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1911-14

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PART 2.

TIDAL OBSERVATIONS

BY
A. T. DOODSON, D.Sc.

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No 6

PART 2.

TIDAL OBSERVATIONS

BY

A. T. DOODSON, D.Sc.

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TIDAL OBSERVATIONS.

By A. T. Doodson, D.Sc.
(Tidal Institute, University of Liverpool.)

With three Plates and seven Text Figures.

INSTALLATION AND OPERATION OF TIDE-GAUGES.

Section 1.

THE TIDE-GAUGE AT CAPE DENISON, ADELIE LAND.

By Robert Bage, B.E., R.A.E., Field Recorder.*

1. The Location of the Observing Station.

The location where the tide-gauge was set up on the Boat Harbour, at Cape Denison, is 67° 00·0′ S. Latitude, 142° 40′ E. Longitude. The coastline in that locality is indicated in the map (Fig. 1). The instrument was set up in the winter on the frozen surface of the ice covering the Boat Harbour, a small shallow bay adjacent to Winter Quarters. An enlarged plan showing the location of the tide-gauge on the bay-ice and of the immediate neighbourhood of the Hut is furnished in Figure 2.

The hurricane winds from the ice plateau of the continent to the south, murky with drift snow, constantly swept down over this bay-ice rendering the duties of the Tide Recorder difficult and often hazardous. No small amount of ingenuity was necessary to maintain the instrument in operation, under the unusual conditions of great cold and dense drifting snow propelled by winds which at times reached a velocity of over 100 miles per hour as recorded by the Robinson cup anemometer.

Plate IV illustrates clearly the disposition of the tide-gauge on the bay-ice, located near the left hand margin of the picture. The view is looking north from a point just south of the Hut. The tide-gauge was operated from June 3rd, 1912, to September 9th, 1912.

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* These notes were prepared by Captain Robert Bage, before he was killed on Gallipoli, which unfortunate event happened within the first fortnight of the campaign.—D.M.

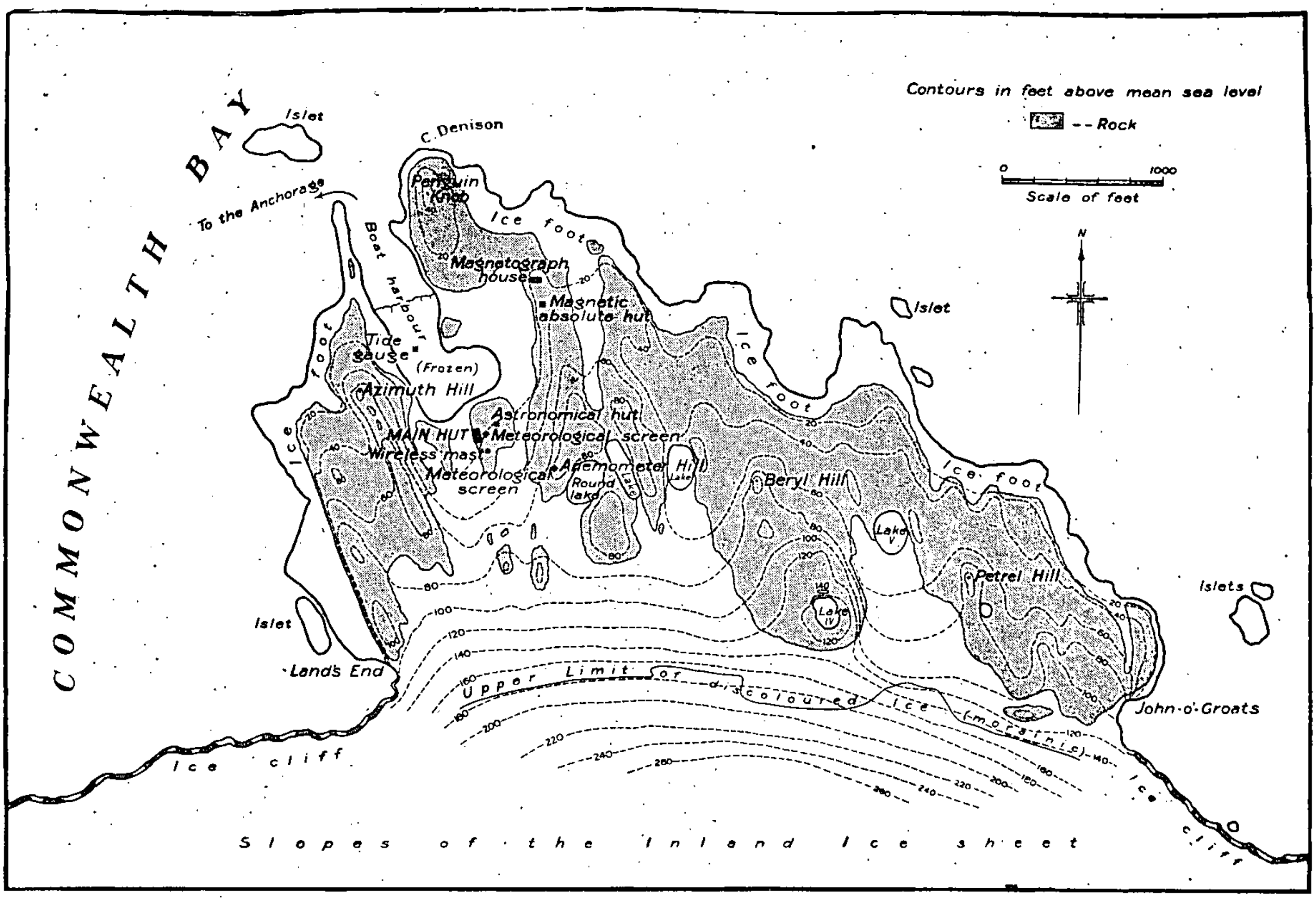


Fig. 1.—Map of the Cape Denison Locality.

2. The Tide-Gauge.

The records were obtained on a Halligan[†] type of recording gauge supplied by the Department of Public Works, New South Wales.

This instrument consists of a wheel about 9 inches in diameter rotated by means of a float wire running in a V thread cut on the rim of the wheel. One end of the wheel spindle carries a small drum about $1\frac{1}{8}$ inch in diameter. This drum also has a V thread cut on it in which runs the pen wire. The pen wire, which is a very flexible steel wire about $\frac{3}{64}$ of an inch in diameter, passes off the drum down to a pulley at the bottom, and thence vertically to a pulley carried at the top of a brass column about 17 inches high and then down through a hole in the base to a 10-lb. counterweight.

The pen is clamped on the pen wire between the two pulleys and moves up and down with the wire. It has an arm about 3 inches long carrying the inker at its extremity, while a short arm projecting at right angles carries a small roller which runs on a vertical guide rod thus keeping the inker pressed lightly against the paper on the drum.

[†] Mr. G. Halligan, formerly Engineer for Harbours and Rivers, in the New South Wales Public Works Department, who originally designed this particular type of recorder, was very helpful to the Expedition, in arranging for this equipment.—D.M.

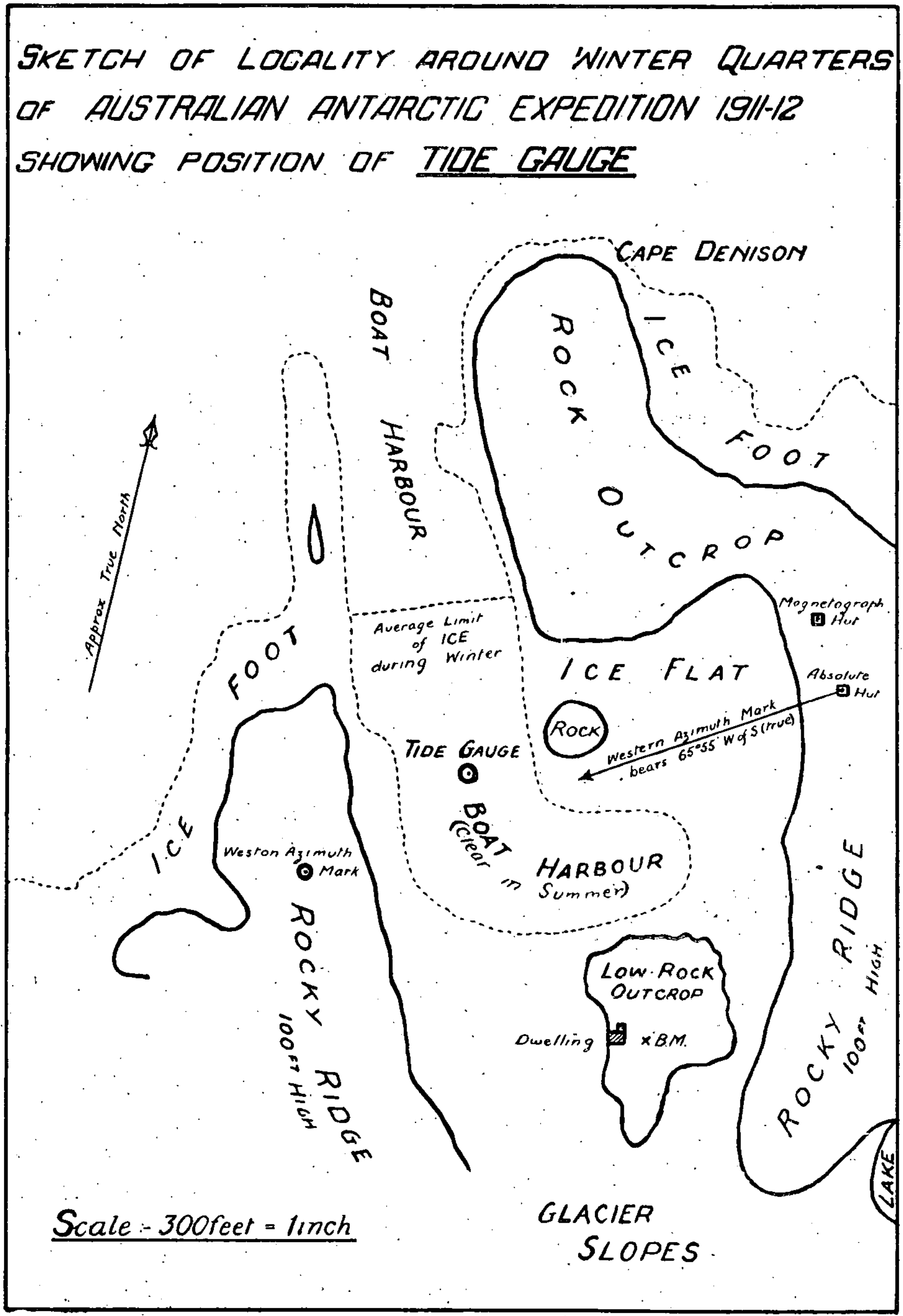


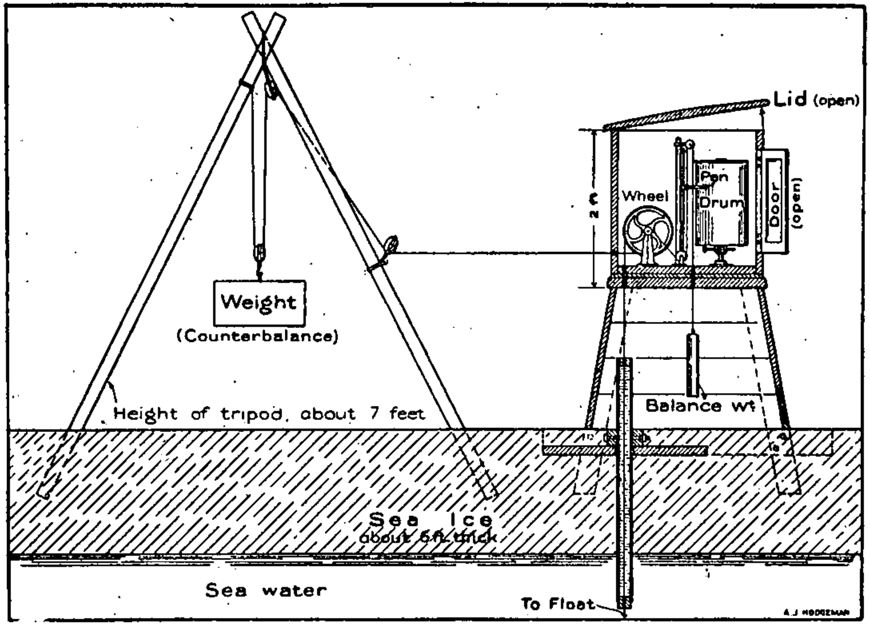
Fig. 2.—Location of Tide-Gauge at Cape Denison.

The drums (of which two were provided) were of aluminium about 13 inches long and 8 inches in diameter. They are carried vertically on a fixed pivot and each contains its own clockwork, the final rotary movement being obtained by a pinion projecting from the bottom of the drum engaging in a spur wheel fixed to the base of the instrument. The drums turned once in 48 hours and ran for 8 days. The scales of the records were about 1½ inches to 1 foot vertically and ½ inch to the hour horizontally.

The counterweight referred to above is, in the usual arrangement as a fixed gauge, sufficient to keep the float-wire taut. Under Antarctic conditions, however, a fixed gauge is impracticable owing to the freezing up of the float, so it is necessary to place the gauge on floating ice and anchor the end of the wire to a sinker on the bottom.

3. Installation on the Ice of the Boat Harbour.

Owing to the high winds prevailing at Commonwealth Bay, the only safe sea-ice formed was the small area at the head of the Boat Harbour, so here of necessity the gauge was placed over only 16 feet of water. On May 26th, 1912, a hole was dug in the young ice, then only 2 feet thick, and a box containing three hundredweight of stones was dropped in with wire attached.



THE TIDE-GAUGE.

The rise and fall of the tide is coincident with the movements of a perpendicular wire to which the *Float* is attached. The *Wheel* is revolved, and through wire connections (indicated above) displaces vertically the *Pen*. This traces a record on paper folded on the *Drum* which is driven by clockwork. In all weathers, the box was enveloped in drift-proof canvas.

The wire, which was of very flexible galvanised steel about $\frac{5}{32}$ inch in diameter, was then threaded through a 7-foot length of 1 in. diameter galvanised iron pipe. The pipe was then clamped vertically over the anchoring box of stones, the upper end of the pipe remaining 1 foot 6 inches above the surface of the water in the hole in the ice. It was soon frozen in firmly. Kerosene oil was poured slowly into the pipe until it would rise no further, thus showing that all the water in the pipe had been displaced. It was found that the oil then stood 2 inches below the top of the pipe. A hardwood plug with a central hole just large enough for the wire to pass freely through it had previously been inserted in the bottom end of the pipe to reduce the escape of kerosene by mingling with the sea water.

On the bay-ice, over the pipe, a box was placed mouth downwards, with four legs fixed to it which were frozen firmly in place in the ice (Fig. 3). To the top of the box the gauge, in its case, was screwed, the main wire passing up from the pipe through the bottom of the case to the large wheel, while the pen wire passed down into the box which effectually sheltered the counterweight. A small door in the side of the box gave access for cleaning out drift snow and refilling the pipe with oil, which latter operation was performed only once. The instrument case above was completely enclosed in a canvas bag which was lashed up firmly to prevent flapping. This bag was found to be very efficient in keeping out drifting snow (see Plate V, Fig. 1).

The main wire passed once round the wheel and then out through the back of the box and a small conical tube in the canvas bag. It then continued horizontally to a tripod of three boat oars, the blades of which were frozen about a foot into the ice, the up-wind leg being also loaded with about 1 cwt. of rock. Under this tripod a stone was suspended from the wire. Different weights were tried, but finally one of about 80 pounds weight was adopted. Small pulley blocks were arranged so that the travel of this stone was reduced to half that of the wire. This made the tension on the wire 40 pounds.

To prevent the stone swinging in the wind, long copper wires were carried from it to each leg of the tripod. These wires allowed enough range up and down, yet were stiff enough to damp the swinging of the stone and prevent it becoming too violent.

This method of working the gauge of course involves renumbering the height graduations on the records, because the high tides show at the bottom of the papers and low tides at the top.

4. CALIBRATION.

The instrument was set up on May 26th, 1912, but had to be reset several times to different zeros till June 3rd following, when a mark was made both on wheel and wire. This was checked frequently and no relative motion could be detected.

The only probable causes of change of zero are therefore—

(i) *Error of Setting of Papers on Drum.*—The papers were always placed on drums with their bottom edges resting on the lower flange of drum. Up till August 7th it was not noticed that the papers were cut at irregular depths so each record up to that date must be corrected for that irregularity. After 7th August all papers were cut at 8 feet 4 inches.

(ii) *Rise of Surface of Ice (with Instrument) above Water Level due to Thickening of Ice (including Settling of Box in Ice, if any).*—This was checked by three readings of height of a step on frame of box above water level obtained by cutting a hole through the ice just alongside the gauge. These readings were :—

May 26	step	0·50	foot above water.
July 16th	,,	0·81	,, ,, ,,
Sept. 9th	,,	0·92	,, ,, ,,

(iii) *Lateral movement of the bay-ice.*—As the water was so shallow this would introduce a relatively large error. No large movement was detected by cross bearings. Minor movement may have occurred, but, as the ice was firmly pinned in the small bay, the possibility of motion was extremely small. Thus errors due to this cause might be expected to be small but irregular.

(iv) *Irregular Bending of the Pen Arm.*—The pen arm was very light and in heavy winds it was often impossible to avoid jarring it when handling. The error could not be more than ·10 foot at the most, but would be irregular.

When the gauge was dismantled on 9th September, 1912, the height graduations on the records were calibrated, the instrument being set up in the Hut with same wires. The latter showed no sensible wear. Several sets of readings were taken which gave the following :—

Movement of Anchor Wire. In feet.	Reading on Drum. In feet.
Zero	Zero
1	0·95
2	1·92
3	2·90
4	3·84
5	4·82
6	5·75
7	6·74
8	7·70

Thus each foot of tidal movement is recorded on the drum as ·96 foot so the drum readings must be increased throughout by 4·2 per cent.

Owing to the constant high winds prevailing at Winter Quarters it was only possible to take two sets of reference levels to the gauge. Bad lighting on one occasion and pressure of other work prevented use being made of any other of the occasional lulls in the almost constant hurricane, on which occasions only could a 3-inch Cary theodolite be safely used. Of the various theodolites available, a 3-inch Cary instrument was selected for this work, as it was the only type with the bubble on the telescope and was accordingly the most reliable as a spirit level. A rock on the west side of Boat Harbour was used as a reference mark (Bench Mark No. 2) and was afterwards connected up with the permanent B.M. near the Hut (see details later). Only one station was necessary and distances to B.M. and gauge were nearly equal (about 50 yards). The readings obtained were as tabulated below :—

1912 July 8th, noon.				1912 August 12th, 12·45 p.m.		
Sight.	Staff Reading.	Tide Gauge Reading at Same Instant.	Tide Gauge Reading corrected for (*a*) Setting of Paper —·08 ft. (*b*) Scale Value +·10 ft.	Staff Reading.	Tide Gauge Reading at Same Instant.	Tide Gauge Reading corrected for Scale Value +·22.
B.M. No. 2 ...	5·62 ft.	....	...	4·09 ft.		
Step on Frame of Tide Gauge. Box	11·56 ,,	2 ft. 9·7 in. = 2·81 ft.	2·83 ft.	6·50 ,,	5 ft. 9·2 in. = 5·77 ft.	5·99 ft.
	11·38 ,,	2 ft. 10·2 in. = 2·85 ,,	2·87 ,,	6·47 ,,	5 ft. 9·2 in. = 5·77 ,,	5·99 ,,
	11·32 ,,	2 ft. 10·8 in. = 2·90 ,,	2·92 ,,	6·34 ,,	5 ft. 10·6 in. = 5·88 ,,	6·10 ,,
	11·36 ,,	2 ft. 10·6 in. = 2·88 ,,	2·90 ,,	6·42 ,,	5 ft. 10 in. = 5·83 ,,	6·05 ,,
	11·37 ,,	2 ft. 10·5 in. = 2·87 ,,	2·89 ,,	6·50 ,,	5 ft. 10 in. = 5·83 ,,	6·05 ,,
B.M. No. 2 ...	5·63 ,,	....	...	4·10 ,,		

By interpolating between May 26th and July 16th for thickness of ice we get height of step above water on July 8th = 0·76 ft. Hence we obtain mean value (rejecting first reading) for height of B.M. No. 2 above zero of gauge = 9·39 feet on July 8th.

By interpolating between July 16th and September 9th for thickness of ice we get height of step above water on August 12th = 0·87 ft. Hence mean value for height of B.M. No. 2 above zero = 9·26 feet on August 12th.

From July 8th to August 12th the box rose ·11 ft. due to thickening of ice, so on August 12th we should expect to have zero of gauge 9·39 + ·11 = 9·50 feet below B.M. on August 12th. Thus there is a rise of zero of ·24 ft. in this period unaccounted for but probably due to errors (iii) or (iv) above.

To obtain the height of zero at the beginning and the end of the series, we can only apply (for lack of other levels) the change due to thickening of ice to the heights of zero on July 8th and August 12th respectively, *e.g.*, on June 3rd water was ·55 ft. below the step and on July 8th, ·76 ft. Hence zero on June 3rd should have been 9·18 ft. below B.M. No. 2, while on September 9th water is ·92 ft. below step and on August 12th ·87 ft.; so on September 9th zero should have been 9·31 ft. below B.M.

Thus the heights throughout the series must be corrected by interpolating for zero between the following values of heights below B.M. No. 2.

June 3rd	9·18 feet.
July 8th	9·39 ,,
August 13th	9·26 ,,
September 9th	9·31 ,,

The drums, as stated, revolved once in 48 hours. Time checks were taken usually daily, being only omitted during the periods of heaviest drifting snow in order to avoid the snowing up of the instrument.

The times were obtained from a wrist watch compared just beforehand with chronometers in the Hut and were noted to the nearest minute on the records. The drum was reset each time to correct Local civil time and small arrow-heads placed on the graph to show the exact time indicated by the pen at the time noted on the paper. Note reproduction of typical record figured in Plate VI.

The errors of chronometers in the Hut on Local Mean time were obtained by observations taken whenever possible with a 6-inch Cary theodolite and are quite reliable. On first setting up the instrument on May 26th several minor mechanical faults were found, but by June 3rd these had been overcome. However, up to July 15th the records were very broken owing chiefly to clock troubles.

The clockwork which was of a very inferior type would not drive at low temperatures. All sorts of expedients were tried but finally by carefully adjusting the escapement and oiling with a mixture of kerosene and good chronometer oil, one clock (No. 5) was persuaded to go, and from that time gave no trouble. The precaution of never bringing it into the Hut had been adopted for some time before this, as moisture from the warm air of the Hut condensed on the cold metal and all bearings would then freeze up on being again exposed to the cold. It was found that the only way for thoroughly removing moisture was to soak the clock in spirits and then bake it gently for some time. The chronometer oil remained liquid over the range of temperature experienced at the tide-gauge (down to —28° F.) but became too thick when even a small amount of drift worked in, hence the necessity for a little kerosene.

A small clock error due to the papers not quite meeting round the drum was also noted on each drum. This was different for each paper as they had to be gummed to the drum and this had to be done very hurriedly owing to freezing of gum.

The ink used was a 50 per cent. solution of glycerine in water coloured with indelible pencil. It was satisfactory and only became slightly viscous at a temperature of —28° F.

Towards the end of the series the records were badly interfered with by the freezing of the main wire in its channel. The bay-ice had thickened to about 5 ft. 6 in. and so extended right down to the bottom of the kerosene-filled pipe. As the ice in the Boat Harbour was all badly cracked, a longer pipe was not then put in, but the instrument was dismantled.

Any special irregularities in records during the last week of the period might be due to ice movements as there was considerable cracking of ice from that time onwards.

At all times the records were affected by marked seiche movements, at least some of which oscillation was due to the pulsation of the hurricane wind bearing down on the bay-ice and driving the off-shore waters before it. This condition was obvious when the wind descended as a succession of violent gusts.

Plate VI is a photographic reproduction of a typical record. It refers to the period 31st July to 7th August, 1912. The seiche movements are well illustrated here.

5. The Bench Mark at Cape Denison.

The main and permanent Bench Mark is the stone surface at the centre of a circular groove 3 inches in diameter cut on the flat top of the largest and highest rock outcropping immediately to the east of the Hut. The letters B.M. are chipped into the rock just near the circle.

The B.M. is on the line of the southern verandah wall of the Hut and is 50 feet from the south-east corner of the same, as illustrated in the diagram.

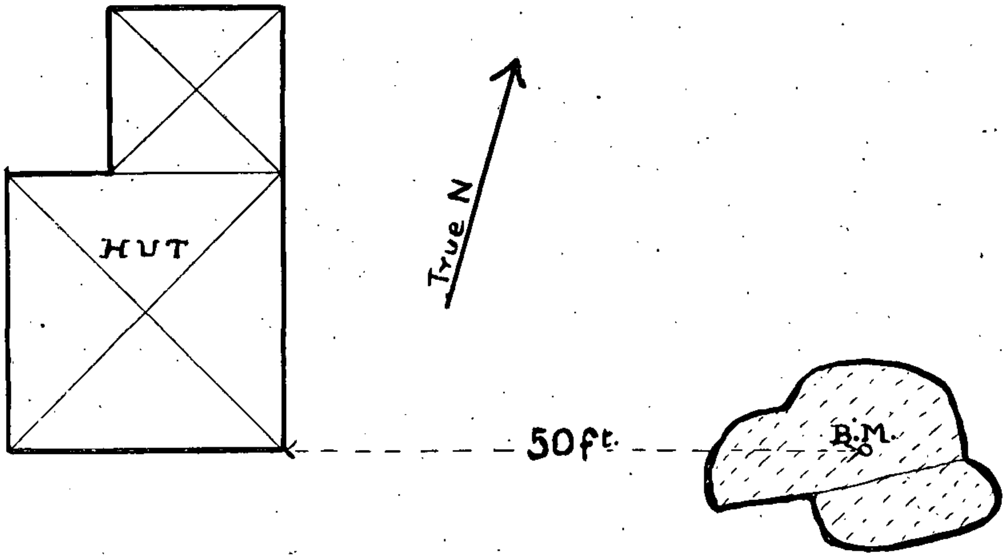


Fig. 4.—Location of permanent Bench Mark at Cape Denison.

In order to fix the level of the B.M. the following set of readings were taken by Mr. C. T. Madigan and Mr. F. L. Stillwell between the temporary bench marks (B.M. 2) and the permanent bench mark (B.M. 1).

Instrument, Cary 3-in. Theodolite. Bubble on Telescope.

Back.	Fore.	Rise.	Fall.	R.L.	
2·60	...	...	...	100·00	B.M. No. 2 near Tide-Gauge.
10·65	3·30	...	0·70	99·30	
11·59	0·26	10·39	...	109·69	
11·07	9·20	2·39	...	112·08	Floor of Hut under Trap Door.
......	0·25	10·82	...	122·90	B.M. No. 1 east of Hut.
1·55	...	...	...	100·00	B.M. No. 2 near Tide-Gauge.
9·30	1·56	...	0·01	99·99	
10·30	0·24	9·06	...	109·05	
7·22	7·22	3·08	...	112·13	Floor of Hut.
8·02	4·25	2·97	...	115·10	
...	0·25	7·77	...	122·87	B.M. No. 1 east of Hut.

Thus, by means of two sets of levels *B.M. No. 2 is 22·88 feet below Permanent Bench Mark near Hut.*

Mean sea level is roughly 3 feet on the Gauge Records. Consequently B.M. No. 1 is about 29 feet above mean sea level.

SECTION 2.

ESTABLISHMENT AND OPERATION OF THE TIDE-GAUGE AT MACQUARIE ISLAND.‡

The tidal records for Macquarie Island were obtained by Mr. G. F. Ainsworth, the leader of the party installed there. The gauge was originally landed at Aerial Cove on Hassleborough Bay on the west side of the island. That location was found to be too much affected by the heavy swell from the west, so that it was found necessary to transfer it to the east coast. The spot finally chosen was close to the Expedition Hut on the shore of Garden Bay, a subdivision of North-East Bay, where preliminary visual observations on a scale painted on a length of timber erected amongst the rocks, showed the spot to be suitable (see Fig. 5).

The set-up was made in a sheltered pool amongst the rocks near the north end of the spit connecting Wireless Hill with the main mass of the island. Plate V, figure 2, shows Leslie Blake, one of the party, leaning against the stand of the instrument.

The tide-gauge instrument was exactly the same type as that already described as used at Cape Denison, except that in this case where it was operating under normal conditions, a float housed in a wide iron pipe open below actuated the mechanism by rising and falling with the tide.

The records extend over the period July 29th, 1912, to June 10th, 1913. For part of the time, on account of a shortage of the squared paper for the drum, the graphs were made on plain paper which are to be measured by reference to a ruled grid.

Eventually during a heavy easterly gale the entire installation was demolished.

Leslie Blake, the Cartographer, cut a permanent bench mark in the adjacent rock. Details of this are noted elsewhere in this series of volumes.

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‡ Notes supplied by the Editor.—D.M.

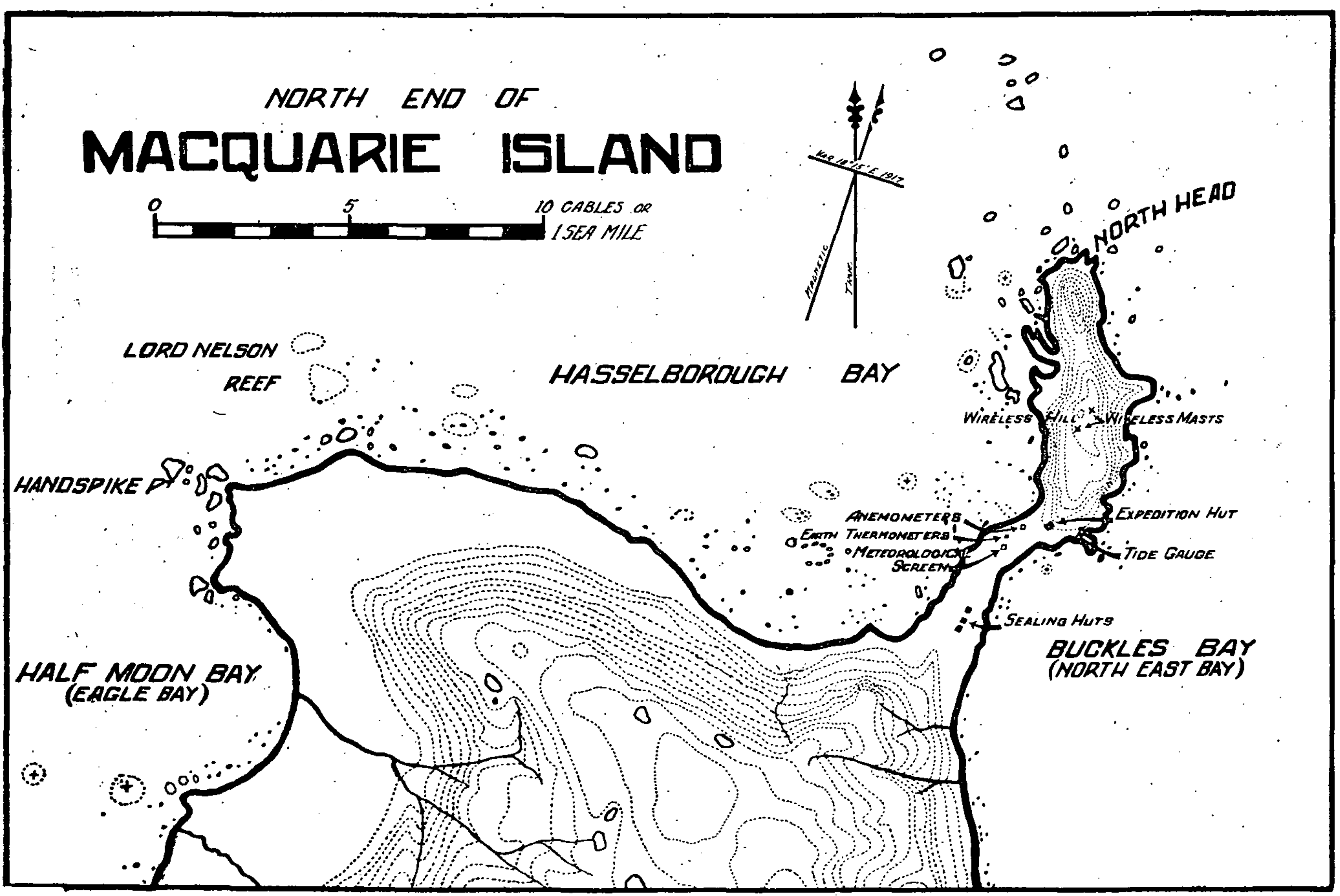

Fig. 5.—Illustrating the location of the Tide-Gauge at Macquarie Island.

REDUCTION AND DISCUSSION

of

TIDE-GAUGE RECORDS

by

A. T. Doodson, D.Sc.

Section 1.

TIDAL OBSERVATIONS AT CAPE DENISON, ADELIE LAND.

1. Data.

The observations were recorded on ruled paper, the scales being 1·5 inches per foot and 0·5 inch per hour, so there was no difficulty in reading the curves. All the necessary notes as to inversion of scale, slightly variable datum line due to fixing of paper, and dates of records had been made on the sheets before they were sent to the Institute. The only defect of these otherwise excellent records was in the seiche motion shown in Fig. 6, but the records were easily read to the nearest tenth of a foot. Typical forms of tide curves are illustrated in Fig. 7. No allowance was made at this stage for any scale errors or variable datum except for the error of setting the paper.

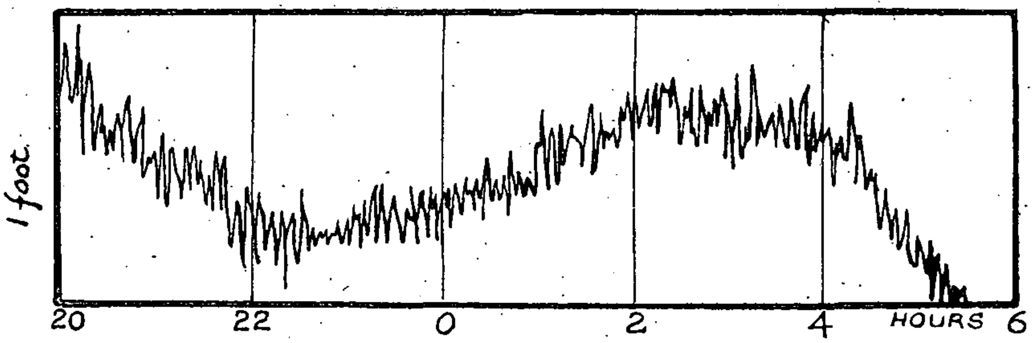

Fig. 6.—Seiches shown on tidal records at Cape Denison, Adelie Land, May 28–29, 1912.

The observations commenced at noon, June 3, 1912, and ended September 9, 1912, and were incomplete on the following days :—June 8, 9, 15, 16, 23, 24, 25 ; July 3, 11, 12, 15, 16, 18, so that a fair amount of interpolation was required to obtain three separate records each of duration of 29 days. It was decided that three sets of observations with their middle days on June 17, July 28, August 26 were most suitable for analysis. A little extrapolation was required for June 3 to complete the sequence.

2. Analyses.

The method of analysis chosen is one that has been specially developed at the Institute for short lengths of records. " Assignments " for constituent-time are not used and the elimination of the effects of constituents other than the one required is accurately effected. It has thus been possible to analyse for the constituents N_2 and Q_1 which have not hitherto been obtained as a rule. In the analyses it has been necessary to assume that the constituents K_2, ν_2, P_1, ρ_1 are related to the constituents S_2, N_2, K_1, Q_1 respectively according to the equilibrium constituents of the tide generating forces. After allowing for the scale error, the results of analysis are as follows :—

Station : Cape Denison, Commonwealth Bay, Adelie Land.
$\lambda = 67° \ 0' \ 0''$ S. $L = 142° \ 40' \ 0''$ E.

Middle Day of Month.	Values of H in feet.						Values of κ in degrees.					
	S_2.	M_2.	N_2.	K_1.	O_1.	Q_1.	S_2.	M_2.	N_2.	K_1.	O_1.	Q_1.
June 17, 1912 ...	·37	·86	·20	·99	·97	·20	28	329	312	4	343	340
July 28, 1912 ...	·46	·91	·19	1·07	·97	·21	30	334	320	2	344	347
August 26, 1912 ...	·48	1·00	·28	1·12	1·00	·24	23	334	312	3	343	325

The mean values, deduced from means of H cos κ, H sin κ are—

	·44	·92	·22	1·06	·98	·21	27	332	316	3	343	337

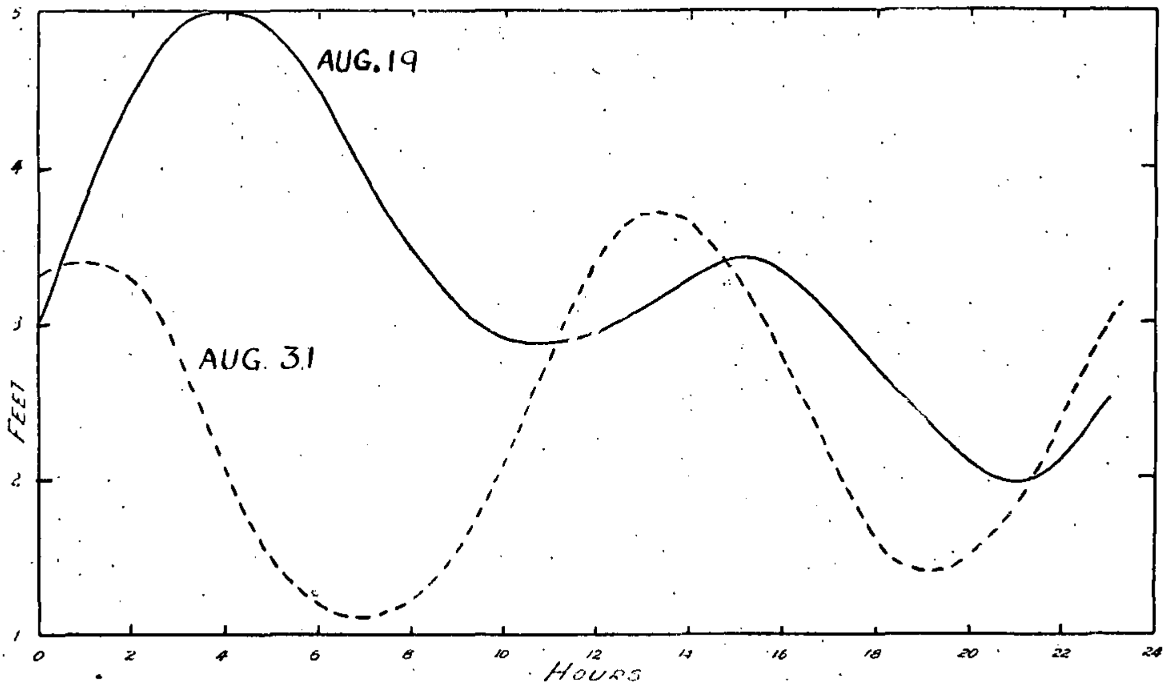

Fig. 7.—Typical tidal oscillations off Cape Denison, Adelie Land.

Inspection shows that all the amplitudes increase progressively from June to August, but that there is no marked progression in the phase-lags. These changes, so far as S_2, N_2, K_1, Q_1 are concerned could, perhaps, be eliminated by suitable modifications of the subsidiary constituents K_2, ν_2, P_1, ρ_1 but it is useless to do so when the variations in M_2 and O_1 would still remain unreduced. The variation is better expressed non-harmonically in relation to the tide as a whole.

Seasonal changes of amplitude (and also of phase) have been noted before in Antarctic tides. Thus Darwin, when analysing the "Discovery" and also the "Nimrod" observations found various progressions but was not able either to prove or disprove their permanent character. The author's opinion is that large variations in ice conditions would tend to cause variations in tidal range, according to the measure of the restrictions set up. These conditions vary from year to year so that analyses for the tides off Cape Denison for another year might not reveal the progression noted above.

The following relations between the constituents are of interest :—

	Actual Amplitude-Ratios.	Equilibrium Amplitude-Ratios.		Phase-differences.	Corresponding. Speed-differences.
S_2/M_2	·48	·47	$S^\circ_2—M^\circ_2$	55°	1·016
N_2/M_2	·24	·19	$M^\circ_2—N^\circ_2$	16°	0·544
O_1/K_1	·92	·75	$K^\circ_1—O^\circ_1$	20°	1·098
Q_1/K_1	·20	·14	$O^\circ_1—Q^\circ_1$	6°	0·544

The age of the semi-diurnal tide is 55 hours. Therefore spring tides occur about 2½ days after full and change of the moon.

Comparisons of the actual amplitude ratios with the equilibrium ratios show that the tide is "normal." Also the phase-differences for each species of tide are roughly proportional to the corresponding speed-differences, though the phase-difference $S_2°—M_2°$ is a little high.

3. SEICHES.

The tidal record was never free from seiche fringes but only on two days was the pen writing finely enough to determine even approximately this period. A portion of the record on these days is shown in Fig. 6. The main period is something like 6 minutes but there are secondary oscillations of a smaller period and amplitude.

The Boat Harbour at Cape Denison is about 1,200 feet long and the gauge was in 16 feet of water. Assuming the average depth of water was 25 feet* then the period of the longitudinal oscillation is given by—

$$\frac{4l}{\sqrt{gh}} \text{ seconds,}$$

---

*The average depth of the Boat Harbour is probably about 15 feet. Its effective length in winter is really greater than indicated on the accompanying plan, for an island off the north-western point almost joins with the western side of the bay. Thus its effective length is probably about 1,800 feet.—D.M.

where l is the length of the bay, h is the depth of the bay and g is the gravitational acceleration. Hence, the seiche period is 170 seconds. This period is only about half that observed but the *ice loading* would increase the period of free oscillation. The approximation is sufficiently accurate to show that the seiches are generated in the known bay.

4. NON-TIDAL VARIATIONS OF SEA LEVEL.

The variations of mean sea level can only be considered in relation to the variations of the datum, and it was thought desirable that the variations in the datum should not be included in the following table of results. This table gives Z, the mean of 25-hourly observations centring noon (local civil times).

Values of Z.

Day.	June.	July.	August.	September.
1	...	2·64	3·14	2·22
2	...	...	2·68	1·69
3	...	...	2·92	1·56
4	2·57	3·32	3·02	2·24
5	2·63	3·44	3·17	2·80
6	2·79	3·31	3·29	2·75
7	...	2·85	3·52	2·68
8	...	2·94	3·51	2·75
9	...	3·04	3·35	...
10	2·76	3·27	3·03	...
11	2·62	...	2·92	...
12	2·67	...	2·73	...
13	2·87	2·92	2·41	...
14	3·04	...	2·72	...
15	...	...	2·66	...
16	...	...	2·40	...
17	3·02	...	2·24	...
18	2·59	...	2·35	...
19	2·83	2·89	3·31	...
20	3·03	2·58	3·13	...
21	2·49	2·37	2·75	...
22	2·60	2·73	2·84	...
23	2·50	3·44	2·84	...
24	...	2·80	2·98	...
25	...	3·00	2·78	...
26	2·70	2·83	2·78	...
27	2·63	3·40	3·30	...
28	3·02	3·28	3·05	...
29	3·41	2·90	2·82	...
30	2·96	2·96	2·69	...
31	...	3·24	2·42	...

If the results are plotted it will be noticed that there are oscillations of mean sea level, with apparently a period of about three days. Such oscillations were noted by Darwin when analysing the "Nimrod" observations. He examined other records from Bombay, Karachi and Aden and found no marked periodicity of this kind. Consequently he made speculations as to the existence of a deep bay, extending to the Pole, and such that its seiches have a period of about three days. Similar speculations, even if justifiable, are out of the question for the present observations. Further, the experience of the writer in connection with meteorological perturbations of sea level and tides has indicated that oscillations of sea level with periods of this magnitude are commonly found in British waters. They are not wholly due to the statical effect of atmospheric pressure but seem to have relation to the average period with which cyclonic disturbances cross the region, both statical variations and wind variations contributing to the variation of sea level.

No reductions of the values of mean sea level recorded above has been attempted; they are simply placed on record.

5. Comparison with the Results of other Expeditions.

The tides near Ross Island have been observed by other expeditions but the stations have been too close together for any general conclusions to be safely drawn regarding the propagation of the tidal motion in these regions. The Cape Denison observations supplement the Ross Island observations very materially. The information yielded by the "Discovery" and "Nimrod" expeditions may be collated with the Australasian expedition as follows :—

Year.	Expedition.	Situation of Gauge.	Latitude.	Longitude.
1902	"Discovery" ...	Near Hut Point, Ross Island	77° 51′ S.	166° 45′ E.
1907	"Nimrod" ...	Near Cape Royds, Ross Island	77° 32′ S.	168° 00′ E.
1912	Australasian ...	Near Cape Denison, Adelie Land	67° 00′ S.	142° 40′ E.

Place.	H in feet.				γ in degrees.			
	S_2.	M_2.	K_1.	O_1.	$S°_2$.	$M°_2$.	$K°_1$.	$O°_1$.
Hut Point	·10	·16	·77	·77	299	37	208	194
Cape Royds	·08	·20	·69	·67	300	32	206	194
Cape Denison	·44	·92	1·06	·98	102	47	220	200

Here γ is the lag of the phase of the tidal constituent behind the phase of the corresponding equilibrium constituent at Greenwich. Replacing "Greenwich" by "the station" we get the definition of κ so that if L is the west longitude (in angle) of the station we have

$$\gamma = \kappa + L \quad \text{for diurnal constituents;}$$
$$\gamma = \kappa + 2L \quad \text{for semidiurnal constituents.}$$

We also have the relations—

Place.	S_2/M_2.	O_1/K_1.	$S°_2—M°_2$.	$O°_1—K°_1$.
Hut Point	·62	1·00	262	−14
Cape Royds	·40	·97	268	−12
Cape Denison	·48	·92	55	−20

Considering firstly the constituents M_2, K_1, O_1 we see that in each case the phases progress westward so that the times of high water for each constituent are later at Cape Denison than at Ross Island. The amplitudes of all these constituents decrease from Cape Denison to Ross Island, but no special significance is attached to the decrement for K_1 and O_1. The variation in amplitude of M_2 must be considered in connection with that of S_2, and the behaviour of this latter constituent is most interesting and instructive. The phase lag changes from 102° at Cape Denison to 300° off Ross Island, while the amplitude falls from ·44 to ·08 at Cape Royds and thereafter increases. We may alternatively study the values of H cos γ, H sin γ as shown below.

Place.	H cos γ.		H sin γ.	
	S_2.	M_2.	S_2.	M_2.
Hut Point	·05	·13	—·09	·10
Cape Royds	·04	·17	—·07	·11
Cape Denison	—·09	·63	·43	·76

It is obvious that for S_2 both H cos γ, H sin γ pass through zero between Cape Denison and Cape Royds and that the zero of H cos γ is probably nearer to Cape Denison than is the zero of H sin γ, but both H cos γ and H sin γ will be small together in a region probably near Cape Adare.

This suggests that the phases decrease from 102° at Cape Denison, through 90°, 0° to 330° near Ross Island, so that the progression of phase for S_2 is westward. The amplitude of S_2 will be very small between Cape Denison and Ross Island and it is concluded that an amphidromic point (for S_2) exists somewhere near Cape Adare. It is now definitely accepted that tidal motion on a rotating earth is generally best represented by amphidromic systems, there being a progression of phase round the amphidromic point, through which all possible cotidal lines pass, and at which there is zero range of tide. Each constituent will have its own set of amphidromic points, but there will be a certain similarity between the sets pertaining, for instance, to semidiurnal constituents. A good example of amphidromic systems is furnished by the North Sea.* In certain cases, as in the Irish Sea, the actual point towards which the cotidal lines run is on land, and on the section of coast cutting the system of cotidal lines we have the values of γ increasing rapidly while the range of tide remains small. Such a system may be spoken of as a degenerate amphidromic system.

For the Antarctic tides under consideration here it seems certain that the constituent S_2 has an amphidromic point near Cape Adare and either very close to land or actually on land. It seems probable that the amphidromic point for M_2 is much further south, probably south-east of Ross Island but if this were so the progression of γ would be in the positive (anti-clockwise direction) and consequently we should expect the same progression for S_2; it follows that the S_2 system would then be degenerate.

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* A memoir on this sea has been recently (1924) sent to the Royal Society by J. Proudman and A. T. Doodson.

SECTION 2.

TIDAL OBSERVATIONS AT MACQUARIE ISLAND.

1. DATA.

The observations were recorded for a few days only on ruled paper, with scales of 2 inches per foot and ½ an inch per hour, but most of the records of the automatic gauge were obtained on ordinary foolscap paper. A datum line, however, was ruled on the paper and the terminal times of the records were given for each day. The wave motion was not very well damped but the records were easily read to the nearest tenth of an inch. Though there is some diurnal tide the motion is chiefly of the semidiurnal type.

The observations were taken for nine months, August, 1912, to May, 1913, and were analysed in separate months of 29 days each.

Standard time, 10 hours fast on Greenwich, was used for the records.

2. ANALYSIS.

The method of analysis utilized is the same as that for the observations taken at Cape Denison, and the following results have been obtained. Here H is the amplitude, and κ is the true phase log., as defined by Sir G. H. Darwin.

Station : Macquarie Island.

Lat. 50° 31′ S. Long. 158° 58′ E.

Middle Day of Month.	Values of H in feet.						Values of κ in degrees.					
	S_2.	M_2.	N_2.	K_1.	O_1.	Q_1.	S_2.	M_2.	N_2.	K_1.	O_1.	Q_1.
1912.												
August 27 ...	·295	·922	·185	·273	·208	·046	39	17	2	26	20	24
September 26 ...	·279	·925	·235	·277	·209	·047	43	17	4	42	17	36
October 25 ...	·219	·924	·242	·264	·222	·053	41	20	358	33	20	341
November 24 ...	·241	·952	·223	·288	·281	·083	39	10	352	29	16	33
December 23 ...	·288	·902	·232	·378	·282	·066	41	12	352	34	9	336
1913.												
January 22 ...	·276	·888	·214	·283	·266	·058	48	17	2	38	9	15
February 20 ...	·274	·863	·218	·275	·227	·071	44	10	348	40	358	349
March 22 ...	·295	·904	·209	·299	·232	·060	39	10	346	32	354	351
May 20	·254	·836	·273	·256	·184	·067	40	0	346	24	343	2
Mean Values ...	·269	·902	·226	·283	·266	·055	42	13	354	33	9	0

The mean values have been deduced from means of H cos κ, H sin κ.

There are a few large variations from the mean values but none of significance except in the case of O_1 where there is a regular decrease in the value of κ, for which no reason can be given or suggested. No seasonal changes can be traced, nor would any be expected so far away from the ice limit.

The relations between the constituents are exhibited in the following table:—

Actual Amplitude Ratios.	—	Equilibrium Amplitude Ratios.	Phase-differences.	—	Speed-differences.
·30	S_2/M_2	·47	29°	$S°_2—M°_2$	1·016°
·25	N_2/M_2	·19	19°	$M°_2—N°_2$	0·544°
·94	O_1/κ_1	·75	24°	$K°_1—O°_1$	1·098°
·19	Q_1/κ_1	·14	9°	$O°_1—Q°_1$	0·544°

In this table the values of H, κ for S_2 are denoted by S_2, $S_2°$ respectively. The ratios and phase-differences are fairly normal. The phase-differences within the species are approximately proportional to the speed-differences. The age of the semidiurnal tide is 29 hours.

3. Variations in Sea Level.

The mean sea level for the whole of the period was 2·09 feet above the datum of the observations, and for each calendar month the mean sea level was as follows:—

1912—	August	2·07 feet.	1913—	January	1·89 feet.
	September	2·37 ,,		February... ...	1·69 ,,
	October	2·24 ,,		March	2·03 ,,
	November	2·01 ,,		April	2·25 ,,
	December	2·39 ,,		May	1·94 ,,

The minimum value recorded is 1·2 ft. (in March) and the maximum 3·2 ft. (in September).

4. Propagation of Tides.

We define γ to be the lag of the phase of the tidal constituent behind the phase of the corresponding equilibrium constituent at Greenwich, and L to be the longitude of the station in degrees *west* of Greenwich. For diurnal constituents we take $\gamma = \kappa + L$ and for semidiurnal constituents $\gamma = \kappa + 2L$, where we obtain the following table, using published tables of constants:—

	Latitude S.		Longitude E.		H in feet.				γ in degrees.			
					S_2.	M_2.	K_1.	O_1.	S_2.	M_2.	K_1.	O_1.
	deg.	min.	deg.	min.								
Ross Island	77	51	166	45	·10	·16	·77	·77	299	37	208	194
Cape Denison	67	00	142	40	·44	·92	1·06	·98	102	47	220	200
Gauss Station	66	02	89	38	·39	·76	·64	·68	282	200	277	270
Macquarie Island ...	54	31	158	58	·27	·90	·28	·27	84	55	234	210
Bluff	46	35	168	22	·51	2·86	·06	·11	72	58	306	267
Port Chalmers	45	50	170	42	·25	2·37	·09	·09	120	121	270	245

We note firstly that Cape Denison is west of Ross Island and that the Gauss Station is west of Cape Denison; secondly, that Macquarie Island is approximately half way between Cape Denison and the Bluff.

When discussing the Cape Denison observations it was shown that probably there was an amphidromic point off Cape Adare for the S_2 system of cotidal lines and that the M_2 constants were consistent with a degenerate amphidromic point on the mainland. The Macquarie Island results, if anything, confirm those conclusions. A cotidal line for $\gamma = 60°$ (M_2 system) appears to run from near the Bluff, passing near Macquarie Island to some point a little to the west of Cape Denison. Two cotidal charts for the M_2 system have been published, one by Dr. Harris* and the other by Dr. Sternux. Both suppose that the phase lags (and thus the hours of high water) progress eastwards from Adelie Land to Cape Adare, but this implication is contrary to the facts. Both agree in placing an amphidromic point south-east of New Zealand, approximately 50° S. and 170° E., with phase lags increasing in the clockwise direction. It can be shown that the S_2 system of cotidal lines will exhibit marked resemblances to the M_2 system, with different geographical situations for the amphidromic points. The above table shows that while the amplitude of S_2 is small from Cape Denison to New Zealand, it is very small relatively to the amplitude of M_2 at places on the New Zealand coast, indicating that an amphidromic point for S_2 probably exists comparatively near to New Zealand, but its precise situation cannot be determined without an exhaustive discussion of constants for other stations. However we conclude that an amphidromic point for the M_2 system must exist somewhere in the neighbourhood of New Zealand.

Dr. Sternux places an amphidromic point for the diurnal tides, using $\frac{1}{2}(\kappa_1{}^\circ + O_1{}^2)$ as his data, on the North Island, with phase lags increasing clockwise. His chart indicates that on the coast of Antarctica, south of Africa, the phase-lags progress eastward and that on the Ross Barrier they progress westward, reaching a maximum about $\gamma = 270°$. The results for Cape Denison and Macquarie Island are not opposed to his conclusions in general, but only show that his tides corresponding to $\gamma = 240°$ and 210° need to be shifted somewhat. The amplitudes of κ_1 and O_1 give strong support to the conclusion that an amphidromic point for either system exists on or near the North Island of New Zealand.

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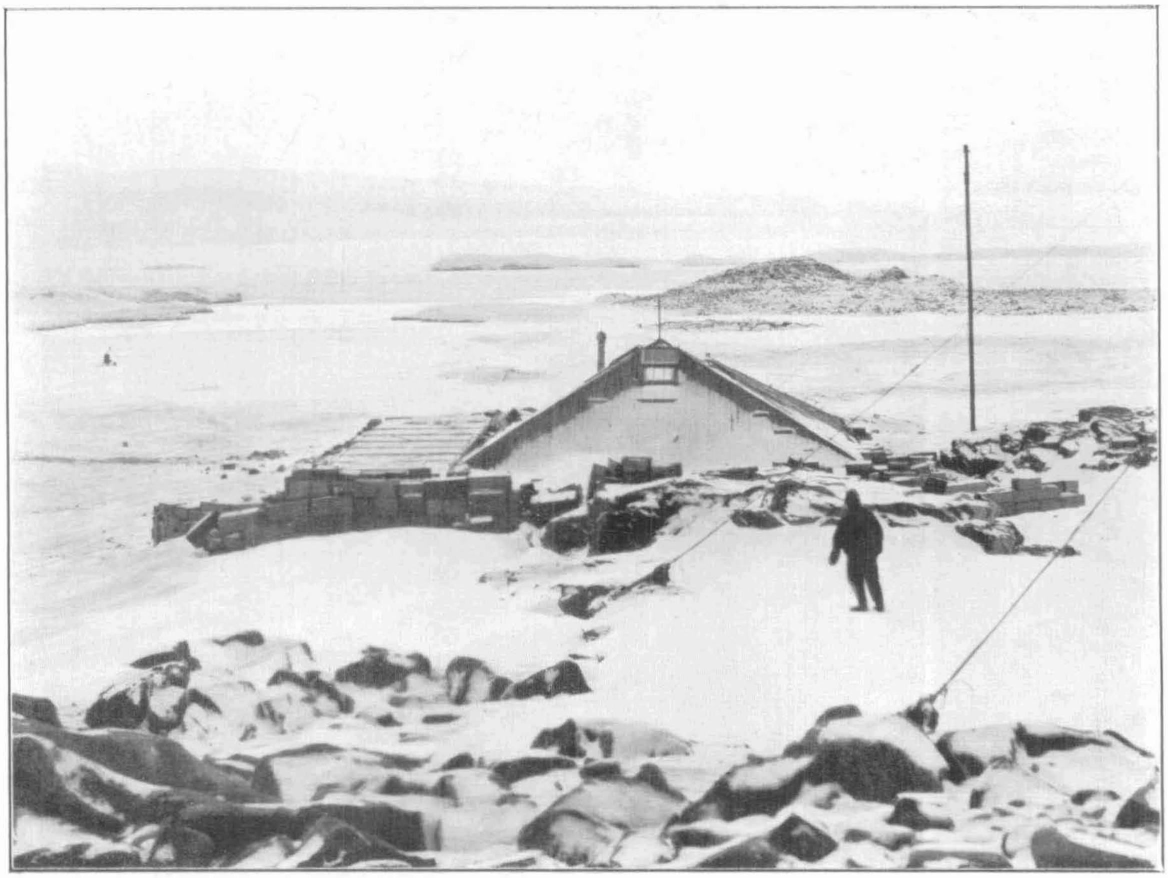
* "Manual of Tides, Part IVa," U.S. Coast and Geodetic Survey Report, 1900, App. No. 7.
* "Die Gezeiten der Ozeane," Sitz. Akad. d. Wiss. Wien, B.129, 1920, and B.130, 1921.

Sydney: Thomas Henry Tennant, Acting Government Printer—1939.



Looking north from the Hut towards the Tide Gauge on the frozen surface of the Boat Harbour; Cape Denison.

FIG. 1.—BAGE AND THE TIDE GAUGE.

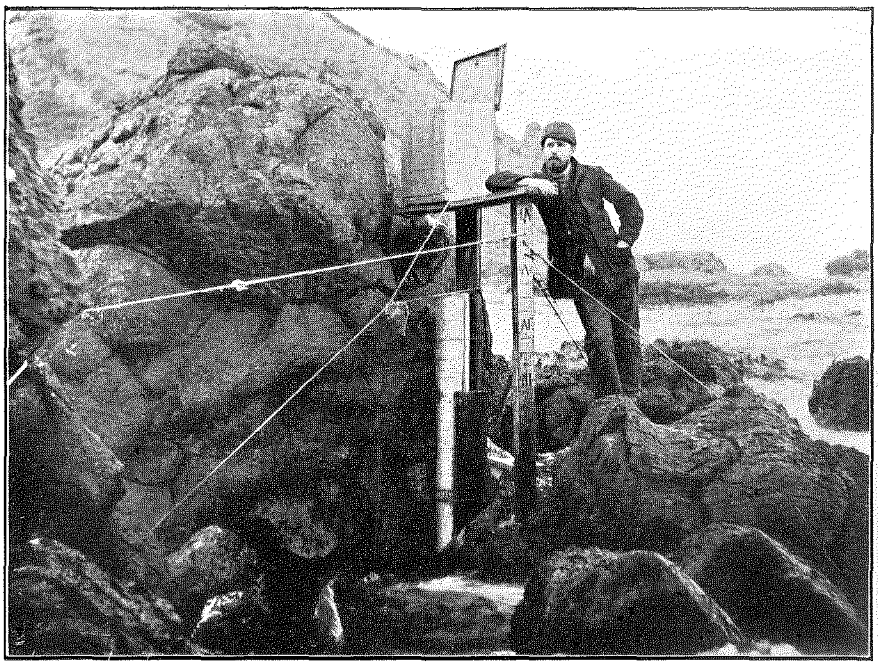
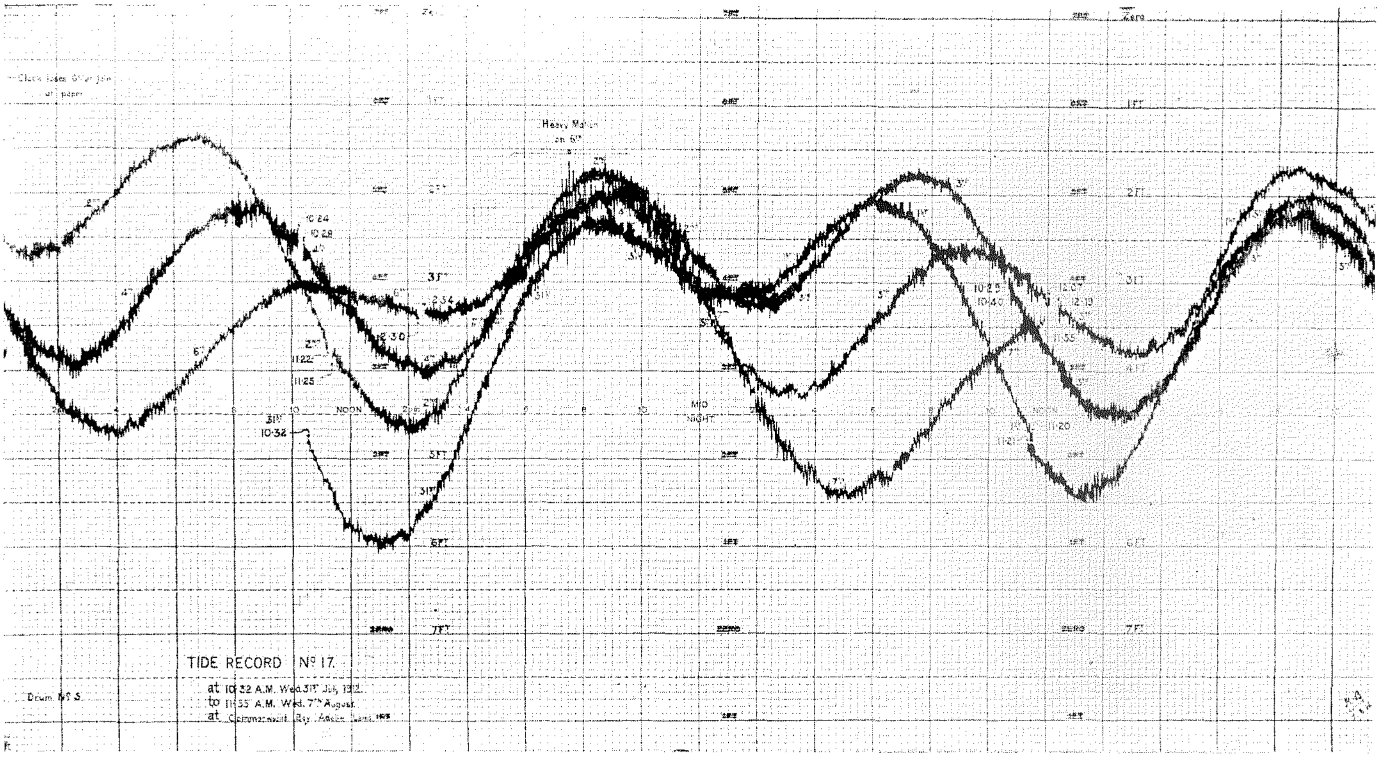


FIG. 2.—THE TIDE GAUGE AT GARDEN BAY; MACQUARIE ISLAND.



A Typical Tide Gauge Record (much reduced); Cape Denison Station.

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