ERGEBNISSE DER STROMMESSUNGEN UND DER OZEANOGRAPHISCHEN

Serienmessungen auf den beiden Ankerstationen der zweiten Teilfarht

(Results of the current measurements and serial oceanographic measurements made at the two anchor stations occupied in the course of the second partial voyage of " Meteor ", 1938)

by O. v. SCHUBERT.

REPORT

In this additional pamphlet which appeared with some delay on account of the war, O. v. Schubert gives the final results of the observations conducted in 1938 by the research vessel " Meteor " at two anchor stations in the North Atlantic, for the main purpose of investigating internal waves. New publications concerning the results are still in course of preparation. A short advance report was published in the additional pamphlet of January 1939 of the *Annalen der Hydrographie,* whose main passages were translated and reproduced in vol. XVI, n° 2 of the *Hydrographic Review,* page 46.

ANCHOR STATION 385

The first anchor station was occupied in latitude 16° 48',5 N. and longitude 46° 17',1 W. for 60 hours, from February 12 to February 15, 1938. It was located on the Atlantic Ridge, 700 miles from the nearest mainland ; the anchor cast at a depth of 2.950 meters with a scope of cable of 5.000 meters must have gripped a rocky bottom, because, on weighing, the cable broke a few hundred meters in front of the anchor.

This anchoring took place at the southern limit of the N. E. trade winds. The wind was fairly light during the first 36 hours (9 to 11 m./sec.), starting at 70°, it turned gradually down to 40°, subsequently, on February 14th, it blew more rapidly northward, reached 347° at 15 hours and returned to 11° right to the end of observations, its force running from 7,7 m./sec. at 13 hours to 13,89 m./sec. at 22 hours.

Under the combined effect of wind and current, the vessel remained comparatively steady with pendular motions of 13° to 42°. This oscillation seems to have been at its lowest when wind and current were fairly strong and in different directions; the vessel became, on the contrary, unsteady when both forces went down or assumed the same direction.

For the whole duration of the anchoring, hourly serial observations of temperature and salinity were made at 11 depths : surface 5, 15, 50, 60, 70, 80, 90, 100, 120 and 150 meters. At first, an isothermal layer about 60 meters thick was met with, then temperature and salinity changed rapidly, the temperature gradient reaching its maximum between 90 and 100 meters, with a value of 0°,091 per meter, and that of density being 0,029 per meter. Density increased between 60 and 140 meters and reached a maximum of 36,95 ‰ at 100 meters and even occasionally 37,10 ‰. The salinity gradient was highest between 70 and 80 meters and reached the value of + 0,01 ‰.

Density then diminishes, passing at 800 meters through a minimum of 34,80 ‰, then increases up to 35,02 ‰ at 1.600 meters and subsequently diminishes slightly down to the bottom. Temperature goes on diminishing right to the bottom, while salinity and density go on increasing.

It is worth noticing that salinity and density are greater at the surface than at a depth of 5 meters, while temperature is lower, the difference reaching 0°,40 with an average of 0°,17. This anomaly can be explained as regards temperature by the annual variation which reaches its fullest surface cooling effect in February-March. It may also be that a surface current brings about an inflow of colder and more salt water. However, this unstable stratification, near the surface, does not seem to be associated with the time of the year nor with any particular weather condition and not even with a special region. The heavier water may be kept in equilibrium on the surface by turbulence friction or by the friction which slackens its rate of fall. Surface water density may also be diminished by small air bubbles mixed with it by the stirring movement of waves and of which no account was taken when calculating density according to temperature and salinity. Such calculation shows that the weight of one cubic meter of surface water exceeds by about 50 grammes that of a cubic meter of a depth of 5 meters. This difference would disappear if the latter contained 50 cm³ of air.

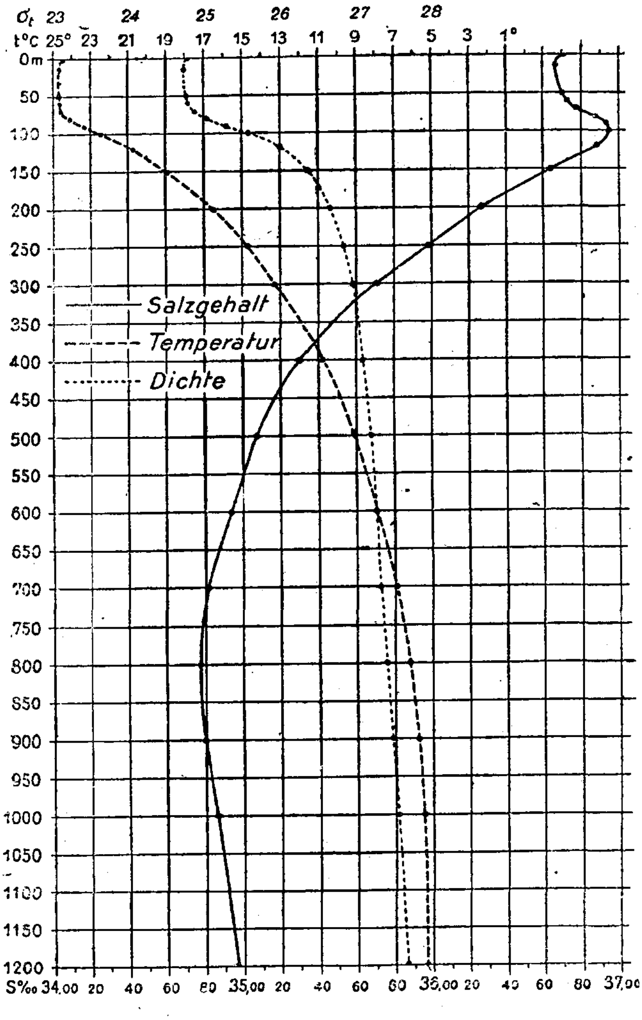

Fig. 1
Vertical curves of a series.

Time changes in oceanographic data are very small above 70 meters and have no periodic character. At a greater depth, temperature shows clearly a 12 hours period. The amplitude of oscillation grows up to depths of from 90 to 100 meters, which corresponds to the spot where the gradient is highest, subsequently, amplitudes go on diminishing.

As regards salinity, a 12 hours period is admitted at depths of 70 and 80 meters, which is no longer discernible at 90 and 100 meters, but re-appears at 120 meters and 150 meters; although with a phase differing by 180°. This is easily explained by a reference at fig. 1 in which the salinity curve changes its direction at 100 meters, so that a rise of the bodies of water must produce an increase in salinity at 80 meters and a decrease at 120 meters and vice-versa. These various gradients must also affect amplitudes.

The agreement between isotherms and isohalines is not bad, it shows a vertical displacement of water reaching 50 meters in a few hours, which diminishes as one goes up, since the tidal wave is at most of the order of the decimeter at the surface. The 24° isothermal phase is o h. 24 (lunar time) the demi-amplitude 12 m. 1 and the period 12 hours lunar.

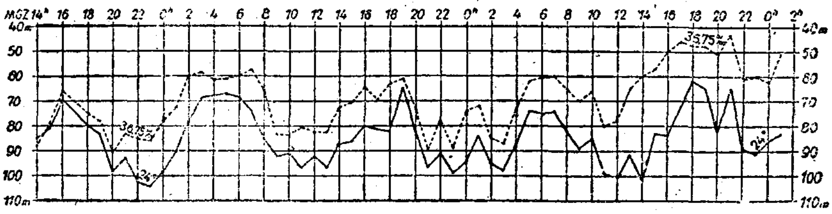

FIG. 2

Depth position of the isotherm of 24° and isohaline of 36,75 ‰

The relationship between salinity and temperature shows a very regular rate when employing mean values but differs according to series, which shows the importance of time variations.

Current measurements were effected by means of two "Böhnecke apparatuses" whose description was reproduced in vol. XV, n° 2 of the *Hydrographic Review*, p. 83. With the starboard side apparatus, suspended by a single wire, measurements were made as far down as 800 meters. The current was observed hourly for 10 minutes at depths of 5, 15,30 and 50 m. It has been planned to observe for 20 minutes every two hours at depths of 100, 300, 500 and 800 meters, but on account of damage, as from February 13th, observations had to be confined to 500 meters. Current oscillations respond to a 12 hours tide with a phase which is nearly opposite, at 300 meters, to that observed at the surface.

TABLE N° 1

Harmonic analysis of the components of the tidal current. — Station 385.

12 HOURS TIDE

Depth in meters	Component N. S.			Component E. W.			Permanent Current	
	Mean	Cm./sec.	Phase	Mean	Cm./sec.	Phase	Direction	Velocity
5	— 13,3	6,3	7 h. 3	— 22,8	4,3	10 h. 7	S. 60° W.	26,4
15	— 13,6	8,7	6 h. 5	— 20,3	5,4	10 h. 7	S. 56° W.	24,4
30	— 11,3	8,8	6 h. 8	— 16,9	2,7	8 h. 8	S. 56° W.	20,3
50	— 12,4	11,1	6 h. 6	— 13,6	3,8	11 h. 7	S. 48° W.	18,4
100	— 7,5	2,7	10 h. 7	— 10,3	3,6	4 h. 2	S. 54° W.	12,7
300	— 2,1	8,0	10 h. 9	— 9,6	9,4	4 h. 6	S. 78° W.	9,8
500	— 2,2	6,3	10 h. 7	— 6,2	1,1	6 h. 2	S. 70° W.	6,6
800	— 3,7	6,5	12 h. 5	— 10,6	3,1	3 h. 5	S. 71° W.	9,8

24 HOURS TIDE

5	— 13,3	5,4	7 h. 8	— 22,8	6,2	11 h. 0
15	— 13,6	5,2	6 h. 6	— 20,3	5,9	11 h. 5
30	— 11,3	4,4	4 h. 2	— 16,9	3,0	12 h. 6
50	— 12,4	3,3	7 h. 3	— 13,6	4,4	12 h. 4
100	— 7,5	1,6	7 h. 0	— 10,3	2,2	10 h. 8
300	— 2,1	3,1	7 h. 5	— 9,6	3,7	3 h. 6
500	— 2,2	2,2	9 h. 4	— 6,2	1,7	17 h. 7
800	— 3,7	3,8	21 h. 2	— 10,6	3,7	18 h. 3

A great difference is noted between phases as depth increases, which result is opposite to that furnished by the observations made at the anchor station on the "Meteor's" great expedition.

Table 2 gives the characteristics of the current ellipses.

TABLE N° 2

Values of the current ellipses for 1/2 day and 1 day.

Depth	Main direction		Phase		Intensity		R' : R		Direction of	
in meters	12 hours	24 hours	12 hours	24 hours	12 h.	24 h.	12 h.	24 h.	12 h.	24 h.
5	N. 16° W.	N. 52° E.	7 h. 0	9 h. 7	6,4	7,5	0,640	0,444	with the sun	
15	N. 25° W.	N. 57° E.	6 h. 2	10 h. 0	9,4	6,4	0,425	0,718	—	
30	N. 9° E.	N. 27° W.	6 h. 8	2 h. 7	8,9	4,6	0,258	0,587	—	
50	N. 17° W.	N. 17° E.	6 h. 6	11 h. 5	11,6	4,6	0,146	0,696	—	
100	N. 53° W.	N. 70° E.	10 h. 2	9 h. 5	4,4	2,5	0,113	0,480	—	
300	N. 50° W.	N. 54° E.	10 h. 6	5 h. 0	12,3	4,2	0,073	0,548	with	against
500	N. 7° W.	N. 20° E.	10 h. 8	9 h. 0	6,3	3,4	0,111	0,411	against	with
800	N.	N. 44° E.	0 h. 5	19 h. 8	6,5	4,9	0,477	0,408	with the sun	

It shows that the phase difference in the semi-diurnal tide is abôut 4 hours between the surface and a depth of 800 meters. The relation $\frac{R'}{R}$ of Table 2 is that of the minor to the major axis of the ellipse. This relation, for the semi-diurnal tide, is theoretically equal to 1,033 sin φ, and therefore 0,298 in the present case, which is very near to that of 0,280 furnished by the average of the obtained values. For diurnal tide, the theoretical figure would be 0,575, that furnished by the average is 0,563 ; the difference between the various values being very small. Theory also indicates that rotation must have the same direction as that of the sun, which agrees with observations, with one exception for the semi-diurnal tide and two for the diurnal tide. The duration of observations was too short to allow a precise determination of the period of inertia oscillation : theoretically it is equal to $\frac{12}{\sin \varphi}$ hours, or in the present case 41 h. 5.

In order to determine what is called here permanent current (grundstrom) an average was taken of all the observed values and it was assumed that all periodic elements were thus eliminated. The direction of the permanent current is generally S. W., it varies but little with depth and turns with the sun its velocity exceeds 20 cm./sec. in the surface layer. It decreases according to an almost linear law with a gradient of 0,144 per meter down to a depth of 100 m.; from 100 to 150 meters, the decrease is still almost linear but with a lesser gradient of 0,012 per meter. The direction of the current varies in all depths within a range of about 30°; this variation is practically the same at different depths down to about 300 meters under which there is nearly no more change in velocity.

ANCHOR STATION 438

The second anchor station was occupied in latitude 30° 1',6 N. and longitude 43° 47',6 W. for 60 hours from April 26 to 28 1938.

It was located on the Atlantic ridge about 800 miles to the North of the previous one. The anchor, dropped at a depth of 2.210 meters with a scope of cable of 4.000 meters, had a tight grip on the bottom. It was weighed in a distorted condition, the end of the cable being rubbed up white, which goes to prove that the bottom was rocky and that the vessel had not drifted.

During the observation, the wind varied but little in force and direction, coming generally from N. N. E. It oscillated between 10° and 60° with a mean velocity of 6 m. 8/sec., varying from 4,6 to 9,1.

The current was slow at a depth of 5 m.; its highest velocity being 27 cm./sec. It oscillated between 335° and 214°, without any sign of tide.

The forces of the current and wind were less than at the previous station, the vessel's heading was steady. The harmonic analysis furnished an oscillation amplitude of heading of 3°,3 with a phase of 4 h. 2 for à 12 hours period.

The tidal current at a depth of 5 meters, had an amplitude of 7,4 cm./sec. and a phase of 3 h. 3.

The serial temperature and salinity measurements were made at the nine following depths : 0, 100, 150, 200, 300, 400, 500, 650 and 800 meters. The depths at which samplings were actually made did not differ by more than from 2 to 5 meters at 500 meters, 5 meters at 650 meters, and 8 to 11 meters at 850 meters. The vertical gradient was very low, the values obtained for salinity are too high by 1 to 2 hundredths per 1.000 at 800 meters, those for temperature by 1 to 2 tenths of degree.

TABLE N° 3

Mean vertical structure. Station 438

Depth in meters:	0	100	150	200	300	400	500	650	800
°C temperature...	19,07	18,16	17,86	17,63	17,07	16,04	14,62	12,10	9,78
0/00 Salinity......	36,61	36,51	36,46	36,43	36,36	36,19	35,96	35,61	35,39
Density............	26,51	26,41	26,41	26,48	26,55	26,67	26,81	27,05	27,30

The structure of the bodies of water is quite different from that which was found at the previous station. While the density gradients in the homogeneous surface layer were from 0,01 to 0,02, their values at station 438, were from 0,0006 to 0,0017. The latter value corresponding to the 650-800 meters layer and lower limit of the troposphere, which, at this depth, is separated from the stratosphere by a higher gradient.

It was for this reason that the depth levels taken for measurements were different from those selected at the previous station. These conditions were less favourable to the study of internal waves whose existence is bound up with that of steep vertical gradients.

The steepest temperature gradient is found in the 500-650 meters layer, where it reaches 0°,0168 per meter. The steepest salinity gradient : 0,0023 per thousand per meter, occurs in 400-500 meters and 500-650 meters layers. A series of observations made from surface to bottom at much nearer depths revealed no stratification anomaly.

Time temperature and salinity variations are small on account of the low vertical gradient. Differences in temperature reach 0°,68 at the surface 0°,17 at 200 meters, 0°,56 at 500 and 650 meters (they reach 3° to 4° in the discontinuity layer at station 385). The greatest salinity oscillations are 0,10 ‰ at the surface and at 500 meters (against 0,48 ‰ at 80 meters, at station 385) the smallest oscillation is 0,05 ‰ at 200 meters.

TABLE N° 4

Time oscillations and vertical gradients of the oceanographic elements.

Depth in meters	Temperature		Salinity		Density	
	Oscillation	Gradient	Oscillation	Gradient	Oscillation	Gradient
0	0,68°	0,0091	0,10 0/00	0,0010	0,17	0,0016
100	0,46°	0,0060	0,08 0/00	0,0010	0,09	0,0008
150	0,42°	0,0016	0,09 0/00	0,0006	0,08	0,0006
200	0,17°	0,0056	0,05 0/00	0,0007	0,05	0,0007
300	0,47°	0,0103	0,09 0/00	0,0017	0,11	0,0012
400	0,52°	0,0142	0,08 0/00	0,0023	0,08	0,0014
500	0,56°	0,0168	0,10 0/00	0,0023	0,09	0,0016
650	0,56°	0,0155	0,09 0/00	0,0015	0,07	0,0017
800	0,51°		0,07 0/00		0,07	

Analysis discloses periodical oscillations of the elements whose amplitude is very small but whose phases are in good agreement.

TABLE N° 5

Phase values of the 12 h. period oscillation for temperature, salinity and density.

Depth	Temperature	Salinity	Density	Average
100 meters..............	1 h. 7	2 h. 3	3 h. 3	
150 —	2 h. 0	0 h. 4	4 h. 5	2 h. 1
200 —	1 h. 7	1 h. 1	1 h. 9	
300 —	5 h. 6	5 h. 6	4 h. 2	6 h. 3
400 —	6 h. 9	7 h. 6	6 h. 4	
500 —	6 h. 8	6 h. 7	7 h. 4	6 h. 3
650 —	2 h. 7	1 h. 9	1 h. 5	
800 —	4 h. 1	1 h. 6	3 h. 7	2 h. 6

An analysis of the time changes in temperature, salinity and density shows that they agree to indicate, at depths of 300 to 500 meters, a phase lag of about 4 hours in comparison with the surface layer.

Current measurements were made in the same manner and according to the same programme as at the first station. This programme was however subject to some delays and important omissions owing to damages to the clock work of the instruments. Periodic changes of about 12 hours at depths of 5 to 50 meters were disclosed, but, at greater depths, measurements are inadequate and their results can only be accepted with reservation.

TABLE N° 6

Harmonic analysis of the tidal current components.

12 HOURS TIDE

Depth in meters	Components N. S. Mean	Cm./sec.	Phase	Components E. W. Mean	Cm./sec.	Phase	Permanent current Direction	Velocity
5	+ 0,1	7,4	3 h. 3	— 13,5	3,3	6 h. 1	W.	13,5
15	+ 0,9	5,2	3 h. 8	— 13,5	2,4	6 h. 6	N. 86° W.	13,6
30	— 3,3	6,1	3 h. 5	— 10,6	4,5	6 h. 6	S. 73° W.	11,1
50	+ 0,7	7,2	4 h. 2	— 12,3	5,5	6 h. 6	N. 87° W.	12,4
100	+ 0,4	3,8	3 h. 1	— 11,7	1,4	6 h. 1	N. 88° W.	11,8
300	— 1,9	4,0	2 h. 6	— 12,0	4,3	6 h. 4	S. 81° W.	12,1
500	— 1,5	2,0	3 h. 9	— 7,5	4,3	6 h. 6	S. 78° W.	7,7
800	+ 0,2	3,3	3 h. 8	— 4,3	1,7	4 h. 9	N. 89° W.	4,3

24 HOURS TIDE

Depth in meters	Components N. S. Mean	Cm./sec.	Phase	Components E. W. Mean	Cm./sec.	Phase
5	+ 0,1	4,6	6 h. 5	— 13,5	4,6	10 h. 2
15	+ 0,9	7,9	6 h. 3	— 13,5	6,4	8 h. 9
30	— 3,3	5,3	5 h. 2	— 10,6	6,1	10 h. 5
50	+ 0,7	4,1	8 h. 1	— 12,3	4,5	7 h. 4
100	+ 0,4	4,3	7 h. 0	— 11,7	1,7	8 h. 8
300	— 1,9	6,1	23 h. 4	— 12,0	4,7	4 h. 5
500	— 1,5	2,0	5 h. 3	— 7,5	0,2	7 h. 4
800	+ 0,2	4,4	21 h. 8	— 4,3	7,6	2 h. 2

This table shows that the component phases for the 12 hours period vary but little with depth ; but those of the current ellipses are more divergent ; in particular, there is a phase discontinuity of about 4 h. 4 between 300 and 400 meters ; which result tallies with those of the temperature and salinity measurement analysis.

The tidal current amplitudes are greater for the first 50 meters than for the following, although still small ; the mean value at 50 meters is 5,4 cm./sec. and the maximum 7,6 cm./sec., against 8,2 and 12,3 cm./sec. at the previous station at a depth of 300 meters.

The current ellipse amplitudes have a mean value of 6,0 cm./sec. and a maximum of 9,6 cm./sec. at a depth of 15 meters.

The relation of the minor axis to the major axis of the ellipses in this latitude must be theoretically 0,517 for the semi-diurnal tide and 0,995 for the diurnal tide. Calculation gives as an average 0,473 and 0,395 for the 8 depths. The agreement is adequate only for the semi-diurnal tide. The direction of rotation is like that of the sun, according to theory.

TABLE N° 7

Values of semi-diurnal and diurnal ellipses.

Depth in meters	Main direction 12 hours	24 hours	Phase 12 hours	24 hours	Intensity 12 h.	24 h.	R' : R 12 h.	24 h.	Direction of rotation 12 h.	24 h.
5	N. 3° E.	N. 46° E.	3 h. 3	8 h. 4	7,4	5,7	0,432	0,526	with the sun	
15	N. 3°5 E.	N. 37° E.	3 h. 8	7 h. 3	5,2	9,6	0,434	0,344	—	
30	N. 20° E.	N. 64° E.	4 h. 0	9 h. 1	6,3	6,3	0,666	0,792	—	
50	N. 24° E.	N. 48° E.	4 h. 7	7 h. 8	7,6	6,1	0,644	0,098	against the sun	
100	North	N. 20° E.	3 h. 1	7 h. 2	3,8	4,6	0,368	0,152	with the sun	
300	N. 50° W.	N. 21° E.	1 h. 4	0 h. 4	4,9	6,3	0,633	0,695	—	
500	N. 75° E.	N. 5° E.	5 h. 8	5 h. 3	4,4	2,0	0,386	0,050	—	
800	N. 65° E.	N. 72° E.	4 h. 0	1 h. 7	3,6	7,8	0,222	0,500	—	

The permanent current remains almost exactly West down to a depth of 100 meters ; it has however an appreciable South component towards 30 meters, then towards 300 and 500 meters. Its velocity diminishes almost linearly with depth, with a gradient of 0,0166 per meter.

SUMMARY

Confining oneself to a study of the semi-diurnal tide, one may draw some conclusions in connection with internal waves.

The structure of bodies of water was very different at the two stations. At the first station, the vertical movement can be inferred from serial measurements only between 50 and 150 meters. It occurs with the Greenwich 24 hours lunar phase. When the horizontal current at depths of 0 to 50 meters reaches its maximum —(about 6 h.), the bodies of water of the layers between 50 and 150 meters occupy their highest position and the vertical movement is non-existant.

At station 458, calculation for depths of 100, 150 and 200 meters, gave the mean value 2 hours (Greenwich lunar time) of the phase of time changes of temperature and salinity, which tends to show that at that time temperatures and salinities are at their highest. As these two elements diminish with depth, it is also at that time that bodies of water occupy their deepest position and that vertical movement is non-existent. For depths of 300, 400 and 500 meters, the mean value of the phase is 6 h. 3 ; between 650 and 800, it is 2 h. 6. Therefore when the movement is downward in a middle layer, it is upward above and under and vice-versa. The variation of the tidal horizontal movement lags as depth increases, like at station 385. It was possible to ascertain that phase changes of horizontal and vertical movements were related to the changes of gradients and also that, in spite of the smallness of gradients, the arrangement of the vertical structure of bodies of water has a decisive effect on the formation of internal waves.

The results which have been obtained do not all agree with those furnished by the "Meteor's" great expedition ; the conclusion to be drawn thereof is that the problem of internal waves is so intricate that it can only be clarified by many subsequent measurements to be effected with a constantly improving technique.

Horary measurements of temperature of surface water and of air 9 meters above afford some interest because they were the first measurements of the kind to be made during a few days in the open sea from an anchored vessel.

The two stations were separated by more than 13° in latitude and only 2° 29',5 in longitude, that is practically 10 minutes time. The hours are those of the 45° zone. 5,1 minutes should therefore be added to those of station 385 and 4,8 minutes taken off from those of station 438. The duration of observations was too short to produce results of any value. We may however state that the water temperature varied by 0°,502 at the most northerly station and by 0°,422 at the most southerly ; this was consistent with previsions. The air temperature varied from 3°,8 to 2°,47 which is much more than was anticipated. Minimum hours at station 385 were 0 hour for water and air ; at station 438, 4 hours for water and 3 hours for air. Maximum hours were 13 hours and 12 hours at station 385 ; 15 hours and 14 hours at station 438. Such hours, particularly minimum hours cannot be stated very accurately.

The report also contains many tables and figures which we have not reproduced, together with an appendix giving all the results of serial measurements.

P. V.