RELATIONS BETWEEN SEA WAVES AND MICROSEISMS

By Dr. G. E. R. DEACON, F.R.S.
Admiralty Research Laboratory, Teddington

ONE of the possibilities suggested by Admiralty research on waves and swell during the past two years is that of obtaining information about the wind and waves in a distant storm area by examining the first swell that reaches the coast[1,2].

By comparing wave recordings and the winds over the ocean, it has been demonstrated that all wave-periods are generated in a storm, up to a maximum which depends on the greatest wind strength. The longest waves are the first to arrive on a distant coast, since although they are not generated until the wind reaches its greatest intensity, they travel faster than the shorter waves generated in the early part of the storm. They arrive at the distant coast as very low swell, which is usually not visible because it is obscured by shorter waves generated in the coastal region or in another storm. To make sure of detecting it, routine wave recordings must be submitted to frequency analysis in sufficient detail to allow the amplitude of each wave-length to be measured.

The first indication which the wave spectra show of a distant storm is usually a narrow band of activity of periods between 18 and 24 sec., and the appearance of such a band generally implies that heavy swell will follow. The indication is not altogether reliable, because the long periods may come from a very distant storm, too far away to produce heavy swell at the recording station. A precise indication of the distance of the storm can be obtained from the subsequent spectra.

By choosing examples of storms of limited extent and duration for which there are adequate meteorological observations, a fairly accurate estimate can be made of the time at which successive wave-periods begin and cease to be generated; and by comparing these estimates with the times at which the same periods begin and cease to arrive at the distant recording station, it has been shown that the different periods travel independently across the ocean at speeds which correspond very closely to their theoretical group-velocities. This result makes it possible to use the measured times of arrival of the different wave-periods to calculate the distance of the storm from the recording station.

The wind strength in the storm can be estimated from the maximum wave-period, using an empirical relation which has been found to hold reasonably well for North Atlantic storms. For winds stronger than 30 knots, it has been found that the speed of the gradient wind in the strongest part of the storm has the same numerical value as three times the maximum wave-period. It is interesting to note that since the wave-velocity—as distinct from the group-velocity—in deep water is approximately three times the wave-period, the fastest waves travel at about the same speed as the gradient wind, which is possibly a measure of the strongest gusts at the surface.

There is some difficulty in following the track of a storm over a long distance unless its intensity varies sufficiently from time to time to give rise to a succession of recognizable wave-bands, so that the extended storm can be treated as a succession of small storms; but there is much in the new techniques that can be used to obtain information about approaching swell and distant storms, and further progress is being made.

The information is of practical value in countries the weather and harbours of which are influenced by storms passing over oceans in which few meteorological observations are made. In many respects the usefulness of the information is limited, because it comes too late owing to the long time which elapses between the generation of the waves and their first arrival on the coast. This time lag would be avoided if microseisms could be used instead of waves, the travel time of the microseisms being negligible in comparison with that of the waves.

The idea is not a new one. Linke[3] sought to use microseisms for weather forecasting, and Bernard[4] found that they might be useful for forecasting waves on the coast of French Morocco. He showed that a day-to-day graph of the swell on the coast of French Morocco had the same shape as a day-to-day graph of the amplitude of the microseisms at Strasbourg, except that the peaks of microseismic activity preceded the peaks of wave activity by one to three days according to the distance of the wave-generating area from the coast. He concluded that the waves and microseisms are generated simultaneously in the storm area, and that the microseisms precede the waves because of their greater velocity (approximately 2½ miles/sec.). This suggests a useful method of predicting swell, but an examination of the literature reveals many uncertainties.

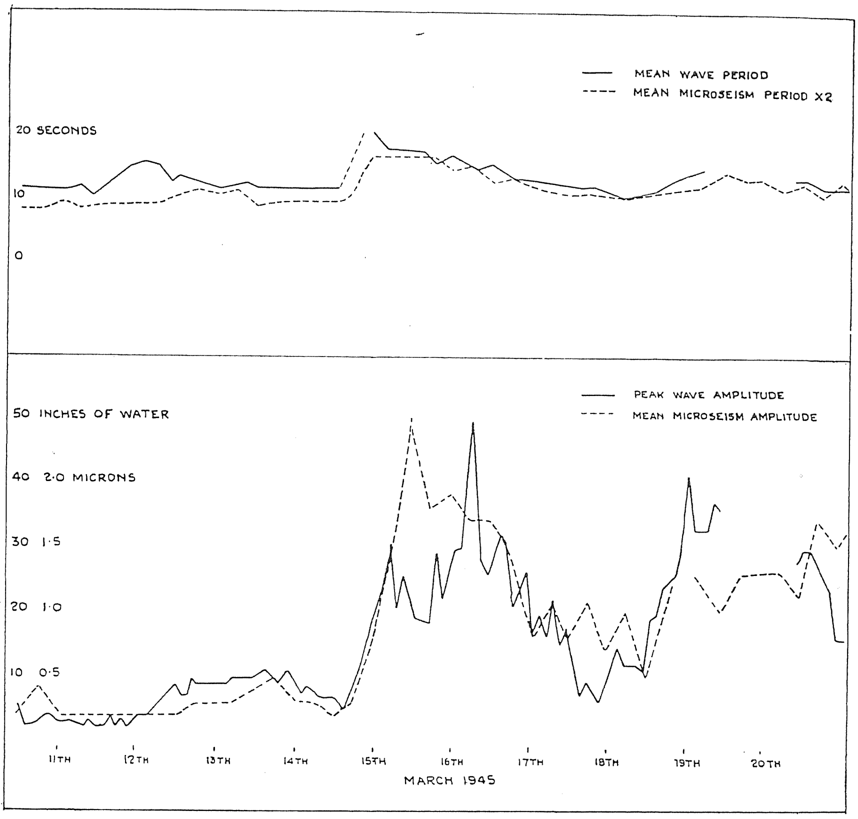
The term microseism should probably include all movements registered by a seismograph that are too small to be regarded as earthquakes; but there seems to be a general consent to use the name for the more or less sinusoidal oscillations, with periods up to 10 sec., that cannot be attributed to local factors such as traffic, or varying wind pressure on tall objects near the observatory. It was soon recognized that they were in some way associated with wave activity on neighbouring seas and oceans, and three outstanding hypotheses which have been put forward to explain them are listed below. A fourth which may supersede them will be mentioned later.

(*a*) Waves in a coastal region. Wiechert maintained that microseisms could be explained by the impact of waves against a steep rocky coast, and this view was supported by Gutenberg and others. Leet[5], at Harvard, concluded that although surf was probably the dominant factor, insistence on steep rocky coasts was inadequate to explain the activity from certain directions.

(*b*) Waves in the open ocean. To explain why the largest microseisms produced by a storm in the Bay of Bengal were recorded several hours before the storm reached the coast, Banerji suggested that pressure waves are transmitted to the sea bottom, which is set in vibration and the motion propagated along the sea bed.

(*c*) Atmospheric oscillations. Gherzi found that large microseisms were recorded on the China coast when there were cyclones over the sea, but not when the waves were due to monsoon winds. He suggested that the microseisms may be caused by atmospheric oscillations or 'pumping' near the centre of a cyclone. The possibility that they may be formed by atmospheric oscillations over the land has also been mentioned.

Most of the conclusions that have been reached are of a tentative nature. If two or more sources of microseisms are operating together, especially in the presence of qualifying geological and topographical features, special methods will be needed to discriminate between them. One hypothesis or another can be held to explain a series of measurements, but in the absence of sufficiently comprehensive observations it is usually not difficult to suggest an alternative.



COMPARISON OF THE AMPLITUDES AND PERIODS OF THE PRESSURE VARIATIONS BELOW WAVES AT PERRANPORTH WITH THE AMPLITUDES AND PERIODS OF MICROSEISMS RECORDED AT KEW

In the past few years, more detailed observations have been made by J. J. Shaw, Tromsdorff and others, largely with the object of obtaining detailed information about the direction from which the microseisms are travelling. Ramirez[6], at St. Louis, used instruments at the vertices of a right-angled triangle the shorter sides of which were about 6 km. long. He found that individual microseismic waves could be detected at each of these stations, and calculated the direction of propagation from the small differences between the times of arrival at the three corners of the triangle. Simultaneous observations at Florissant, 22 km. distant, were also used.

The first result was a confirmation of the general belief that the source of microseisms is not to be found over the land but over the ocean. The direction from which the microseisms travelled was calculated for all large microseismic storms, and in that direction there was always a deep barometric depression over the water. No correlation could be obtained with microbarometric variations or pressure distribution over the land. No special attempt seems to have been made to correlate the microseisms with surf on the Atlantic coast, but it is concluded that although the beating of the sea waves against rocky coasts may explain some of the microseisms, it will not explain those of a barometric depression far out over the sea. These are said to reach their peak and subside long before the storm waves reach the coast.

The results obtained by Ramirez were the chief factor in persuading the meteorological branch of the U.S. Navy to initiate a comprehensive research project to determine whether microseismic recordings could be used for tracking hurricanes. The first recording station was set up in Cuba in 1944, and two others, in Porto Rico and Florida, came into use in 1945. Each station had three seismometers at the vertices of an equilateral triangle the sides of which were 8,000 ft., and in the two later stations each instrument, suitably mounted in a vault, was connected to a central recording apparatus by cable and the three traces recorded side by side on the same drum. The movements and variations in intensity of storms over the neighbouring ocean were known with some certainty from observations made on regular meteorological flights.

The results of the first two years work are described by Gilmore[7], who concludes that the dominant microseisms recorded during a storm are in some way caused by a deep barometric depression or strong wind over the ocean, and transmitted directly from the storm centre. He says that the data rule out even a possible chance that they could be associated with surf. He admits that his results do not disprove that microseisms are generated by surf, but he is satisfied that the dominant 2–7-sec. oscillations are not produced by it. Most of the conclusions are drawn from records taken at the station in Cuba, but afterwards cross-bearings were obtained from the three stations. So far as this region is concerned, the technique seems to afford a satisfactory method of tracking storms.

On the European side of the ocean the task appears more difficult. The work of Wiechert and Gutenberg is sufficient to establish the importance of the effect of waves in the coastal region. More evidence has been obtained by comparing wave measurements at the Admiralty station at Perranporth with the vertical microseismic component at Kew. Only two months records have been examined, but they are sufficient to show that the microseismic activity at Kew is related to the wave-height on the Atlantic coast of Britain.

One example of such a comparison, using the wave pressures recorded by an instrument laid in 70 ft. of water at Perranporth, is shown in the accompanying graphs. Further evidence is given in a second paper by Bernard[8], in which the wave characteristics on the coast of Morocco are compared with the microseismic activity at Averroës on the same coast, as well as with the recordings at St. Maur, near Paris. The microseisms in Morocco reach their peak activity at the same time as the waves on the coast, and Bernard is convinced that they are produced as the waves approach the coast. He still attributes the peak values at St. Maur, which are reached one to three days before those in Morocco, to microseisms transmitted directly from the storm centre; but with our present knowledge of the propagation of waves and the experience gained by comparing the waves at Perranporth with the microseisms at Kew, it seems more reasonable to attribute them to wave activity on the coasts of France and the British Isles. Swell moving eastwards from most depressions in the North Atlantic Ocean reaches these coasts one to three days before swell from the same depression moving south-east reaches the coast of Morocco. The evidence available so far suggests that microseisms transmitted directly from the storm centre will have to be detected in the presence of oscillations of greater amplitude produced by waves in the coastal region.

The existing explanations of how a deep barometric depression over the ocean, or the entry of waves into a coastal region, produce microseisms are not satisfactory. The most obvious difficulty in explaining the origin of microseisms in deep water was that the amplitude of sea waves decreases exponentially with depth, so that there is no movement in deep water. Whipple and Lee[9] showed that in a compressible medium there would also be shock waves; and other authors, taking the elasticity of the sea bottom into account, have sought to explain microseisms as a result of such shock waves. A serious objection to this explanation, and to the view that microseisms could be produced by the impact of waves against a steep rocky coast, is that since the waves are short compared with the wave-length of the microseisms, the pressure variations due to them would tend to cancel out, so that the total effect is likely to be small. Bernard[8] answers this objection by assuming that the microseisms are produced in places where the interference between wave trains gives rise to standing oscillations. He maintains that such oscillations can be expected in the centre of a cyclone and quotes a reference by Charcot to the pyramidal waves found in the storm centre; he also postulates their existence in a coastal region where the coast or a submarine bank is sufficiently steep to cause reflexion.

A new consideration is introduced by the discovery that the microseism periods are approximately half the wave-periods. Bernard was the first to emphasize this relation, made apparent by his comparison between the microseism and wave-periods in Morocco, and it was later discovered independently as a result of the comparison of the waves at Perranporth and the microseisms at Kew. These are both examples of the effect of waves in a coastal region; but the same relation appears to hold for microseisms generated in a storm area, since those recorded by Ramirez and Gilmore are half the most probable wave-periods. The theory of the generation of microseisms must therefore explain a frequency doubling.

Longuet-Higgins and Ursell, in work which it is hoped will be published shortly, have pointed out that Miche[10] in a theoretical paper on waves has shown that the average pressure on the sea bottom below a standing wave varies sinusoidally with twice the frequency of the wave, and with an amplitude which does not decrease to zero with increasing depth. Expressing the problem more precisely than Bernard, they have extended the work of Miche to more general wave systems. In particular, they have shown that when wave patterns containing predominant groups of swell of the same period cross in opposite directions, the mean pressure on the sea bottom over the whole area varies with twice the frequency of each wave train, the amplitude of the variations being proportional to the product of the amplitudes of the separate wave trains. Such wave patterns can be expected near the centre of a cyclonic disturbance owing to interference between the waves generated in opposite quadrants, and near a coast owing to reflexion from the shore. A quantitative comparison of the expected and observed results has been made for Perranporth and Kew with satisfactory results. To make a similar estimate for a storm centre in deep water requires further knowledge of the sea conditions.

This new theory of the generation of microseisms possesses some very attractive features. It can explain why microseisms may be produced in a cyclonic disturbance, but not by a monsoon wind, and near a rocky coast, without excluding coasts that are less steep; the necessary wave interference may not be found in every depression, nor in waves approaching the coast from every direction. In particular, it shows how pressure variations of the right period can be produced over relatively large areas of the sea bottom.

As proved with ocean waves, a better understanding of microseisms will be obtained when account is taken of possible interference between microseismic waves from different sources. Although Gilmore describes striking successes in tracking a cyclone by microseismic direction-finding, the more general problem, for countries farther removed from the cyclone track, will involve the discrimination between microseisms generated in a storm area and those generated near the coast. The techniques developed for wave analysis are likely to prove useful; and to obtain sufficiently precise and comprehensive data to allow a detailed study of microseismic generation, microseisms and waves must be studied together. The results are likely to be of practical value, and the subject has many aspects of interest to oceanographers and geophysicists.

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[1] Deacon, G. E. R., Occasional Publications of The Challenger Society, No. 1 (1946).
[2] Barber, N. F., and Ursell, F., *Nature*, **159**, 205 (1947).
[3] Linke, F., *Ergeb. könig. Geo. wiss. Göttingen, Math. Phys. Klasse*, 7 (1909).
[4] Bernard, P., *C.R.*, 205, 163 (1937).
[5] Leet, L. D., *Beitr. z. Geophys.*, **42**, 232 (1934).
[6] Ramirez, J. E., *Bull. Seismol. Soc. America*, **30**, 35 and 139 (1940).
[7] Gilmore, M. H., *Bull. Seismol. Soc. America*, **36**, 88 (1946).
[8] Bernard, P., *Bull. Inst. Oceanographique, Monaco*, 38, No. 800 (1941).
[9] Whipple, F. J. W., and Lee, A. W., *Roy. Ast. Soc., Geophys. Supp.*, 3, 287 (1935).
[10] Miche, M., *Ann. des Ponts et Chaussées*, **114**, 25 (1944).