A Study of the Effects of Local and Distant Weather on Sea Level in Hawaii

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ABSTRACT

A spectral analysis of sea-level data from Hilo, Hawaii (19° 44′ N, 155° 04′ W) shows a peak near 0.4 cycle per day (cpd) which is absent from all other Hawaiian tide stations that have been examined. A cross-spectrum study of the Hilo sea-level record with local weather variables shows some coherence, but not enough to ascribe the entire sea-level activity of the peak to local weather. An attempt was made to correlate the sea-level record with more distant weather. To do this, surface atmospheric pressure values were obtained on a 10° grid of 16 points in the Pacific Ocean, encompassing the Hawaiian Islands, and were correlated by cross-spectrum analysis with Hilo sea level. The results indicate that weather at some distance away is related to Hilo sea-level variations, with a suggestion that the entire activity of the 0.4-cpd peak may be ascribed to weather over a broad region around the Hawaiian Islands.

The sea-level record at Honolulu has a smaller peak near 0.5 cpd. The same analysis showed considerably less coherence, although the possibility of weather inducement of the peak cannot be disregarded.

No single measure of weather activity shows either peak, and the reason for the ocean's predilection for frequencies of 0.4 and 0.5 cpd has not been definitely established.

1. Introduction

Studies of the effect of local weather on the variation of sea level at given coastal places have been carried out for centuries, and are too numerous to be listed here. In recent decades, it has been found that where the correlation between weather and sea level is definitely established, it is usually not sufficient to explain all of the sea-level variation. The residual sea-level variation which remains after one removes that correlated linearly with local weather variables has been ascribed to nonweather phenomena, nonlinear weather response, and to the effects of weather at a distance. A storm will induce movements of the water in its vicinity, which will propagate out of the storm region and produce disturbances in current and sea level at distant places. Gravitational and planetary waves are two of the possible ways in which this propagation of energy can take place. Even where the observed sea-level activity is strictly produced by local weather, it may be that the measured local weather variables do not account for the entire activity of sea level. This is because meteorological instruments are not perfect, and their locations are not necessarily representative of local weather. This can lead into a philosophical discussion of what is meant by "local" weather. It is surely no surprise, even at the relatively low frequencies with which we are concerned here, that the weather "coherence distance" is limited, and more of the sea-level activity can be "accounted for" by considering weather over a larger area.

If more and more variables are to be brought into a linear regression scheme, one should be cautioned about interpreting the significance of the results. It is obvious that a least-squares regression scheme, which is usually used, will give lower residuals each time the sea-level record is regressed onto another series, even if the new series has negligible real effect. It is helpful to consider an "unbiased" residual spectrum, such as that suggested by Groves and Hannan (1968), which eliminates the largest source of bias. The relationship between the biased and unbiased estimates is given by

$$R_u = \frac{\nu R_c}{\nu - 2p},$$

$$C_u = C_c - \frac{2p}{\nu - 2p} R_c,$$

where R and C represent residual and coherent spectra, the subscripts u and c indicate unbiased and computed, ν is the degrees of freedom, and p the number of series regressed upon. The values of multiple coherence are similarly biased, but here it is found convenient to provide confidence intervals (see Groves and Hannan, 1968). In some of the computations it is found that the corresponding confidence intervals do not even contain the calculated value of the multiple coherence because of this bias.

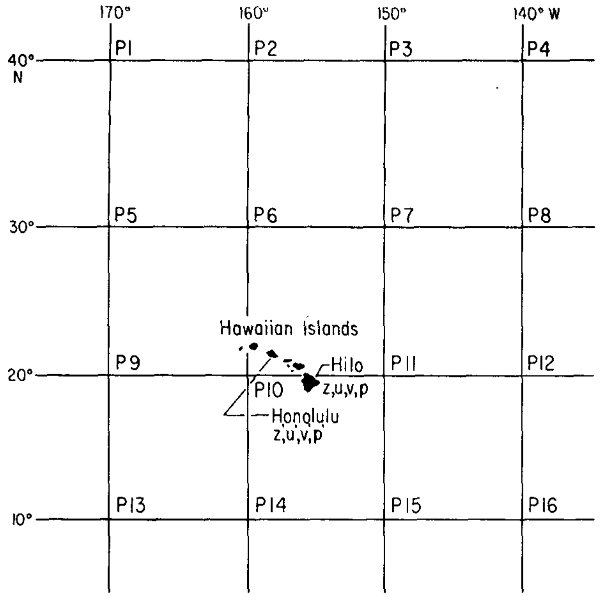


FIG. 1. Locations of Hilo and Honolulu, Hawaii, and the 16 points comprising the present lattice.

2. The data

Continuous hourly series of tidal heights z, north-south (u) and west-east (v) components of surface winds, surface atmospheric pressure p (all at Hilo), and the corresponding values (z',u',v',p') at Honolulu were prepared by editing the existing tabulations. Furthermore, 16 points near the Hawaiian Islands were chosen (Fig. 1) and pressure values at these points ($p1,p2, \ldots,p16$) were read from surface weather maps at 6-hr intervals. The weather maps were available from the Weather Bureau, Honolulu. These 16 series, together with the original 8-hr series were then digitally filtered to suppress the tides and higher frequencies and decimated to 12-hr intervals. Finally, these series were filtered by a high-pass filter to reduce the usual rise in spectral density toward zero frequency. Thus, the data in the final analysis consisted of 24 simultaneous series ($z,p,u,v,z',p',u',v',p1,p2,\ldots,p16$) of 2606 values each at intervals of 12 hr covering the period from January 1951–July 1954.

After its mean was subtracted, each series was divided into 42 overlapping equally spaced segments of 120 values each. Each segment was faded (tapered) in and out with a Lanczos-squared data window (Holsten

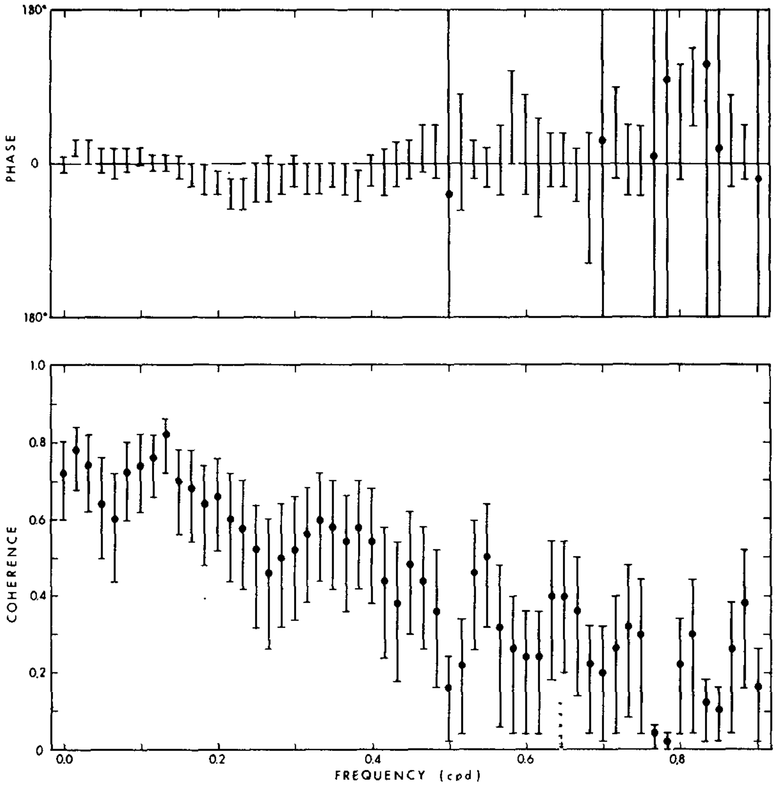


FIG. 2. Coherence and phase between $p1$ and $p5$. The dots are estimates of coherence values and error bars indicate 95% confidence limits in this and all subsequent figures. The 95% confidence limit for the null hypothesis that the two series are incoherent is 0.25. The estimates of phase values lie in the center of the indicated regions of uncertainty. Where the confidence limits extend beyond the figure, dots are provided to show these estimated values. A positive phase (upper half of phase diagram) indicates $p5$ leads $p1$.

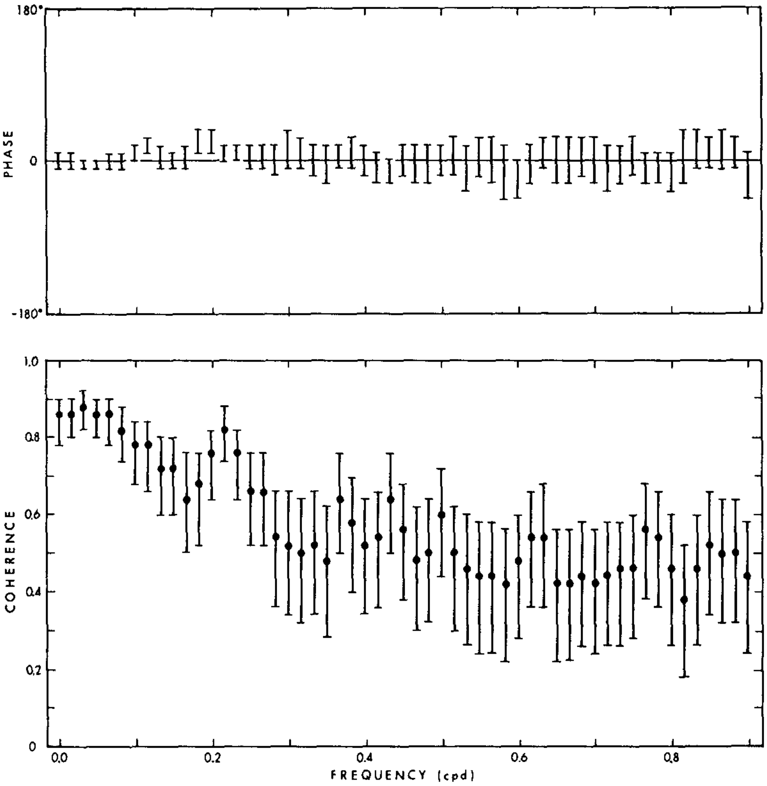


FIG. 3. Coherence and phase between $p11$ and $p12$. A positive phase indicates $p12$ leads $p11$.

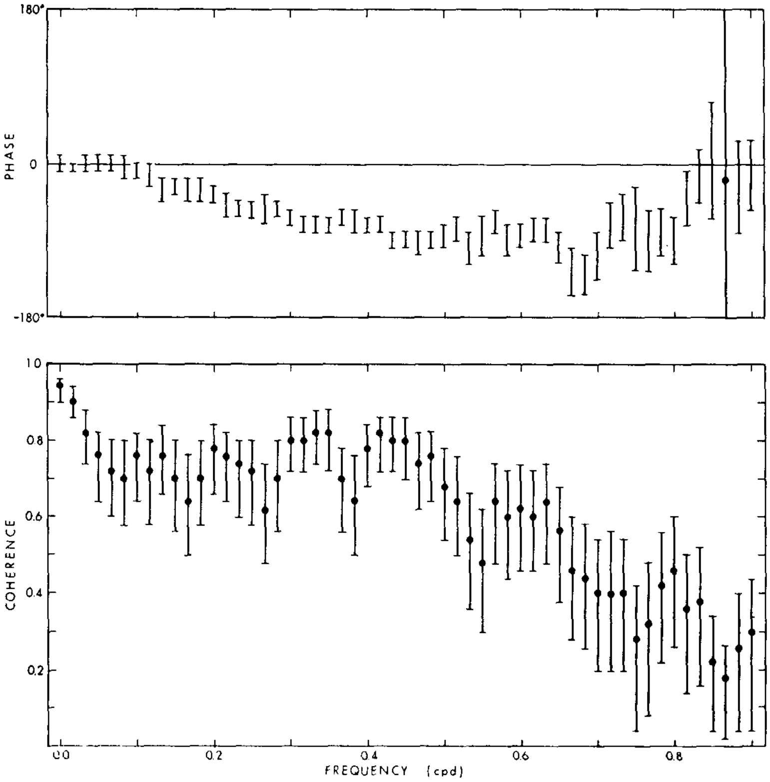
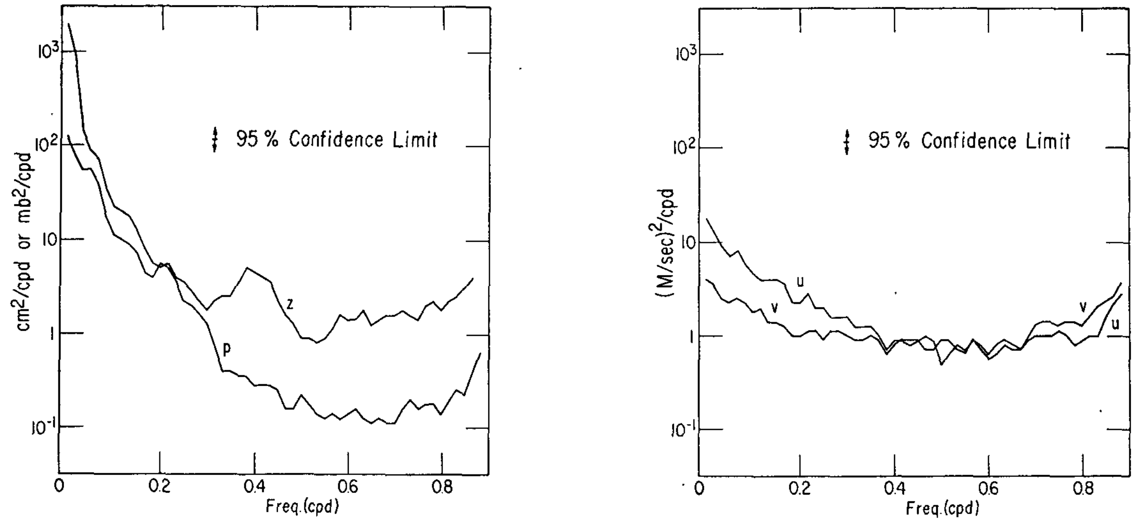


FIG. 4. Coherence and phase between $p2$ and $p3$. A positive phase indicates $p3$ leads $p2$.



a. b.

FIG. 5. Power spectra of Hilo sea level z and pressure p, a., and Hilo north-south (u) and west-east (z) components of winds, b.

and Groves, 1966) to reduce the effect of energy in frequency bands other than that under consideration. The 61 pairs of Fourier coefficients were computed and were appropriately averaged over all the segments to form the cross-spectrum matrix for each of the 61 frequency bands. [This is the "faded overlapped segment" method described by Groves and Hannan (1968).] Each of these 24th-order spectral matrixes was finally corrected for all previous filtering. The results are valid from zero out to about 0.9 cpd (cycle per day), after which overfiltering severely reduces the precision of the computed values.

3. The weather pattern

Relations between the 16 pressure series were first examined. Coherence and phase between pressure series from adjacent points along a given meridian show similar character throughout the area considered. A typical example is shown in Fig. 2. The coherence is high up to 0.4 cpd. The phase is consistently near zero in this frequency range.

Pressure series from two latitudinally adjacent points are more highly coherent, but two general types of relations are found. In one type, coherence is high within the entire frequency range from 0.0–0.9 cpd, and the phase difference is consistently near zero (Fig. 3). All six latitudinal pairs in the southern half of the lattice exhibit this feature. In the other type, the phase difference increases as the frequency increases up to about 0.7 cpd, with fairly high coherence (Fig. 4). This feature is seen in all latitudinal pairs in the northern half of the lattice.

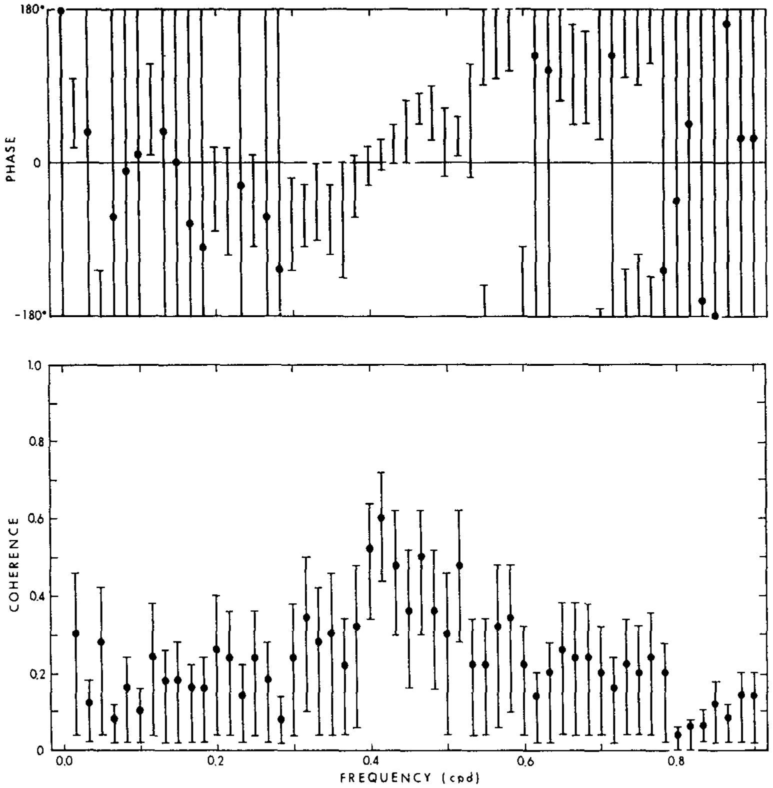
The lack of phase difference along meridians together with this increasing phase difference along lines of latitude is consistent with the model of a disturbance moving eastward at an approximately constant speed.

4. The relation between weather and Hilo sea level

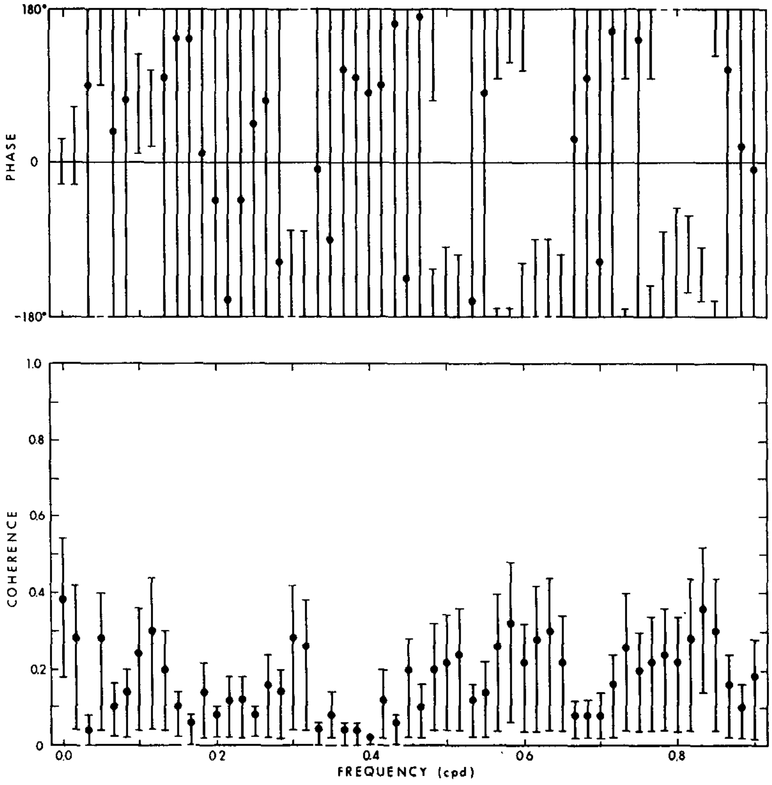
Cross-spectrum analyses between sea level at Hilo, and the 22 weather series were made. Figs. 5a and 5b show the power spectra of z, p, u and v, while examples of coherence and phase are shown in Figs. 6a–g. The first three parts of Fig. 6 demonstrate that sea level is more coherent with pressure than with wind components; the last five imply that the farther the distance between two points, the smaller the coherence between the sea level at one point and the pressure at the other. It is noted however that even $p1$, which is farthest from Hilo, has significant coherence with z at some frequencies.

A regression of Hilo sea level z on the three weather variables u, v, and p at Hilo was calculated. The original spectrum, the residual spectrum and the coherent spectrum are shown in Fig. 7a. It is noted that both residual and coherent spectra are unbiased estimates. The most striking feature in the original spectrum is a large energy peak around the frequency of 0.4 cpd. The hypothesis is made that the sea level is influenced by the local surface weather. Since the weather effect on sea level may not be determined completely by observations from a single weather station, the problem is to find the appropriate combination of weather variables which influences the Hilo sea level. The residual spectrum in Fig. 7a contains appreciable energy around a frequency of 0.4 cpd. That is, the three weather variables at Hilo alone do not account for the peak very well.

Three more variables (u',v',p') at Honolulu were added and a similar regression analysis made. In this case the unbiased residual sea-level spectrum was lower

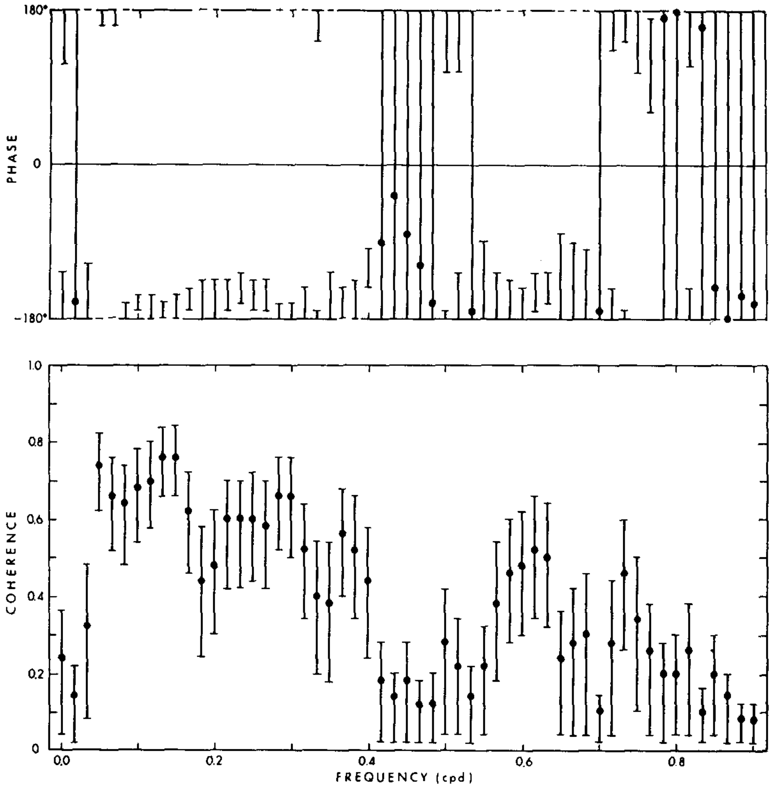


a. North-south surface wind.

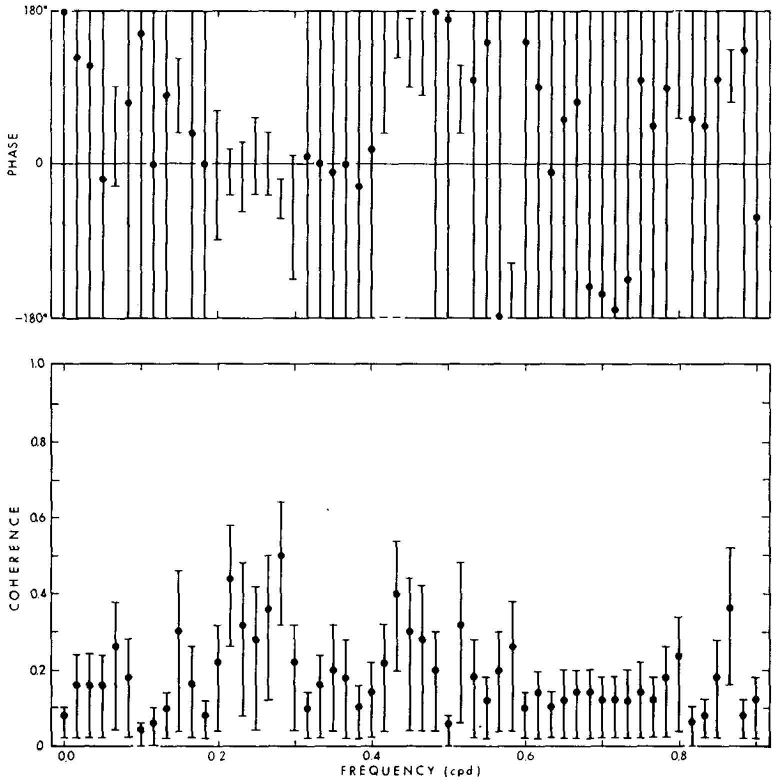


b. West-east surface wind.

FIG. 6. Examples of coherence and phase between sea level z and various weather phenomena at Hilo. A positive phase indicates that the weather factor leads the sea level.

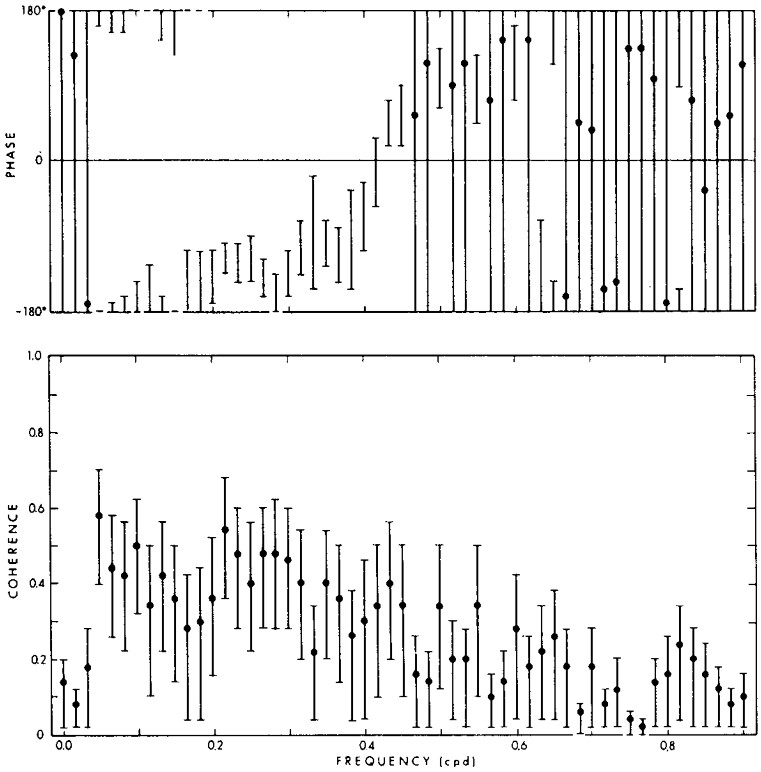


c. Surface pressure.

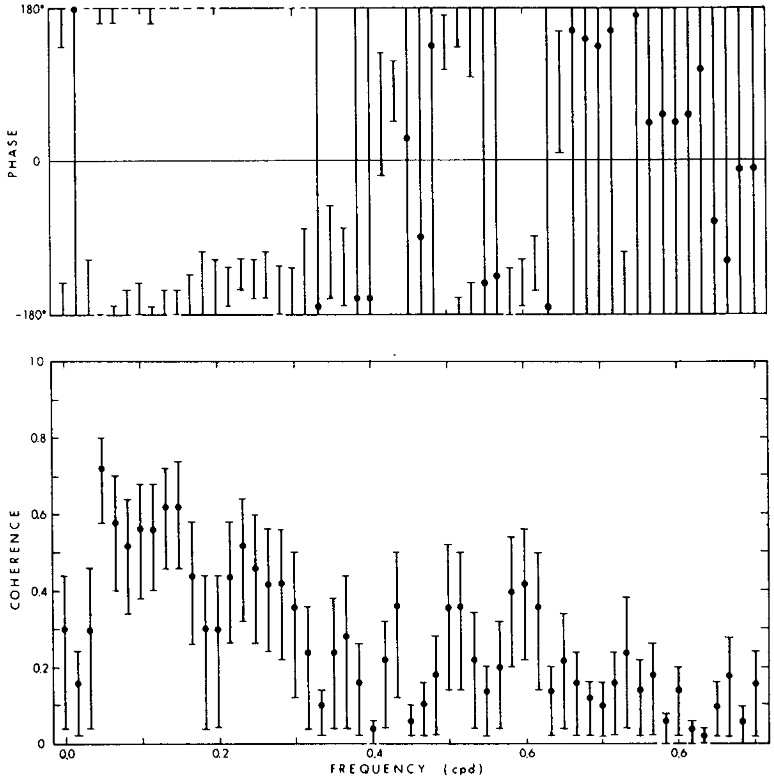


d. Pressure at grid point 1.

FIG. 6. (*continued*)

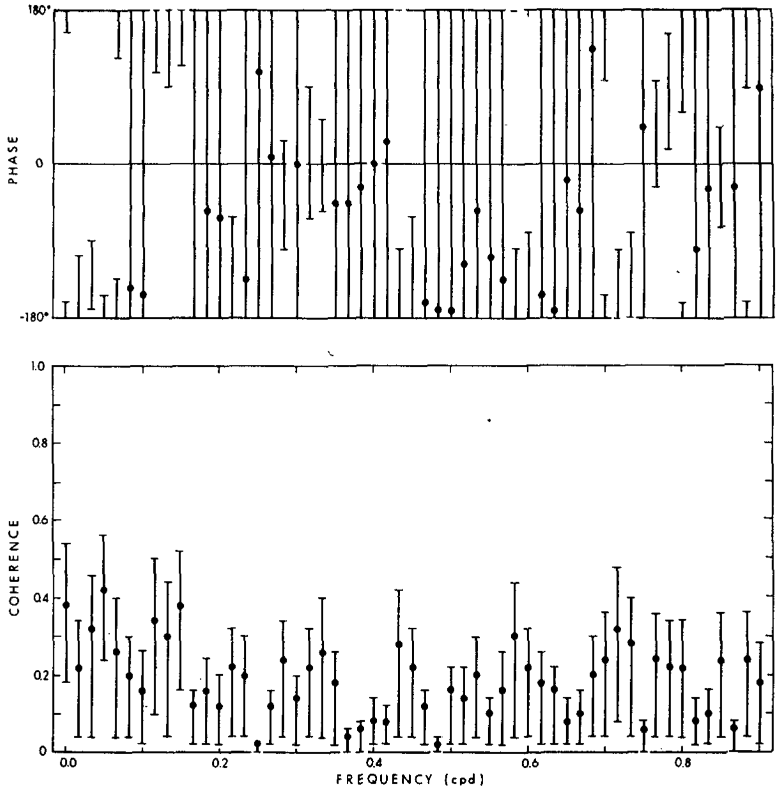


e. Pressure at grid point 6.



f. Pressure at grid point 10.

FIG. 6. (*continued*)



g. Pressure at grid point 12.

FIG. 6. (*continued*)

over most of the frequency range. Then the pressure series were added one by one and the same procedure repeated. If the addition of a pressure series gave a lower residual sea-level spectrum at the 0.4 cpd peak, the series was retained; otherwise, it was excluded. By this means, those weather variables which gave the optimal results were selected. They were u, v, p, u', v', p', $p5$, $p6$, $p7$, $p8$, $p9$, $p10$, $p11$ and $p12$. The results of the regression of z on these 14 weather series are shown in Figs. 8a and 8b. The greater part of the peak seen in the original spectrum is missing from the residual spectrum in Fig. 8a. The weather-coherent spectrum has a comparatively large sharp peak centered at 0.4 cpd. This suggests that this wave with a 2.5-day period at Hilo is induced by weather, and that the weather forcing function acting on the Hilo sea level is represented not only by the locally recorded weather at Hilo, but also by the weather at some distance away.

Since some portion of the peak still remains in the residual spectrum, the 14 weather series do not necessarily account for the entire activity of this peak. This may be due to the fact that the assumption of the linear relation between sea level and weather is not exactly correct. Or perhaps the choice of the grid points for pressure is not adequate. The addition of more pressure series from the west and east side of the present pressure lattice might lower the residual sea-level spectrum. The exact size of the region which determines the weather effect on the Hilo sea level is not determined by these results. However, Hilo sea level is evidently influenced by the weather at least over the rectangular region surrounded by 140W, 170W, 20N and 30N.

The figure of multiple coherence (Fig. 8b) appears unusual in that the confidence regions do not include the estimates, because of the strong biasing of the estimate of multiple coherence. For instance, although the estimated value is 0.80 at 0.2 cpd, the confidence intervals indicate that the true multiple coherence probably lies between 0.48 and 0.78.

For the sake of comparison, the biased estimates of both residual and coherent spectra are shown in Fig. 9. Here the residual spectrum is very low and the coherent spectrum very high. But this is because of the strong biasing effect incurred by taking so many series. If more series are added to the original 14 series, the coherent spectrum becomes higher, even if these series are completely incoherent with z. This is not the case for the unbiased spectrum. In fact, the addition of the other weather series to the fourteen lowers the unbiased coherent spectrum.

The entire analysis described above was repeated for the case of the Honolulu sea level, but it was found that the weather is considerably less coherent with the Honolulu sea level; the results are not presented here.

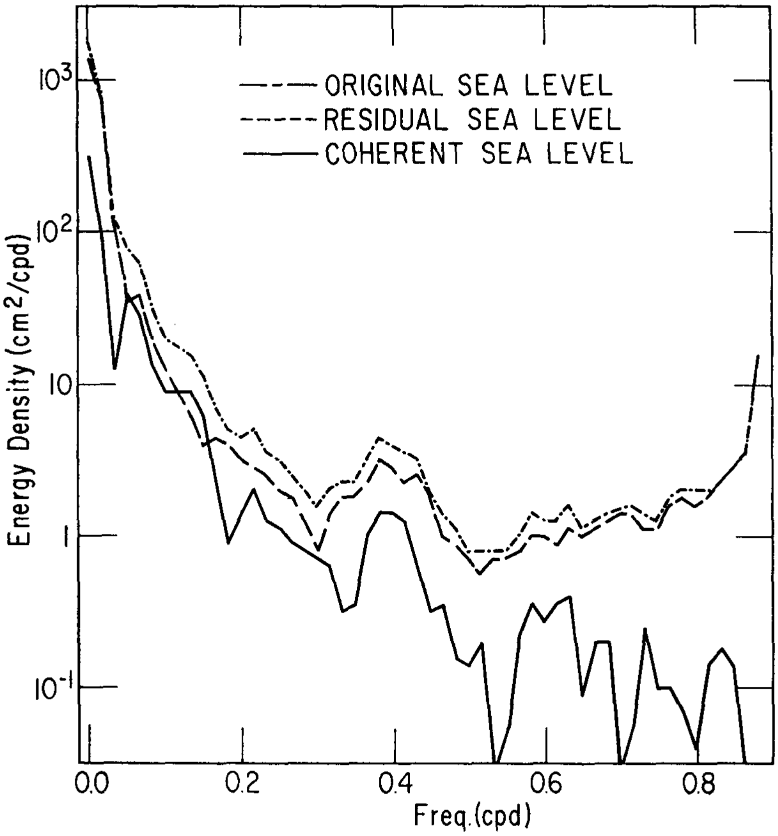


Fig. 7a. Original spectrum and unbiased estimates of residual and coherent spectra for z on u, v and p.

5. Discussion

The region of the sea surface whose overlying weather has the largest effect on Hilo sea level at the 0.4-cpd peak can be described as follows. It is elongated in the east-west direction and contains Hilo near its southern boundary. That is, the region is displaced somewhat northward from Hilo. The region contains eight of the pressure points on the criterion that the pressure records from these points lower the unbiased residual sea-level spectrum in the 0.4-cpd peak. The pressure records from the points outside this region raise the unbiased residual sea-level spectrum.

It might be thought that the weather north of Hilo might be more effective than the weather south of Hilo because of its location on the northern shore of the

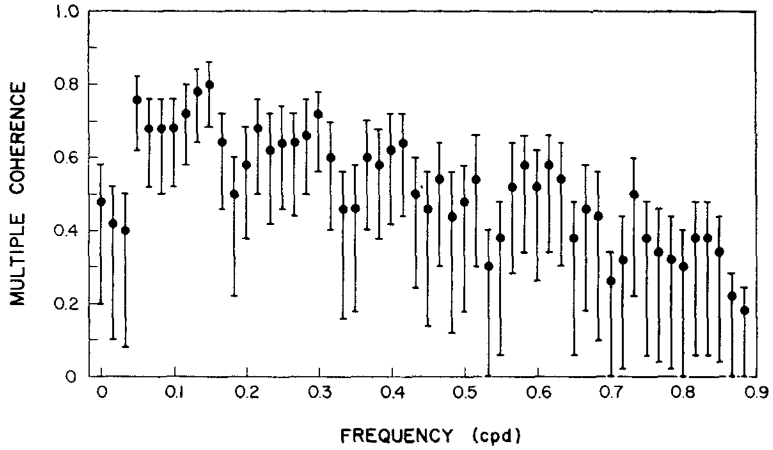


Fig. 7b. Corresponding multiple coherence. Note that the values of multiple coherence (dots) are biased estimates.

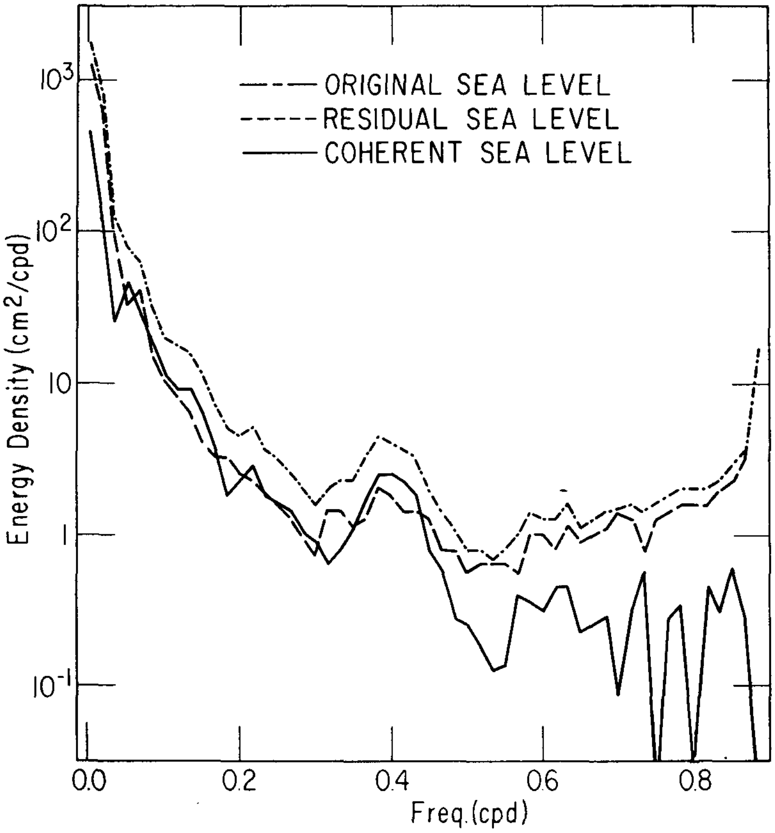


FIG. 8a. Original spectrum and unbiased estimates of residual and coherent spectra for z on u, v, p, u', v', p', $p5$, $p6$, $p7$, $p8$, $p9$, $p10$, $p11$ and $p12$.

island. This simple explanation is not borne out by the Honolulu analysis. Honolulu, lying on the southern shore of Oahu Island, might have been expected to relate more to weather south of Oahu, but this was not noted.

The details of the propagation of weather-induced disturbances in sea level remain to be studied. Longuet-Higgins (1965) has looked into planetary waves as the means of propagation of such effects, but the complicated bathymetry of the region makes direct application of this theory impossible.

The number of possible interesting combinations that could have been used in the regression scheme was so large that we purposely limited the study to the few that were described.

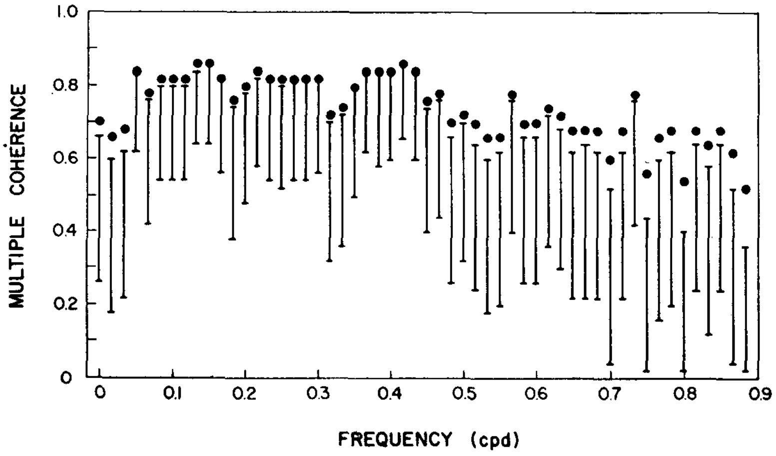


FIG. 8b. Corresponding multiple coherence.

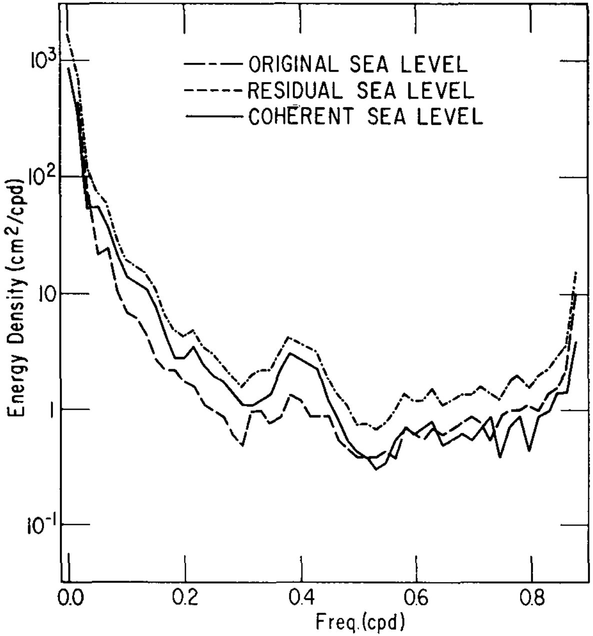


FIG. 9. Original spectrum and biased estimates of residual and coherent spectra for z on u, v, p, u', v', p', $p5$, $p6$, $p7$, $p8$, $p9$, $p10$, $p11$ and $p12$.

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