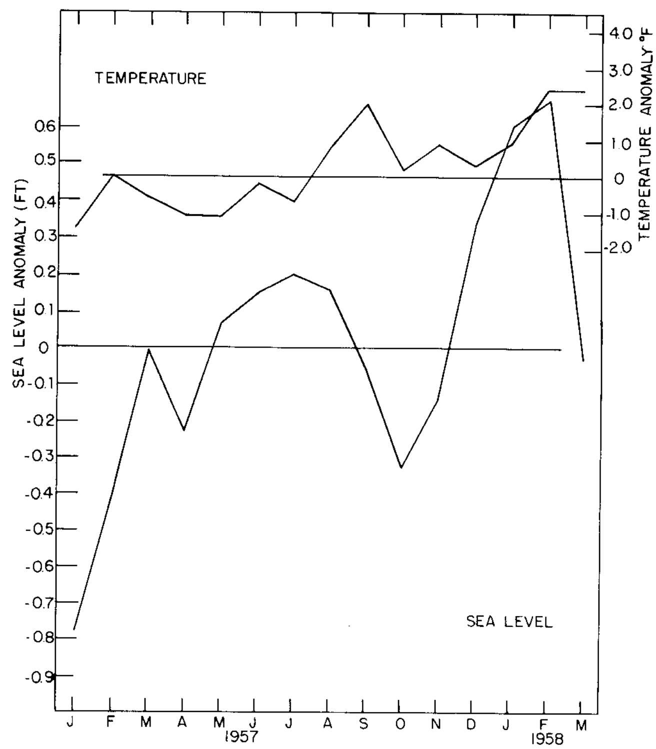

FIGURE 98. Ketchikan, Alaska, sea water temperatures and sea level anomalies, January 1957-March 1958.

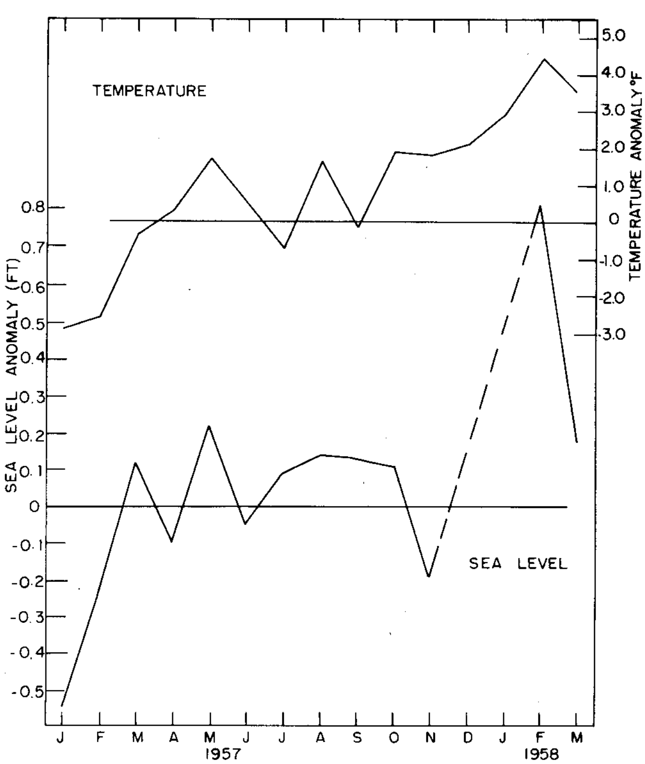

FIGURE 97. Neah Bay, Washington, sea water temperatures and sea level anomalies, January 1957-March 1958.

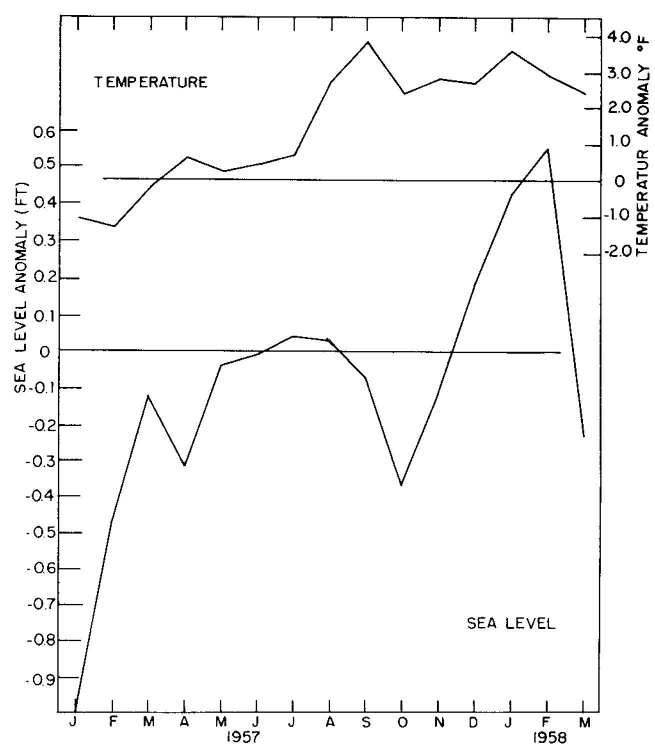

FIGURE 99. Sitka, Alaska, sea water temperatures and sea level anomalies, January 1957-March 1958.

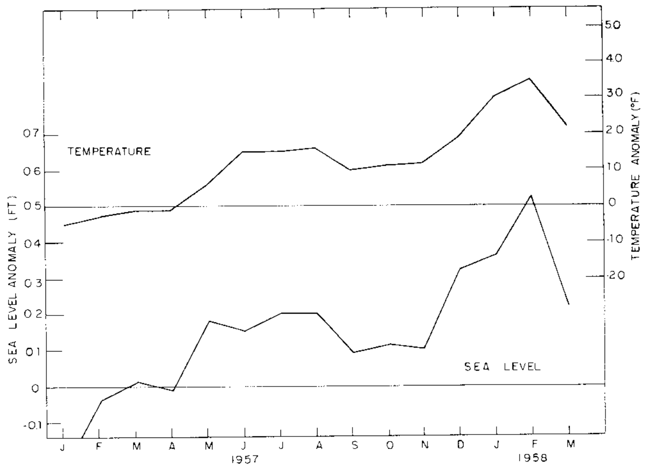

FIGURE 100. Mean coastal water temperature and sea level anomaly, La Jolla to Sitka, January 1957 through March 1958.

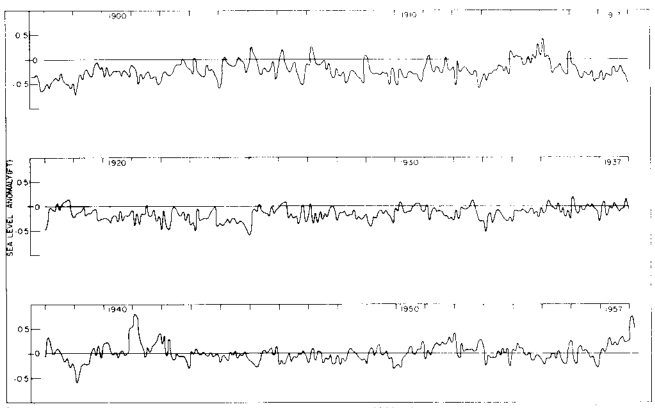

FIGURE 101. San Francisco (Presidio) California, monthly sea level anomaly August 1897 through March 1958 referred to 19-year monthly means 1938-1956.

water temperature from an annual mean of 64°F. at Los Angeles to 49°F. at Sitka. The temperature response to upwelling depends upon the difference between surface water temperature and the temperature of the upwelled water. Assume a constant temperature for water at depth, then the temperature response to upwelling will be less farther north. The range of the temperature anomaly is about the same from south to north, but the range of the sea level anomaly increases going from south to north, so that by the time we get to Sitka, the difference in sea level anomaly between January 1957 and January 1958 is nearly 1.5 feet. I envisage both the temperature and the sea level changes as resulting from the changes in the coastal wind pattern. As Stommel brought out, we are in fact dealing with two different problems—we must think of this facet I am discussing only in terms of the coastal problem for I have only coastal data. We have nothing farther out than the length of our longest pier at our tide stations.

This is strictly the coastal effect, and I think of the winds as producing both the temperature and sea level effect in this manner. The temperature effect is the well-known, well documented, colder water with upwelling. The sea level effect I picture as an equilibrium condition with your strong northerly components keeping the upwelling mechanism operating and keeping sea level at a reduced or lower level. Thus when the northerly components of the winds diminish, the upwelling mechanism slows down so the colder water is not pushed away from the coast and sea level tends to rise to establish a new equilibrium with the wind. There are other things, of course, which will give you a tie-in between sea level and water temperature. One thing, for example, is the atmospheric or barometric tide. If you tend to think of the sea as an inverted barometer, then the same atmospheric pressure changes that change the wind pattern will also affect sea level. When June Pattullo, et al. (1955), did their work, their global treatment—the data off the West Coast, show that when they corrected the recorded sea level values for atmospheric pressure, the change was small, and in addition the corrected values were out of phase with the recorded values. This suggests that at least out here, in what she called the California Current area, atmospheric pressure changes were apparently not important as they were in Bay of Bengal and some other parts of the world. Personally, I feel that this whole problem of the interrelationships of sea level, water temperature, barometric pressure, and winds, needs a lot of good basic research. It is as complex as it is interesting. The IGY island observations will provide some important data on this, and the whole problem must be attacked, I feel, primarily by using the actual observed data, of which we need much more.

DISCUSSION

Munk: We were worrying about the problem of the direct barometric pressure effect last night. If you have a pressure anomaly like the one you investigated, sea level responds as an inverted barometer in a few days. Joe Reid's study indicated the steric height change amounted to about 7 cm. You recorded about 15 cm. The difference of roughly 10 cm. is perhaps due to the inverted barometer effect. This would require a pressure anomaly of minus 10 millibars.

What strikes me is, Stewart mentioned that when you get further north the ratio between surface temperature and sea level was not as large. I think that you would get a better agreement if you actually made a straightforward inverted barometer calculation. The rise in sea level above and beyond the inverted barometer effect may correlate far better with the temperature.

Stewart: I find it hard to believe, Dr. Munk, that this would not be the case, particularly when you have high sea level anomalies with the amazingly high anomalies in pressure. I am sure that there is a bearing there, however at the same time, large pressure anomalies like this will also produce large wind anomalies. I think this is part of it too. We have to be able to sort these things out—which is the inverted barometer effect, and which is direct wind effect?

Munk: I think you are right. I think the pressure is more important than wind. I base this on the fact that for the annual pressure term you get very nearly the same result over enormous regions (like all of Northern Europe), with stations located in different aspects to the prevailing winds.

Stewart: Are you able to remove the annual pressure term from sea levels?

Munk: Yes, but it is relatively unimportant. To the case you have discussed, the yielding under superficial atmospheric pressure may amount to half the recorded change. For the seasonal variation the pressure effect is of the order of 10 percent of the recorded variation.

Stewart: I will be interested to see, as we get into this more, the relationship or relative importance of the inverted barometer effect and the wind effect. I naturally champion wind at this point of the game. The work that Miller did at Atlantic City and DeVeaux's work at Charleston both show a definite sea level response to variations in wind direction and velocity.

Munk: The wind tide is very critically dependent on the slope bottom. For that reason the East Coast with its extremely gradual continental shelf is sensitive to the wind effect, but off the American West Coast this is not so.

Stewart: Do you feel that the temporary response that is observed is due then to the redistribution of mass? Would not this tend to give you, with upwelling, south flowing geostrophic currents coming from this redistribution of mass and bringing cold water down from the north?

Munk: May I introduce a useful nomenclature? Call a barotropic fluctuation one that is due to a variation in water mass in a unit column. The induced pressure changes are uniform from top to bottom, and so are the related horizontal gradients and geostrophic currents. A *baroclinic* variation is due, in part, to variations in specific volume; as an extreme case of baroclinicity we have an *isostatic* condition for which the mass per unit volume remains unchanged. The seasonal variation in low and moderate latitude appears to be isostatic. A pressure recorder at the sea bottom would record no change. Geostrophic currents are then limited to those upper layers in which the specific volume is altered.

Stewart: I would like to see at some time all of our tide stations up and down the coast have associated with them a pressure recorder on the bottom.

Fleming: I think we are oversimplifying a lot of these points. Actually the relationship between sea level and surface temperature are fairly fortuitous. Please do not overemphasize these correlations because you could have the opposite under different physical setups. You could have the inverse relationships.

Stewart: If we consider all the stations, the increase in sea level anomaly average 0.3 foot per degree rise in the temperature anomaly, but this is surface data only.

Fleming: Does this have a physical meaning?

Stewart: I think it possibly does. In terms of the sea level anomaly it might be accounted for sterically, but we have no information on how far down the temperature increase extends. Actually, I do not believe the sea level rise is primarily steric, but the range of the temperature anomaly during these eighteen months appears to be just about the same from south to north, whereas the sea level anomaly increased from south to north.

Namias: There is a high correlation between monthly mean temperatures in the lower troposphere and surface water temperatures over this area the past two years.

Stewart: Apropos of the air temperature, I noticed one thing that is especially interesting. Working with air temperature data from three weather stations near three of our tide stations, we found that 33 out of 42 station months had higher water temperatures than air temperatures. The air temperatures even though anomalously high, could not have been the prime cause for the higher water temperatures. The converse appears more likely.

Fleming: A few cases where we had anomally high sea levels in the Puget Sound we find that primarily this was a barometric response rather than a wind effect. This again is a local situation. The water in the Puget Sound may respond more to barometric pressure changes than that of the open ocean.

Stewart: There is another thing that might produce the higher sea levels in the north. If you look at it on a globe, Sitka and Ketchikan, which show the greatest increase in sea level, are at the head of what might be considered a large embayment where it would be expected that the wind setup would be greater. I do not know the whole problem of what is causing this variation in sea levels. It is something we will have to attack more completely. At some places, like South Carolina, it may be primarily direct wind effect; at other places it may be primarily barometric, and at still other places it may be primarily steric. In some places the three may be so combined that it is impossible to separate them. It is the sort of problem that needs lots of data to work with, and the Coast Survey has long series of good data that can be applied to this.

Fleming: I would like to add the hydrostatic effect. Accumulation of fresh water from the Columbia River for example. This is going to be a factor all the way from the Columbia up into Alaska—fresh water discharged into the ocean.

Stewart: Apropos of exactly that, in connection with our present surveys of New York Harbor, we compared the Geological Survey's river gaging records with our tide gage records trying to see if we got an increase in harbor level with an increase in the river flow. By plotting up the curves for river discharge and harbor level, we found that the curves were very similar. However, peaks in the harbor level came a day or two *before* the same peak in the measured river flow at the Green Island gaging station in the Hudson River. So I think what was happening was that the same storm that dumped the water upon the watershed also caused a wind setup in the harbor so that we got the effect of higher sea level in the harbor before the water actually came down.

Munk: Gordon Groves really did a very complete study of sea level. Day by day values of sea levels for three months were used, with the tides removed by numerical filtering. With each storm the sea level fluctuated more or less according to the inverted barometric rule; perhaps two-thirds of the fluctuations could be accounted for in this simple manner. The foregoing remarks apply to the frequency of major storms: one to two cycles (or cyclones) per week. Miller, Groves and I now have a "sub-diem" project under way to nail down by means of cross-spectral analysis the frequency dependence of the inverted barometric responses in the frequency range from 1 to 200 cycles per year.

Stewart: There is one other facet on this that I feel I should touch on just briefly—the long period aspect. The figure 91 for Los Angeles and figure 92 for Santa Monica, point this up. Los Angeles and Santa Monica are perhaps twenty miles apart, yet the anomaly at Santa Monica both temperature-wise and sea level-wise is greater than at Los Angeles, although the curves are very similar. The reason for this, I believe, is that the Santa Monica anomalies are referred to the period 1947-1956, which was a period of generally lower sea levels and lower water temperatures. Los Angeles on the other hand, has a much longer period to which the recent anomalies are referred. Consequently, the anomaly at Santa Monica appears greater in these warm years (1957-1958) than at Los Angeles where we have a much longer period of record. Figure 101 is a plot of the monthly anomalies of sea level at San Francisco from August, 1897, up through March 1958. Notice that the years 1940 and 1941 which we have mentioned before as being anomalous years temperature-wise, are also anomalous years with respect to sea level. The horizontal line represents the 1938-1956 monthly means, so the deviation of the curve above or below that line represents the deviation each month from the 1938 to 1956 value for that month. The annual cycle has essentially been removed. The reason that they are below the line most of the time is that there has been over the past fifty years an average increase in sea level along this coast at the rate of about .005 foot per year. Note in December of 1940 and in early 1941 the anomaly comes way up to a maximum of nearly a foot. In February of 1941 sea level was 0.8 foot higher than the long-term February mean. It was quite high throughout most of 1941; very comparable to the situation in 1958. 1957 is considerably higher—note how it jumps up in January 1958! This plot is well worth pursuing at your leisure and comparing with some of the long-period data available from the other sources here. I think that with a plot like that and with comparable temperature data and with weather data, it would be well worth while looking for cycles in this thing. Maybe in the end it will be up to the weather people actually to give us the mechanism whereby we can predict when we will have lean years and fat years in the fishery industry.

Munk: Haubrich and I have obtained the power spectrum from mean monthly sea levels for all stations (one dozen) having more than a century of record. For frequencies lower than the annual frequency the spectrum is a typically noisy (or continuous) spectrum, with no significant frequency "lines", not even well developed broad bands. It is then predictable only in the sense the stock market is predictable.

LITERATURE CITED

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