

MICROSEISMS IN THE 11- TO 18-SECOND PERIOD RANGE

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ABSTRACT

Storm microseisms in the 11- to 18-second period range recorded at Palisades and Bermuda are attributed to ocean swell of identical periods in the vicinity of the seacoast near the seismograph station. Evidence is based on travel time, correlation with wave-recorder data, and dispersion of the waves from hurricane Dolly, which remained in deep water when near the Palisades station and passed at a speed greater than the group velocity of ocean swell.

Ground-particle motion is longitudinal, with little or no vertical component.

With some qualifications, the results agree with the classical surf theory of microseism generation. Certainly, the energy is transferred to the earth within the littoral zone.

INTRODUCTION

VIRTUALLY all the abundant literature on the subject of storm microseisms deals with waves of periods of the order of 10 seconds or less. At the Palisades and Bermuda stations, three-component seismographs of exceptional long-period response frequently record microseisms of longer periods, sometimes as high as 18 and possibly 20 seconds.

This paper describes a study of these microseisms, and the ocean waves near shore with which they are associated, for two months each of the hurricane seasons of 1954 and 1955. This choice of interval is not meant to imply that the microseisms occur only during hurricane seasons; although no quantitative study has yet been made, they are known to occur during other times of the year, particularly the winter. However, the hurricanes serve conveniently as strong, discrete sources of both the microseisms and the ocean waves.

INSTRUMENTATION

Microseismic data for this paper have been taken almost exclusively from two similar three-component seismographs. The complete Palisades unit began operation prior to the hurricane season of 1954, the Bermuda unit prior to the hurricane season of 1955. The instruments consist of three matched pendulums (N-S, E-W, Z), with free periods of approximately 15 seconds. The pendulum is coupled through an electromagnetic transducer to a Benioff model 6,000 galvanometer with a free period of about 75 seconds. Damping is electromagnetic. In addition to the ordinary earthquake waves, these instruments have, on occasion, recorded surface waves with periods as great as 450 seconds,¹ although the magnification is very low at such long periods.

At Palisades, when long-period waves of large amplitudes are detected on the long-period seismographs, the same waves may be seen, sometimes quite clearly, on a set of instruments of intermediate periods with a response like that of Galitzin seismographs. The free period of these pendulums is 12 seconds; of the galvanometers, 15 seconds. In general, however, the high level of microseisms with periods less than 10 seconds tends to obscure the longer waves on these instruments.

Manuscript received for publication June 15, 1956.

¹ M. Ewing and F. Press, "Mantle Rayleigh Waves from the Kamchatka Earthquake of November 4, 1952," *Bull. Seism. Soc. Am.*, 44: 471-479 (1954).

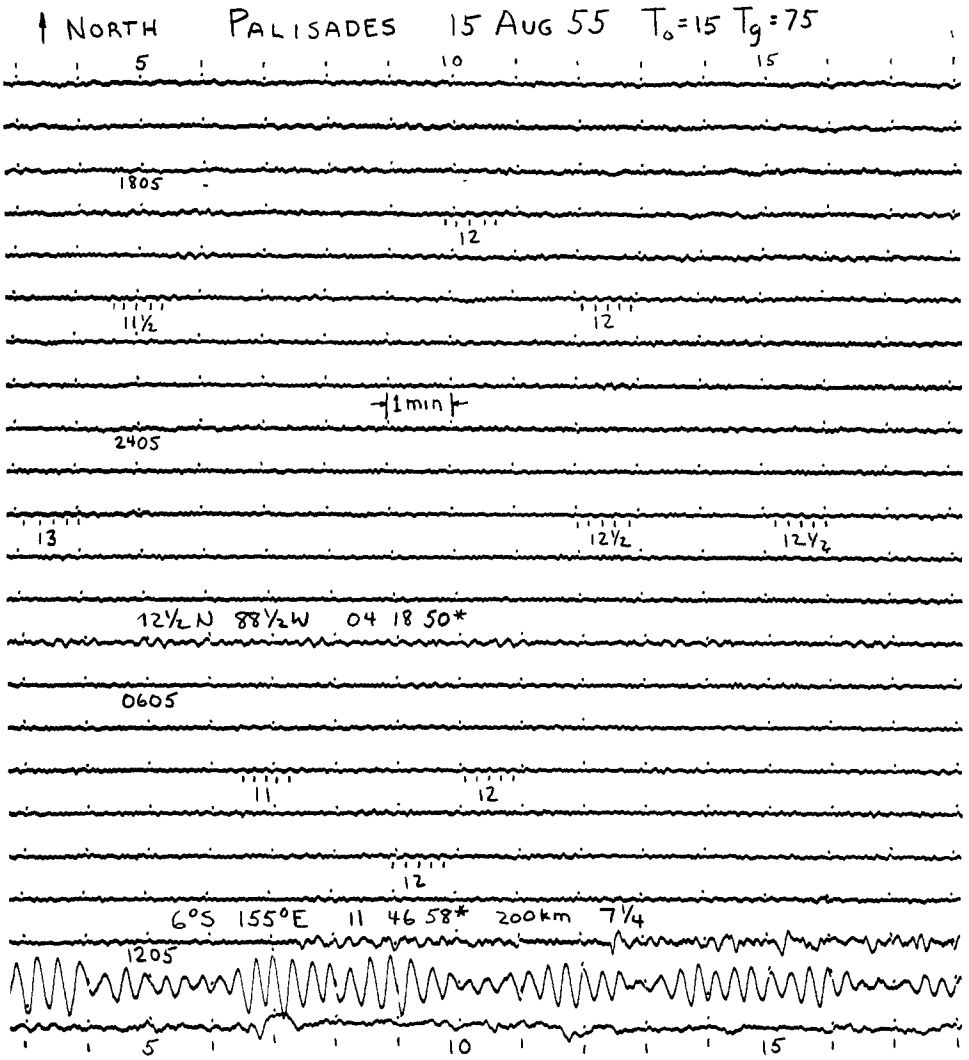


Fig. 1. Seismogram, long-period microseisms.

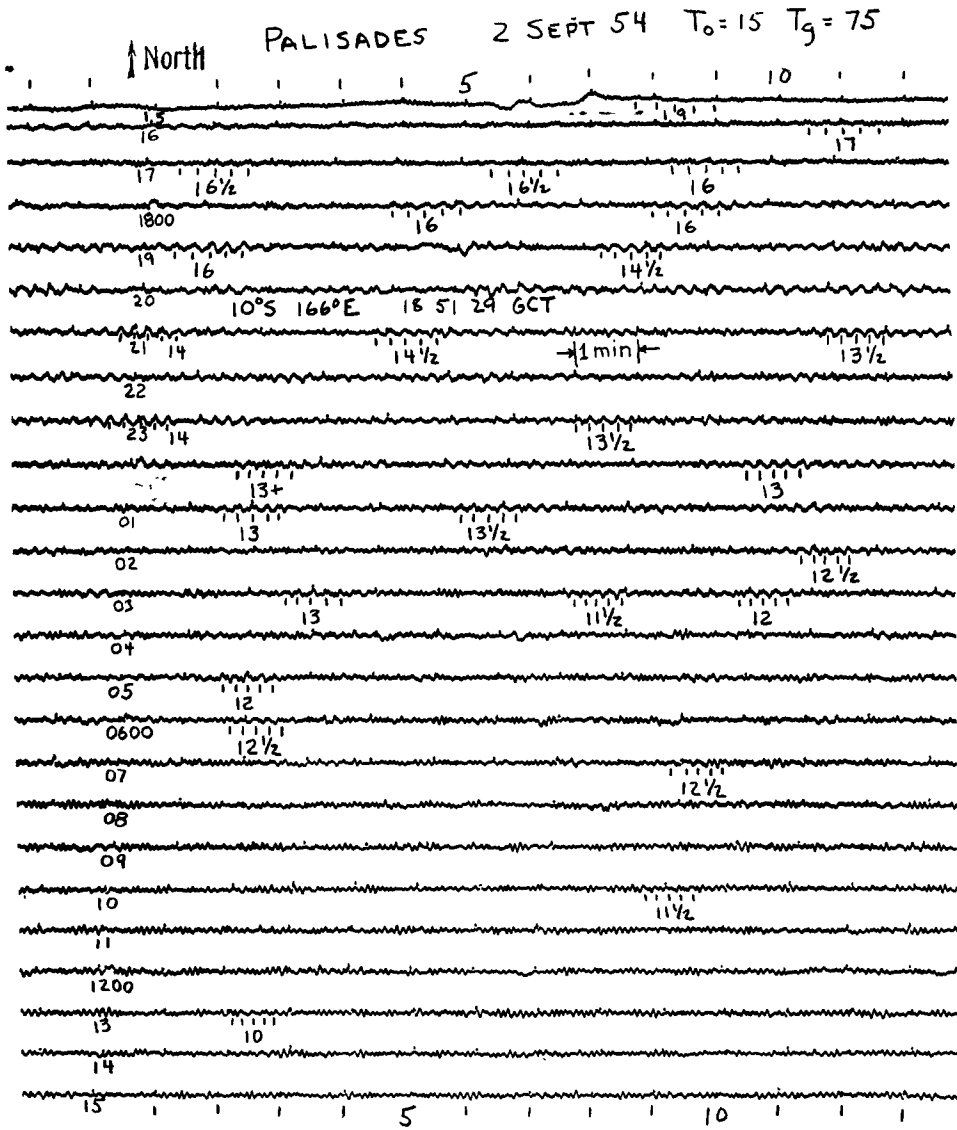


Fig 2. Seismogram, hurricane Dolly, N-S.

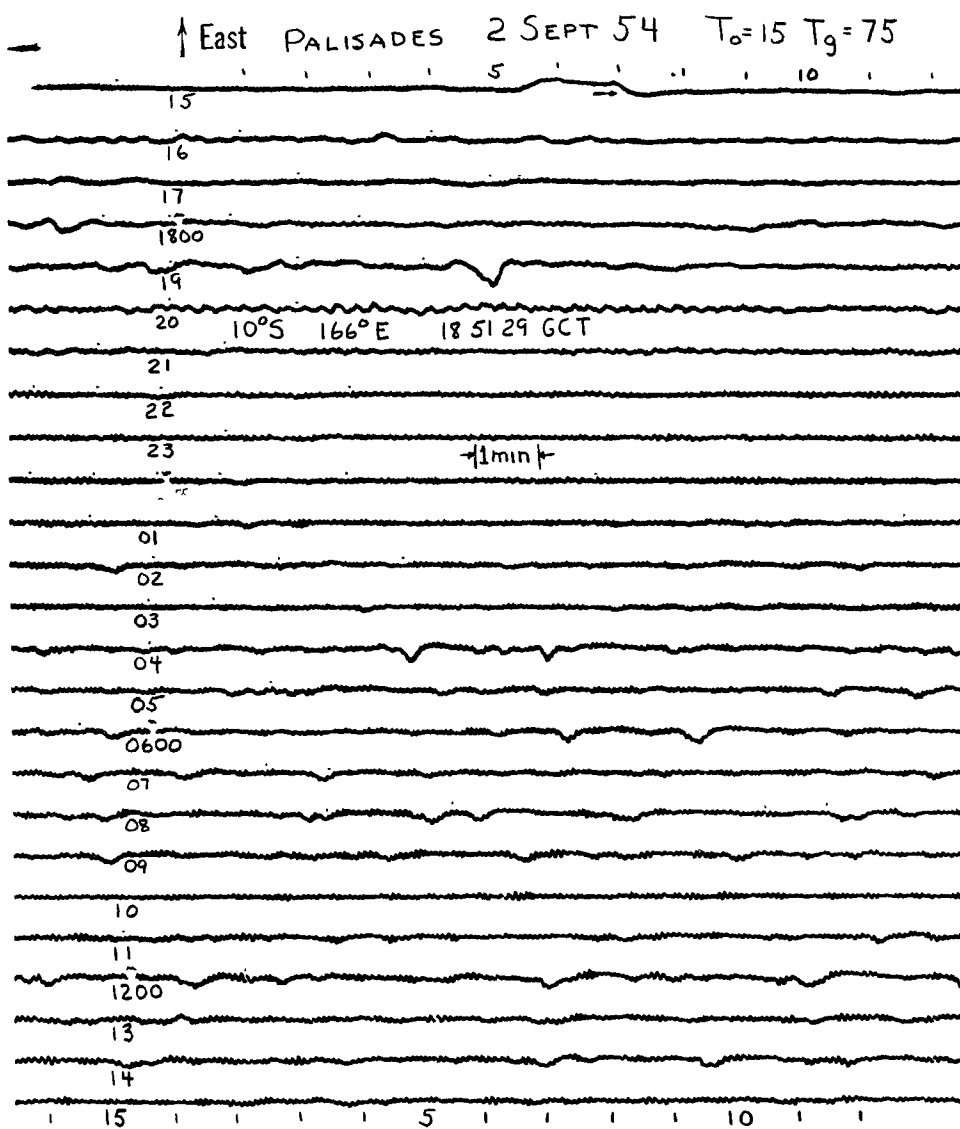


Fig. 3. Seismogram, hurricane Dolly, E-W.

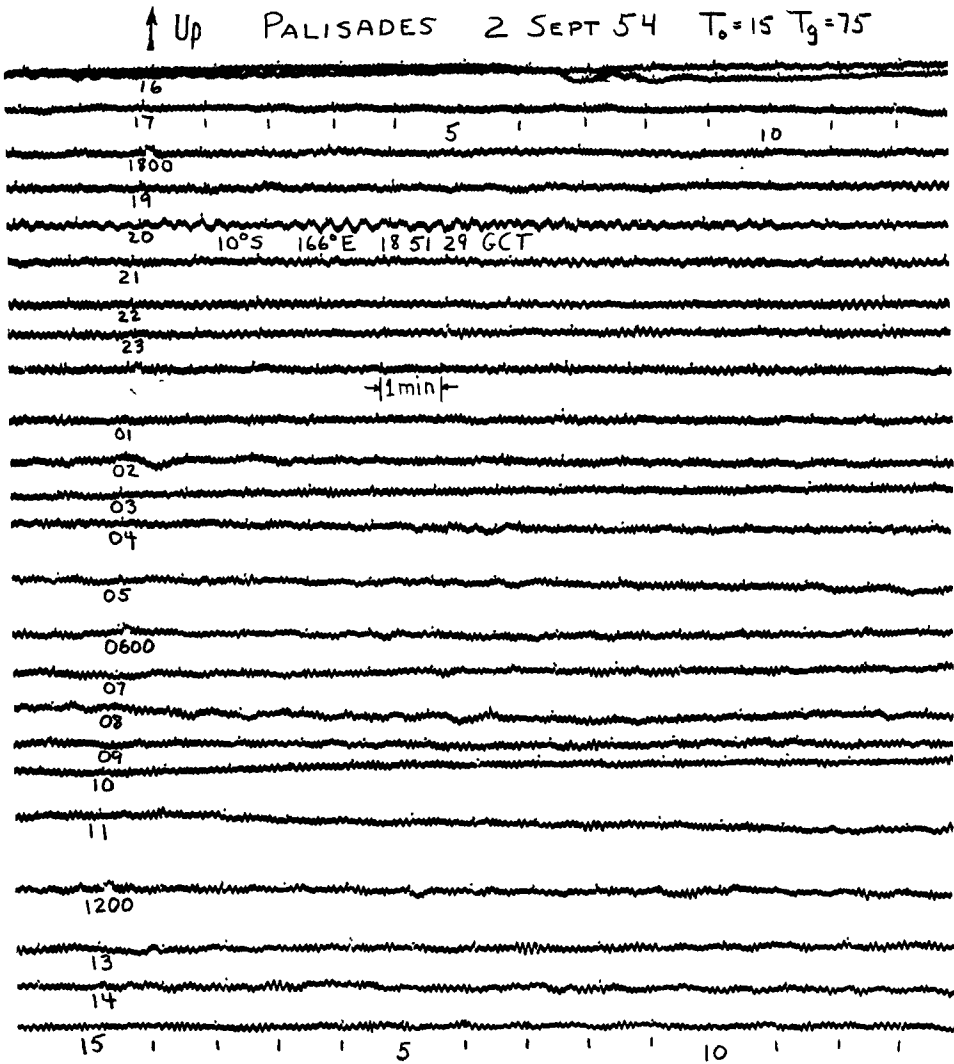


Fig. 4. Seismogram, hurricane Dolly, Z.

The wave recorder at Bermuda is an experimental one for which no quantitative amplitude calibration is available as yet. Response is good, however, in the 10- to 20-second range. The instrument is about one mile off the south shore of Bermuda in 60 to 65 feet of water. It ran during the season of 1954, and September, 1955.

The wave recorder at Gilgo Beach on the south shore of Long Island was a standard installation of the U. S. Beach Erosion Board and covered the 10- to 20-second period range adequately. It was at a depth of approximately 30 feet, and ran intermittently during the season of 1954.

APPEARANCE OF SEISMOGRAMS AND GROUND-PARTICLE MOTION

Figure 1 shows a seismogram during a typical storm of these long-period microseisms. If the effect of the shorter-period background is disregarded, the long-period waves are fairly regular and seem to have the familiar "beat" pattern common to storm microseisms of shorter periods. Periods are noted on the record.²

The long-period microseisms appear in storms lasting sometimes less than a day, sometimes several days. In general the amplitudes gradually increase and then gradually subside. In these respects the long-period microseisms are quite similar in appearance to microseisms of shorter periods.

In one respect, however, they are different. At Palisades the ground motion is almost entirely on the N-S component. Vertical motion is undetectable and E-W motion rarely present and then weakly. Figures 2, 3, and 4 show the three components of the Palisades instrument during the same time interval. No long-period activity is detectable on the E-W or vertical components of motion. Surface waves in the same period range from an earthquake in the Santa Cruz Islands may be seen recorded with approximately equal amplitude on all three components.

At Bermuda no vertical component is detected, but the E-W instrument occasionally shows measurable waves, although during the same interval these are almost always of smaller amplitude than those of the N-S component. Despite the small amplitudes, it is occasionally possible to determine that the two horizontal components of motion have phase differences of 0° or 180°.

Maximum ground motion, throughout the study, is of the order of two microns.

DATA PRESENTATION

Figures 5 through 8 show plots of long-period microseismic amplitudes at the Palisades and Bermuda stations versus time for the major parts of the hurricane seasons of 1954 and 1955. Amplitudes are given in millimeters of trace deflection. Dashed lines indicate intervals during which no long-period waves could be detected, although the possibility remains that waves of small amplitudes may have been obscured by short-period waves of large amplitudes. Periods in seconds are given by the numbers plotted at intervals under the amplitude curves.

The times during which hurricane tracks were charted by the U. S. Weather Bureau are also indicated. The solid black triangles superimposed denote the time

² Throughout this study, periods were estimated by measuring several successive peaks in well-defined beats. This situation could be improved by harmonic analysis of the record, but the ideas presented here are clearly established without this additional effort.

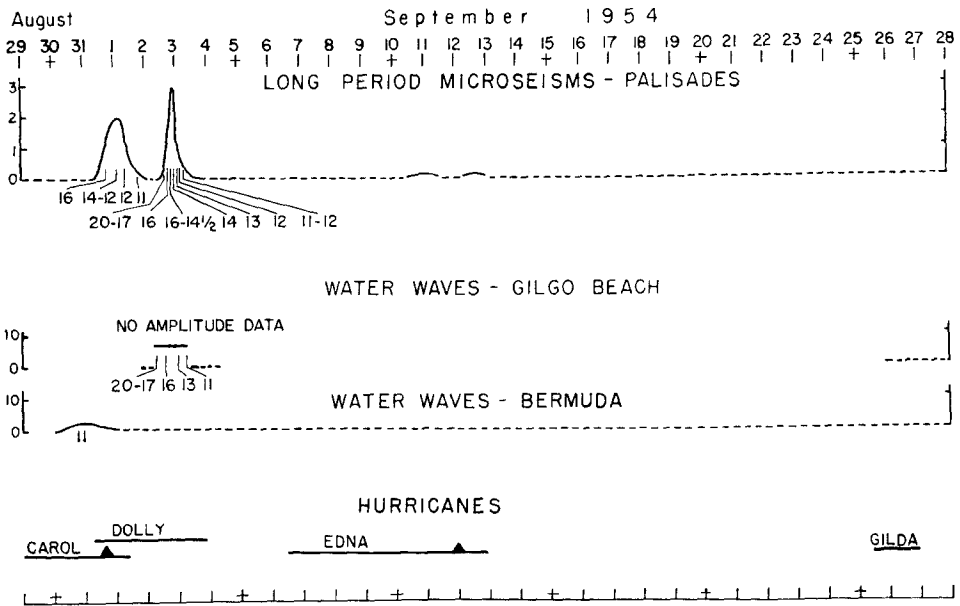


Fig. 5. Microseism, wave, and hurricane data, 1954.

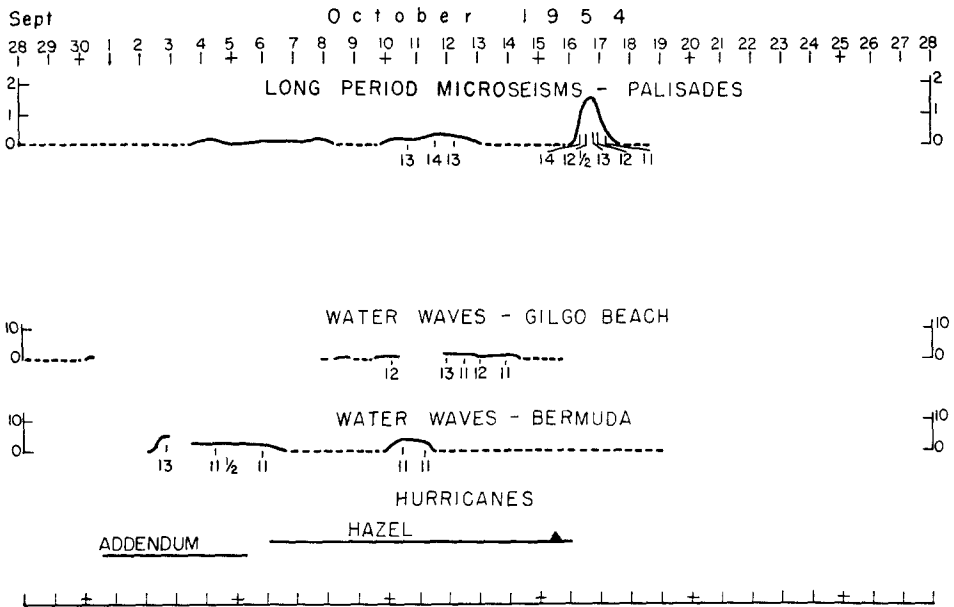


Fig. 6. Microseism, wave, and hurricane data, 1954.

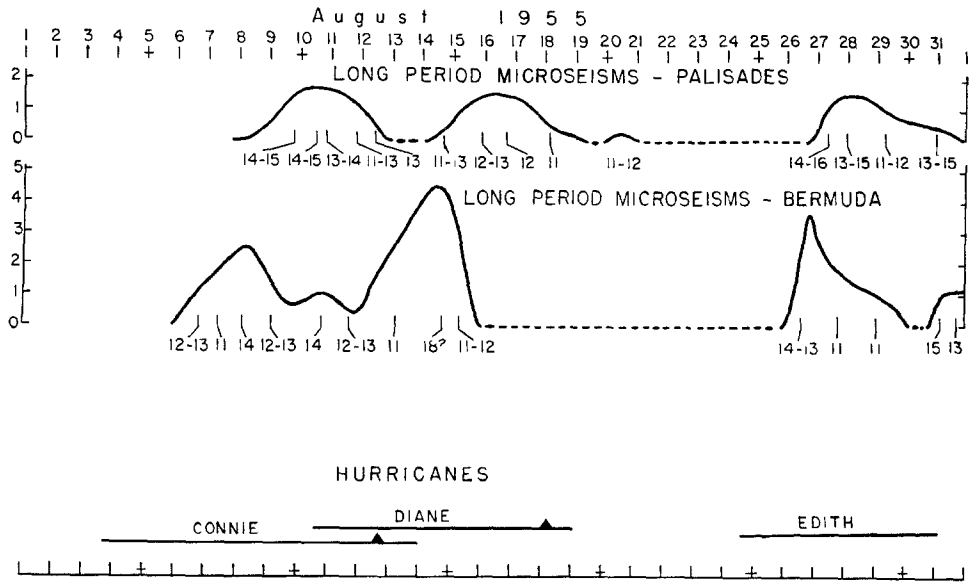


Fig. 7. Microseism, wave, and hurricane data, 1955.

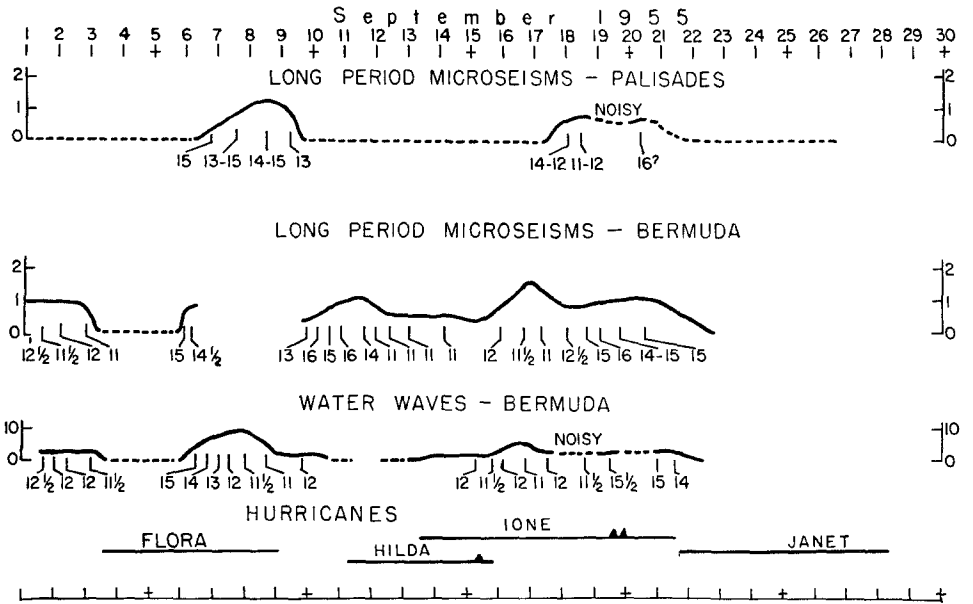


Fig. 8. Microseism, wave, and hurricane data, 1955.

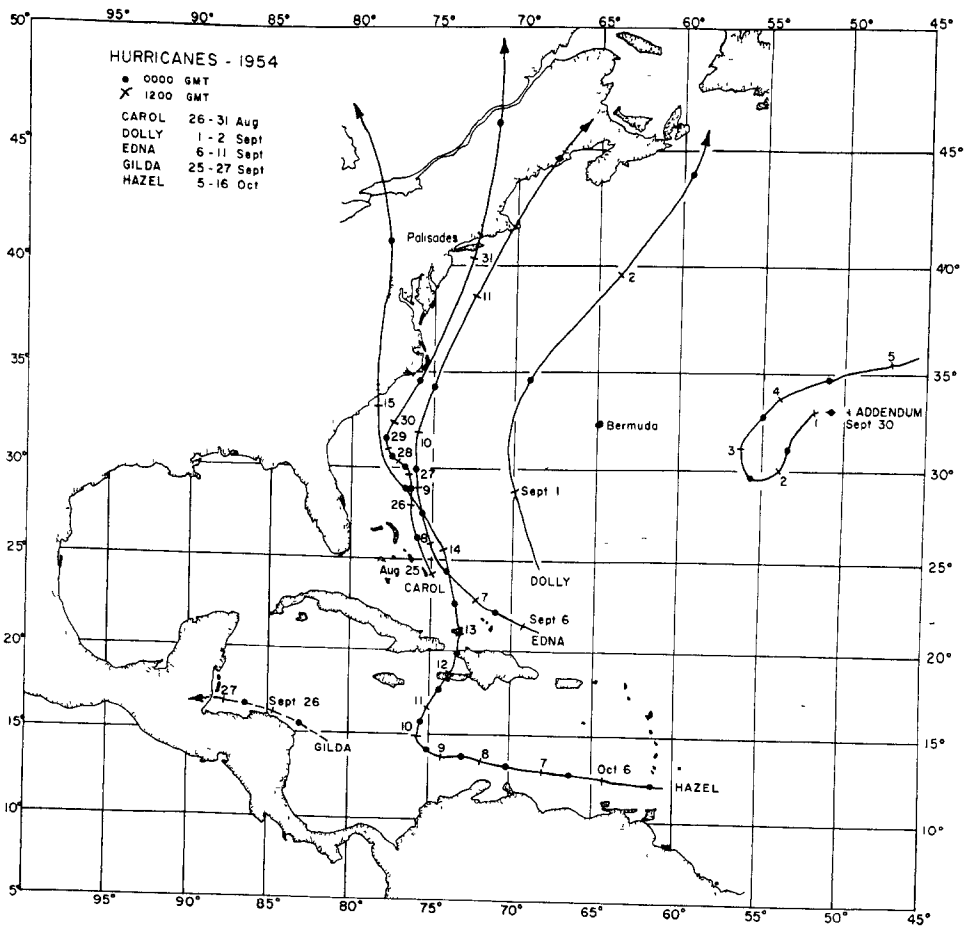


Fig. 9. Hurricane tracks, 1954.

at which the hurricane center crossed the coast line. Hurricane tracks for 1954 and 1955 are shown in figures 9 and 10.³

Water-wave data from the wave recorders at Bermuda and Gilgo Beach, Long Island, are also plotted for the intervals during which they are available. A sample wave record from Bermuda is shown in figure 11.

DATA ANALYSIS AND INTERPRETATION

There is a clear correlation between the times of occurrence of the long-period microseisms at Palisades and Bermuda, the long-period water waves at Gilgo Beach and Bermuda, and the hurricanes in the Atlantic. In fact, one set of wave-and-microseismic data from October 1 to October 8, 1954, which during the early part

³ W. R. Davis, "Hurricanes of 1954," *Monthly Weather Review*, 82: 370-373 (December, 1954); G. E. Dunn, W. R. Davis, and P. L. Moore, "Hurricanes of 1955," *ibid.*, 83: 315-326 (December, 1955).

of the study did not correlate with a hurricane, was completely explained when the Weather Bureau published an addendum to the original hurricane list of 1954.⁴

A general correlation between meteorologic disturbances over the sea and shorter-period microseisms is common and hence not surprising where the long-period microseisms are concerned. The controversial part of the studies on short-period microseisms has to do with mechanism by which the energy in the hurricane is

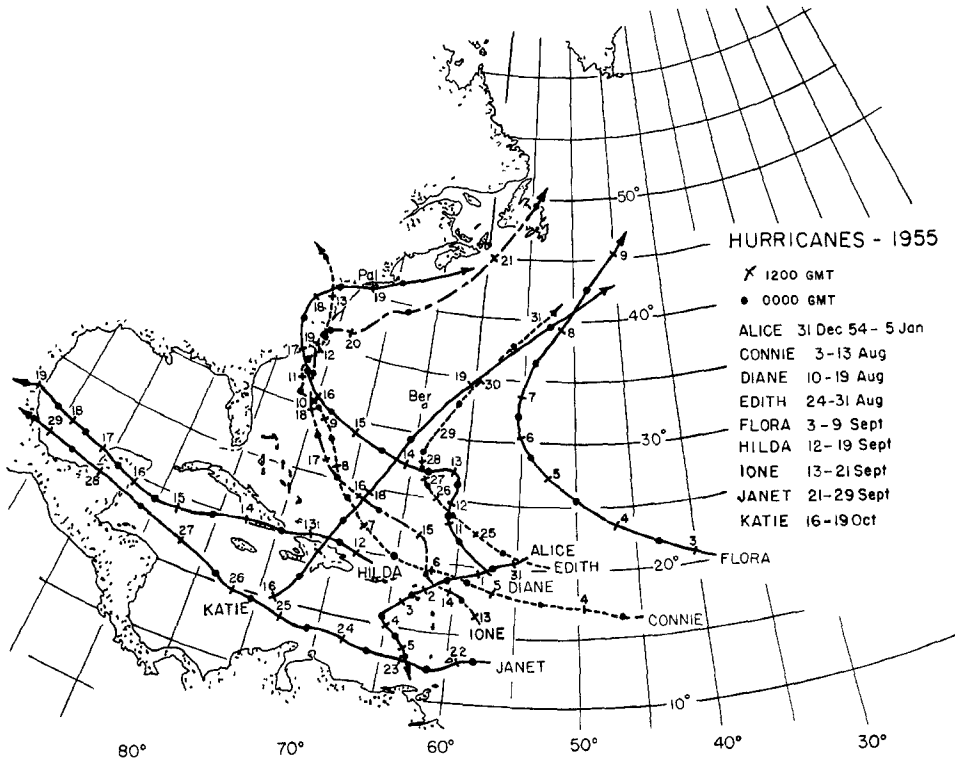


Fig. 10. Hurricane tracks, 1955.

transmitted to the ground beneath the station, the data often being ambiguous or difficult to analyze. Data on the long-period microseisms, however, are somewhat more amenable to a study of this particular aspect.

A delay of the order of one or two days between the time of arrival of the maximum amplitudes of the long-period microseisms at Palisades as compared with time of arrival at Bermuda is indicated by figures 5 through 8, best by figure 7.

This delay might be attributed in some manner to a change in the position of the storm center; but, as will be seen, a more satisfactory solution is to attribute the delay to a very slowly propagating wave over this segment of the path. Since elastic waves in the earth, water, or even the air, travel with a speed that is much too large to account for this delay, the only possible choice is ocean swell or gravity waves in water.

⁴G. E. Dunn, W. R. Davis, and P. L. Moore, "Addendum to 'Hurricanes of 1954,'" *ibid.*, 83: 314 (December, 1955).

Figure 12 shows a plot of phase and group velocity of gravity waves in deep water versus period. The group velocity for the period range under consideration varies from about $\frac{1}{3}^\circ$ to $\frac{1}{2}^\circ$ per hour. This is usually much greater than the speed of the storm center. Since the distance between Bermuda and the coast near Palisades is about 11 degrees, a travel time of 22 to 33 hours would be required, assuming, for simplicity, deep water along the entire path. This is just the order of magnitude of the observed value and so provides one confirmation of the gravity-wave hypothesis.

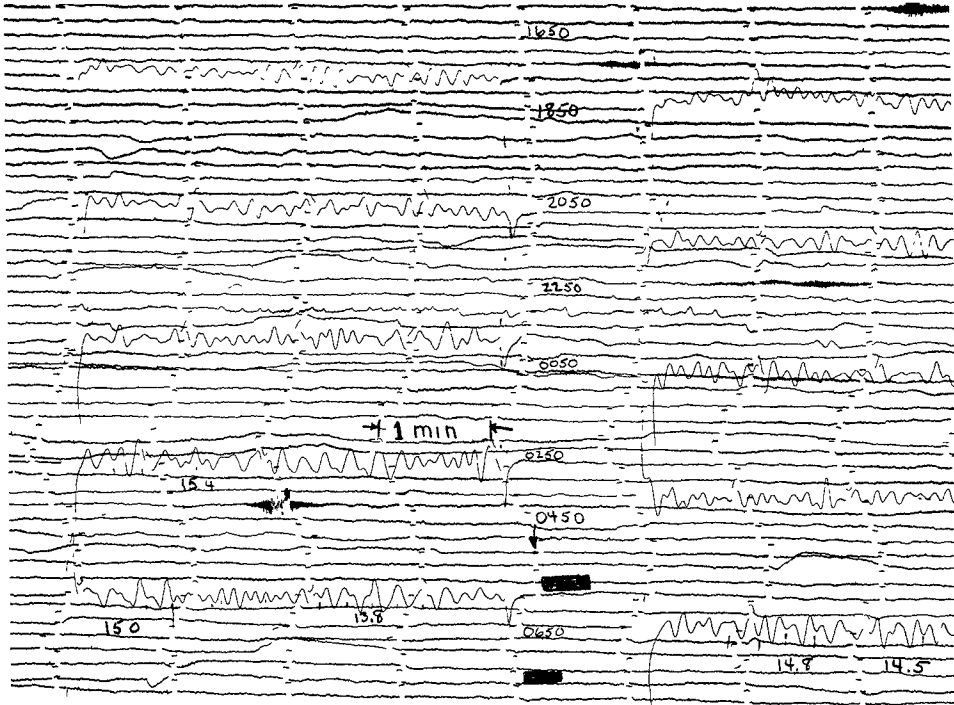


Fig. 11. Wave record, Bermuda.

When the arrival time of the beginning of microseismic storms at Bermuda, the group velocity of gravity waves in deep water, and the hurricane track are known, it is possible to deduce the point at which waves left the storm. For example, microseisms of 12- to 13-second period from hurricane Connie began at about 0000 H on August 6, 1955. Water waves of this period have a group velocity of about $0^\circ 35'/\text{hr}$. The beginning of the track as plotted by the Weather Bureau is, on the morning of the 3d, 60 to 72 hours earlier, at a distance of about 24° from Bermuda or the equivalent of 69 hours travel time. This check is good, remarkably so in the light of the simplifying assumptions about the nature of the source, propagation effects, the inaccuracies in the weather data—particularly in the early stages of development,—and the somewhat arbitrary decision with respect to the time the disturbance becomes a hurricane. Similar checks may be obtained from other storms. Hurricane Hazel in 1954 is interesting in that it appears to have radiated waves to

Bermuda and Palisades prior to entering the Caribbean, then ceased to radiate through the barrier of the West Indian island arc, then radiated again to Palisades while off the coast of the southern United States. There seems to be a general tendency, to be discussed later, for storms to radiate gravity waves best toward the left when they advance rapidly, but the slow velocity of Hazel in the Caribbean area favors a more symmetrical radiation. Thus correlation with geography, where Hazel is concerned, fits well with the gravity-wave or ocean-swell hypothesis.

Another and more direct line of evidence is the comparison of microseisms with waves recorded at near-by beaches. Throughout the period of the study there is good correlation, with respect both to period and to amplitude, between micro-

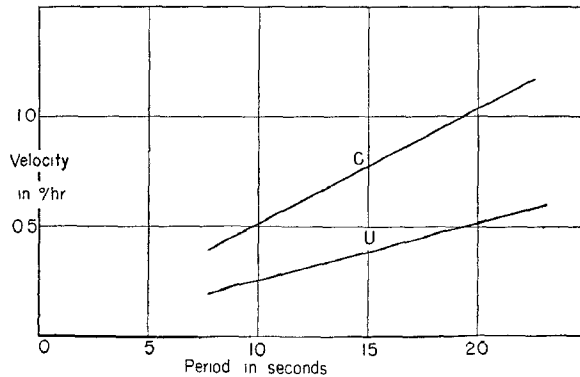


Fig. 12. Phase and group velocity, water waves.

seisms at Palisades and Bermuda, and waves at Gilgo Beach and Bermuda respectively. The only exception is between September 10 and September 15, 1955, at Bermuda, when microseisms were recorded and waves were absent. Since the wave recorder is to the south of Bermuda and since hurricane Flora was far to the northeast, it appears that the microseisms were caused by waves from the northeast, from which direction the wave recorder was shielded by the island. The only other storm at this azimuth from Bermuda is hurricane Edith, of 1955. For this storm, microseisms of strong amplitude and water waves of small amplitude were recorded; however, Edith passed much closer to the island, thus introducing near source effects which are difficult to evaluate.

There is a practical difficulty in correlating wave and microseismic data. When the long-period phenomena are of relatively small amplitude on the record, they tend to be obscured by the shorter-period, larger-amplitude disturbances, except in the occasional intervals when the shorter-period disturbances die down. Since most wave meters sample about ten minutes out of every four or six hours, they are likely, on a statistical basis, to distinguish long-period waves of small amplitude less frequently than the continuously recording seismograph. Thus, we might expect the seismograms to indicate long-period waves more often than the wave records.

However, in spite of this difficulty and others of a minor nature, there is, in general, excellent correlation between long-period microseisms and waves at near-by coasts. This case is strengthened by the pattern of changing periods in the swell

which correlates with the microseisms. In general, the periods tend to decrease with time throughout the storm.

THE SPECIAL CASE OF HURRICANE DOLLY

The pattern of decreasing periods throughout the storm is particularly striking in the waves and microseisms of hurricane Dolly, in September, 1954. Figures 2 and 5 show that the periods decrease regularly from 18 or 20 to about 10 or 11 seconds and

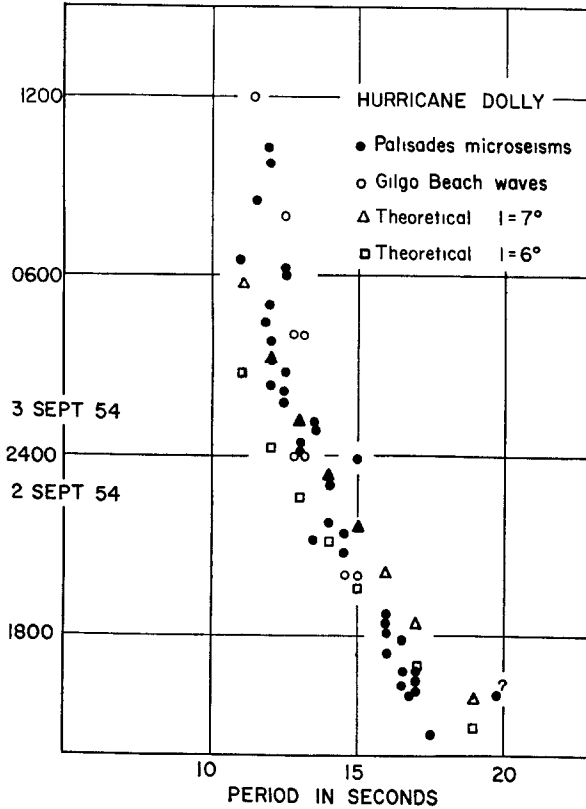


Fig. 13. Time vs. period, hurricane Dolly.

that the entire storm had a very short duration. The wave recorder at Gilgo Beach was not always working properly in September, and it was extremely fortunate that the meter operated during the storm. Amplitude data are unreliable, owing to an instrumental defect, but period data are satisfactory.

Figure 13 is a plot of time versus period which clearly shows the correlation between wave and microseism period throughout the storm and, in addition, the gradual decrease of period with time.

Dolly presents a unique situation which suggests a simple explanation of this dispersion. Whereas most hurricanes travel slowly, in comparison with the velocity of gravity waves in water, Dolly sped past the Palisades station at a speed greater than the group velocity of gravity waves of all periods noted in the study. This

means that instead of the complicated distribution in time and space of waves of various periods radiating from a slowly moving source, the radiation from Dolly follows a relatively simple pattern, similar, for example, to the bow wave of a ship which exceeds the group velocity of the waves.

A straight-line approximation to Dolly's path is shown in figure 14. Assuming, for simplicity, that the storm moved at constant average velocity, V , along this path, that the disturbance concentrated at a point rather than over an area, and that the deep-water formula for gravity-wave velocity holds over the entire path, it is easy to compute the theoretical dispersion at Gilgo Beach. The method is adapted from Lamb,⁵ using $\cos \theta = U/V$, where U is the group velocity. The points computed

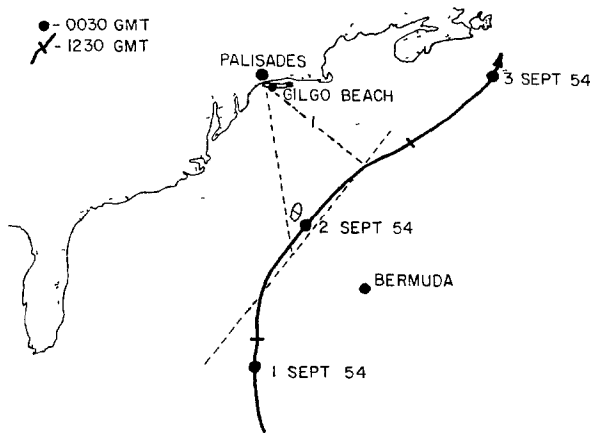


Fig. 14. Track of Dolly.

are shown in figure 13. In order to get some idea of the effect of the broad source area, values of 6° and 7° for the distance, l , from Gilgo Beach were chosen for the computations. It is clear that dispersion in the water waves alone accounts for the observed dispersion in the microseisms.

DISCUSSION AND CONCLUSIONS

The data from this study indicate that ground motion with periods of 11 to 18 seconds recorded at Palisades and Bermuda is due to meteorological disturbances over the sea, and that, furthermore, the energy is radiated from the storm as ocean swell and transferred to the ground at or in the vicinity of the coast, without change of period.

Surf theory.—The data do not show details of the mechanism of energy transfer. It seems certain, however, that this occurs in the region between the shore and the depth where the water becomes too deep for the wave to “feel” the effect of the bottom and thus to transfer momentum and energy to the earth. This region may extend to sea well beyond the breaker zone, and it is partly for this reason that the term “surf” has not been used freely. Although the results of this paper are in accord with many of the ideas of the classical “surf” theory of microseismic generation,

⁵ H. Lamb, *Hydrodynamics* (New York: Dover, 1945), p. 433.

the term "surf theory" has connotations which do not fit this particular case. One of these, the extent of the conversion zone, has already been mentioned. A second is the implication that the microseisms are generated by waves "pounding against rocky coasts." Clearly, the coast of Long Island cannot be classed as rocky, but rather as sandy and gently sloping. As for Bermuda, there is some complication owing to the presence of coral reefs. Apparently, for the situation in which waves strike a gently sloping beach, there are no studies of the amount of energy transferred to the ground; but it is known that the energy reflected from the shore as water waves is then extremely small. Thus, since most of the wave energy is dissipated when the wave strikes the coast, it is not illogical to assume that a small fraction of this energy is converted to seismic waves.

Relative energies.—Several calculations of the relative energies have been reported. Byerly⁶ assumed two-dimensional propagation and used the following formulas:

$$\text{Energy of a wave in deep water, } E = \frac{\rho g L h^2}{16T}$$

$$\text{Energy of a seismic wave (approximate), } e = fE = \frac{7.06\pi\rho a_H^2 V^2}{T}$$

Assumed value, this paper

where g	= acceleration of gravity	980 cm/sec. ²
L	= wave length	3.6×10^4 cm.
h	= height of water wave	50 cm.
T	= period	15 sec.
ρ	= density of medium, water or rock	1 or 2.7 gm/cc.
a_H	= horizontal amplitude of ground motion	2×10^{-4} cm.
V	= velocity of propagation	3×10^6 cm/sec.

Assuming the reasonable values shown in the right-hand column,

$$f \cong 4 \times 10^{-5}$$

Although the assumptions and approximations involved are many, this fraction is so small that the energy relationship does not appear to present any difficulty.

Additional experimentation on the problem of energy transfer from waves at a shallow beach to the ground would be of interest. This might be accomplished by laboratory tests or by installing instruments near the coast. It is conceivable that there might be an optimum angle of beach slope for transfer.

Ground-particle motion.—Particle motion is always in the direction of the source. On the rare occasions when, at Bermuda, amplitude could be measured on two components, the direction always agreed with that computed by the swell theory. This is the direction to the storm center at the time the waves left it, and not necessarily the direction to the center when the waves arrive.

Lack of a vertical component is attributed to proximity of the stations to the

⁶ P. Byerly, "Microseisms at Berkeley and Surf on Near-by Coasts," *Bull. Seism. Soc. Am.*, 32: 277-282 (1942).

coast. Both stations are within about one wave length of the coast. A greater distance would be required before free surface vibrations of the crust (Rayleigh and Love waves) could develop their characteristic appearance. The possibility that these are Love waves radiated from some part of the New England coast is ruled out on the basis of the close correlation between arrival times of waves and microseisms, particularly from hurricane Dolly.

Longuet-Higgins theory.—The data argue strongly against theories, such as that of Longuet-Higgins, which require interfering wave trains as a means of transferring energy to the ground beneath the sea. First, there is very little likelihood of interfering wave trains off Long Island and Bermuda, owing to the discrete nature of the distant source and the low reflection coefficients of the shallow beaches. There is even less likelihood that such interferences might originate from two independent sources and arrive at times coordinated with the hurricanes as described. Second, the interfering-wave-train theories require the period of the waves to be twice that of the microseisms. There is no indication of this in the wave records, nor would waves of such periods account for the dispersion in the storm from Dolly. Furthermore, waves of periods as high as 30 or 40 seconds are virtually unknown in the oceans, and certainly, if present, are not of great amplitude. In more than two years at sea, wave recorders on submarines, used in conjunction with gravity-measuring apparatus, have yet to record wave periods higher than 22 seconds. Third, the unusual particle motion, purely horizontal and longitudinal, is very difficult to explain if it is necessary to start with a vertical impulse at some part of the ocean bottom. Fourth, the short-period microseisms during hurricane Dolly are not half the wave period recorded by the wave recorder at Gilgo Beach. Thus, the interfering-wave-train theory fails completely in the explanation of the long-period microseisms.

Extension of results to shorter periods.—Although the data of this study include no periods of less than 11 seconds, it is interesting to speculate on the relation between the long-period microseisms and those of shorter periods. There was some indication, in the course of the study, that the range might easily be extended to periods as low as 10 and possibly 9 seconds. The chief difficulty in extending to even shorter periods is the lack of good wave data. Periods of 5 to 9 seconds which might be correlated with wave data are easily obscured by microseisms of shorter period, 2 to 5 seconds, for which wave data are frequently poor owing to the depth of the wave-sensing devices.

An additional difficulty in associating the long-period microseisms with those of shorter periods is the peculiar particle motion. If it can be proved that this is truly a near source effect and that the energy radiates from this near source area as one or more of the familiar types of elastic waves, the case for similarity with the short-period waves will be strengthened. Conversely, recordings of short-period microseisms taken near to the coast line might indicate the same unusual particle motion. If such facts can be ascertained, then this study would provide evidence in favor of of the surf theory, with the modifications specified, for the origin of at least a part of the shorter-period microseisms.

Work of Banerji.—The only previous study known to the authors of regular microseisms of such long periods is that of Banerji,⁷ who studied microseisms of

⁷ S. K. Banerji, "Microseisms Associated with Disturbed Weather in the Indian Seas," *Phil. Trans. Roy. Soc. London*, ser. A, 229: 287-329 (1930).

10- to 30-seconds period, recorded at Colaba. He correlated the appearance of these waves with winds of velocity greater than 20 miles per hour. At Colaba this is primarily the sea breeze. After tests to establish that the microseisms were not due to the force of the wind against the building, Banerji concluded that the waves must be due to the ocean swell in the vicinity of the coast. He showed that the microseisms began somewhat before the sea breeze, indicating that the action of the wind on the water at a distance from the coast accounted for the swell, which, in turn, generated the microseisms. This is in complete agreement with our results.

Radiation pattern.—A qualitative picture of the radiation pattern of swell from a hurricane may be obtained from the data of this study. When the storms are moving slowly in the low latitudes, there appears to be an appreciable amount of swell radiation toward the right, as evidenced by the waves and microseisms at Bermuda, Gilgo Beach, and Palisades. Indeed, if the storm were stationary, the radiation pattern would be expected to be symmetrical. However, as the storm moves into the area between Bermuda and the east coast of the United States and begins to travel with greater speed, the data indicate strong radiation of swell toward Palisades and very little radiation toward Bermuda. The best examples of this are hurricanes Carol, Dolly, and Hazel, of 1954.

Applications.—Several possible applications of this study suggest themselves. One of these would be the use of seismograms to study ocean swell. Although, at first glance, substitution of a seismometer for a wave meter seems a rather indirect approach, there are several practical advantages. At the seismograph stations which operate long-period recorders, there are backlogs of records available from instruments which have operated continuously in the past. The dispersion study of hurricane Dolly clearly indicates the value of a continuous recorder. Most wave recorders do not operate continuously, and only a relatively few wave recorders of any sort have operated consistently. In fact, the lack of wave data of any type, particularly on the east coast, is surprising. The sustained effort made by the U. S. Beach Erosion Board in this direction is highly commendable, but the number of stations, limited by the funds available, is inadequate in many respects.

An additional advantage of a seismograph as a wave recorder, especially on an island station, is its sensitivity to waves from all azimuths. A wave recorder, on the other hand, may be shielded from waves from a large sector by the island. This point is illustrated with respect to hurricane Flora, previously discussed.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to the personnel of the Geophysical Field Station of Columbia University for the use of the Bermuda data, in particular Mr. D. H. Shurbet for the seismograms and Mr. Frank Watlington for the wave data; similarly, to Mr. Joseph Caldwell and Mr. Robert Harris of the U. S. Beach Erosion Board, for the use of the Gilgo Beach wave records.

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