MICROSEISMS AND WEATHER FORECASTING

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ABSTRACT

Microseisms are more or less regular elastic surface waves recorded continuously by sensitive seismographs. They may be propagated to great distances except where the energy is dissipated at geological discontinuities. Microseismic waves arriving at a seismographic station can be used to locate the direction of the source. The accuracy of such azimuth determination from differences in arrival times at three stations on a triangle with sides one or two miles long is investigated. Certain types of microseisms are correlated with atmospheric disturbances and can be used in weather forecasting and especially in locating tropical disturbances. Publications referring to this method are mentioned. The method's routine application by the U. S. Navy Department in locating hurricanes in the Caribbean area is discussed, as well as the precautions which must be taken in drawing conclusions from the amplitudes of microseisms.

Sensitive seismographs continuously record movements of the earth's crust which are due partly to meteorological causes and partly to traffic, industry, etc. (fig. 1). These movements are called microseisms. Hundreds of papers have been published dealing with microseisms. The following contain many references: Gutenberg (1924; 1932; 1936), Krug (1937), Ramirez (1940), Kishinouye (1940), and Gilmore (1946).

Microseisms may be caused, for example, by rain, wind, ocean waves, surf, and freezing of the ground. All these types of microseisms differ in appearance. This paper deals with only two types: microseisms connected with extratropical storms and those connected with tropical storms. It is to be expected that the mechanisms in these two types should differ noticeably, because in the second instance there is a larger amount of energy locally but the area affected is much smaller than in the first instance.

It was recognized rather early that several types of microseisms are strongly correlated with atmospheric disturbances, and attempts were made to use the correlation in weather forecasting. The first actually to use microseisms for this purpose was Linke (1909), who found that microseisms at Apia, Samoa, increased considerably with an approaching storm and that the recorded waves were the more irregular and their periods the smaller, the closer the center of the storm was to Apia. He used the observations to predict the approach of a storm or the change in its path. Gutenberg (1924; 1932) pointed out, with examples, that it is possible to find the approximate path and intensity of storms approaching Europe by plotting relative amplitudes of the microseisms at a number of selected stations and considering the amplitude changes with time.

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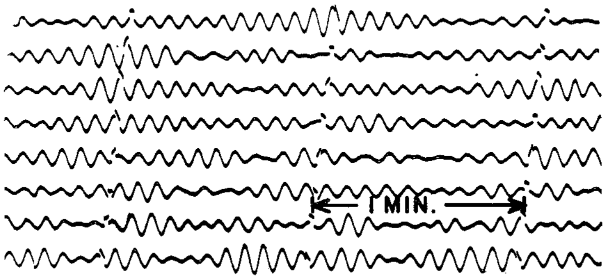

FIG. 1. Microseisms recorded at Pasadena, California.

Gherzi (1930; 1932) pointed to the close relation between microseisms at Zi-ka-wei (near Shanghai) and tropical cyclones approaching China. Banerji (1935) studied in detail the microseisms in India and their relationship to the tropical disturbances of that region; he was finally led to use the amplitudes of microseisms recorded there in the routine location of hurricanes (oral communication, 1946).

Repetti (1933) studied the relationship between typhoons and microseisms in Manila. He found that typhoons approaching the Philippines from the east do not normally give rise to microseisms at Manila until the center of the disturbance has reached such a position to the northeast of Manila that its southwest wind is felt on the west coast of Luzon. A typhoon crossing the Visayas produces little or no microseismic effect in Manila. When a typhoon crosses Luzon not more than 200 km north of Manila the microseisms become extraordinarily conspicuous. Microseisms in Japan produced by typhoons were discussed by Wadati and Masuda (1935) and by Kishinouye (1940).

A tropical disturbance near the coast of Mexico south of Lower California produced noticeable microseisms at Pasadena (Gutenberg, 1936, p. 160).

To get more accurate data on the relationship between storms and microseisms, attempts were made rather early to determine the direction from which microseisms were arriving. Hecker (1915) used two instruments located at various distances from each other to get some information as to the speed of microseisms and the direction of their arrival at Strasbourg. The war prevented the completion of the project. Shaw (1922) installed two instruments, 4 km apart, near West Bromwich, England, for the same purpose but did not achieve good success. Experiments of a similar kind but with less accuracy in time determination were made in Japan by Kishinouye (1935). Lee (1935b) tried to use the amplitude ratio of the two horizontal components to determine the direction of approach of microseismic waves in Great Britain.

The first partly successful experiments were those by Krug (1937), who used four portable seismographs near Göttingen, Germany. He found that the microseisms came from a northeasterly direction and that their speed was only slightly more than 1 km/sec. Better results were obtained there by Trommsdorff (1939), who used three or four sets of instruments with two or three components each. The direction of the arriving microseismic waves coincided very closely with the direction to the center of low-pressure areas and showed variations of about 90° within two days, in close agreement with the actual movement of the disturbances.

A very thorough study of the direction of arrival of microseisms near St. Louis, Missouri, and their relationship to low-pressure areas was made by Ramirez (1940) under the supervision of Macelwane, using one "tripartite station" (three instruments at the corners of a triangle with sides not exceeding a few miles).

All experiments described thus far used only occasional records of microseisms. In 1944 Captain H. T. Orville, U.S.N., of the U. S. Navy Department, became impressed by the previous results and overcame all obstacles in starting the first routine use of microseisms in locating hurricanes. As the first part of this Navy project, a tripartite station was installed at Guantanamo Bay, Cuba, by Lt. Commander M. H. Gilmore, U.S.N.R., under the supervision of Captain W. Loveland, U.S.N. The results gained during that year resulted in the installation of two additional tripartite stations in 1945, at Richmond, Florida, and Roosevelt Roads, Puerto Rico, and to a further extension of the project in 1946, including the installation of stations in the western Pacific.

Most of the results presented in the rest of this paper are based on data obtained by the Navy project, partly on study of original records by the author, partly on readings made by Lt. Commander Gilmore, who is still supervising the project, by Lt. (j.g.) Roush (Richmond), and by Ensign Pringle (Guantanamo Bay). Data for amplitudes of microseisms at San Juan, Puerto Rico (fig. 4), are based on records written at the San Juan station of the U. S. Coast and Geodetic Survey; the measurements were made under the Navy project.

The author is indebted to Captain Orville for his permission to use the material, to him, to Captain Loveland, and to Lt. Commander Gilmore for their aid during visits in 1945 and 1946 to the Caribbean area, especially to all the stations, and for suggestions made during discussions of the results.

A description of the stations and a detailed discussion of the data have been given by Gilmore (1946). A preliminary summary of the history and results of the project was released by the Navy Department on 15 November 1945. A more detailed pamphlet, including parts of the reports of the author,[2] has been published by the U. S. Navy Department.[3]

There is little doubt that microseisms are surface waves which decrease exponentially with depth, although direct measurements of the amplitudes down to a depth of about 1 km are inconclusive (Gutenberg, 1932, p. 290; Krug, 1937, pp. 329, 343). Theoretically the decrease in amplitude with depth depends on the structure (see, for example, Lee, 1932a; 1932b; 1934a). In general, in surface waves the amplitudes decrease with depth corresponding to a factor $e^{-2\pi ah/L}$ where L is wave length, h is depth, and a is a constant depending on the structure below the point of observation. From the observation of surface waves in earthquakes Gutenberg (1945) found approximately $a = 0.3$. According to this value, most of the energy in surface waves is propagated within a layer having a thickness equal to the wave length; only a small percentage of the energy penetrates below that depth. As the speed of microseisms is in general between $2\frac{1}{2}$ and 4 km/sec, their period usually between 3 and 7 sec, and consequently their wave length usually between 10 and 20 km, their energy should be propagated mainly within the uppermost 20 km of the earth's crust.

This has an important effect on the microseisms. In geologically undisturbed areas they are propagated to great distances, since the absorption factor for surface waves is relatively small. Microseisms originating in or near Norway are clearly propagated to the east as far as central Asia (fig. 2c; Gutenberg, 1921). On the other hand, the same microseisms decrease noticeably in amplitude in southerly directions, where they cross the discontinuities between the geologically oldest parts of northern Europe and the younger areas of central Europe and between the latter and the still younger Alpide belt. Microseisms originating in the region of Great Britain show rela-

[2] B. Gutenberg, "Microseisms," Report to the U. S. Navy Department, 1945.

[3] U. S. Navy Department, Chief of Naval Operations, Aerology Section, "Navy hurricane microseismic research project," Navaer 50-IR-189, 14 pp., 1946.

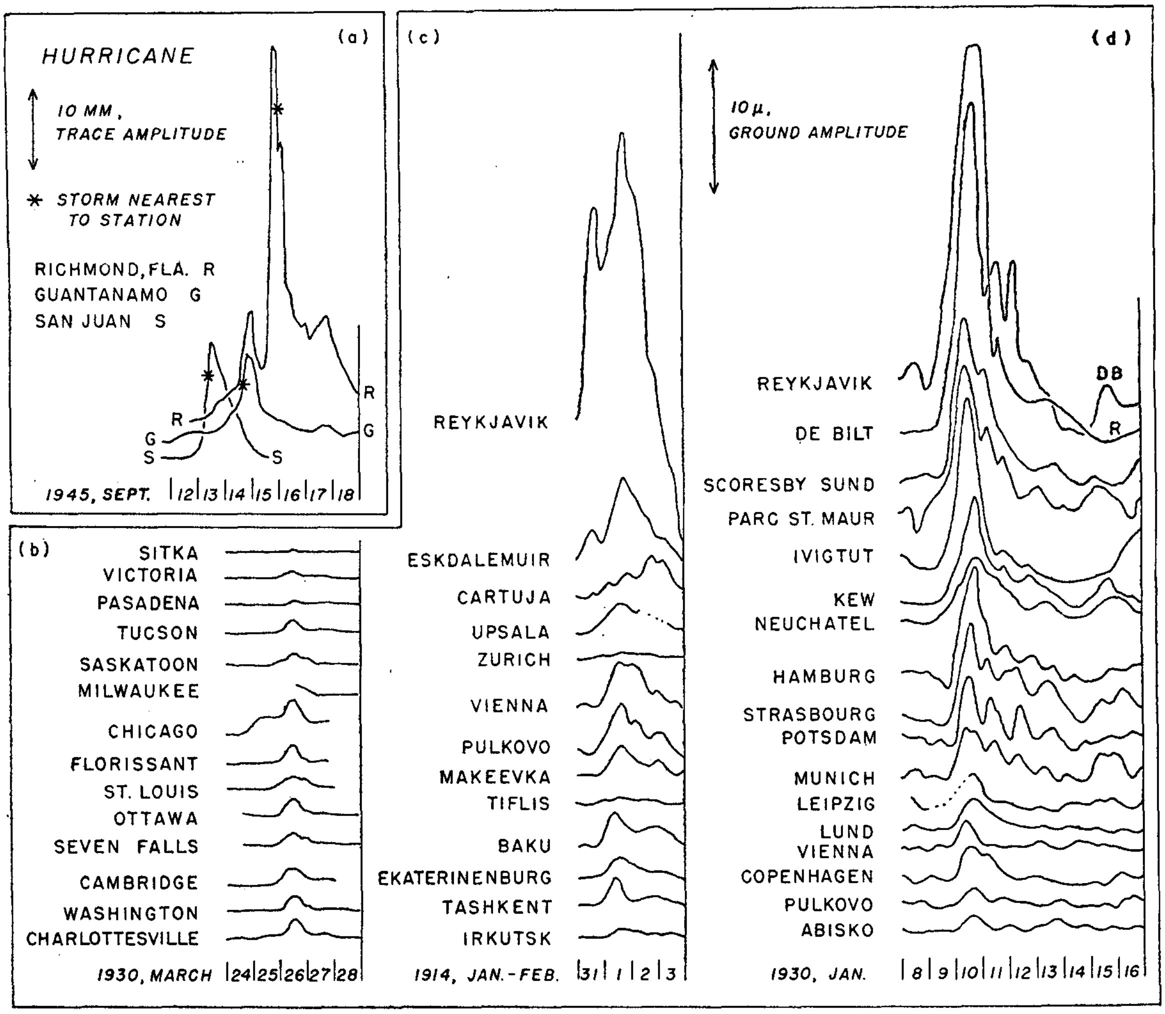

FIG. 2. Amplitudes of microseisms: (a) in the Caribbean during a hurricane (from Gilmore, 1946, p. 111); (b) in North America during a storm in eastern Canada (from Gutenberg, 1931, p. 13); (c) in Europe and Asia during a storm approaching northern Norway (from Gutenberg, 1921, p. 12); (d) in Europe and Greenland during a storm north of Scotland (from Lee, 1934b, p. 7).

tively large amplitudes only in the sector of central Europe with similar geological history, while microseisms originating in southwestern Europe show large amplitudes mainly in the area of the Alpide region. It is quite evident that the discontinuities which separate these geologically different areas and extend downward to a depth of at least an appreciable fraction of the wave length of microseisms reflect or refract a part of the energy. Similarly, microseisms originating in the neighborhood of the Canadian shield are propagated to great distances over the United States and Canada and decrease noticeably only after passing the Rocky Mountain area into the Pacific belt (fig. 2b).

The importance of the boundaries between geological units and the effect of deep geological discontinuities in decreasing the amplitudes of the microseisms were pointed out first by Gutenberg (1921) and later confirmed by many (for example, Lee, 1932a; 1932b; 1934b; Murphy, 1946).

The propagation of the microseisms in the Caribbean area contrasts strongly with that in the continents. The microseisms decrease rapidly from island to island in the Antilles (figs. 2a, 3, 4). While they reach maxima simultaneously over large areas in Europe or the continental United States, the maxima in the Caribbean are related much more to the proximity of the storm center. Apparently the unusually deep discontinuities between the strongly fractured blocks in the Caribbean prevent most of the energy from spreading from one geological block to the next. Such effects must be considered whenever microseisms are used in forecasting in an area which is strongly disturbed geologically (for similar conditions in Japan, see Wadati and Masuda, 1935).

In the western Pacific the station at Guam is operating with one instrument until the remaining equipment for a tripartite station arrives. Microseismic records are available for the time of the typhoons of 22–31 July and 11–19 August, 1946. In both instances, microseisms increased rapidly when the typhoon crossed the boundary in the Pacific ("Andesite Line") east of the Marianas Islands. This increase may have been partly due to an increase in the

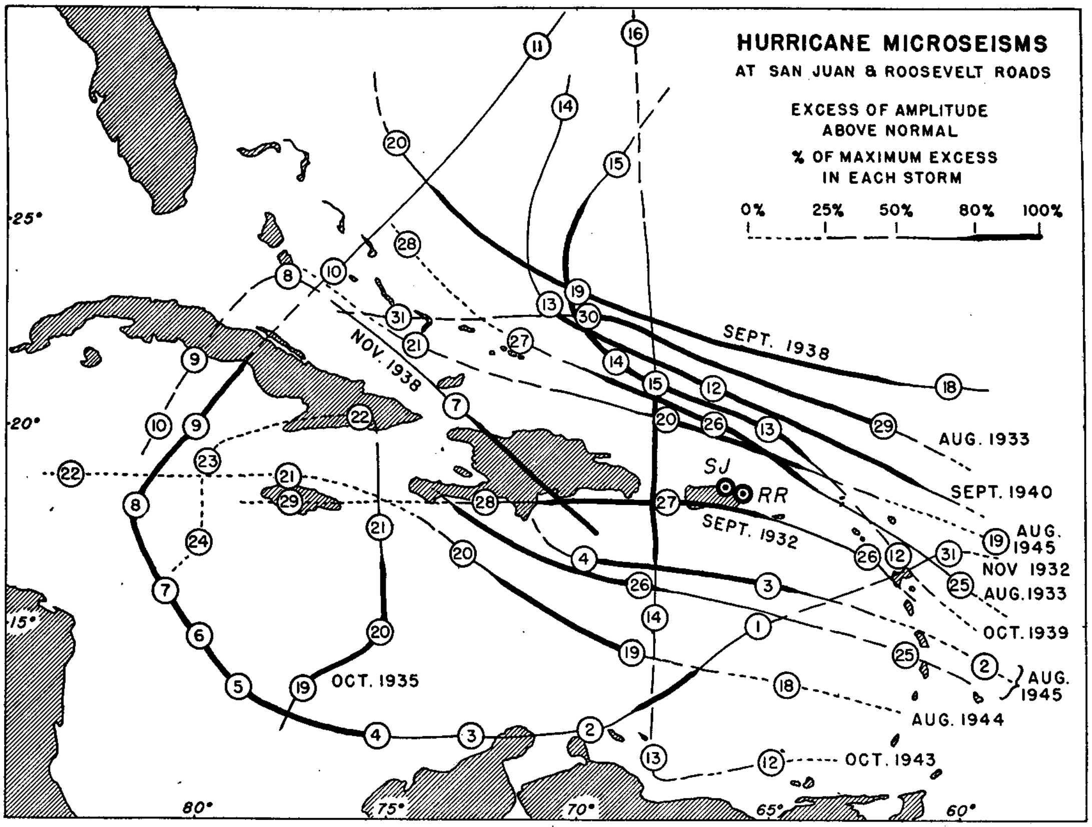

FIG. 3. Tracks of hurricanes in the Caribbean Sea with indication of relative amplitudes of microseisms at San Juan and Roosevelt Roads, Puerto Rico.

intensity of the typhoon, which, in both cases, was first located 12 hours after the rapid increase of the microseisms had started. However, the microseisms remained rather large as long as the typhoon remained on the same geological unit with the station. They decreased only slowly as the typhoon moved away from Guam, and their amplitudes were still more than twice their normal value when the typhoon passed the unit's western boundary, at Japan and the Ryukyu Islands, over 1000 miles away.

In comparing results from station to station the effect of the ground on the recorded amplitudes must be considered (see, e.g., Gutenberg, 1932, p. 272; Lee, 1932a; 1932b; 1934a; 1934b; 1935a). For example, ground saturated with water is more likely to vibrate with large amplitudes than solid rock, thus providing "increased sensitivity." However, the greater complexity of the records from such stations is a disadvantage and frequently more than offsets the advantage of the greater amplitudes. For this reason the Richmond station of the Caribbean network did not give quite as regular records as the station at Guantanamo Bay. The station installed in 1946 on loose sand at Corpus Christi, Texas, records very rapid changes and by far the largest amplitudes. On the other hand, the stations with smallest amplitudes are Roosevelt Roads and Trinidad, but their records can be interpreted more easily.

Many of the investigations deal with the problem of what type of movement occurs in the microseisms. There is little doubt that microseisms are surface waves, but there are two types of such waves: surface shear waves, or Love waves, in which the particles move parallel to the surface of the earth and perpendicular to the direction of propagation; and Rayleigh waves, in which the particles move in ellipses with the longer axis vertical and the shorter axis in the direction of propagation. The few authors who have studied this question agree that in microseisms Rayleigh waves prevail (e.g., Lee, 1932a; 1932b; 1935b; Ramirez, 1940). Additional information is now available from the records made in 1944 at Guantanamo Bay, where two north–south components and two east–west components were used. Fig. 5 gives the ratio of the east–west to the north–south component as a function of the azimuth of the arriving waves. For each component the average of the readings from two different instruments was taken. It is evident that in waves arriving from a westerly direction (azimuth near 270°) the east–west component is much larger than the north–south component (possibly affected partly by different sensitivity of the instruments) and that in waves arriving from southern or northern directions the north–south component seems to predominate slightly. For this reason it is important to have all instruments in a tripartite station oriented

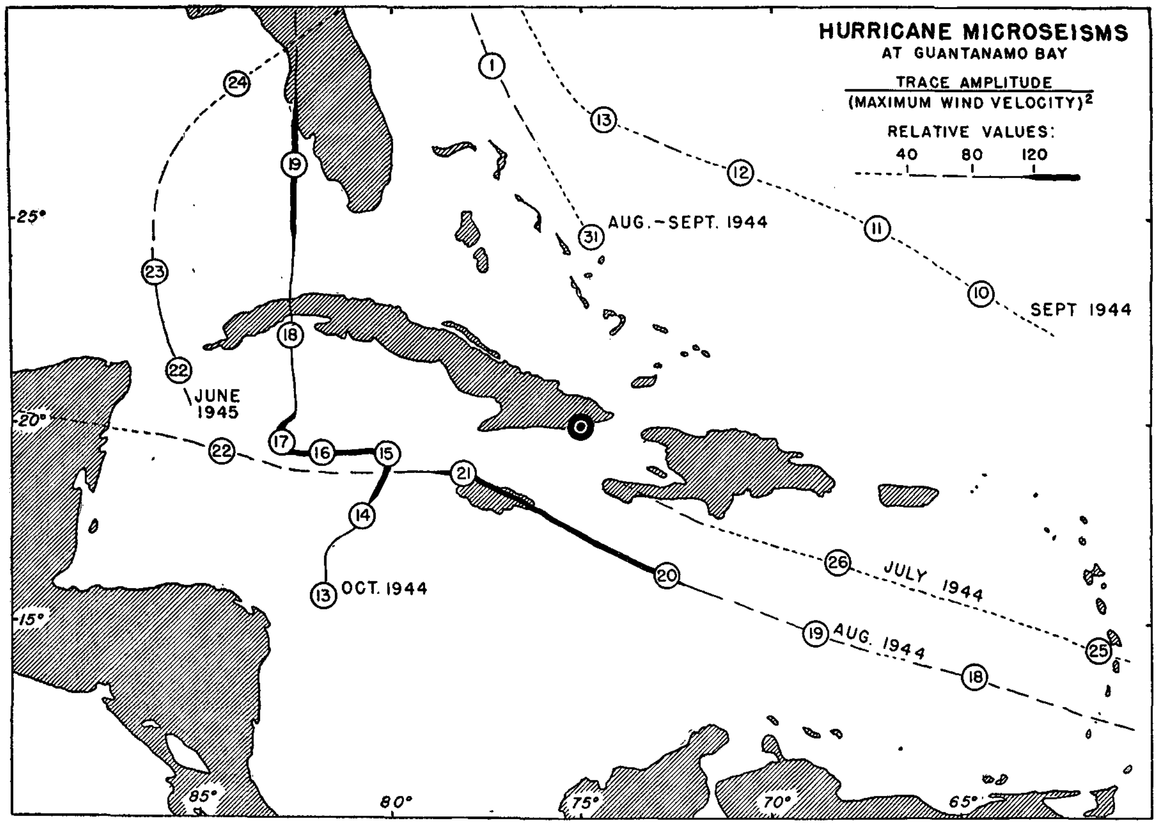

FIG. 4. Tracks of hurricanes in the Caribbean Sea with indication of relative amplitudes of microseisms at Guantanamo Bay, Cuba, divided by the square of the wind velocity in the central area of the hurricane.

in the same azimuth, as otherwise one instrument is affected more by the Love waves and another more by the Rayleigh waves, which differ slightly in speed. In the calculations it is assumed that all waves have the same speed, as otherwise the determination of the azimuth becomes unduly complicated. In order to get reliable results and the largest amplitudes possible at each station of the Caribbean network,

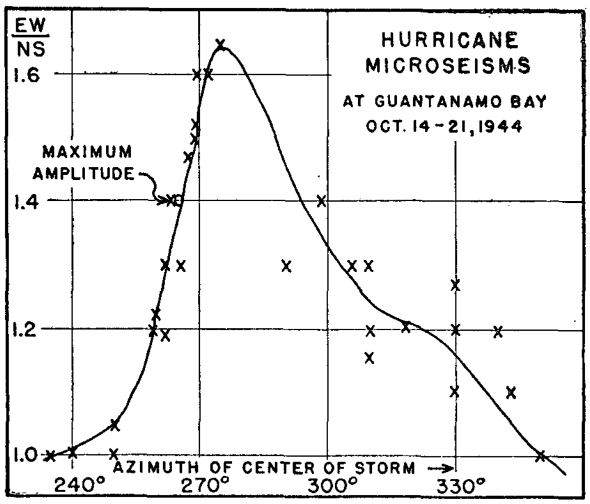

FIG. 5. Ratio of east–west component of microseisms to the north–south component at Guantanamo Bay, Cuba, as a function of azimuth toward the hurricane center, 13–21 October 1944.

Gilmore has the three instruments turned from time to time in such a way as to record approximately the component toward the storm center.

Many investigators have found that the period of the microseisms (usually between 3 and 8 sec, if the source is more than 50 miles away) and the regularity of the waves depend on the distance to the source. In general, with increasing distance the period of the waves increases and the waves tend to become more regular (see, e.g., Gutenberg, 1932, p. 278; 1939, p. 367; Banerji, 1935, p. 729; Sezawa and Kanai, 1939). Also, the periods frequently increase with increasing amplitudes.

The cause of the microseisms is still not well understood. There is little doubt that the energy originates from the energy of the storm. It also has been found repeatedly that the microseisms usually decrease when the storm passes from sea to land. However, it must be considered that storms frequently decrease in intensity at such a time. The problem is still more complicated by the fact that storms over certain parts of the ocean produce large microseisms at a given station while storms at a much smaller distance are not accompanied by noticeable increase in microseisms. For example, at Pasadena low-pressure areas over the Pacific to the west, even if they are strong, do not produce an increase in microseisms, while storms approaching the Alaskan area are usually indicated by a large increase in microseisms. The geology between the source and the station certainly plays an important role.

Figs. 3 and 4 show the close relationship between hurricanes in the Caribbean and the corresponding microseisms at two of the stations. In fig. 4 the amplitudes of the microseisms were divided by the square of the maximum wind speed to emphasize other effects.

A very peculiar decrease in microseisms occurred during the hurricane of September 1945; the microseisms at Richmond decreased to about half when the hurricane passed to water only a few feet deep near Andros Island but afterward increased when it reached the deep water close to the coast of Florida. The maximum amplitudes at Richmond were recorded just before the hurricane reached land and decreased rapidly afterward, even while the storm center was still approaching the station. This and similar results by other authors leave little doubt that the actual source is connected with storms affecting the ocean, in all probability with high ocean waves. Several authors have considered rather rapid changes in air pressure (pumping) during storms as the cause of the microseisms. Such changes may occasionally be one of the contributing causes, but comparison of microseisms at Pasadena with records of microbarographs at the same place has not shown any relationship between microseisms and pressure waves of about the same period.

The author, following an original idea of Wiechert (1904), previously considered the surf to be the main cause of microseisms produced by extratropical low-pressure areas. Many authors have found a very strong correlation between microseisms and the ocean waves driven by a storm against steep, rocky coasts. Calculation shows that adequate energy may well be produced by ocean waves driven against a long, steep coast if only a tenth of one per cent of the energy of the ocean waves is effective in shaking the coast (Gutenberg, 1931, p. 21). On the other hand, in all instances of hurricanes in the Caribbean, the surf in the area affected was negligible for most of the time during which the microseisms were recorded; no large effect of the surf can be expected in hurricanes or typhoons, as the area they affect strongly is relatively small in diameter.

In hurricanes (and partly in extratropical disturbances) high ocean waves probably are the original source of the microseisms (Gutenberg[2]). However, it is not yet clear how the energy is transferred to the bottom of the ocean. The hydrodynamic theory of waves on the surface of a perfect fluid indicates that the pressure disturbance decreases exponentially with depth. Banerji (1935) points out that this theory cannot be applied, since ocean waves are generally rotational and viscosity cannot be neglected; he has made a number of experiments in a small basin to show that actually waves are transmitted to greater depths. Scholte (1943) has shown that, in addition to hydrodynamic waves, compressional (elastic) water waves, with amplitudes decreasing only very slowly with depth, are set up which very well may be the cause of microseisms produced by high waves. It is hoped that recording of pressure waves at various depths in the ocean will contribute to the solution of this question in the near future.

It has often been pointed out that the periods of the microseisms do not agree with the periods of the cause, whatever the cause may be. However, this would not present any difficulty, as, from theory as well as from observation, any irregular short-period elastic movement changes in course of time into a more regular movement with increasing periods (see, for example, Gutenberg, 1931, p. 2).

During winter, microseisms have frequently been recorded in the Caribbean area without any hurricanes present. However, in all these instances there was an area with strong winds not far from the station. Usually in the Caribbean, as well as elsewhere, such microseisms differ in their appearance from those produced in hurricanes. Similarly, Banerji and Gherzi have pointed to the difference between microseisms due to cyclonic storms and microseisms produced by monsoon winds.

As is evident from the preceding part of the paper, microseisms can be used in different ways in weather forecasting and especially in locating storms. Periods, the form of the microseisms, which are more or less smooth waves, the amplitudes and especially changes in amplitude, and finally the direction of arrival should be used jointly whenever possible.

The accuracy with which the direction of the storm can be located from a tripartite station depends very much on the conditions. The following equations have been used by Gilmore (1946) in the Caribbean area:

$$\sin \alpha = t_1 v/a \qquad (1)$$

and

$$\tan \alpha = \sin \epsilon/(k - \cos \epsilon) \qquad (2)$$

where

$$k = t_1 b/(t_2 a). \qquad (3)$$

In both, α is the angle between the wave front and the side of the triangle which is used, v is the speed of the microseisms, t_1 and t_2 are the observed time differences along the sides of length a and b respectively, and ϵ is the angle between the sides a and b. (Equations for x/y and for $\tan \varphi$ by Krug, 1937, p. 336–337, and the similar equations of Ramirez, 1940, p. 62–63, are not correct.) Another method for rapid location of the azimuth of the source from the station can be obtained by plotting regularly the time differences between the three points of the triangle as functions of the azimuth calculated by equation (2) (Gutenberg[2]). Curves based on these points as well as on the

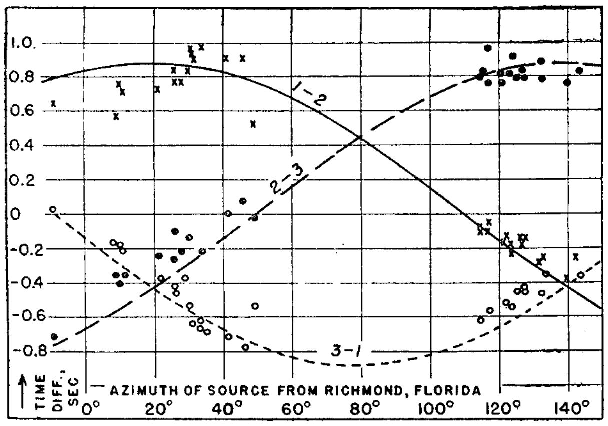

FIG. 6. Observed time differences along the three base lines at the tripartite station at Richmond, Florida, as functions of the azimuth toward the hurricane center, and corresponding calculated curves (based on the assumptions that the microseismic waves have a speed of 3.3 km/sec, that the azimuth of line 1–2 is 200°, and that the instruments are on an equilateral triangle with sides of length 9565 feet = 2.917 km).

properties of the triangle (which give the zero points and the azimuths corresponding to the maximum time differences) can be used to find the azimuth of the source, if the differences in arrival time of a given microseismic wave at the three stations are known.

Fig. 6 shows a section of such a graph for Richmond, Florida. The figure indicates systematic deviations in the azimuths corresponding to the maxima. These azimuths (about 20° for line 1–2, about 140° for line 2–3) depend only on the directions of the sides of the triangle. From the original data it seems that the observer had a tendency to overestimate the larger time differences (or underestimate the smaller). The sum of the time differences between successive instruments, 1–2, 2–3, 3–1, should be zero; however, in his measurements (independent for the three differences) the largest is usually greater than the sum of the other two. The observed azimuths of the zero points fit the calculated values (110° for 1–2, 50° for 2–3, 350° for 3–1) better than those of the maxima.

Equation (1) may be used to determine the speed of the waves for a specific station. For Richmond the values plotted in fig. 6 (using the time differences along the three base lines separately) gave 3.6 ± 0.3 km/sec for line 1–2, 3.7 ± 0.4 km/sec for line 2–3, and only 2.7 ± 0.1 km/sec for line 3–1 (for which no data near the maximum or minimum are available). The lack of agreement is at least partly a consequence of the systematic errors. The curves plotted in fig. 6 are based on the average of all data, 3.3 km/sec, together with the measured directions of the base lines. The observations fit the calculated curves fairly well; in general, the observed points outside the maxima scatter from the average values by not more than about ±10°.

The data obtained at Guantanamo are in even better agreement, due partly to the better ground at that station, partly to the lower speed, about 2.6 km/sec, perhaps partly to the greater experience of the observer. On the other hand, the results found at Roosevelt Roads show considerably poorer agreement, and deviations of as much as 40° occur; this is due partly to the fact that the wave speed there is much higher (perhaps near 4 km/sec).

In order to get a better idea of the relationship between the accuracy in azimuth determination, the base length, and the speed of the recording drum, Lt. Commander Gilmore, in conjunction with Lt. Roush and Ensign Pringle, made experiments using different base lengths and different recording speeds. It was found that at the average station a base length of about one mile and a recording speed of 2 mm/sec gave optimum results. If the base length is increased, the time intervals and the accuracy in the determination of their ratios increase also. However, the identification of corresponding points on the three records becomes more difficult. If the recording speed is increased, the waves on the record get flatter and again the identification of points on the seismograms is more difficult. Theoretically the relationship between base length and recording speed for a given accuracy in determining the azimuth can be calculated by differentiating equation (2). Assuming to a first approximation that the triangle is equilateral and that the errors δt in the determination of two time differences are equal, one arrives at the following equation:

$$\delta\alpha = (1/a)f(\alpha)\ v\ \delta t \tag{4}$$

where $\delta\alpha$ is the error in the resulting azimuth α, v the speed of the waves, a the length of the bases, $f(\alpha)$ a function of α (and ϵ) with values between about 1 and 2, and δt the error in the determinations of the time differences. From (4) follows the approximate equation (5) for the product, base length a in km and drum speed s in mm/sec, if δD is the accuracy in measuring the difference in position between maxima of corresponding waves on the various records:

$$as = \tfrac{3}{2}v\ \delta D/\delta\alpha. \tag{5}$$

If the azimuth is required within 10°, $\delta\alpha = 0.17$ radians. Supposing that $\delta D = 0.1$ mm, we find approximately $as = v$ (km/sec). For an average speed of 3 km/sec this gives $as = 3$. The resulting drum speed of 2 mm/sec for a base length of $1\frac{1}{2}$ km agrees very well with the results of the experiments mentioned above.

Requirements for a maximum accuracy by this method have been discussed by Hecker (1915, p. 29).

From what precedes there can be no doubt that microseisms are a valuable means for locating storms, especially hurricanes and typhoons. Just as in regular weather forecasting, the accuracy of the results depends on the distribution of available stations.

A number of tripartite stations are highly desirable. Where the microseims are propagated over considerable distances, that is, where no deep discontinuities exist, it should be easy to get intersections of azimuths by using a few tripartite stations. The stations in the Caribbean thus far have provided only one instance (with several observations) where the amplitudes at two stations were large enough to permit the determinations of azimuths simultaneously. The intersection of the calculated lines was close to the actual center of the hurricane (Gilmore, 1946).

The main advantage of the method is that in most instances the microseisms begin to increase early enough to provide an effective warning of an approaching hurricane. For example, preceding the hurricane of 1–5 October 1945 the microseisms started to increase at Guantanamo Bay on 29 September, reached their maximum (about three times their normal amplitude) during 30 September, with bearings to the south of west, and continued rather large for several days. The hurricane was located first from airplanes on 2 October in nearly the direction from Guantanamo indicated by the microseisms. The meteorological data available were not sufficient to give any definite information before 2 October. There have been other instances where the microseisms indicated the forming or approaching of a hurricane one or two days before it was actually located.

In interpreting the amplitudes, care must be taken to avoid misinterpretation of changes, especially if the hurricane approaches very shallow water or land; a decrease in amplitudes does not necessarily mean a decrease in the intensity of the storm, and, if a hurricane passes across deep geological discontinuities, a rapid decrease in microseisms is to be expected, regardless of the change in intensity of the hurricane (compare figs. 3 and 4). On the other hand, consideration should always be given to the fact that storms and waves not connected with a hurricane may also be the source of microseisms.

The data now available leave no doubt that microseismic hurricane detection speeds up the location of a forming or an approaching hurricane. This method of detection may save much more in lives and in property values in one single instance than the cost of installing and maintaining the instruments for one year.

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