OCEAN WAVES AND SWELL

by G.E.R. Deacon, D.Sc., F.R.S.

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In view of the interest and possible applications of the study of waves it is doubtful whether the subject has received sufficient attention. Although much has been done, there are many questions of primary importance which cannot be satisfactorily answered. Thorade, probably the most authoritative German oceanographer, maintained in 1931 that theory and observation had not gone sufficiently hand in hand. Mathematicians have been too much occupied with theoretical problems, while many observers, unable to follow the language of the mathematicians, have worked without such precise formulation of their problems as would direct their attention to the observations most likely to further the investigation.

Sverdrup, Johnson and Fleming (1942) make similar remarks. While paying tribute to the work of Gerstner, Cauchy and Poisson, Stokes, Kelvin, Rayleigh, Lamb and other mathematicians, they observe that theoretical investigations have preceded the accumulation of exact information as to the nature of the phenomena, and describe some of the early work as more mathematically beautiful than practically applicable. They make special mention of the work of Jeffreys, who has done much to bridge the gap between the theoretical worker and the more general student in his notes at the end of the book on Ocean Waves by Cornish (1934).

The difficulties encountered in the study of ocean waves are familiar in any oceanographical problem. The controlling factors cannot be varied at will, and the effect of each has to be discovered gradually by observing it under a wide range of conditions. Because of their magnitude and complexity they are difficult to imitate in the laboratory. Expense is another obstacle ; sooner or later one needs a ship and costly equipment.

Like many other fundamental studies, the investigation of waves was notably advanced during the war, because reliable information was needed for military purposes, and adequate facilities were made available for research. In this paper it is intended to summarize the information published before the war, and to indicate the advances that have been made, or those that will be made in the next few years.

WAVES IN A STORM AREA.

There is some difficulty in explaining the exact mechanism by which the wind begins to make waves on undisturbed water ; in particular, how it gives rise to oscillatory movements instead of simply driving the water before it. It has been demonstrated theoretically that the boundary surface between two fluids moving with different velocities, one above the other, is unstable while it is level, so that the wind sweeping over the surface of the sea is likely to deform it, but it is not clear how a particular type of oscillation grows.

Two types of movement are involved in the motion of a wave, the most obvious being the forward movement of the wave form. The water itself does not move continuously ; observation of a floating mark shows that the small advance made with a wave-crest is followed by a return in the trough to almost the original position. Theory, and studies of artificial waves, have shown that the paths of the water particles in waves in deep water are approximately circles. but not exactly, because the forward movement at the crest is slightly greater than the backward movement in the trough. At the surface the diameter of the circular orbit is the same as the height of the wave, but the amplitude of the movement falls off rapidly with depth.

The growth of waves once they are formed is attributed mainly to the greater pressure of the wind on their windward slopes. Jeffreys, who demonstrated this mathematically, concluded that the effect of the frictional drag of the wind, a second factor which might be expected to contribute to the development and growth of waves, was negligible. Thorade (p. 48) argues, however, that the evidence is not sufficient, and Sverdrup, in work not yet published, maintains that the effect of frictional drag must be taken into account. If the pressure of the wind is the only factor, waves cannot travel faster than the wind which makes them, but if the effect of frictional drag is considerable, the maximum velocity of the waves may be slightly greater than that of the wind. The evidence on this question is conflicting, and more observations are necessary to decide it ; Thorade emphasizes that in making such observations due regard must be paid to the sharp decrease in wind velocity which is known to exist very close to the surface.

The rate at which waves increase in height in a steady wind is not uniform, the growth being rapid at first and then slower. For a particular wave it has been shown that the limit is probably reached when the height grows to about 1/7 of the wave-length. When the wave is as steep as this the crest becomes a sharp ridge and curls over. Thus short waves will soon break and cover the sea with whitecaps, but longer waves, which can build up to a greater height without becoming unstable, continue to grow. Theoretically there is an upper limit when the waves travel as fast as the wind, or slightly faster if the effect of frictional drag is considerable ; this maximum velocity fixes a maximum wave-length. It is not hnown exactly how the long waves develop ; Jeffreys concludes that the tendency for them to predominate when a strong wind has been blowing for a long time is due to their being able to store more energy than shorter waves.

It is generally agreed that the most striking feature of waves in a storm area is their irregularity, and the predominance of short-crested waves (short ridges of water in comparison with the long ridge of a long-crested wave). Jeffreys (p. 138) has remarked that they may be the resultant of long-crested waves crossing at an angle " so that the whole of the waves produced by a wind can be regarded as a combination of swells of different lengths, whose directions are grouped about that of the wind, but not coinciding with it ". He also believes that the long waves which predominate after a strong wind has been blowing for a long time tend to be long-crested, and sometimes, as recorded by Cornish (p. 3) one sees " a magnificent procession of storm waves sweeping across the sea from horizon to horizon ".

When the wind falls, or the waves travel out of the storm area, they assume a rounder form and greater regularity, changing from waves to swell. The short and short-crested waves decay most rapidly and long-crested swells tend to predominate. One reason suggested by Jeffreys is that the short-crested waves will tend to separate into two long-crested parts, which will not go to the same distant observation point.

THE FORM OF DEEP SEA WAVES.

The profile of a wave or swell has been found to approximate to the shape of a trochoid, the curve traced by a point on the spoke of a wheel imagined to roll along the underside of a level surface. Such a curve can vary from the limiting form of the straight line traced by the centre of the wheel to the sharp-crested cycloid traced by a point on the circumference, but it has been shown that waves depart from the shape of a trochoid before they reach such a sharp-crested form. Michell has calculated that a wave becomes unstable when the angle between the forward and rear slopes of the crest is 120°, and the ratio of height to length 1/7. In practice there is some evidence that the limit is reached sooner.

When the amplitude of the wave is small the trochoidal shape approximates to that of a sine curve, and using this simplification the speed, length and period of the wave are related by the formulae

$$\text{Speed in knots} = 3.1 \times \text{Period}$$
$$\text{Length in feet} = 5.1\ (\text{Period})^2$$

where the period is measured in seconds. By means of these formulae, measurements of one of the variables can be used to calculate the other two, and if all three are measured the adequacy of the simple theoretical treatment can be tested. Such an investigation made by Krümmel (1911), using wave observations from many deep-water areas, showed that if reasonable allowance was made for variations in the reliability of the data, the agreement between theory and observation is very satisfactory. The comparison also suggested that the length of a wave is the most difficult of the three characteristics to estimate.

FORECASTING WAVES AND SWELL.

The only systematic swell forecasts made before the war were those of the French swell-prediction service on the coast of French Morocco, where heavy swell often makes communication between anchored vessels and the shore difficult, and sometimes impossible. With the help of observers stationed in the Azores, and on the coast of Portugal, and with some reports from ships, they were able to trace an outstanding swell on the coast of Morocco to its origin, generally in a depression moving across the North Atlantic Ocean, sometimes as far north as Iceland. Various types of depression were classified, and with the help of a number of rules, including an allowance for the effect of favourable or contrary winds in the path of the swell, they were able to make useful predictions of the state of the anchorages. The foundation of the predictions was mainly the reports from the Azores.

The wartime requirement was more comprehensive, being in general terms the prediction of waves and swell from meteorological data and forecasts. It was met by the Naval Meteorological Service, who made the best possible use of all previous data and conclusions, filling the gaps as quickly as possible with new observations. The empirical formulae relating wave-height, wind-strength and other characteristics, put forward during the past 100 years proved inadequate, but useful tables were compiled, and the first instructions for predicting waves and swell were issued in 1942. Similar work was undertaken in the United States with the active help of the Scripps and Woods Hole Oceanographical Institutions.

Detailed agreement was not reached, but the Admiralty Swell Forecasting Section, staffed with both United States and British officers, was able to make reasonably accurate forecasts when they had accurate meteorological data and forecasts. The starting point of a prediction is a meteorological chart on which one has to distinguish *generating areas* in which a strong wind blows towards the scene of the prediction, or in a direction inclined at not more than 30° to the direct line. The average wind speed in the generating area is estimated from the isobar spacing, some allowance being made for the lesser speeds at the beginning and end of the storm, when the wind was rising and falling. The length of the generating area, known as the *fetch,* which may be bounded by a coastline or change in wind speed and direction, is also important. The effect of the wind also depends on its *duration,* which includes an allowance for the waves already present when the wind rises. If the area for which the prediction is required is exposed to ocean swell, detailed information is needed from distant storm areas from which swell may have been travelling towards the area for several days, and an allowance has to be made for the effect of favourable or contrary winds during this long journey. If the prediction is to include an estimate of breakers and surf some general information is required of the depth contours and beach slope.

Using tables and graphs showing the effect of the different factors the Swell Forecasting Section began by making experimental predictions for the English coast, and then routine predictions for the Normandy beaches and approaches. A review of their work, when the landings were complete, showed that when the winds forecasts were correct to within 1 unit of the Beaufort Scale and 2 points of the compass 85 per cent. of the predicted wave-heights were correct to within 1 foot for waves less than 5 feet high, and 2 feet for waves higher than 5 feet. Such agreement is remarkable, and it can probably be attributed to some extent to the detailed experience gained by the forecasters in their limited area, which allowed them to modify the rules every now and then to suit their own ideas. Their task was made somewhat easier by the absence of swell from the Atlantic Ocean, partly due to the forecasts being limited to the summer months, and partly because the beaches were screened from the west.

On a coast which is exposed to ocean swell the effect of the swell from storms, even several thousands of miles distant, may be more important than the effect of local winds. An approximate rule formulated by Commander Suthons of the Naval Meteorological Service states that swell loses 1/3 of its height in travelling a distance which, measured in nautical miles, has the same numerical value as the wave-length measured in feet. Swells longer than 1,000 feet are common, and these will lose only 1/3 of their height in travelling 1,000 miles. The famous rollers of Ascension and St. Helena are very spectacular, and have caused great damage, in spite of the fact that they have travelled at least 3,000-4,000 miles.

As the swell enters coastal waters it undergoes more striking modifications Its velocity becomes noticeably reduced at soon as the depth of water is less than a quarter of a wave-length, and if it approaches the coast at an angle this change in velocity causes it to turn more or less parallel to the shore. The phenomenon is very similar to the refraclion of light or sound waves, and the swell is made to bend round headlands, and into bays according to similar laws. The height of the swell also changes as it moves into shallow water, a small decrease being followed by steeper and steeper growth, till the crest rises sharply above the general water level just before the wave breaks.

The height of the breakers on the beach depends on the heigt and length in deep water, and to some extent on refraction. A low long swell will rise to about twice its deep water height, while a short steep wave will not perceptibly increase. Refraction may decrease the height of a wave by increasing the length of its crest, spreading the energy over a broader front. If part of a coastline and the adjacent sea-bottom contours are straight, the waves will be more or less the same height at all point along it; but if the bottom contours are irregular the waves will be more refracted in some places than others, and although the coast is straight the waves may be twice as high at one part of the coast as at another. They tend to be focussed where a shoal extends out below the water, and dispersed, to give quieter conditions, above a submarine gully. The effect can be calculated if the bottom topography is fairly well known. Special problems arise where there are steep slopes or vertical walls.

The depth of water in which a wave breaks is generally 3/2 and 2/3 of the wave-height. The movement of the water in the wave is then mainly forward, and the undertow and rip-currents associated with them are not fully understood.

MEASUREMENTS OF WAVES.

Until recently measurements of waves have been made almost entirely by visual observations. In deep water the wave period is measured by timing the successive appearances of a patch of foam on the wave crests. Wave-length is estimated by comparing the distance between wave crests with the length of the ship, or by using a small float paid out astern on a measuring line ; and velocity by measuring the time taken by a wave to travel a measured distance along the ships side. Estimation of height is the most difficult, the best method being to find some height above water level at which the wave crest can be seen in line with the horizon. All the measurements are made more easily when the ship is hove-to. The chief difficulty in devising any kind of recording instrument is that there is no stationary surface from which to start the measurements. Use has to be made of the rapid decrease in wave motion with depth : Froude was the first to measure waves against a graduated pole, held upright and steady by a long wire which anchored it to a large drogue sunk well below the surface. Stereophotography has also been used, but it is a most laborious task to measure one picture.

From the shore the task is easier, wave heights can be measured against poles driven into the bottom or with a telescope and graticule. In the United States a float recorder installed at the end of the Scripps Institution Pier was used, and the waves were also photographed against the background of the pier.

More ambitious recording instruments, allowing routine measurements in exposed sites up to a mile or more from the coast, were ready in this country for use before the invasion of Normandy. A sensitive pressure-measuring instrument was placed on the sea bottom, and the pressure fluctuations below the waves were recorded electrically in a hut on shore through a cable. The pressure fluctuations depend on the wave-length and the depth of water as well as the wave-height, but the corresponding wave heights can be calculated from the record with reasonable accuracy. They were laid by scientists attached to the Admiralty's Mine Design Department, several of whom, notably C. H. Mortimer, continued to develop wave-recording techniques as part of their work when they joined a newly formed oceanographical group in the Admiralty Research Laboratory in the summer of 1944. The next advance was to use echo-sounding wave-recorders which stand on the sea bottom, pointing upwards, recording. echo-profiles of the surface. The idea was not a new one, having been used with apparatus supplied by Messrs. Hughes to measure tides and waves at Dover in 1939, but considerable development was necessary before a more or less permanent installation could be laid at the end of a long cable. Two types are now available, a permanent-station type made by the Anti-Submarine Establishment, and a semi-portable type made in the Admiralty Research Laboratory.

INTERFERENCE BETWEEN WAVES.

As often happens in the investigation of a natural phenomenon, better observations emphasize the complexity of the phenomenon, and then point the way to further, more satisfactory investigation. In this instance the new wave records emphasized the widespread interference between waves of different lengths. A clear example was seen by a small party making visual observations and wave-recordings off the north coast of Cornwall in July 1944. Three wave recorders laid at distances of approximately 1,000, 2,000 and 3,000 yards were used. It would have been very convenient if a particular wave could have been identified and measured as it passed each of the recorders in turn, but this was never possible either with single waves or with groups of waves. New crests formed and old ones disappeared between each pair of recorders.

The explanation is that the observations were not being made on a simple train of waves but on the combination of a number of waves of different lengths. The observed pressure fluctuations were the resultant of the pressure fluctuations in these different waves which sometimes add and sometimes subtract, and the actual appearance of the surface was the resultant of their combined vertical displacements. In such a combination the relation of the individual waves to each other, and therefore the surface profile, varies with distance, because the individual waves travel with different velocities. If one could follow a surface wave (crest to crest) it would be seen to be continually changing its length, period and velocity. When one has such an opportunity it is often seen that a wave crest cannot be followed very far before it loses its identity among other crests which rise in its place.

Similar considerations explain why waves often travel in groups, a sequence of high waves being followed by a sequence of low waves. This is often noticeable in a ship, two or three violent movements being followed by a quieter period. The intervals between the prominent groups depend on the range of wave-lengths present, so that it is not necessarily the fourth, fifth, seventh or tenth wave which is always the highest. Generally there are so many wave periods present that although some repetition is obvious the intervals are very irregular. Certain geographical regions may be found to have fairly characteristic rhythms, because the range of periods present depends on the intensity, size and distance of the storm, which may often be more or less the same for those regions.

The observations and wave-recordings were examined on the spot by Barber, Ursell and Darbyshire, whose names will go down in the history of the subject. Mathematicians and observers had come together, and although statistical analysis, using crest to crest measurements, was given a thorough trial they soon reached the conclusion that no fundamental advance could be made in the study of waves till a method was developed by which a complex wave-record could be resolved into its individual waves, in sufficient detail to allow the amplitude of each wave-length present to be measured.

One immediate benefit of such analysis would be the possibility of recognizing the low long swell which travels fastest and is the first to arrive from a distant storm, but on its arrival cannot usually be detected because it is obscured from visual observation by the shorter and higher waves caused by local winds. An interesting example was seen in Harlyn Bay, where a 14-second swell could be seen in a quiet cove sheltered from the west wind, but not among the short waves in every other part of the bay.

FREQUENCY ANALYSIS OF WAVES.

The first step in the separation of different wave lengths was to obtain the wave record in black and white as in figure 1. This was done by arranging the recording system to move a line of light backwards and forwards across the photographic recording paper, instead of the usual spot of light. At the same time a time-scale was printed along the edge of the record by interrupting a fixed lamp every 20 seconds.

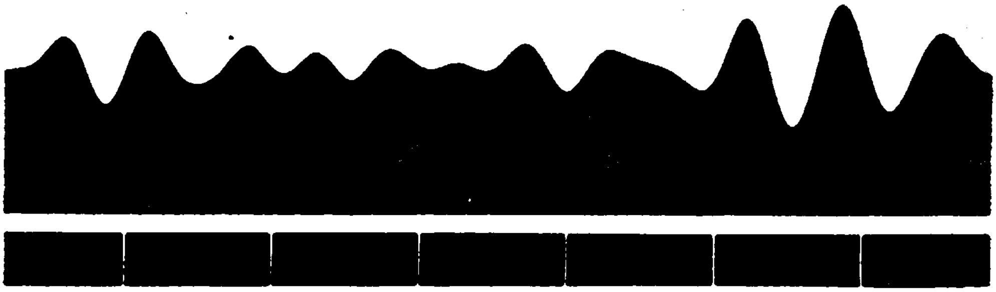
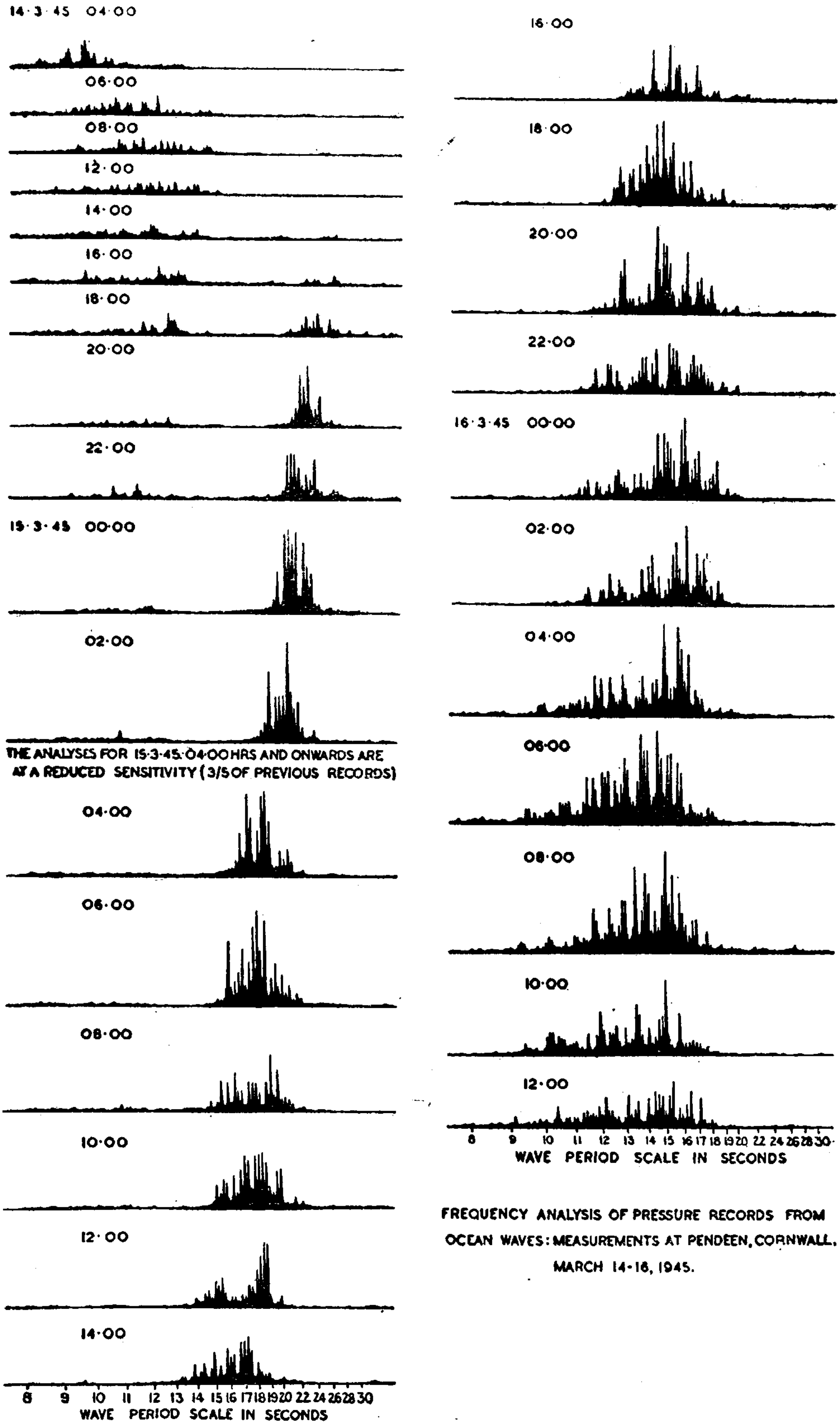


Fig. 1

A pressure "wave record". Time scale: 20 seconds between white marks. Pressure scale: the largest fluctuation near right edge of record corresponds to three feet of water. The measurements were made at a depth of 100 feet.

Twenty minutes was chosen as the most suitable length of wave record for analysis, and this length of record, about 8 feet long, is fastened round the circumference of a flywheel which carries it past an optical system in which a steady light shines across the record through a narrow slit. The light which is scattered back from the record is measured by photocells,



THE ANALYSES FOR 15·3·45 04·00 HRS AND ONWARDS ARE AT A REDUCED SENSITIVITY (3/5 OF PREVIOUS RECORDS)

FREQUENCY ANALYSIS OF PRESSURE RECORDS FROM OCEAN WAVES: MEASUREMENTS AT PENDEEN, CORNWALL, MARCH 14-16, 1945.

Fig. 2

and as the wheel rotates the electrical output of these photocells varies in accordance with the width of the white parts of the record passing the slit. In this way the wave profile is measured as a varying electrical current, the frequency of the variations being multiplied by the rotation of the wheel, one of the advantages of this multiplication being to bring the frequencies into a range for which a simple resonant selective system could be developed.

One of the simplest methods used to examine any particular wave-length in the record is to use the resonance of a tuning fork built into a system which picks out a certain frequency (in this case 128 cycles a second) which corresponds to a long wave length on the record when the wheel is rotating fast, and to a short one when the wheel is rotating slowly. In operation the wheel is turned by hand to about 4 revolutions a second, and then allowed to slow down under its own friction. As the speed of the wheel decays the tuning-fork system examines each wave-length in turn from the longest to the shortest and measures their amplitudes. The output is amplified and recorded on a moving-paper pen recorder, the result being a graph of the amplitudes of successive wave periods. There is no difficulty in identifying the wave periods in the analysis, because a period scale is written on the analysis by a second pen worked by a second analysing system working off the known, 20-second, time marks along the edge of the wave record.

Several ideas incorporated in the analyser are not new ; the great advance is the use of the continuously decaying speed of the wheel. With a receiving circuit of the right selectivity, an analysis can be made with more than sufficient detail in a reasonable time. The present models analyse a 20-minute record in about 10 minutes ; the record has to be put on and taken off, but the rest of the operation is automatic.

A good indication of the advantages that can be obtained by the frequency analysis of ocean waves is afforded by the analysis of 20-minute wave records taken automatically every 2 hours between 14 March and 19 March 1945, by a pressure recorder lying in 17 fathoms, 4,000 feet N.W. of Pendeen lighthouse near Land's End.

Early on 14 March calm weather extended over a wide area west of the British Isles, and the wave analysis showed only small waves and swell with a maximum period of about 14 seconds (fig. 2). During the afternoon a much longer swell began to arrive and the analysis showed periods of 20 to 24 seconds. This was the low long swell, only a few inches high when first measured, which has travelled fastest and arrived first from a deep depression which developed 500 miles S.E. of Newfoundland two days before, on 12 March. A meteorological chart showing the conditions at 18.00 hours on 12 March is shown in figure 3. As shorter swell followed the longest, the wave band broadened and moved towards the shorter periods, and by 17 March (figure 4) the sea near Land's End looked as if it might become as calm as it was on 14 March. This trend was interrupted during the night by the arrival of 18 to 20 second waves from a second depression following 2,000 miles behind the first. The new wave band was not as narrow as that which arrived on 14 March, and there was not the same extensive area of calm weather over the eastern half of the ocean. The same broadening towards shorter periods and increase in amplitude can, however, be distinguished (*).

During the year for which such analyses have now been made, waves of 20 to 24 seconds period have often been detected, but the periods of the waves breaking on the beach were generally much less because of interference with shorter waves. The longest waves to have been seen breaking on our coast seem to be the 22.5 seconds waves observed by Cornish (p. 14) at Bournemouth after an Atlantic gale in 1899.

Sufficient analyses have now been made to show that the method offers a means of distinguishing between the waves from different storm areas, and by virtue of such separation affords more accurate data for the study of the influence of wind velocity, fetch and duration, and the subsequent changes between the storm area and the coast.

To simplify the work diagrams were prepared to show the intensity, extent and duration of the wind in the various generating areas, the average wind strength being plotted at intervals of 100 miles every 6 hours. Distance from 0 to 2,800 miles was measured from left to right, and time in hours and days from top to bottom, so that the path of waves of any particular period can be represented by a line sloping upwards to the right, the slope being a measure of the rate of travel of the waves of that period.

(*) The separate peaks in any of the frequency analyses must be regarded as an approach to a Fourier Amplitude analysis, in which the spectrum would consist of a set of isolated ordinates at periodicities which are harmonics of the total length of the record. It is the general outline of the analysis that is significant ; a group which stands substantially above the background, or appears in a number of consecutive analyses, shows the presence of waves of that period, and the height of the group is related to the amplitude of the waves.

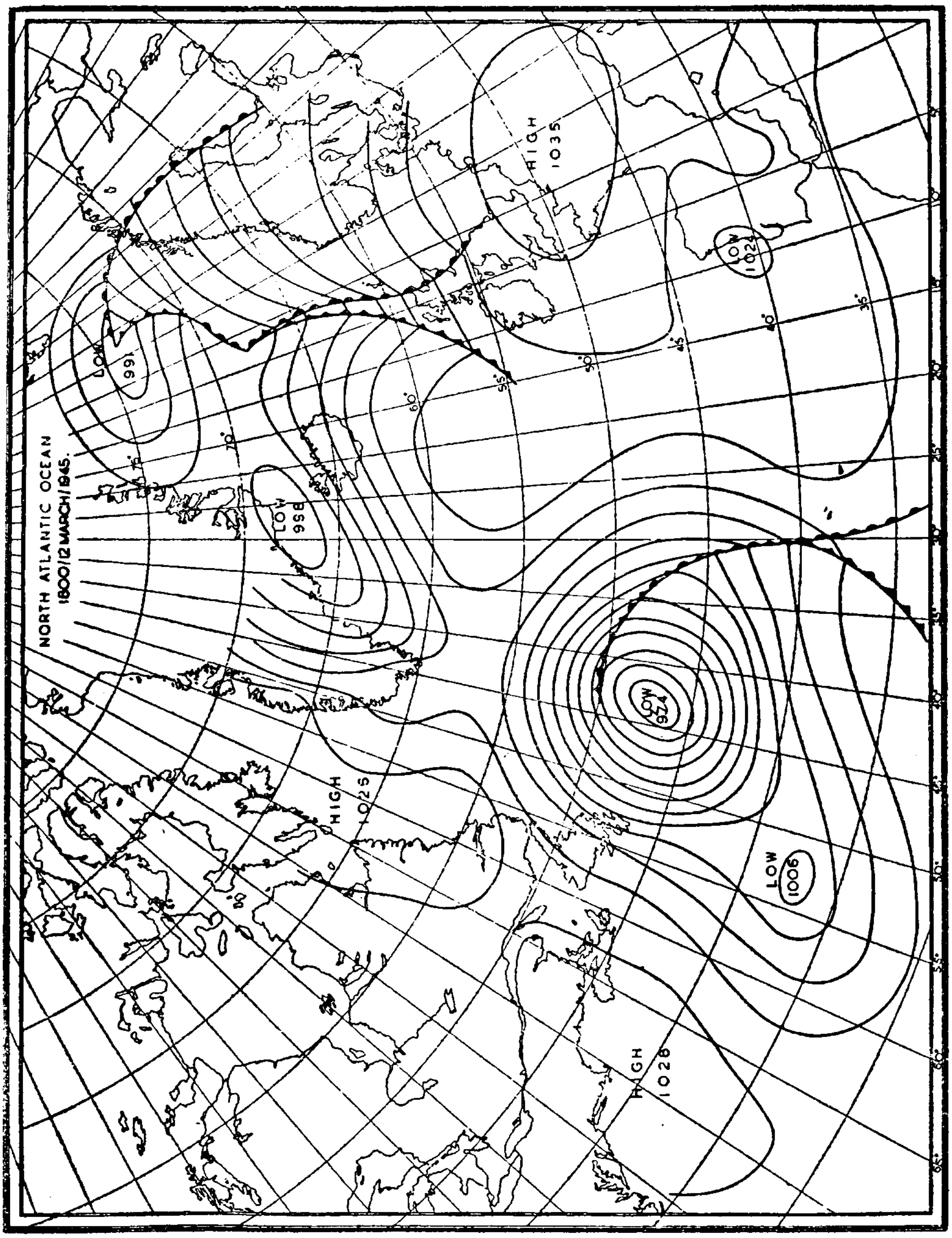


Fig. 3

Meteorological chart for North Atlantic Ocean at 18.00 hrs. 12 March 1945.
The isobar spacing is 4 millibars.

In drawing such a line it was known that swell advances across the ocean at a speed which is only half that of its individual waves. The rate of advance depends on the rate of transmission of energy. If an observer could fix his attention on waves passing from a storm area into calm water, he would see the first wave continually decrease in height till it became too small to identify, the loss of height being explained by the potential energy of the wave being used to supply kinetic energy to the undisturbed water. The second wave, moving into water already in oscillation, loses height less rapidly so that the disturbance moves ahead into the calm water, but with a velocity which has been shown to be only half the velocity of the individual waves. This is only a crude explanation ; the actual problem, in the presence of waves of different periods, appears very difficult.

Frequency analysis which allows more accurate measurement of the time taken by a swell to travel from a storm area to the coast gives new data for the investigation of the problem, but also emphasizes a further complication, the probable increase in length, velocity and period of swell after it leaves the storm area. The theoretical reasons for assuming that there is such an increase appear to be questionable, but there is accumulating evidence in support of it. Thorade (p. 65) shows that wave-periods reported from storm areas are consistently shorter than those reported from distant coasts on which the swell breaks, and although this may be due to greater interference with short waves in the storm area it cannot be ignored. He also quotes an example, based on reports from ships, of the rate of advance of swell increasing with distance from a storm area. The analyses at Pendeen have also given a strong indication that longer wave-lengths are recorded in swell from distant storms than from local storms of comparable intensity. The measurements of the time taken by swell to travel from distant storm areas are not conclusive since it is difficult to decide the starting time within 6 hours or so, but generally there is better correlation between the wave analyses and wind charts when a small increase in velocity with distance is assumed. The increase is an essential part of the United States forecasting technique.

One of the outstanding requirements is the frequency analysis of waves in a storm area and frequency analysis of the resulting swell when it arrives at the distant recording station, and it is hoped to make such analyses in mid-Atlantic and in Cornwall before the summer. Eventually it may be possible to have a network of stations, extending as far as Ascension and St. Helena. Observers in such places exposed to heavy swell could be very useful in making swell predictions. Another outstanding requirement is equipment to measure the direction of swell, to study the interference between waves from different directions ; this also is being developed. Most of the apparatus in use or in prospect so far is meant for research purposes, and to obtain all the necessary detail it is elaborate, but efforts are being made to find simpler methods that will encourage more widespread observation, perhaps with some sacrifice of detail. For example it may be found that sufficient information can be obtained about wave periods in different parts of the ocean by recording the movements of certain types of vessels. Preliminary experiments with a trawler have shown that useful information about wave periods can be obtained from the frequency analysis of the pitching of the ship.

This account of waves and swell has dealt mainly with the more or less fundamental aspects to which the attention of the oceanographical group at the Admiralty Research Laboratory has been directed. It leaves unmentioned much work on forecasting, breakwaters, beaches, waves in tidal streams, and other problems. A fair summary of the present position is that wartime requirements have attracted much attention to the subject, and methods of recording and analysis have been developed, or are within reach, which should allow considerable advances to be made within the next few years.

In conclusion, sincere acknowledgment is made to earlier and contemporary workers on the subject, to whom it is difficult to do justice in a short paper, especially at a time like this when there is so much work that is not published. We have had very useful discussions with Commander C. T. Suthons of the Naval Meteorological Service, Professor H.U. Sverdrup of the Scripps Institution of Oceanography, and Dr. T. F. Gaskell, once secretary of the Beach Reconnaissance Committee. The extension of wave recording and analysis could not have been done without the close support given to oceanographical research by those responsible for research in the Admiralty, particularly Dr. C. S. Wright, Dr. J. E. Keyston and Dr. A. B. Wood. I have said little about the individual efforts of members of the oceanographical group, but they will soon publish their work in detail.

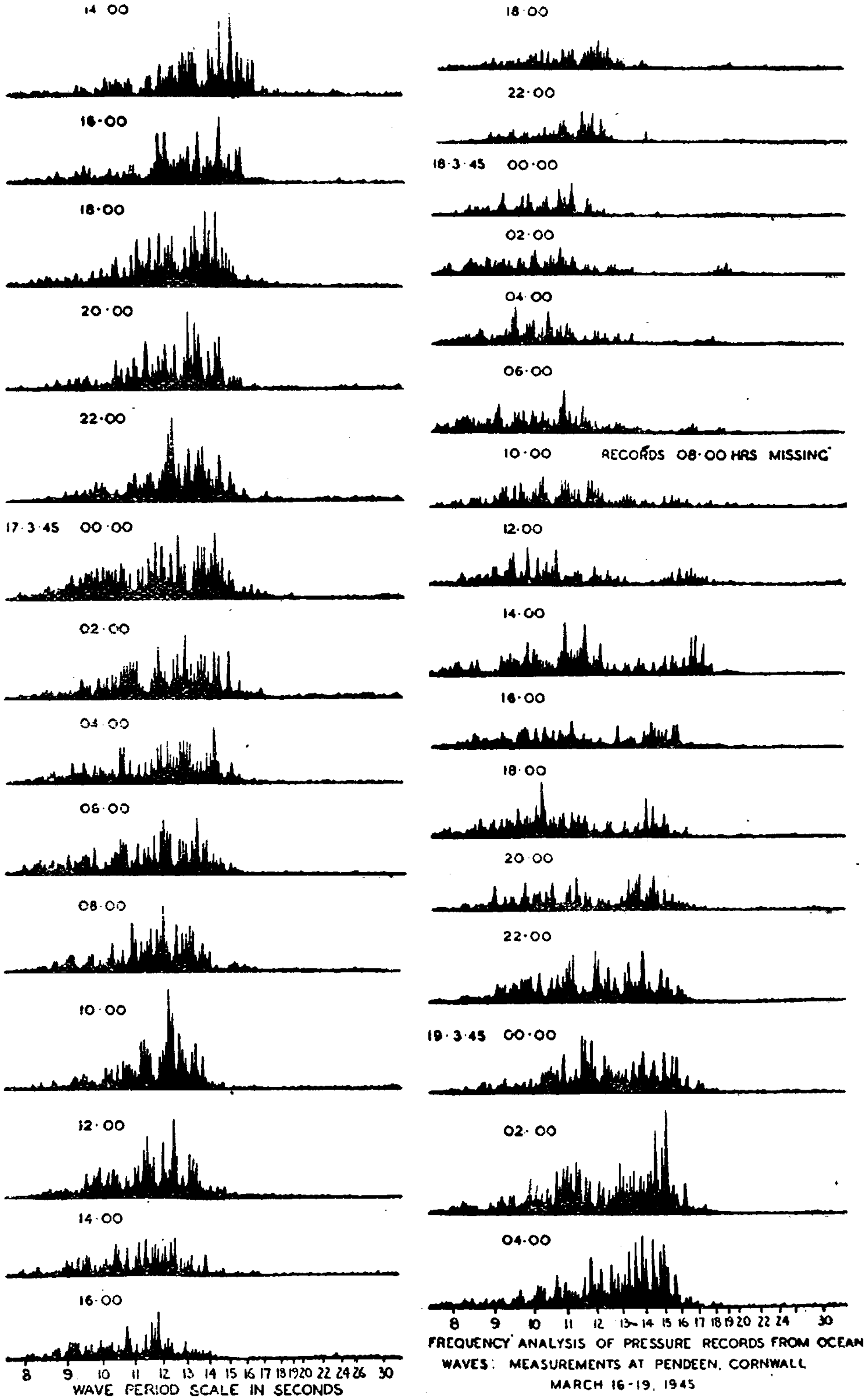


Fig. 4
Frequency analysis of wave records, 17-19 March 1945.

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