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ceptibility of bismuth with the large value of its rotational coefficient, and with the large decrease which can be produced both by transverse and longitudinal magnetization in the thermal conductivity, the electrical conductivity, and the thermoelectrical power of the metal, we must be driven to the conclusion that magnetism in all metals exerts two distinct influences ; one by rotation of the molecules about their axes, the other in some way which is not yet understood. In such metals as iron, and to a less extent in cobalt and nickel, the first of these influences probably plays a not unimportant part ; but in such metals as bismuth, antimony, and tellurium, the second must entirely predominate.

XXI. *Observations on the Height, Length, and Velocity of Ocean Waves.* By Hon. RALPH ABERCROMBY, *F. R. Met. Soc.**

THE interest in ocean waves has so much declined in recent years, that physicists have perhaps scarcely realized how much more easily measurements can be taken now than formerly.

In the old days wave-heights could only be ascertained, more or less, by estimation ; while the length and speed could only be determined by a common watch. Now-a-days the aneroid can easily measure small vertical heights to within one or two feet ; while the fly-back chronograph enables time to be measured to the $\frac{1}{5}$ th second, without taking the eye for one moment off the object to be watched.

The following observations were taken on board the S.S. 'Tongariro,' in various parts of the S. Pacific between New Zealand and Cape Horn, in the month of June 1885.

Height was measured by a $4\frac{1}{2}$ -inch aneroid with a very open scale, divided to the $\frac{1}{100}$ th inch ; so that the readings could be taken at a glance to 0.025 inch, or, when time allowed, to 0.020. The instrument is an extremely good and accurate barometer. The altitudes were all calculated on the simple assumption that a difference of 1 foot in height is given by a difference of 0.001 inch of pressure. Any error which could arise between this reduction and that by a more rigorous method would be far less than the other errors of observation.

* Read February 25, 1888.

So far the observation was simple enough ; but the great difficulty arose when the height of the eye above the sea-level, at the moment of observation, had to be estimated. For instance, when the barometer was at its lowest point the surface of the water might be 10 feet below the eye ; but when the crest of the wave rushed past, the height might be reduced to 1 or 2 feet. Here I had to trust to my own estimation by eye, aided by a few rough measurements with a piece of string down the ship's side. The principal uncertainty of the results depends on errors of this estimation. I do not think that the aneroid errors would ever be more than 2 or 2·5 feet, while those of estimation might be at least 2 feet either way.

Length and velocity were determined by standing in a suitable position with a chronograph, and measuring (1) the interval between the time when two successive crests reached the stern, and (2) the time that the crest of the first wave took to run the length of the ship. Then the length of the ship, her speed, and course relative to the direction of the wave's progress being known, the velocity and length of wave could be readily calculated by the following formulæ :—

Let t = time from crest to crest, in seconds ;

T = time of first crest running the length of the ship,
in seconds ;

l = length of wave, in miles ;

v = velocity of wave, in miles per hour ;

k = speed of ship, in miles per hour ;

L = length of ship, in fractions of a mile ;

θ = angle between course of ship and direction of wave-progress.

Then, for a following sea,

$$v = L \cos \theta \frac{3600}{T} + k \cos \theta ;$$

$$l = (v - k \cos \theta) \frac{t}{3600}, \text{ in miles,}$$

$$= (v - k \cos \theta) \frac{t}{3600} \times 5280, \text{ in feet.}$$

The calculations were made with sufficient accuracy by means of a slide-rule.

It is manifest that it is only possible to obtain an approximation to any of the desired data. Standing near the stern it is not easy to observe the precise moment when the crest reaches the bow; two successive waves rarely run in exactly the same direction; and, with a heavy following sea, the ship yaws about so much that the angle between her course and that of the waves can only be estimated approximatively.

I found great advantage in using cards for the original records, as observations must often be made in rain, sleet, spindrift, and frequently at temperatures near the freezing-point, when the fingers are apt to get benumbed.

The following are some of my most interesting results :—

June 8, 1885, lat. 47° S., long. 175° W.—Sea too irregular to measure individual wave-heights or lengths, but the barometer indicated about 12·5 feet for the vertical motion of the point of observation below decks. Then, pretty constantly, the surface of the sea was about 7 feet below the port-hole in the troughs, but only 1 foot at the crest. This would give the waves an average height of about 18·5 feet.

The velocity of the waves could be got much better. Five observations gave the accordant speeds of 29, 28, 31, 33, and 30 miles an hour, or an average of 30·2 miles.

The following data were used in the calculation :—Ship, length 380 feet; course S.E.; Speed 14 knots. Sea running to S.S.E., and therefore following.

June 10, 1885. Lat. 51° S., long. 160° W. Height.—I found it impossible single-handed to estimate the height of the water at the moment the aneroid was read, so I took a constant difference of 6 feet for the difference of the height of the eye at trough and crest. The following is an example of the readings :—

Trough.	Crest.	Difference.	Diff. height eye, trough and crest.	Estimated height, in feet.
28·955	28·975	·020	6	26
·97	·985	·015	6	21
·9675	·985	·0175	6	23·5
·960	·980	·020	6	26

These waves were not consecutive, and the difference between the extreme heights is a good deal larger than the height of any single undulation. The highest reading of the series (not given here) was 28·99, the lowest 28·955, which would give a difference in height of 35 feet.

The length and velocity were measured on deck just before the heights, under the following conditions :—

Ship: length 380 feet, course E.S.E., speed 14 knots. Sea running to S.E., and therefore following.

The following are some of the best observations :—

Time of crest, running length.	Time between two crests.	Velocity. Calculated.	Length. Calculated.
12·5	19	32 miles.	507
11·0	15	35 „	470
9·0	...	39·5 „	
16·0	17	28·5 „	358

This sea would have been logged as 6 or 7 on the ordinary scale of 0-8. The wind was blowing a moderate to hard gale from N.W. with heavy squalls, and was logged 7 on Beaufort's scale of 0-12. During some of the squalls, with thunder and lightning, the force rose to 8; and though the ship was never nearly pooped, we managed to split a topsail. I think this might be taken as a fair average sea in the S. Pacific. The waves were far too irregular to allow of any attempt being made to determine the ratio of height to length or velocity.

July 16, 1885. Lat. 55° S., long. 105° W.

Trough.	Crest.	Difference.	Diff. of height eye.	Estimated height.
29·38	29·4025	·0225	6	28·5 feet.
·38	·42	·040	6	46 „
·3775	·40	·0225	6	28·5 „
·38	·41	·030	6	36 „

The readings in the trough belonging to this series are remarkably uniform.

Length and velocity were measured from deck under the following conditions :—Ship, length 380 feet ; speed, 14 knots ; course to E. ; sea from W., and therefore right aft.

Time of crest, running length.	Time between two crests.	Velocity. Calculated.	Length. Calculated.
12 ^{''} 5	14 ^{''} 25	35·5	445
12·5	16·5	35·5	485
8·0	16·0	47·5	765

This was the heaviest sea we encountered during the whole voyage. The wind was blowing a hard gale from S.W., with squalls of hail and sleet. The sea was certainly high, but did not appear excessively so to the eye. The ship broached to and lay in the trough of the sea for nearly half an hour while a gland in the engine-room was being packed ; but no harm was done beyond splitting a topsail. The ship rolled tremendously, but no seas swept over her.

Under these circumstances the height of 46 feet, given by one set of observations, seems excessive. The actual vertical lift of the cabin was undoubtedly 40 feet ; for, as I noticed it at the time, there is not a mistake in the records. Any error in the true height must come from the estimate of 6 feet for the difference of the height of the eye on the crest and in the trough.

It will be noticed that the relation of length and velocity to height is very irregular ; but this is due to the character of the waves, and not to errors of observation. On all the days the waves were running irregularly. We never saw crests nearly a mile long chasing one another with a well-defined trough between them ; but the seas were so confused, that sometimes after one big crest nothing followed but some small waves. There was nothing to call a cross sea ; but there were many series of waves of different lengths running pretty much in the same direction, which were constantly interfering with one another. An eye estimate of height is

always delusive, but I was surprised that the waves measured as much as they did. I have seen a heavier sea in the Atlantic; so that if we take only 40 feet as the highest of this series, it is perfectly certain that much greater heights are sometimes attained.

Fitzroy says that, even during many years spent at sea, a man only observes really high waves once or twice during a lifetime; and this view is confirmed by every sailor I have conversed with. Taking my own measurements as representing only ordinary seas, I am certain that 60 feet at least from trough to crest must be attained by exceptional waves.

It may be interesting to compare the results given here with those obtained by other observers. The following figures, except those in the last line, are taken from Dr. Krummel's *Oceanographie*.

Table of the Maxima Dimensions of Waves.

Authority.	Locality.	Height, in feet.	Velocity, m.p.h.	Length, in feet.	Period, in seconds.
Lieut. Pâris	Indian Ocean.		33·6	374	7·5
Admiral Molter...			80·0	2703	23·0
Captain Ross * ...	Near C. Good Hope.	22·97	90·0	1902	
Captain Chûden..	33° S., 107° W.	33-36		984-1312	
D'Urville		98·0			
Scoresby.....		42·0			
'Novara'		36·0			
'Challenger'		23·0			
Abercromby	S. Pacific.	46·0	47·5	765	16·5

It is manifest, from an inspection of the above table, that the discrepancies are enormous. I cannot but think that the extreme lengths recorded by Admiral Molter and Captain Ross must have not allowed for the interference of following waves. No doubt such lengths might be observed between two notable crests, but most probably there would be some smaller undulation between. I never took the time between two crests unless they manifestly belonged to a simple wave.

The three sets of observations before noticed were taken on the only three days on which at all big waves were met with. They serve to show the difficulties of wave-measurement; but the greatest obstacle is the uncertainty of meeting first-

* Dr. Krummel's figures do not agree with those given in other places for Capt. Ross's results.

class specimens. If ever a wave-measuring party should be organized, I think it should be arranged as follows.

Three observers, A, B, and C, would be necessary. A would command the party, say when the instruments were to be observed, note personally the height of the deck from the water, and enter all the readings on a suitable card. B would have a suitable aneroid, and confine his whole attention to that instrument. C would be furnished with two chronographs.

When a crest touched the stern of the ship, A would give a signal, on which B would read his aneroid, while C started both his chronographs. A would first note the height of the deck by marks on the ship's side; and, if need be, read a simple clinometer to allow for the roll of the ship before entering the records of his assistants. When the crest reached the bow, A would give another signal for C to stop one chronograph. In the trough, B would read his aneroid, while A noted the height of the water; and, finally, as the next crest came on, B would read his aneroid, C would stop his second chronograph, while A noted the height of the water and entered all the records.

By this means, and with a careful selection of tolerably undeformed waves, I think that the measurements of undulations could be much more satisfactorily obtained than heretofore; and I only regret that the means at my disposal did not enable me to do more towards this important line of research.

SUMMARY.

The results of this paper may be summarized as follows:—

Several sets of observations between New Zealand and Cape Horn, with an aneroid barometer and chronograph, gave for the largest waves a height of 46 feet, a length of 765 feet, a speed of 47 miles an hour, and a time-period of 16·5 seconds.

As nothing but the ordinary heavy weather of these latitudes was experienced, it is certain that waves must sometimes attain a height of at least 60 feet.

Really big seas are of very rare occurrence.

The great discrepancies in the observed elements of waves given by different observers is doubtless due to the varying lengths of every series of undulations, which therefore always make a more or less confused sea.