NORSK POLARINSTITUTT
SKRIFTER NR. 133

DEN NORSKE ANTARKTISEKSPEDISJONEN, 1956—60
SCIENTIFIC RESULTS NO. 9

VIDAR HISDAL

ON THE TIDES AT NORWAY STATION

AND ADJACENT COASTAL AREAS OF ANTARCTICA

NORSK POLARINSTITUTT
OSLO 1965

DET KONGELIGE DEPARTEMENT FOR INDUSTRI OG HÅNDVERK

NORSK POLARINSTITUTT
Middelthuns gate 27 b, Oslo 3, Norway

Short account of the publications of Norsk Polarinstitutt

The two series, Norsk Polarinstitutt — SKRIFTER and Norsk Polarinstitutt — MEDDELELSER, were taken over from the institution Norges Svalbard- og Ishavs-undersøkelser (NSIU), which was incorporated in Norsk Polarinstitutt when this was founded in 1948. A third series, Norsk Polarinstitutt — ÅRBOK, is published with one volume per year.

SKRIFTER includes scientific papers, published in English, French or German MEDDELELSER comprises shorter papers, often being reprints from other publications. They generally have a more popular form and are mostly published in Norwegian.

SKRIFTER has previously been published under various titles:

Nos. 1—11. Resultater av De norske statsunderstøttede Spitsbergen-ekspeditioner.
No. 12. Skrifter om Svalbard og Nordishavet.
Nos. 13—81. Skrifter om Svalbard og Ishavet.
» 82—89. Norges Svalbard- og Ishavs-undersøkelser. Skrifter.
» 90— . Norsk Polarinstitutt Skrifter.

In addition a special series is published: NORWEGIAN—BRITISH—SWEDISH ANTARCTIC EXPEDITION, 1949—52. SCIENTIFIC RESULTS. This series will comprise six volumes, four of which are now completed

Hydrographic and topographic surveys make an important part of the work carried out by Norsk Polarinstitutt. A list of the published charts and maps is printed on p. 3 and 4 of this cover.

A complete list of publications, charts and maps is obtainable on request.

ÅRBØKER

Årbok 1960. 1962. Kr. 15.00.
Årbok 1961. 1962. Kr. 24.00.
Årbok 1962. 1963. Kr. 28.00.
Årbok 1963. 1965. Kr. 35.00.

NORSK POLARINSTITUTT
SKRIFTER NR. 133

DEN NORSKE ANTARKTISEKSPEDISJONEN, 1956–60
SCIENTIFIC RESULTS NO. 9

VIDAR HISDAL

ON THE TIDES AT NORWAY STATION

AND ADJACENT COASTAL AREAS OF ANTARCTICA

NORSK POLARINSTITUTT
OSLO 1965

Received for publication November 1964

Printed February 1965

PUBLISHED BY NORSK POLARINSTITUTT
On sale only through our distributor
UNIVERSITETSFORLAGET
Postboks 307 - Blindern, Oslo 3

Contents

Tide gauge diagram

Abstract

Practically the whole coast of the Atlantic sector of Antarctica is covered by floating glaciers, the so-called ice shelves. It is therefore a complicated task to measure the tidesin these areas. During the stay of the Norwegian Antarctic Expedition, 1956–60, at Norway Station (70° 30′ S, 02° 32′ W) attempts were made at recording the variations, due to the tides, of the depth at the front of the ice shelf. Two more or less continuous but very short records were obtained, the first one lasting about 3.2 days, and the second one about 2.2 days. For both observation periods the greatest difference between a high water level and the preceding or succeeding low water level is about 1.5 m. The measurements furthermore reveal that the diurnal constituents are comparatively large. In order to estimate the amplitudes and phases of the four major constituents (M_2, S_2, K_1 and O_1), the data are analysed by means of the prediction equations of the so-called "Admiralty method". The heights of the tide are considered as known, while the harmonic constants represent the unknown quantities. The equation system was solved by means of the method of least squares. The 1½ hourly heights computed by means of the found harmonic constants are compared with the observed heights. The agreement between the two sets of data is surprisingly good.

The movement of the ice shelf in time with the tide must have had a certain influence on the air pressure at Norway Station, and the pressure observations are analysed in an attempt to find periodic components corresponding to the tidal constituents. As far as the M_2 constituent is concerned, there is a good correspondence between the result of this analysis and that of the tidal measurements. Furthermore, the harmonic constants found for the tides at Norway Station agree well with those found for stations farther to the east and to the southwest.

The conclusion is, that although we cannot expect our estimates of the harmonic constants to be very precise, they seem to be sufficiently reliable to give useful preliminary information on the character of the tides in the region considered.

Tides at Norway Station

Introduction

Except in the last decade, relatively few scientific expeditions have visited Antarctica, and even smaller is the number of expeditions that have carried through systematic observations of the tides. This may, in part, be explained by the observational difficulties met with because of the sea ice, and because of the fact that several of the expeditions had their base on the ice shelf; the floating glaciers which cover large portions of the coastal areas. In addition to the difficult topographic conditions at the front of the ice shelf, the nearest fixed reference point is the sea bottom, mostly at a depth of some hundred metres.

Valuable information about the tides at ice shelf stations may be obtained by indirect methods, by analysing elements which are affected by the vertical motion of the station. Thus the tidal movement must have a certain influence upon the observations of the surface air pressure. However, the shortness of the observation series hitherto available as well as other difficulties, make the interpretation of the results obtained fairly complicated (HISDAL, AMBLE and SCHUMACHER 1956). Very precise gravity recordings may give more conclusive results (PRATT 1960, THIEL *et al.* 1960).

On the Norwegian Antarctic Expedition, 1956–60, attempts were made at measuring directly the tidal movements at the front of the ice shelf, near the expedition base, Norway Station, at 70° 30′ S, 02° 32′ W (see map, Fig. 1). The depth at the front was about 260 metres.

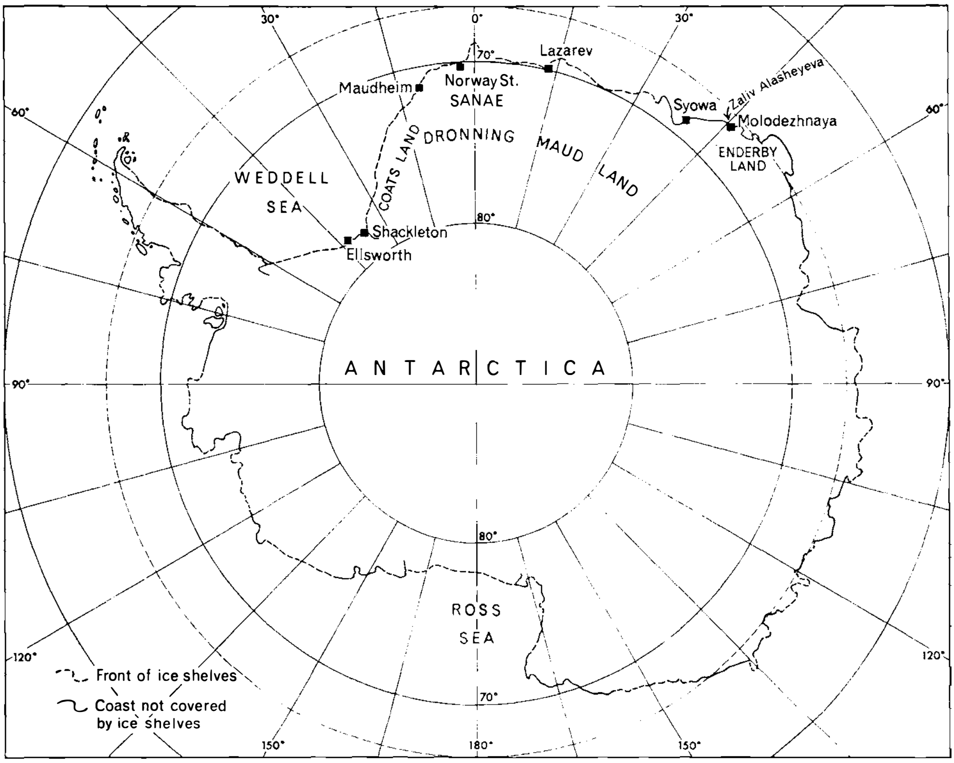

Fig. 1. *Map showing the position of the stations mentioned in the text.*

The first attempt was made on the sea ice in a bay in the ice front (Tottanbukta) during the winter 1958. The ice was thick (at least 1.5 m) and had lain undisturbed for months as the two expedition members SNUGGERUD and HOCHLIN put up a frame work on the ice for the tide gauge. However, the night before the instrument was to be mounted, the weather suddenly deteriorated. The wind grew to hurricane force (number 14 in the extended Beaufort scale), the ice was broken up and some equipment was lost. The most serious loss was a large part of the expedition's supply of wire intended for the tidal measurements. But fortunately the recorder itself was in safety.

The next attempts were made by HELLE and NERGAARD at the ice front itself in a neighbouring bay (Polarsirkelbukta) during the following summer, and they succeeded in obtaining two more or less continuous but rather short records of the tide.

In the following discussion it is assumed that at or near the ice front there is no, or practically no difference, between the amplitude and phase of the tidal movement of the ice shelf, and the corresponding characteristics of the tides in the neighbouring sea.

Method of observation

The tide gauge was of the ordinary self-registering type and of German manufacture (OTT-Schreibpegel, Type X). However, since the problem was not the usual one to measure the movements of a float by means of a recording mechanism at a fixed point, but, on the contrary, to measure the varying distance between a fixed point (on the sea bottom) and a floating recorder, the transfer system had to be somewhat specialized, as illustrated by Figs. 2 and 3.

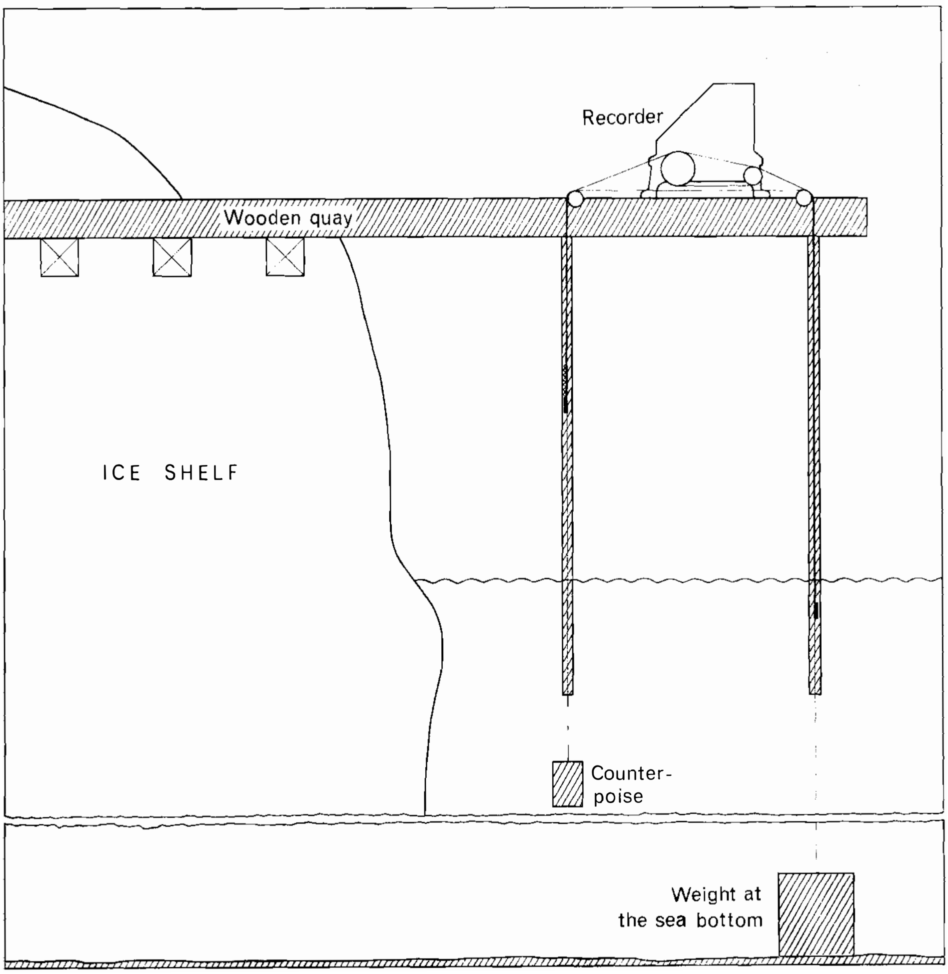

Fig. 2. *Arrangement of tide gauge.*

A small wooden quay was built for the recorder at the discharging berth in Polarsirkelbukta. Here, a valley had formed at the edge of the ice shelf and the front towards the sea was only a couple of metres high (see Figs. 3 and 4).

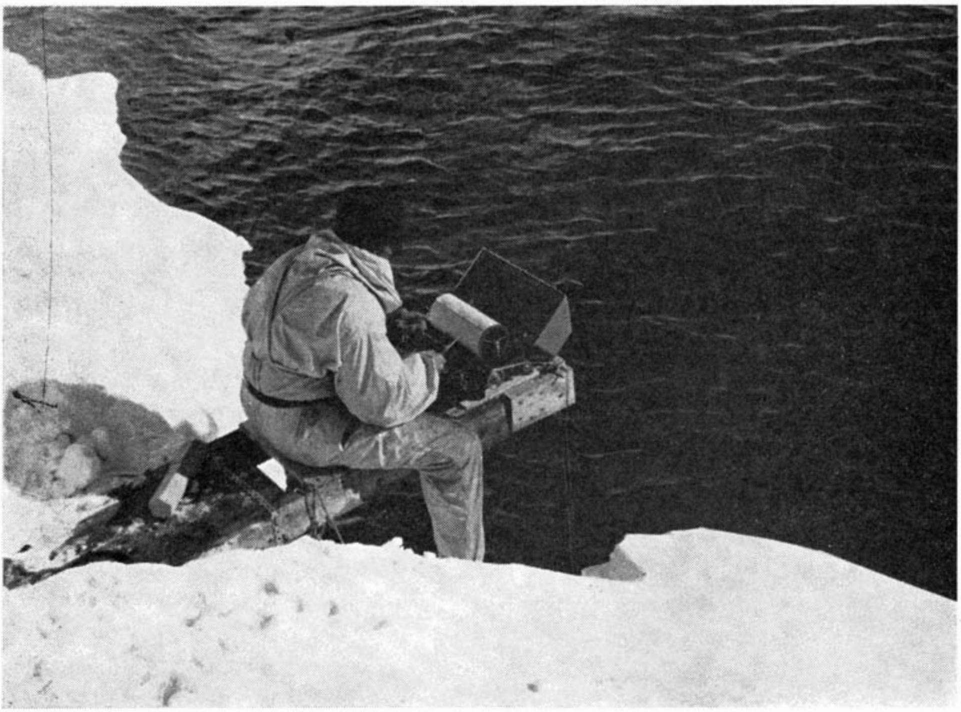

Fig. 3. *The quay with the recorder.*

Fig. 4. *View of the ice front in Polarsirkelbukta. The quay with the recorder is barely visible somewhat to the right of the middle of the picture. To the left, on the ice shelf, is seen a small, movable hut.*

The weight at the sea bottom (about 60 kg) was connected with a counterpoise by means of a 0.8 mm thick piano wire. The wire went down into the sea through rubber tubes, which were filled with paraffin to prevent freezing.

In order to reduce the influence of frictional forces, all wheels in the transfer system had ball bearings. As would be expected, however, there proved to be a certain backlash in the system, primarily, it may be supposed, because of friction and the elasticity of the wire. The magnitude of this effect was determined by pulling the weight wire in one direction and then allowing it to go back as long "as it would". Afterwards the procedure was repeated by pulling the wire in the other direction. The difference between the positions of the pen in the two cases was taken as a measure of the backlash. To make this as small as possible, counterpoises of different weights were tried. The heavier the weight, the greater the friction in the wheels. A counterpoise of 14–16 kg seemed suitable. On the marigram shown at the end of the paper (Fig. 10), the distance between the two horizontal lines at the beginning and, in some cases, also at the end of each individual tidal curve indicates the magnitude of the backlash. In the middle of each of the two observation periods the weight of the counterpoise was reduced a few kg to about 14 kg, and we observe that the backlash at the same time decreases from 5–10 cm to 2–4 cm. If the counterpoise was made still lighter, it did not manage to keep the wire sufficiently tight.

As expected, the measurements met with considerable difficulties, resulting, among other things, in some breaks in the recordings. The reasons for these breaks are briefly indicated along the tide curve in Fig. 10. The most marked irregularities of the curve are due to pressure of floes against the wire. During the early morning of 2 December 1958 the wind increased and the bumping of the floes against the wire proved to be too great a strain. It broke and nearly all the wire that was left from the unsuccessful attempt in winter was lost. There was nothing to do but to wait for the expedition ship with further supplies.

Shortly after the arrival of the ship the last attempt was made. After less than two days of registrations the wire broke close to the weight on the sea botton. A new weight was lowered and the registrations continued. But during the following night a smaller part of the ice front close to the quay broke out and the quiver set up in the ice made the drum of the recorder jump out of its bearings. More serious, however, was the discovery made on the next day, that a crack had formed in the ice just behind the observation point and that the quay had started to sink. The gauge had to be dismounted as rapidly as possible.

Observational data

The first observation period lasts about 3.2 days, starting at 21^h on 28 November 1958, and the second one lasts about 2.2 days, starting at 18^h on 5 January 1959. During the breaks in the records on 29 November and 7 January (see Fig. 10) the reference level of the tide curve was shifted, and it is not possible to interpolate the missing parts of the tide curve with sufficient reliability. In the two cases when the counterpoise was changed, however, the reference level may be supposed to be nearly unaltered. The course of the tide curve for these comparatively short breaks is indicated by broken lines (short dashes) in Fig. 10.

The recordings have to be corrected for the backlash described in the preceding section. As is apparent from Fig. 10, this is done by reducing the recorded height when the tide is falling by a value equal to the backlash. The corrected parts of the tide curve are indicated by broken lines (long dashes).

In spite of the many observational difficulties the recordings look fairly satisfactory. A few typical features may be mentioned. The rather large diurnal inequalities clearly show that the diurnal constituents are of great significance. The greatest height difference between a high water level and the preceding or succeeding low water level is about 152 cm for the first observation period and about 155 cm for the second one. In this connection it should be pointed out that the first period starts well over two days after full moon and the second one ends well over one day before new moon. In all probabability, therefore, the observation periods do not include either the time of spring tide (i. e. maximum range of the semidiurnal tide) or the time of neap tide. The time difference between the moon's transit through the local meridian and the next high water ("the high water lunitidal interval") is about four hours during the first observation period. During the second period this time interval is about twice as great, a further indication that the part played by the lunar semidiurnal constituent is not dominating. During the first period the declination of the moon is northerly and, as would be expected, its upper transit is followed by the lower high water, while during the last period, when the moon (like the sun) has a southerly declination, the upper transit is succeeded by the higher high water.

Harmonic constituents

Generally, the aim of an analysis of tidal data is to find the "best" fit of a sum of simple harmonic terms to the observed tide, assuming the angular speeds of the individual terms to be equal to those of the harmonic constituents of the tide generating potential. Owing to the shortness of our observation periods, the ordinary methods worked out for this purpose are not applicable.

As far as we can see, the most expedient procedure in the present case will be to base the analysis on the prediction equations for the height of the tide at further specified days and hours, with the difference that now the height of the tide is known, while the harmonic constituents represent the unknown quantities. This method has been used by PRATT (1960) in his previously mentioned tidal analysis of gravity measurements.

We have kept to the so-called Admiralty method of prediction (cf. DOODSON and WARBURG 1941), which is based on the principal lunar and solar semidiurnal constituents (M_2 and S_2) and the luni-solar and lunar diurnal constituents (K_1 and O_1). Assuming certain equilibrium relations to be valid, however, these constituents are modified in such a way that, to a large extent, the effect of the other constituents is taken into consideration. Each of the four modified principal constituents may be written:

$$\mathrm{BCH} \cos (\mathrm{nt-g-b-c}),$$

where H is the amplitude, n the angular speed, t the time, and g the phase lag. B, C, b and c are all parameters varying with time. Besides correcting for nodal variations, they serve the above mentioned purpose of making allowance for the influence of constituents other than the four principal ones. The parameters are easily computed by means of the data given in the Admiralty Tide Tables, Part III (1941).

In addition to the tidal movement the gauge will record such systematic variations as a sinking of the weight on the sea bottom into the bottom sediments, a sinking of the quay due to compression of the underlying snow, and a displacement of the ice front. For the short time intervals under consideration, we have assumed these variations to be approximately linear, so that they may be included in a term $q_j t$, where the constant q_j may differ from the first to the second observation period ($j = 1, 2$). There are other possible effects, due to, for example, an insufficient allowance for the minor harmonic constituents, or to local or distant influences of wind and air pressure on the sea level in the observation area.[1] The changing direction and speed of the streams at different depths may cause the wire between the sea bottom and the gauge to deviate more or less from a rectilinear course. These and similar effects are symbolized by the term $r(t)$. The height read on the marigram, $h(t)$, above an arbitrary zero line, may then be written:

$$h(t) = p_i + q_j + r(t) + \sum BCH \cos(nt-g-b-c),$$

where p_i is the height of a mean sea level above the chosen zero line. We have four independent zero lines, one for each of the four intervals in which the observation periods are divided (see p. 9). The last term is the sum of the modified M_2, S_2, K_1 and O_1 constituents.

The value of $h(t)$ is read on the marigram for $1\frac{1}{2}$ hourly intervals.[2] This give 83 equations by which to determine 14 unknown quantities, viz. p_i ($i = 1, 2, 3, 4$), q_j ($j = 1, 2$), H and g for each of the four major constituents. Assuming $r(t)$ to be a comparatively small residual term of more or less random character, we want to find "the best" solution of the equation system by the method of least squares, i. e. by minimizing $\sum r(t)^2$. The solution of the normal equations is obviously a job for an electronic computer, and was carried out at the Mathematical Institute of Oslo University. As to the harmonic constituents, the results are given in Table 1. Evidently, it is of no interest to give the values of p_i. They are used to fix a common level for the tidal curves in Fig. 10. For q_1 we get 0.201 cm/hour and for q_2 0.246 cm/hour, which means a slight positive trend during both observation periods, as indicated by the rectilinear broken lines in Fig. 10.

Table 1. *Harmonic constants for Norway Station.*

Amplitudes (H) in cm. Phase lags ($\varkappa$) referred to the local meridian.

M_2		S_2		K_1		O_1	
H	$\varkappa$	H	$\varkappa$	H	$\varkappa$	H	$\varkappa$
33.2	169°	22.5	194°	24.9	345°	31.0	331°

---

[1] During both observation periods the weather conditions at Norway St. were stable. During the first period the air pressure varied between 987.9 mb and 990.3 mb, and during the second period between 981.7 mb and 984.8 mb. The winds were weak to moderate, blowing along the coast or towards the ocean.

[2] It seems pointless to choose a shorter interval, as this would mean an increase of the computational work without a corresponding increase in the accuracy of the results.

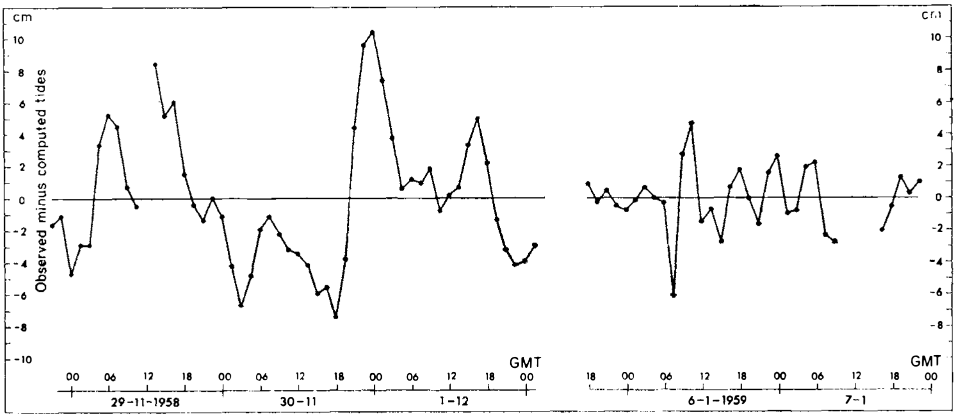

Fig. 5. *The variation of the difference, r(t), between observed and computed tides.*

As a check on our results we have by means of the values found for the 14 unknown quantities calculated the height of the sea level for 1½ hourly intervals, using the above mentioned prediction equations. These calculated heights are represented by small rings in Fig. 10. It appears that the differences between the calculated and observed heights are small. Their standard deviation, which may be considered as an estimate of the standard deviation of r (t), is not greater than 3.86 cm. In view of the many observational difficulties, this result seems surprisingly good.

Fig. 5 shows the variation of r (t). While the series of the second observation period looks quite haphazard, that of the first period seems to contain a systematic component. This impression is supported by statistical tests. We have tried to relate the changes of r (t) to meteorological phenomena (pressure and wind), but with no great success. Due to the modest magnitude of r (t) we have not found it worth while to enter into a detailed examination concerning this point.

It is not possible to compute with any degree of accuracy the confidence intervals of the estimated amplitudes and phases of the harmonic constituents. If we consider the length of the two observation periods and of the interval between them, we find that during the first and longest observation period the M_2 and S_2 constituents complete 6.16 and 6.38 cycles respectively. The relative shift of the phases is thus quite small. From the middle of the first to the middle of the second observation period, however, the corresponding relative shift of the phases is close to half a cycle. We may expect, therefore, that we have succeeded fairly well in separating M_2 and S_2. Regarding the two diurnal constituents, the situation is somewhat less favourable. During the first observation period K_1 completes 3.20 cycles and O_1 2.96 cycles, and from the middle of the first to the middle of the second period the difference between the phases of the two constituents change with about 0.3 cycles.

Some verification of our results is obtained in the following discussion, where these are compared with other information about the tides at Norway Station and adjacent areas.

Influences on the air pressure observations

The movement of the ice shelf in time with the tides must have had a certain influence on the air pressure at Norway Station.

The station was situated at about 30 km south of the front of the ice shelf, and the distance from the station to the nearest point where the ice "went ashore" was, as far as could be judged by the position of the strand cracks, about 6 km (towards the west).

It is difficult to form an *a priori* idea of the degree to which the tidal movement of the ice shelf, at different distances from its front, may be retarded and its amplitude changed as compared with the tides of the adjacent ocean, i. e. the degree to which frictional forces or some sort of "shallow water constituents" come into play. At present there is no empirical and, consequently, no reliable theoretical basis for answering this question.

Previously, the air pressure observations from Maudheim (71° 03′ S, 10° 56′ W) have been analysed in an attempt to find periodic components corresponding to the tidal constituents M_2, K_1 and O_1 (HISDAL *et al.* 1956). Conclusive results were obtained only in the case of the former constituent. Regarding S_2, it was not possible to isolate a corresponding pressure oscillation, due to the fact that the amplitude and phase of the relatively great semi-solar pressure wave in the atmosphere itself were not known.

In the paper referred to above is given a method of testing the significance of the amplitudes of harmonic terms contained in the air pressure series considered. Supposing the statistical properties of the air pressure, especially the course of the corellogram curve, to be approximately equal at the two "neighbouring" stations Maudheim and Norway Station, we may estimate significance limits of the Fourier amplitudes computed from our pressure series for periods corresponding to those of the tidal constituents.

At Norway Station the air pressure was read every third hour in the period 1 April 1957 to 31 December 1959, i. e. 1005 days in all. In January 1960 the station was taken over by the Republic of South Africa and the name was changed to SANAE. The three-hourly pressure observations for the period 15 January 1960 to 31 January 1962 (747 days) were kindly provided by the Weather Bureau in Pretoria. In the following we use the name Norway Station when we refer to the former period and the name SANAE when referring to the latter period.

For the whole observation period the estimated 95 % significance limits of the amplitudes for the M_2, K_1 and O_1 periods equal 15, 54 and 61 microbars respectively. This would correspond to height differences of about 12, 42 and 47 cm. Judging by the amplitudes of the corresponding tidal constituents found in the preceding chapter, viz. 33 cm for M_2, 25 cm for K_1 and 31 cm for O_1, there should be a fair chance of getting comparatively reliable information about the influence on the observed air pressure of the semidiurnal lunar constituent, while the influence of the two diurnal constituents is likely to be severely obscured by sampling fluctuations.

In order to reduce to some degree the masking effect of the large scale pressure fluctuations, we have left out all days with pressure tendencies greater than 10 mb. This applies to four days in the Norway Station period and two days in the

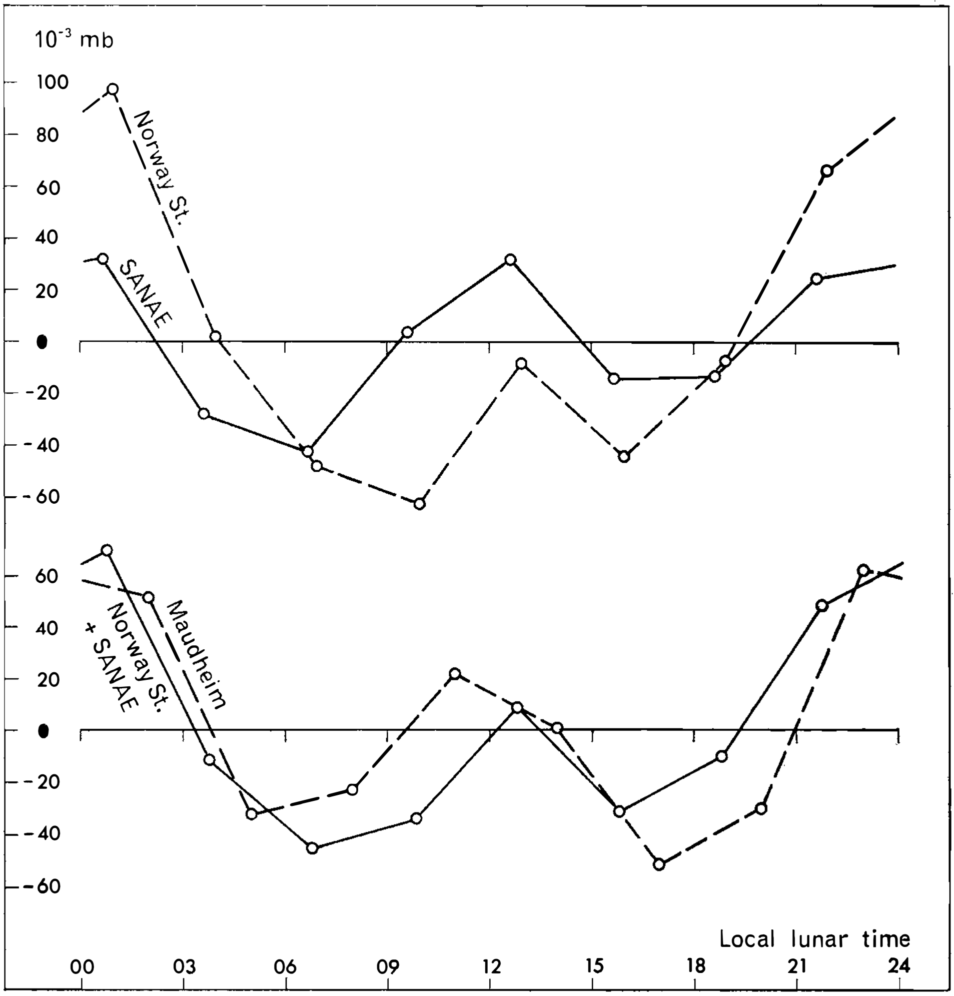

Fig. 6. *Mean pressure variations in the course of a lunar day.*

SANAE period. The reduction of the observation material is thus negligible.

The amplitudes and phases of the three harmonic components are found by the same method as that applied for the Maudheim series, and further details on this point may be found in the work dealing with the pressure observations from this station. The analysis is carried out for Norway Station and SANAE separately.[1]

Fig. 6 (upper part) shows the mean pressure variation during a lunar day. For both periods the three-hourly means have two maxima and two minima in the course of the day, and, except for the first minima, they occur simultaneously, or very nearly so in the two cases.[2] In the lower part of the same diagram is shown

---

[1] The fact that we have used station level pressure for Norway Station, but had to use sea level pressure for SANAE, is of minor importance for our calculations and may safely be neglected. The height of the barometer above sea level was about 55 m.

[2] It appears that here and in Fig. 7 the mean values for the two observation periods do not occur at the same hours. This is due to the method used when synchronizing the pressure observations with respect to the considered component of the tide-generating potential. For the sake of con-

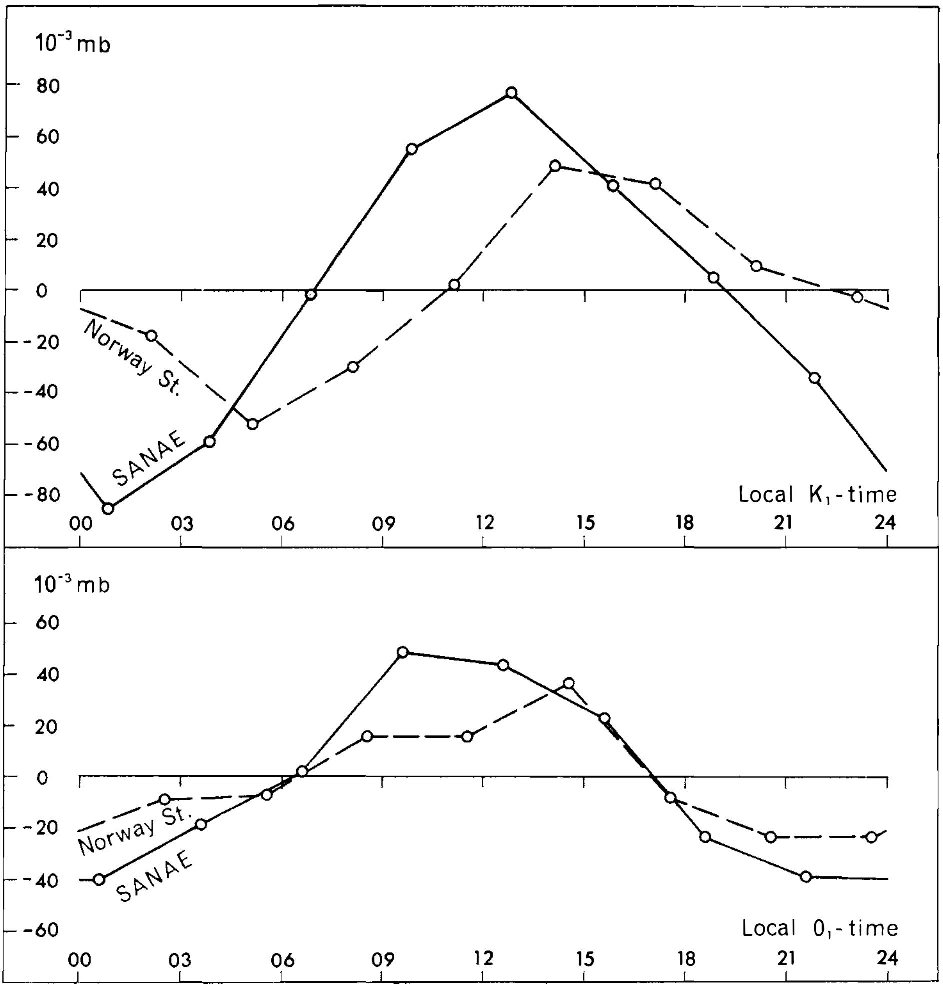

Fig. 7. *Mean pressure variations in the course of a K_1- and a O_1-day.*

the mean variation for the whole observation period both for Norway Station – SANAE and for Maudheim (691 days). We see that the magnitude of the variations as well as the times of occurrence of the maxima and minima agree fairly well in the two cases.

The mean pressure change in the course of a K_1- and a 0_1-day is represented in Fig. 7. In all cases we have a clear tendency to a wave-shaped variation with the same period as the corresponding harmonic constituent. However, as previously demonstrated (HISDAL *et al.* 1956), this fact is of little conclusive value, since it may be due exclusively to the strong persistence tendency of the air pressure. The two 0_1-"waves" have nearly equal phases, whereas the phases of the K_1-"waves" do not agree particularly well.

venience the phase lag of the observation at 00 GMT relative to the time of maximum potential is provisionally put equal to zero for a certain day in each of the two periods and transferred to the correct phase lag at a later stage of the synchronizing procedure. The two days are placed so as to allow for the variation of the nodal correction of the phase.

A function of the form:

$$f(t) = A \cos (\omega t - \varphi)$$

is fitted (in the least square sense) to the data represented in Figs. 6 and 7. The result is given in Table 2.

Table 2. *Harmonic constants of the mean pressure variations for periods equal to those of the tidal constituents M_2, K_1 and O_1.*

Amplitudes (A) in microbars. Phase lags (φ) referred to the time of maximum of the considered tide-generating potential in Greenwich.

	M_2		K_1		O_1	
	A	φ	A	φ	A	φ
Norway St. observations	43	16°	44	252°	26	179°
SANAE observations	39	353°	75	197°	48	174°
Whole observation period	40	7°	51	221°	35	176°

In accordance with the features revealed by the diagrams, the phase lags for the two observation periods are in comparatively good agreement as far as the M_2- and O_1-"waves" are concerned. For K_1 the difference is quite large, corresponding to a time interval of 3.7 K_1-hours. Regarding the amplitudes, they agree well in the case of M_2, but differ considerably in the case of K_1 and O_1.

The results are in accordance with the suggestions made above on the basis of a comparison between the estimated 95 % limits of amplitudes produced by chance and the expected magnitude of the pressure amplitudes due to oceanic tides. The fact that the two phase lags are nearly equal in the case of O_1, should in this connection be considered a mere coincidence. In order to reduce the sampling fluctuations for the two diurnal waves to a magnitude equal to that of the M_2-wave in the present case, the observation period had to be extended to 75 years.

We then turn to the question of interpreting the data given in Table 2:

Firstly, there is a tide in the atmosphere itself, which in all probability has the same constituents as the oceanic tide. The semidiurnal lunar constituent has been computed for a long series of stations in lower latitudes (cf. CHAPMAN 1951, and CHAPMAN and WESTFOLD 1956). The amplitude decreases towards the poles, and it seems unlikely that it will exceed 10 microbars at Norway Station. If referred to the local meridian the phase lag is in all regions investigated so far close to 0°, which for Norway Station means a lag of 5° when the Greenwich meridian is used as a reference. As seen from Table 2, this value is practically the same as that found for φ in the case of the semidiurnal lunar pressure variation (7°). It seems likely, therefore, that with the accuracy reckoned with here, the effect of this constituent of the atmospheric tide may be allowed for by a direct subtraction of amplitudes. Nothing is known about the magnitude of the atmospheric tidal components corresponding to K_1 and O_1. If the equilibrium relations apply, the amplitudes of these latter oscillations should not exceed 4–6 microbars.

Secondly, the tidal movement of the ocean surface forces an alternating rise and fall upon the adjacent isobaric surfaces of the atmosphere. Due to the moderate velocity of the tidal wave, this effect is probably considerably reduced by compensating air streams. The vicinity of the continent too is likely to have a reducing influence, and we have supposed the pressure variation which originates in this way to be so small that it may be neglected.

The third effect to be considered, is the oscillations of the air pressure caused by the changes in time with the tide of the distance between the barometer level and the mean sea level. This is the effect to be compared with the tidal constituents found in the preceding chapter. We have reduced the pressure amplitude corresponding to the M_2 period by 10 microbars and consider this as a lower limit of the part due to the oceanic tides. The K_1 and O_1 amplitudes are not reduced (see above). Furthermore, the amplitudes for all three constituents are corrected for a small nodal variation and then divided by 130 microbars, which, under the conditions considered here, is approximately equivalent to a height difference of 1 m. We obtain: for M_2 30 cm (not reduced) and 23 cm (33 cm), for K_1 44 cm (25 cm) and for O_1 33 cm (31 cm). The values in parentheses are those obtained by the direct measurements of the tide (cf. Table 1).

As to the phase lags of the pressure oscillations, they have obviously to be changed by 180° in order to be comparable to those of the oceanic tides. Putting

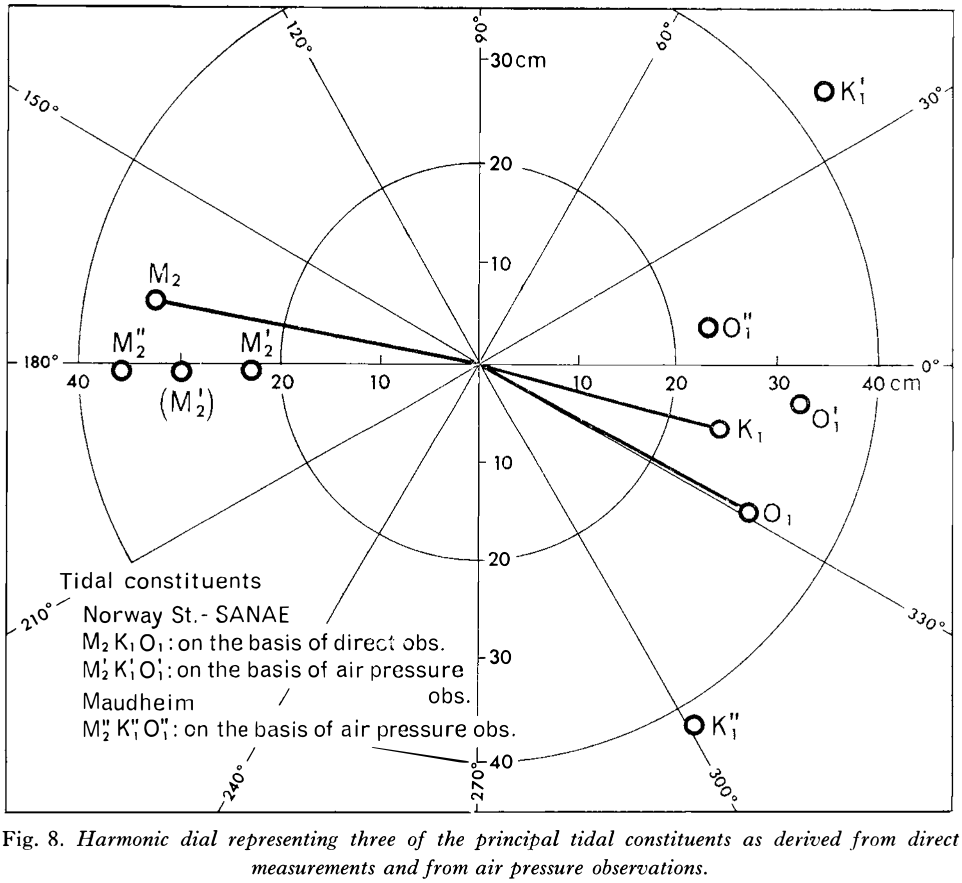

Fig. 8. *Harmonic dial representing three of the principal tidal constituents as derived from direct measurements and from air pressure observations.*

as before the values of Table 1 in parentheses, we have for M_2 187° (174°), for K_1 41° (348°) and for O_1 356° (334°), all phase lags being referred to the Greenwich meridian.

In Fig. 8 the comparison is made graphically. In addition, we have here entered the components found when analysing the pressure data from Maudheim. All distances between the points based on the pressure observations, and the corresponding ones representing the direct tidal observations are smaller than the sampling fluctuations to be expected on the basis of the 95 % significance limits referred to earlier in this chapter, although the distance between M_2 and $M_2^{'}$ is very close to this limit. (The point marked ($M_2^{'}$) is based on the unreduced pressure component.)

If we want to look for indications of systematic features, we may note that all points based on the air pressure observations at Norway Station – SANAE are somewhat retarded with respect to the corresponding points based on direct observations, suggesting a retardation of the tidal movement of the inner part of the ice shelf in relation to the movement at the front. For the semidiurnal lunar constituent this retardation amounts to about 0.4 solar hours. The $M_2^{'}$ amplitude is only 70 % of that of M_2, which, in addition, may indicate a damping influence of the ice shelf on the tides as one approaches the continent. The corresponding amplitude for Maudheim is nearly equal to the M_2 amplitude. This station was situated only 2.5 km from the ice front, while, as previously stated, the corresponding distance in the case of Norway Station was about 30 km. However, these suggestions are only tentative. Several factors of uncertainty are involved: (1) the great sampling fluctuations to be expected, especially for the diurnal waves, (2) the tentative character of the interpretation of the pressure oscillations in terms of corresponding oscillations of the sea level, and, also, (3) we do not know how close the true tides at Maudheim and Norway Station agree.

Comparison with the tides at adjacent stations

In the region considered the word "adjacent" must of course not be taken too literally. There is some information on the tidal movement at Lazarev (69° 55' S, 12° 58' E) given by Dubrovin (1962). About 10 km north of the station an iceberg was grounded at a depth of 140 m. By means of a primitive apparatus the vertical (and horisontal) motion of the sea ice relative to a fixed point on the side of the iceberg was recorded for a few short periods at the end of September 1960. On the basis of these data a tidal curve was later drawn for a period of 29 hours. This curve is shown in Fig. 9 together with the predicted curve for Norway Station for the same period ("Admiralty method of prediction"). For the sake of comparison the first minimum of the two curves is put equal to zero, and the abscissa is given in local mean time. We see that the ranges of the tide as well as the general form of the variations at the two stations agree remarkably well. However, the two maxima are much more close together at Lazarev than at Norway Station. The time difference between the maxima at the former station, about 6.3 hours, seems improbably small. It is tempting to think that since the

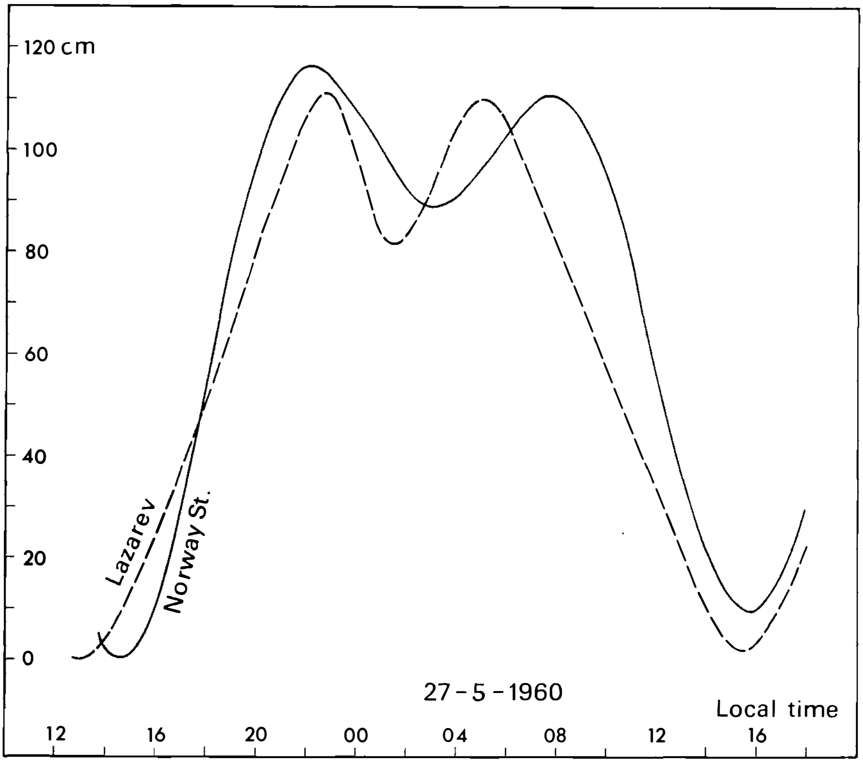

Fig. 9. *Tidal curve for Lazarev (based on a somewhat unreliable registration) and the predicted curve for Norway Station for the same period.*

measuring device at Lazarev contained no time recording mechanism, the times of the extremes were difficult to ascertain, while, on the other hand, the values of the ranges are quite reliable.[1]

In Table 3 are given the constants of the four principal constituents for the nearest stations with tidal data to the east and to the southwest of Norway Station (see map, Fig. 1). In the case of the two Weddell Sea stations, which, like Norway Station, were situated on an ice shelf, the vertical motions of the ice were determined by means of very exact gravity measurements. For Shackleton two different methods of analysis were tried, the "Admiralty method" and a "least square method" corresponding to that applied for Norway Station. The phase lag of M_2 given by the least square method seems very improbable and deviates considerably from that obtained by the former method. In all probability this is due to some error made during the calculation procedure (cf. PRATT 1960). We have therefore kept to the tidal constants found by the Admiralty method (given in Table 6 of PRATT's work).

---

[1] After the present work had been finished, a paper by SHESTERIKOV and DUBROVIN (1963) was brought to the author's notice. Here an attempt is made to compute the harmonic constants for Lazarev, using the curve shown in Fig. 9 and the relationship between the amplitudes and phases of the major constituents at Zaliv Alasheyeva and at Shackleton. However, the values arrived at must be considered most uncertain and they are not entered in our Table 3. The two authors make the same suggestion as that made by us above regarding the reliability of the time of the extremes.

Table 3. *Harmonic constants for some Antarctic stations between 46°E and 42°W.*

Amplitudes (H) in cm. Phase lags (ϰ) referred to the local meridian.

Station	Position	M_2		S_2		K_1		O_1	
		H	ϰ	H	ϰ	H	ϰ	H	ϰ
Zaliv Alasheyeva	67° 40′ S, 45° 47′ E	19.0	160°	18.5	177°	21.8	4°	21.8	350°
Syowa	68° 59′ S, 39° 35′ E	17.9	154°	20.2	171°	20.4	351°	21.5	337°
Norway Station	70° 30′ S, 02° 32′ W	33.2	169	22.5	194	24.9	345°	31.0	331°
Shackleton	77° 59′ S, 37° 10′ W	61.9	205°	44.5	222	20.4	8°	27.7	342
Ellsworth	77° 43′ S, 41° 08′ W	44	208°	23	239			22	345

From the tabulated data we see that the phase lags of M_2 and S_2 increase by about 50° from east to west. At the same time the amplitudes increase, at any rate if the values of Shackleton are considered representative of the conditions at the head of the Weddell Sea. Regarding the diurnal constituents the phase lags have a minimum and the amplitudes a maximum for Norway Station, but the variations are here far less.

The tabulated ratios of the semidiurnal amplitudes as well as those of the diurnal amplitudes are somewhat greater for the easterly than for the westerly stations. For the semidiurnal constituents the ratios are greater than the corresponding equilibrium value, whereas they are smaller than the equilibrium value for the diurnal constituents. The differences between the phase lags ("the ages") keep within comparatively narrow limits, indicating that this tidal parameter may be considered quasi-constant for the whole area considered.

We may observe that the ratio of the sum of the diurnal amplitudes to the sum of the semidiurnal amplitudes (not tabulated) is about ½ for Shackleton, and close to 1 for the stations farther east. This means that for all stations considered the tidal curve is of a mixed but predominantly semidiurnal form.

In the table are furthermore given the cotidal hours of the different constituents. It may be mentioned that for the distance from Zaliv Alasheyeva to Norway Station the time of propagation of the constituents of the equilibrium tide would be 3.2 lunar-, solar-, K_1- or O_1-hours respectively. The differences of the cotidal hours of the observed tides are somewhat greater than this value for the semidiurnal constituents, but definitely smaller for the diurnal constituents. Looking at the cotidal charts published by Dietrich (1944), which obviously had to be highly hypothetical in the area under consideration, we find that for all four constituents the course of the cotidal lines have to be changed considerably in order to be in accordance with the cotidal hours tabulated here.

Conclusion

Although we cannot expect the harmonic constants for Norway Station to be very precisely determined, the good correspondence between observed and pre-

Table 3. *(Cont.)*

				Cotidal hours				Length of obs.period	Data taken from
H_S/H_M	$\varkappa_S$-$\varkappa_M$	H_K/H_O	$\varkappa_K$-$\varkappa_O$	M_2	S_2	K_1	O_1		
0.97	17°	1.00	14°	2.3	2.8	21.2	20.3	15 days	Shamont'yev (1963)
1.13	17°	0.95	14°	2.5	3.1	20.7	19.8	7 days	Oura (1964)
0.68	25°	0.80	14°	5.8	6.7	23.2	22.3	3.2 + 2.2 days	
0.72	17°	0.74	26°	9.3	9.9	3.0	1.3	Two months (gravity rec.)	Pratt (1960)
0.52	31°			9.7	10.7			One month (gravity rec.)	Thiel *et al.* (1960)

dicted tides, and also the results of comparisons with other relevant data, seem to show that they are sufficiently reliable to give useful preliminary information about the character of the tides in this region of Antarctica. This applies especially to the semidiurnal tides.

Acknowledgement

I am greatly indebted to Mr. S. HELLE, leader of the Norwegian Antarctic Expedition, 1956–60, who was in charge of the tidal measurements at Norway Station, and to Mr. N. NERGAARD, member of the same expedition, who undertook a large part of the work in connection with these measurements.

My thanks are also due to Mrs. NATASCHA HEINTZ for translating the Russian papers referred to in the present discussion, and to Mr. B. EVENSEN for preparing the diagrams for publication.

References

Admiralty Tide Tables, Part III, 1941. Hydrographic Department, London.

Chapman, S., 1951: Atmospheric tides and oscillations. *Compendium of meteorology*. 510–530. Boston.

— and K. C. Westfold, 1956: A comparison of the annual mean solar and lunar atmospheric tides in barometric pressure, . . . *Journ. Atmos. Terr. Phys.* **8,** 1–23. London.

Dietrich, G., 1944: Die Schwingungssysteme der halb- und eintägigen Tiden in den Ozeanen. *Veröff. Inst. Meeresk. Univ. Berlin.* A (41). Berlin.

Doodson, A. T. and H. D. Warburg, 1941: *Admiralty manual of tides.* Hydrographic Department. London.

Dubrovin, L. I., 1962: On the ocean level fluctuations in the Lazarev Station area. *Bul. Soviet Ant. Exp.* (37), 25–28. Leningrad. (In Russian.)

Hisdal, V., O. Amble and N. J. Schumacher, 1956. *Norw.-Brit.-Swed. Ant. Exp., 1949–52. Scient. Res.* **1,** (2 A). Oslo.

Oura, H., 1964. Private communication.

Pratt, J. G. D., 1960: Tides at Shackleton, Weddell Sea. *Trans-Ant. Exp., 1955–58. Scient. Rep.* (4). London.

Shamont'yev, V. A., 1963: Tides in Zaliv Alasheyeva. *Bul. Soviet Ant. Exp.* (43), 31–32. Leningrad. (In Russian.)

Shesterikov, N. P. and L. I. Dubrovin, 1963: Tides in the Lazarev Station area. *Bul. Soviet Ant. Exp.* (44), 39–42. Leningrad. (In Russian.)

Thiel, E. *et al.*, 1960: Gravimetric determination of ocean tide, Weddell and Ross Seas, Antarctica. *Journ. Geophys. Res.* **65,** (2), 629–636. Washington.

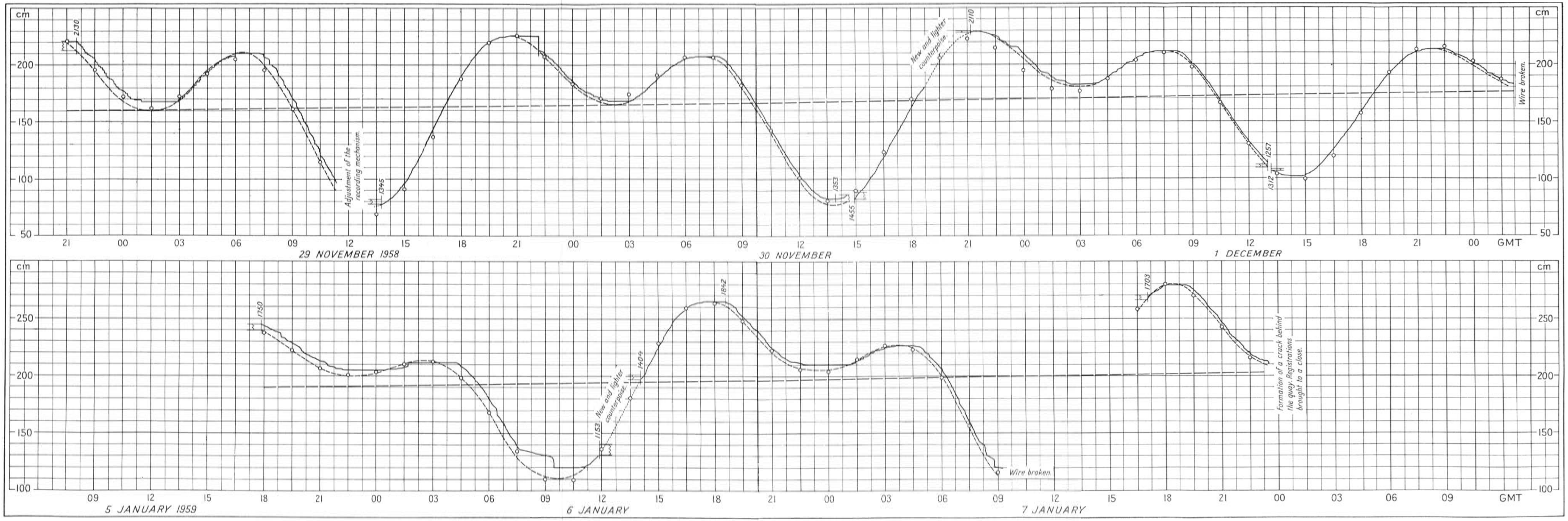

Fig. 10. *Tide gauge diagrams for Norway Station. The rings represent values calculated by means of the harmonic constants.*

SKRIFTER

Skrifter Nr. 1—99, see numbers of Skrifter previous to Nr. 100.

Nr.

100. Padget, Peter: *Notes on some Corals from Late Paleozoic Rocks of Inner Isfjorden, Spitsbergen.* 1954. Kr. 1.00.
101. Mathisen, Trygve: *Svalbard in International Politics 1871—1925.* 1954. Kr. 18.00.
102. Rodahl, Kåre: *Studies on the Blood and Blood Pressure in the Eskimo, and the Significance of Ketosis under Arctic Conditions.* 1954. Kr. 10.00.
103. Løvenskiold, H. L.: *Studies on the Avifauna of Spitsbergen.* 1954. Kr. 16.00.
104. Hornbæk, Helge: *Tidal Observations in the Arctic 1946—52.* 1954. Kr. 2.50.
105. Abs, Otto und Hans Walter Schmidt: *Die arktische Trichinose und ihr Verbreitungsweg.* 1954. Kr. 4.00.
106. Major, Harald and Thore S. Winsnes: *Cambrian and Ordovician Fossils from Sørkapp Land, Spitsbergen.* 1955. Kr. 4.00.
107. Feyling-Hanssen, Rolf W.: *Stratigraphy of the Marine Late-Pleistocene of Billefjorden, Vestspitsbergen.* 1955. Kr. 22.00.
108. Feyling-Hanssen, Rolf W.: *Late-Pleistocene Deposits at Kapp Wijk, Vestspitsbergen.* 1955. Kr. 3.00.
109. Donner, J. J. and R. G. West: *The Quaternary Geology of Brageneset, Nordaustlandet, Spitsbergen.* 1957. Kr. 5.00.
110. Lundquist, Kaare Z.: *Magnetic Observations in Svalbard 1596—1953.* 1957. Kr. 6.00.
111. Sverdrup, H. U.: *The Stress of the Wind on the Ice of the Polar Sea.* 1957. Kr. 2.00.
112. Orvin, Anders K.: *Supplement I to the Place-names of Svalbard. Dealing with new Names 1935—55.* 1958. Kr. 13.00.
113. Soot-Ryen, Tron: *Pelecypods from East-Greenland.* 1958. Kr. 4.00.
114. Hoel, Adolf and Werner Werenskiold: *Glaciers and Snowfields in Norway.* 1962. Kr. 40.00.
115. Groom, G. E. and M. M. Sweeting: *Valleys and Raised Beaches in Bünsow Land, Central Vestspitsbergen.* 1958. Kr. 3.00.
116. Svendsen, Per: *The Algal Vegetation of Spitsbergen.* 1959. Kr. 7.00.
117. Heintz, Natascha: *The Downtonian and Devonian Vertebrates of Spitsbergen. X. Two new Species of the Genus Pteraspis from the Wood Bay Series in Spitsbergen.* 1960. Kr. 3.00.
118. Rodahl, Kåre: *Nutritional Requirements under Arctic Conditions.* 1960. Kr. 8.00.
119. Rapp, Anders: *Talus Slopes and Mountain Walls at Tempelfjorden, Spitsbergen.* 1960. Kr. 25.00.
120. Orvin, Anders K.: *The Place-names of Jan Mayen.* 1960. Kr. 14.00.
121. Carstens, Harald: *Cristobalite Trachytes of Jan Mayen.* 1961. Kr. 3.00.
122. Holland, Michael Frank William: *The Geology of Certain Parts of Eastern Spitsbergen.* 1961. Kr. 12.00.
123. Lunde, Torbjørn: *On the Snow Accumulation in Dronning Maud Land.* 1961. Kr. 9.00.
124. Rønning, Olaf I.: *Some New Contributions to the Flora of Svalbard.* 1961. Kr. 3.00.
125. Manum, Svein: *Studies in the Tertiary Flora of Spitsbergen, with Notes on Tertiary Floras of Ellesmere Island, Greenland, and Iceland. A Palynological Investigation.* 1962. Kr. 26.00.
126. Hoel, Adolf and Johannes Norvik: *Glaciological Bibliography of Norway.* 1962. Kr. 30.00.
127. Gobbett, Derek John: *Carboniferous and Permian Brachiopods of Svalbard.* 1963. Kr. 32.50.
128. Wilson, Ove: *Cooling Effect of an Antarctic Climate on Man.* 1963. Kr. 4.00.
129. Løvenskiold, Herman L.: *Avifauna Svalbardensis.* 1964. Kr. 44.00.
130. Lid, Johannes: *The Flora of Jan Mayen.* 1964. Kr. 14.00.
131. Vinje, Torgny E.: *On the radiation balance and micrometeorological conditions at Norway Station, Antarctica.* 1964. Kr. 10.00.
132. Vigran, Jorunn Os: *Spores from Devonian deposits, Mimerdalen, Spitsbergen.* 1964. Kr. 8.00.
133. Hisdal, Vidar: *On the tides at Norway Station and adjacent coastal areas of Antarctica.* 1965. Kr. 4.00.

CHARTS

				Kr.
501	Bjørnøya	1: 40,000	1932	10.00
502	Bjørnøyfarvatnet	1:350,000	1937	10.00
503	Frå Bellsund til Forlandsrevet med Isfjorden	1:200,000	1932	10.00
504	Frå Sørkapp til Bellsund	1:200,000	1934	10.00
505	Norge–Svalbard, northern sheet	1:750,000	1933	10.00
506	» » southern »	1:750,000	1933	10.00
507	Nordsvalbard	1:600,000	1934	10.00
508	Kongsfjorden og Krossfjorden	1:100,000	1934	10.00
509	Frå Storfjordrenna til Forlandsrevet med Isfjorden	1:350,000	1946	10.00
510	Frå Kapp Linné med Isfjorden til Sorgfjorden	1:350,000	1946	10.00
511	Østgrønland, fra Liverpool Kyst til Store Koldeweys Ø (rev. 1958)	1:600,000	1937	10.00
512	Jan Mayen	1:100,000	1955	10.00
513	Svalbard-Havner	various	1959	10.00
514	Barentshavet	1:2,000,000	1960	10.00
515	Svalbard–Grønland	1:2,000,000	1962	10.00

The charts are distributed by Norges Sjøkartverk, Stavanger.

MAPS

General, geographical, topographical, and technical maps:

DRONNING MAUD LAND

				Kr.	
Giæverryggen	F 5	1:250,000	1962	5.55	
Borgmassivet	F 6	1:250,000	1962	5.55	
Kirwanveggen	F 7	1:250,000	1961	5.55	
Ahlmannryggen	G 5	1:250,000	1961	5.55	
Jutulstraumen	G 6	1:250,000	1961	5.55	
Neumayerskarvet	G 7	1:250,000	1961	5.55	
Jutulgryta	H 5	1:250,000	1961	5.55	
H. U. Sverdrupfjella	H 6	1:250,000	1961	5.55	
Mühlig-Hofmannfjella Sør	J 6	1:250,000	1962	5.55	
Filchnerfjella Sør	K 6	1:250,000	1962	5.55	
Glopeflya	L 6	1:250,000	1964	5,55	
Hoelfjella Sør	M 6	1:250,000	1964	5,55	
Sør-Rondane		1:250,000	1957	5.55	

GRØNLAND, Austgrønland

Eirik Raudes Land frå Sofiasund til Youngsund	1:200,000	1932	2.20	
Claveringøya	1:100,000	1937	30.00	In one volume with index. Limited stock.
Geographical Society-øya	1:100.000	1937		
Jordan Hill	1:100,000	1937		

JAN MAYEN

Jan Mayen		1:100,000	1955	2.20	Preliminary map.
Sør-Jan	Sheet 1	1: 50,000	1959	5.55	Also as supplement to Skrifter Nr. 120.
Nord-Jan	» 2	1: 50,000	1959	5.55	

SVALBARD

Svalbard		1:2,000,000	1958	2.20	Latest edition.
Vestspitsbergen, southern part	Sheet 1	1:500,000	1964	10.00	
Vestspitsbergen, northern part	» 3	1:500,000	1964	10.00	
Kongsfjorden	A 7	1:100,000	1962	5.55	
Prins Karls Forland	A 8	1:100,000	1959	5.55	
Isfjorden	B 9	1:100,000	1955	5.55	
Van Mijenfjorden	B 10	1:100.000	1948	5.55	
Van Keulenfjorden	B 11	1:100,000	1952	5.55	
Torellbreen	B 12	1:100,000	1953	5.55	
Adventdalen	C 9	1:100.000	1950	5.55	
Markhambreen	C 12	1:100,000	1957	5.55	
Sørkapp	C 13	1:100.000	1947	5.55	
Adventfjorden–Braganzavågen		1:100,000	1941	2.20	
Hopen		1:100,000	1949	2.20	Preliminary map.
The Claims to Land in Svalbard		1: 50,000	1927	2.20	each Nos. 1-33.
Bjørnøya		1: 25,000	1925	5.55	New ed 1944 and 1955. Also as supplement to Skrifter Nr. 86
Bjørnøya		1: 10,000	1925	....	6 sheets. Out of print.

The maps are distributed by Norges geografiske oppmåling, St. Olavs gt. 32, Oslo

---

A.W. BRØGGERS BOKTRYKKERI A/S - OSLO

Norsk Polarinstitutt Skrifter Nr. 133. Vidar Hisdal: On the Tides at Norway Station and Adjacent Coastal Areas of Antarctica.