The *Journal of Marine Research* is an online peer-reviewed journal that publishes original research on a broad array of topics in physical, biological, and chemical oceanography. In publication since 1937, it is one of the oldest journals in American marine science and occupies a unique niche within the ocean sciences, with a rich tradition and distinguished history as part of the Sears Foundation for Marine Research at Yale University.

Past and current issues are available at [journalofmarineresearch.org](http://journalofmarineresearch.org).

Yale University provides access to these materials for educational and research purposes only. Copyright or other proprietary rights to content contained in this document may be held by individuals or entities other than, or in addition to, Yale University. You are solely responsible for determining the ownership of the copyright, and for obtaining permission for your intended use. Yale University makes no warranty that your distribution, reproduction, or other use of these materials will not infringe the rights of third parties.

This work is licensed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. To view a copy of this license, visit [http://creativecommons.org/licenses/by-nc-sa/4.0/](http://creativecommons.org/licenses/by-nc-sa/4.0/) or send a letter to Creative Commons, PO Box 1866, Mountain View, CA 94042, USA.
On Weather-induced Long Waves in the Equatorial Pacific

Gordon W. Groves and Motoyasu Miyata

Hawaii Institute of Geophysics
Honolulu, Hawaii

ABSTRACT

The entire available historic record of sea level and surface weather at Canton Island, Phoenix Islands, has been used to study linear relationships in the frequency range 0 to 0.8 cycles per day. Peaks in the sea-level spectrum at periods of four days and five days are strongly coherent with local weather, especially the meridional wind component. Thus the possibility that these oscillations are a manifestation of a global seiche is doubtful. A weaker spectral peak at period 2.7 days is unrelated to local weather. The mechanism of the enhancement at any of the three frequencies has not been determined. The spectra of the local weather records do not exhibit this "fine structure," but there is evidence that the 'appropriate' weather input function does have the four-day peak. It is uncertain whether the five-day peak in sea-level activity results from a peak in the weather input function or in the ocean's response.

Canton Island (2°49'S 171°40'W) in the Phoenix Group is one of the few places in the Central Equatorial Pacific from which moderately long sea-level and weather records are available. The sea-level record from Canton has a remarkable enhancement of activity near the frequency 0.26 cycles per

1. Hawaii Institute of Geophysics Contribution No. 144.
Accepted for publication and submitted to press 4 February 1967.
Figure 1a. Records of sea level, surface wind components, and atmospheric pressure at Canton Island. The regular four-day oscillation in sea level and N-S wind is clearly evident.

day (cpd). Simultaneous plots of sea-level and surface wind components during three months of the northern-hemisphere winter of 1952-1953 show a remarkable correlation between sea level and meridional wind component (Groves 1956). The same plots are reproduced here in Fig. 1 from data that were edited by automatic computer programs (see Appendix). A subsequent cross-spectrum analysis of a two-year simultaneous series of sea-level and surface wind components indicated a significant coherence, but there was no evidence of a corresponding spectral peak in the wind (Groves and Grivel 1962). In that analysis, however, the wind data were not the best, the filtering of the wind data may not have sufficiently reduced aliasing, and an optimum prewhitening procedure was not used. The spectrum of sea level exhibited "fine structure," manifested by a resolved peak at 0.20 cpd (besides the stronger
peak at 0.26 cpd) and a separate smaller peak at 0.37 cpd. The questions of (i) the mechanism of the wind-induced sea-level peak at 0.26 cpd and (ii) the meteorologic or nonmeteorologic origin of the sea-level peaks at 0.20 cpd and 0.37 cpd had not been resolved. Regarding question (i), Ichiye (1959) and Fedorov (1964) investigated the dynamics of weather-induced long waves in the equatorial region, but it is difficult to adapt their results to the present problem. The present study is an attempt to learn something about question (ii).

Records of sea level, $z$, surface atmospheric pressure, $p$, and the North-South and West-East components, $u$ and $v$, of surface wind at Canton Island were used in this study. The details of preparation and analysis of this series are uninteresting and are given in the Appendix. The series were for the period November 1949 through December 1962 and consisted of 9610 appropriately filtered simultaneous values of $z$, $p$, $u$, $v$ at intervals of 12 hours. The linear statistical relationships between the four series were obtained in the form of the fourth-order spectral matrix evaluated between 0 and 0.8 cpd at intervals of 0.005 cpd. Examination of these results showed that none of the interesting spectral features required this much resolution, so “smoothed” spectral matrices at intervals of 0.02 cpd were prepared in order to increase statistical reliability. The results are shown in Figs. 2a, 2b, 2c.
The general features usually noted on sea-level spectra (Groves and Zetler 1964, Munk and Bullard 1963) are noted here: a general rise in activity toward zero frequency, a rise toward 1 cpd, and a low flat trough.

2. Munk (personal communication) has noted that their power spectra are too low by a factor of 10.
in between. The weather \((p, u, v)\) spectra show the same general features. The pressure spectrum near zero frequency is very low—characteristic of low latitudes.

It is seen that there are no sharp features on the weather spectra at the frequencies 0.20, 0.26, and 0.37 cpd. One wonders how the time series (in Fig. 1) that show such a regular oscillation of wind with periodicity near four days can avoid appearing as a sharp spectral feature. Examination of the weather records for other times leads one to the conclusion that the prominence of the four-day oscillation in the North-South wind component, evident in Fig. 1, does not occur often and that the weather records for most of the time have the appearance of rather wide-band noise. However, the coherence between \(z\) and \(u\) at 0.26 cpd is so high that there is little doubt that they are related. The fact that the sea-level spectrum has a peak at precisely this frequency is hard to accept as a fortuitous coincidence. Perhaps the simplest explanation is that the tabulated weather values for Canton Island do not represent the entire weather input function. For example, winds over a large

---

**Figure 2b.** Phase and coherence of \(z\) vs. \(p\). (A positive phase indicates \(p\) leads \(z\)). Dashed line gives 95\% confidence limit for coherence.
area of sea surface may be responsible for the generation of the four-day ocean wave, while Canton Island is intermittently in and out of this area. The ocean wave is then observed at places outside of the area in which it is generated.

Figure 2c. Phase and coherence of \( z \) vs. \( u \) and \( z \) vs. \( v \). (A positive phase indicates \( u \) or \( v \) leads \( z \)). Dashed line gives 95\% confidence limit for coherence.
At least this hypothesis is compatible with a sharp 0.26-cpd peak in the sea-level spectrum, the presence only rarely of such a peak on the weather spectra, and good coherence between sea level and weather.

The energy contained in the sea-level peak at 0.20 cpd is lower by a factor of about 10 as compared with the 0.26-cpd peak. However, the 0.20-cpd peak seems to have the same characteristics as the 0.26-cpd peak; that is, it is present on the sea-level spectrum, absent on the weather spectra, and shows good coherence between $z$ and $u$ (see Figs. 2a, 2c). There is evidence of the 0.20-cpd sea-level peak at Christmas Island with some coherence with Canton Island (Groves and Grivel 1962); this suggests that it is a large-scale oceanic phenomenon, independent of the 0.26-cpd oscillation.
Figure 3b. Partial regression coefficient for $z$ on $p$ (taking into account $u$ and $v$). The top figure shows the phase lead of $z$ relative to $p$. The bottom figure shows the modulus.

The high coherence between $z$ and $v$ at 0.30 cpd is unexplained. The $z$, $p$, $u$, $v$ time series were examined at the time when the 0.20-cpd energy in the $u$ series was abnormally high. Such an occurrence is shown in Fig. 1b. Even in this abnormal case the appearance of the weather records, particularly $u$, does not suggest a narrow-band forcing function (as in Fig. 1a in the case of the 0.26-cpd peak).

On the sea-level spectrum there is a feature at 0.37 cpd that appears as a skewed peak that separates higher values at the lower frequencies from lower
Figure 3c. Partial regression coefficients, $z$ on $u$ and $u$ on $z$. (A positive phase indicates $u$ or $v$ leads $z$). Dashed line gives 95% confidence limit for coherence.
values at higher frequencies. This peak, as is the case with the other two, is absent from the weather spectra. Furthermore, the low coherence suggests that weather plays no part.

A regression of sea level, $z$, onto the weather variables $p$, $u$, $v$ was calculated, departing from the fourth-order spectral matrix of all four variables. A 'residual' sea-level spectrum, consisting of the original energy density minus that which is coherent with the weather variables, is shown in Fig. 3a along with the multiple coherence. The partial regression coefficients of $z$ on $p$ and of $z$ on $u$ and $z$ on $v$ are shown in Figs. 3b and 3c. It is seen that an appreciable portion of the sea-level energy in the 0.20-cpd and the 0.26-cpd peaks is lost from the residual sea-level spectrum. This is compatible with the previously mentioned high coherence between sea level and wind at these frequencies. If these peaks actually are weather induced, one might ask why they are not completely obliterated from the residual spectrum. As previously stated, the reason may be that the locally recorded weather records at Canton Island do not adequately represent the weather-forcing function. In Fig. 3b it is noted that the partial regression coefficient of $z$ on $p$ is low for the frequencies 0.20 cpd and 0.26 cpd, compatible with the observed low coherence, and about equal to one centimeter per millibar and of appropriate phase for direct hydrostatic compensation of the sea surface to pressure at intermediate frequencies. Practically none of the observed sea-level energy density at the 0.37-cpd peak is coherent with the weather variables, again suggesting that weather plays no part. The statistical reliability has not been indicated, but the jaggedness of the curves gives an indication.
The notion that activity at certain frequencies fluctuates with time can be studied by examining the spectral density on the frequency-time plane. The procedure is to consider the frequency spectrum based on a small segment (of the original data series) that corresponds to a particular time (say, the midpoint of the segment). The spectral values thus obtained depend on time. The Canton Island data were examined in this way, and the times of occurrence of relatively high values of spectral density at 0.20 cpd and at 0.26 cpd were noted. In either peak, there is greater than average coincidence of high values of spectral energy density of sea level and of the weather parameters; this is not surprising in view of the high coherence between the entire series. The cross-spectrum corresponding to the times of unusually high activity in each band were averaged together and are shown in Figs. 4a and 4b. The coherence is considerably enhanced, as one would expect. There seems to be only average, or random, coincidence between the simultaneous occurrence of high values of sea level in both peaks.

Acknowledgment. This work was supported by the National Science Foundation through grant GP-4254. The authors are grateful to Richard Haubrich, Jim Larsen, Harold Loomis, Walter Munk, Ron Taylor, and Klaus Wyrtki for their advice, to the U. S. Coast and Geodetic Survey for making available the tide data, and to the U. S. Weather Bureau for making available the weather data. The computations were carried out at the Statistical and Computing Center, University of Hawaii. Part of this study was presented at the Eleventh Pacific Science Congress, Tokyo, 1966.
REFERENCES

AMOS, D. W., and L. H. KOOPMANS

BLACKMAN, R. B., and J. W. TUKEY

FERODOV, K. N.

GOODMAN, N. R.

GROVES, G. W.

GROVES, G. W., and B. D. ZETLER

GROVES, G. W., and F. GRIVEL

ICHIYE, T.

MUNK, W. H., F. E. SNODGRASS, and M. J. TUCKER

MUNK, W. H., and E. C. BULLARD
APPENDIX

Treatment of the Data. Records of sea level and surface weather at Canton Island, Phoenix Islands, were obtained from the U. S. Coast and Geodetic Survey and from the U. S. National Weather Records Center. The entire available record, consisting for the most part of hourly values, or at worst of values every three hours, was used. The records were scanned by automatic procedures for obvious errors in value and in sequence; they were then corrected and stored on magnetic tape. The winds were expressed as the North-South component, $u$, and the West-East component, $v$. The records were filtered digitally to remove diurnal and higher-frequency fluctuations, and values were computed for every 12 hours. Small gaps comprising less than 0.1% of the data were interpolated. The four series were again filtered by a high-pass filter to suppress the usual rise in spectral density toward zero frequency, and the means were subtracted. Each series, consisting of 9610 simultaneous values, was then divided into 50 overlapping equally spaced segments of 400 values each. Each segment was “faded” (tapered) in and out with a “Lanczos squared” data window, and the 201 pairs of Fourier coefficients were computed. Appropriate averages of product pairs of these coefficients over all the segments were computed to form the cross-spectrum matrix for each of the 201 frequency bands. The cross-spectrum matrix was finally corrected for all previous filtering.

The lowest frequency band is centered at 0 and subsequent bands are centered at higher frequencies in 0.005-cpd increments. While the analysis actually was carried out in the range 0 to 1 cpd, the portion above 0.8 cpd is not considered because the filtering procedure reduced the energy in this frequency range by too large a factor. A lower-resolution representation was made by averaging four successive frequency bands together. Here the interval between frequency bands is 0.02 cpd, as is the approximate width of each band. The lowest frequency band is centered on 0.0225 cpd.

The distribution of values of energy density, coherence, and phase, computed from random samples of infinite series, depends on the true cross spectrum of the infinite series and on the “degrees of freedom,” $v$, which is twice the equivalent number of harmonics of the finite sample record lying within the narrow band under consideration (Munk et al. 1959: §4.2, Amos and Koopmans 1963, Blackman and Tukey 1958: §9). If the cross spectrum were estimated by averaging over adjacent harmonics, then the degrees of freedom would be known with certainty, but there is some doubt as to the appropriate value corresponding to the method used in this case. Fortunately, the reliability estimates do not depend critically on the degrees of freedom. Here, we shall take the same value as that appropriate to an estimation of cross spectrum by the Tukey method, $v = 2N/m$, where $N$ is the number of values in the time series and $m$ is the number of frequency bands. This gives $v = 96$
for the original high-resolution calculations, which are not shown. In the lower-resolution representation, the spectral window consists of a "boxcar" of width four values convolved with the spectral window of the higher-frequency spectral window. Since the boxcar is wider than the original spectral window, \( v \) has been taken as twice the number of harmonics in a band of width equal to the frequency separation of adjacent values, which is \( N/m \), where in this case \( m = 50 \). This gives \( v = 192 \), a rather conservative (low) estimate of both \( v \) and statistical significance, for the analyses shown in Figs. 2, 2b, 2c.

The case where parts of the original data series were selected for high activity in the 0.26-cpd or the 0.20-cpd band is somewhat different. Here, according to the above considerations, \( v \) has been estimated by taking four times the number of faded segments of 400 values each (11 for the 0.26-cpd activity, 13 for the 0.20-cpd activity) which were used in computing the spectral matrix. This gives \( v = 44 \) for Fig. 4a, 52 for Fig. 4b.

The distribution of energy-density values is given by the chi-squared law. The 95\% confidence limits are indicated by the vertical arrows on Figs. 2a, 3a, 4a, 5b for each of the variables \( z, p, u, v \). These limits represent ratios on a linear scale of spectral-energy density, so the vertical arrows apply equally well to any part of the plots of log (energy density). The distribution of sample values of coherence, \( R \), has been given by Goodman (1957). Here we wish to examine the hypothesis that the true coherence (for the hypothetical infinite long series, of which the data series are considered random samples) is zero. In this case the cumulative distribution function is

\[
\text{Prob}\{R < x\} = 1 - (1 - x^2)^{v/2}.
\]

The dashed lines on the coherence plots in Figs. 2b, 2c, 4a, 4b show the level that would be exceeded by 5\% of the coherence values computed from randomly related records.

The confidence limits on the sample phase values depend on the true coherence, which varies with frequency and is not precisely determined. An estimate for cases where the coherence is good can be obtained by assuming that the true coherence is 0.5, which is a representative value of the highest sample coherence values computed here. Then, the 95\% confidence limit for any sample phase value, \( \theta \), is \( \theta \pm \Delta \theta \), where \( \Delta \theta = 20^\circ \), assuming \( v = 192 \) for Figs. 2b and 2c (Goodman 1957, Munk et al. 1959).