ANALYSES OF BRITISH ANTARCTIC SURVEY TIDAL RECORDS

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ABSTRACT. The results of tidal analysis of 9 years of sea-level records from the Argentine Islands and short records of ice movement from lake sites in George VI Sound are presented. Diurnal tides are normal throughout but the semi-diurnals show a sharply tuned anti-resonance, most noticeably affecting M_2. The Argentine Islands have the unusual property that their tides can nearly vanish near 2 May and 2 November. Tidal amplitude of sea-level there is significantly lower than that of ice movement recorded in 1935. Tidal ice movement in George VI Sound appears to be very variable in amplitude and phase. The most reliable and consistent ice record was from Ablation Lake, whose results are similar to those from older ice records at Barry Island in Marguerite Bay. Comparison of Ablation Lake with another site 60 km to the south-east shows that tidal phases increase southward in George VI Sound.

THE British Antarctic Survey have recorded tidal motions at a number of their stations, and the writer has been intermittently concerned for several years with their analysis, originally at the IOS laboratory at Wormley (then known as NIO), more recently at Bidston. The work has mostly been done at the request of the Survey for purposes of tidal prediction, but it also has intrinsic interest in determining the character of the tides in part of the Southern Ocean where they are poorly known, and in extracting tidal information from short, rather noisy records made in a difficult environment. Results have been briefly described in occasional typewritten reports but Dr C. Swithinbank recently suggested that a published general survey would be timely and useful.

The records fall into two categories:

i. A long continuous series of sea-levels of several years' duration from the BAS Faraday station at the Argentine Islands (lat. 65°15′S, long. 64°16′W).
ii. Some short series of 15–54 days' duration of vertical ice movement at "lake" sites in George VI Sound near lat. 71°S, long. 68°W.

Their characteristics and methods of analysis are rather different and will be described separately. On the fair assumption that very few readers will be interested in the technicalities of tidal analysis, I shall keep to fairly general terms in describing the results. Fig. 1 shows the general location of the measurements discussed.

TIDES AT THE ARGENTINE ISLANDS (lat. 65°15′S, long. 64°16′W)

The first tidal recordings at the Argentine Islands were made by the British Graham Land Expedition of 1934–37, who also recorded tides at Barry Island in Marguerite Bay (Roberts and Corkan, 1941). The former were made from a ship frozen in Stella Creek (lat. 65°15′S, long. 64°16′W) and lasted about 7 months in 1935.

The BAS tidal recordings at the Argentine Islands were made at the request of, and with a gauge supplied by the (then) National Institute of Oceanography. The gauge was land-mounted at the Survey's station, very close to Stella Creek (Fig. 2), and recorded actual sea-level variations, whereas the earlier records were of vertical ice movement. Regular recording started in December 1957 but was at first restricted to about 4 months in each of the summers of 1957–58 and 1958–59, on account of freezing. The freezing problems were overcome later in 1959 by the use of a heating coil and recording has since been practically continuous from 15 October 1959 to the present. All records up to 28 February 1971 have been digitized at hourly intervals, carefully checked for transcription errors and stored on

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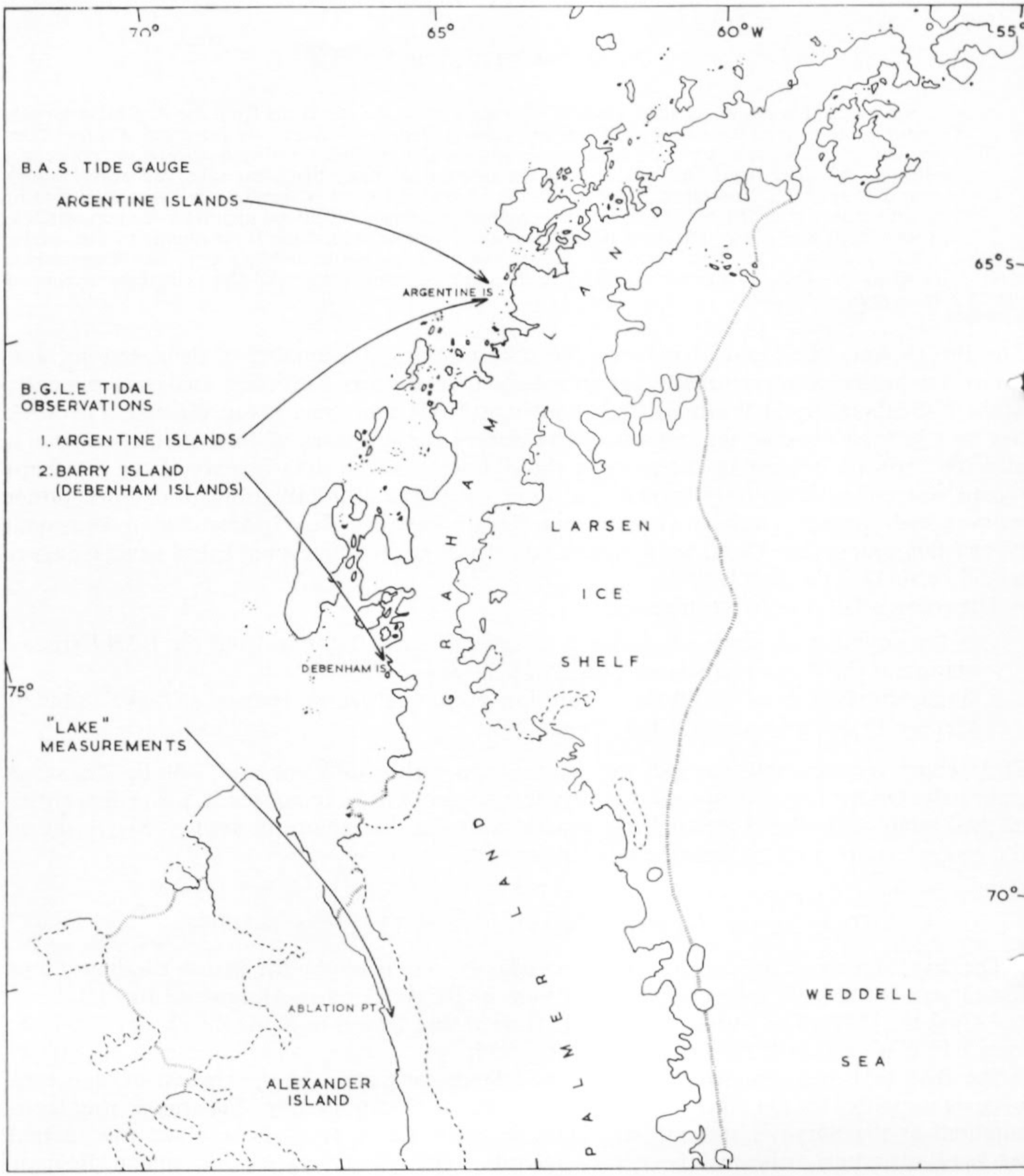

Fig. 1. Location of tidal observations.

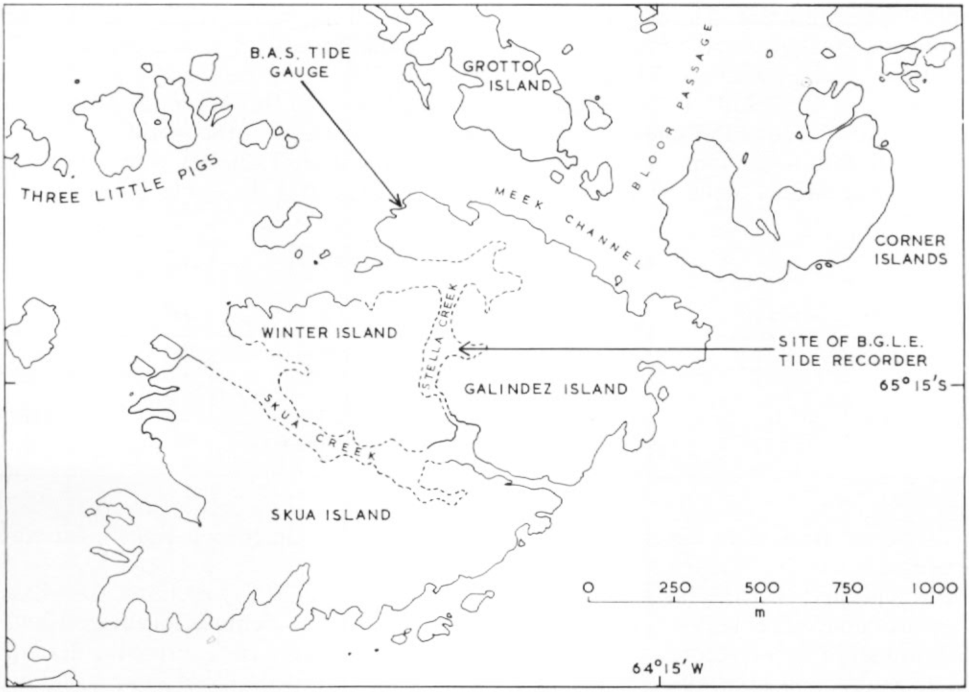

Fig. 2. Site of British Graham Land Expedition measurements of 1935 and British Antarctic Survey measurements of 1957–77.

punched cards at IOS. Occasional lacunae of a few hours' to a few days' duration have been filled by special interpolations.

Long data series of this sort are extremely valuable to tidal scientists. It is sometimes stated that 1 month's data are sufficient to determine the tidal characteristics at an oceanic site, but this is true only when some of the finer details can be inferred from analysis of longer records from the same sea area. For example, the spectrum of the solar tides contains complicated structure in a band width of about 3 cycles year^{-1}, relevant to the distinction between the tidal effects of gravity and solar radiation. This structure cannot be resolved *a priori* from a month's record, and at least a year's data from some other station in the vicinity are necessary. While a year is sometimes considered to be practically the ultimate requirement for good tidal analysis, there exists even finer spectral structure and problems of signal : noise ratio which strictly require several years for reliable resolution. 9 years, representing just over a complete revolution of the longitude of the Moon's perigee, has distinct advantages, and it seems hardly necessary to add that the Argentine Islands site is the only one with a record of this duration in the whole Southern Ocean. An 18 year record would be even more advantageous, and for studies of mean sea-level the value of a tidal series increases indefinitely with its duration, but the present series provides a very satisfactory tidal analysis for use as a reference for shorter records, past and future, in this sea area.

My analysis was confined to the period October 1959–December 1968. I will not bother the reader with the analytical techniques used; they are closely related to those described in, for example, Munk and Cartwright (1966) and Cartwright and Tayler (1971). For practical purposes, most people find the classical harmonic constants most useful, and these are listed in Table III. Here, amplitudes H are given in mm and phases G in deg relative to Greenwich Epoch. Only the diurnal and semi-diurnal species are shown, since nearly all others were found to be insignificant. The only exceptions were in the long-period tides, where the annual component (*Sa*) showed up barely above the background noise with an amplitude of 37 mm and positive maximum about 30 April, and the fortnightly component (*Mf*) with amplitude 24 ± 10 mm and G = 230°. In general, the background noise in the Argentine Islands record was similar to that found at many oceanic coastal sites elsewhere in the world.

It is interesting to compare the leading tidal constants from Table III with those derived from the ice record at Stella Creek (Roberts and Corkan, 1941). In Table I, the latter have

TABLE I. COMPARISON OF MAJOR CONSTANTS

Harmonic constituent		O_1	K_1	M_2	S_2
Stella Creek ice	H	332	375	247	207
	G	69	87	293	31
BAS sea-level	H	289	315	199	180
	G	69.8	81.8	287.3	30.6

been converted from ft to mm and from 60° Mean Time to Greenwich Epoch, for ease of comparison.

Bearing in mind that the early results are based on only two 29 day sections, the phases G are in reasonable agreement, as one should expect for essentially identical localities. However, the amplitudes of the ice records are all consistently higher by about 20%. From the description of the ingenious but homemade recording apparatus used at Stella Creek, one could accept a calibration error of say 5% while the sea-level recorder, a carefully engineered product of Munro Ltd, should be accurate to better than 1% in scale. Corkan's individual 29 day analyses vary from the quoted mean by ±4% in the amplitude of K_1, much less for the other major constituents. The 9 year analysis confirms that there is no significant change in tidal characteristics at the site from one year to another. The differences in amplitude must therefore be accepted as genuine. They imply that in the given situation the vertical tidal movement of a ship frozen in the ice is about 20% greater than that of the local sea-level. In the absence of further information, the author is disinclined to speculate as to the possible cause.

The relatively strong diurnal components of the tide at the Argentine Islands are fairly typical of the Pacific Ocean. More unusual is the near equality of the amplitudes of the principal lunar (M_2) and solar (S_2) semi-diurnal components. In the tide-generating forces, M_2 everywhere dominates S_2 by a factor of about 2.15, and a similar factor applies to the ocean tides in most areas. The near equality here implies a strong suppression of the lunar relative to the solar semi-diurnal tide. In the diurnal tide, the amplitude of K_1 is slightly suppressed relative to that of O_1—their ratio in the tidal forces is 1.41—so that they are also nearly equal in amplitude which is less unusual. These relationships will be examined more closely below in relation to Fig. 4. First let us consider the unusual properties of a tidal regime in which both the diurnal and the semi-diurnal components are dominated by two harmonics of nearly equal amplitude.

Beating between the two major components in each species of tide causes the observed amplitude to vary in a roughly fortnightly cycle between the sum and the difference of the component amplitudes. Since they are here nearly equal, the observed amplitudes will therefore reduce nearly to zero in this cycle. The diurnal phase lags G are not very different, so the diurnal amplitude becomes nearly zero whenever the Moon crosses the Equator. The semi-diurnal phase lags differ by about 103°, so the semi-diurnal amplitude becomes nearly zero about 4 days after the first and last Quarters of the Moon's phase. The cycles of the Moon's phase and of its equatorial crossings are not quite synchronous, so the two events will only occasionally coincide, in fact twice each year. A simple calculation shows that the tidal pattern at the Argentine Islands will fluctuate bi-annually between the two following conditions:

i. Around 1 February and 2 August, the diurnal and semi-diurnal amplitude minima will alternate; at the nearest lunar equatorial crossing (zero declination) the tides will appear to be purely semi-diurnal, while 7 days before and after they will appear to be purely diurnal.

ii. Around 2 May and 2 November, the two amplitude minima will coincide; at the nearest lunar equatorial crossing, sea-level will be almost constant for about 2 days, while 7 days before and after the tide will have a complex wave form.

The two conditions are clearly illustrated in Fig. 3, where actual data from the Argentine Islands record are plotted for two 15 day periods corresponding to i (upper panel) and ii (lower), respectively. The times of lunar equatorial crossing are denoted by the letter E; other letters denote Full Moon, New Moon, First Quarter, Last Quarter, Perigee and Apogee.

Another remarkable though perhaps less interesting feature is that, since the N_2 component is suppressed somewhat more than M_2, the cycle from Perigee (Moon closest to Earth) to Apogee (Moon furthest from Earth) has very little influence on the semi-diurnal tides. On the other hand, since the component Q_1 is enhanced more than O_1 or K_1, the Perigee–Apogee cycle has more than usual influence on the diurnal tides. The diurnal effect is clearly seen in the upper panel of Fig. 3, accounting for the noticeably greater amplitude to the left of the panel than to the right.

We may obtain further insight into the properties discussed in the last few paragraphs in terms of harmonic constituents, by considering the admittance functions of the tides at the Argentine Islands, that is, the relations between the observed tide and the ideal "equilibrium" tide as a function of frequency. These functions are illustrated by the unbroken lines in Fig. 4. In each tidal species, which are separated for fundamental reasons, the upper curve plots the natural logarithm of R, the magnification of the observed tide relative to the (normalized) equilibrium tide, while the lower curve plots its phase lead ϕ in radians. (In the notation of Munk and Cartwright (1966), the two curves constitute the function ln (Z) where Z is the complex admittance.) The frequencies at which the main harmonic constituents occur are shown near the bottom, although they were not used in calculating the admittance curves.

The diurnal admittance shows very little variation beyond a steady decrease in magnification and phase lead over the frequency band. This accounts for the slight reduction in K_1 and enhancement of Q_1 relative to O_1 mentioned above, but otherwise the transformation from an equilibrium tidal form is fairly simple.

The semi-diurnal admittance curves are, however, far from simple. There is a pronounced dip in the magnification at 1.91 cycles d^{-1}, fairly near the frequency of N_2, accompanied by a rapid change in phase. This accounts for the reduced amplitude of M_2 and the considerable "age" of 4 days, already noted, although the effects would evidently be still more exaggerated if the dip in R had happened to occur at a slightly higher frequency.

A similar dip in amplitude (actually reaching R = O), accompanied by a steep phase change, was noted by Cartwright (1971) in the diurnal tides at Simons Bay, South Africa. It seems to be a typical characteristic of an amphidromic region of the ocean, somewhere in which the amplitude of each constituent of a given species will fall to zero. Alternatively, it could indicate a region of selective absorption or dissipation of tidal energy. Tidal dissipation is a subject of wide implications. McMurtree and Webb (1975) and Webb (1976) tended to favour selective absorption in interpreting such systems, whether the peak in admittance be a minimum, or a maximum, indicating a resonance. On the extreme right of Fig. 4 the semi-diurnal admittance is re-plotted in a form advocated by McMurtree and Webb (1975), as an Argand diagram of $Z = X+iY$ with the frequency variation indicated along the locus.

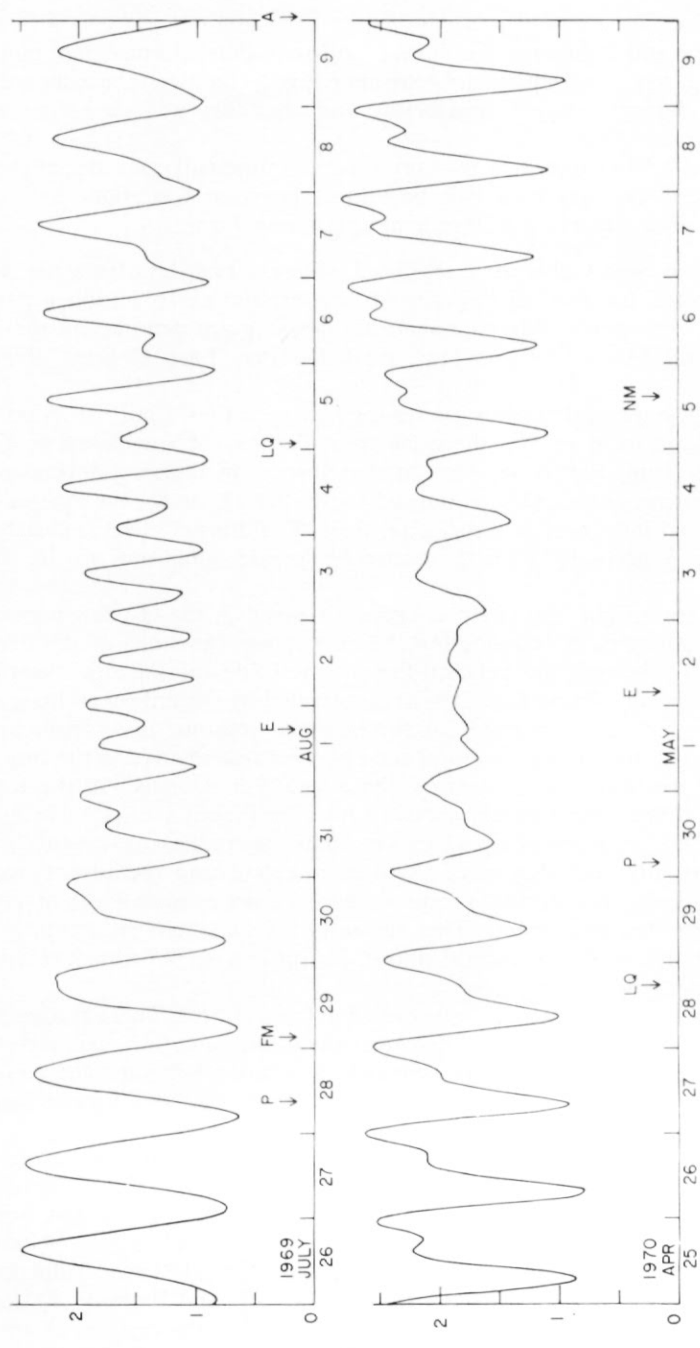

Fig. 3. Two typical tidal patterns at the Argentine Islands.
Upper: alternating diurnal and semi-diurnal waves.
Lower: diurnal and semi-diurnal zeros coincident.
Vertical scale in metres.
E Moon over Equator; FM Full Moon; NM New Moon; LQ Last Quarter; P Perigee; A Apogee.

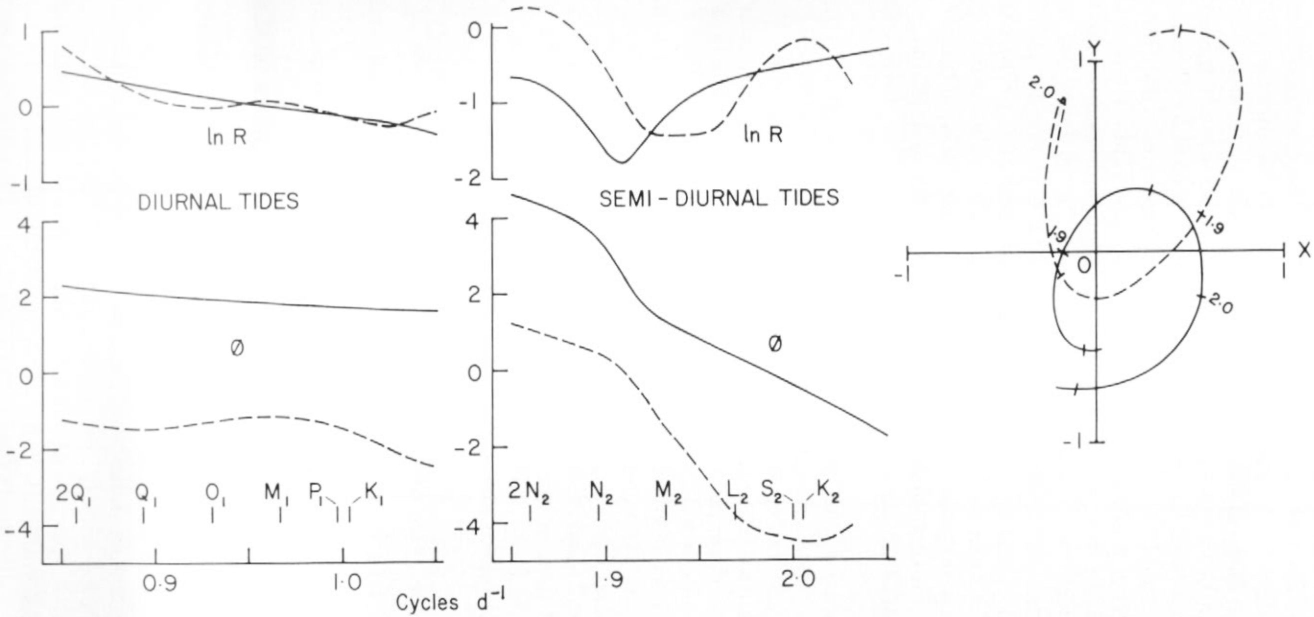

Fig. 4. Left: log-amplitude and phase lead of admittance $R \exp(i\phi)$ to gravitational potential for the Argentine Islands (full curves) and Ablation Lake (broken curves). Right: Argand diagrams of same admittances for semi-diurnal tides only; numbers along curves mark frequency in cycles d^{-1}. (Ablation Lake phases retarded by π in every case.)

The characteristic feature is then a loop surrounding the origin. Other examples of such loops from the Australian coast have been shown by McMurtree and Webb (1975). Their examples progress anti-clockwise with increasing frequency because they represent Z^* rather than Z. They also tend to show a maximum instead of our minimum amplitude.

It would be beyond the scope of this paper to pursue possible mechanisms for tidal dissipation in this region. Little is known about the behaviour of tides near the ice edge, and the possibility of some effect associated with the nearness of the "critical latitudes" where the tidal and inertial frequencies are equal (71° for N_2, 74½° for M_2) requires a profound investigation. On the other hand, the dip in admittance may be merely an amphidromy such as may occur in any frictionless ocean. In their rough sketch of the M_2 cotidal map of the region of Drake Passage, Roberts and Corkan (1941) suggested there is "a tendency for an amphidromic point to be formed in the centre of the strait", but their evidence for this is rather vague. Against this, one would expect an amphidromic area to produce a phase change at any one position of the order of π radians, not a complete cycle of 2π as shown in Fig. 4. Garrett and Munk (1971) showed how resonating (or anti-resonating) oceanic systems can produce phase changes of 2π or more. Further, none of the various computed cotidal maps for the M_2 tide in the world oceans shows an amphidrome west of the Antarctic Peninsula (Hendersho[t], 1977).

Finally, some comment is due on the non-gravitational tidal effects caused directly or indirectly by solar radiation, which were extracted from our 9 year analysis from the Argentine Islands. They are generally rather small. The small seasonal variation of 37 mm amplitude has already been mentioned. The main diurnal radiational tide, mainly concentrated in the harmonic S_1 of exactly 1 cycle per solar day, is quite insignificant at a level of uncertainty of about 3 mm. The semi-diurnal radiational effect on S_2 has an amplitude of 23 mm with maximum at 3 h 36 min o'clock (G = 108°). This again is smaller than usual, although its ratio to the purely gravitational S_2 tidal amplitude (176 mm) is about the same as that deduced for Honolulu by Munk and Cartwright (1966). The extreme smallness of S_1 may be accounted for by the generally small amount of direct solar radiation received at high latitudes. The semi-diurnal radiational tide, on the other hand, is generally thought to be a global oceanic response to the atmospheric S_2 tide, and would therefore tend to keep a roughly constant ratio to the gravitational tide at any locality.

Tidal Records from Moutonnée Lake (lat. 70°52′S, long. 68°23′W)

The records of ice movement at various "lakes" off George VI Sound were very different in character from those of sea-level farther north, discussed above. They were generally only a few weeks long, were subject to recording faults, and their tides were more variable and difficult to define with precision. Details of the recording method used have been described b[y] Bishop and Walton (1977). Briefly, it consisted of a tide gauge mounted on the ice, measuring the length of a vertical wire passed through a hole in the ice and attached to a weight on the sea bed. George VI Sound is permanently covered by ice for a distance of about 450 km, but being typically 25 km wide, more than 500 m deep and open to the ocean at both ends, it should partake of the oceanic tidal movement fairly freely.

The record from Moutonnée Lake was the first received by the author for analysis and was most subject to faults, mostly due to freezing, reflecting the difficulties involved in recording at such a site. It spanned about a month, 3 May–3 June 1972, but only the first 15 days were reasonably continuous with a consistent series of tidal variations. From 19 May the trace was frequently halted by freezing and when this was not the case the tidal variations proved to be progressively inconsistent with the initial part of the record. Analysis was therefore confined to the 15 day period 4–18 May, which itself required occasional "patching" interpolations over short spans of a few hours' freezing.

As suggested in the last section, 15 days' data can only be analysed adequately by assuming some relationship to the tides at another site in the local ocean where they are known accurately from a long analysis. The Argentine Islands are the obvious choice here, although $5\frac{1}{2}°$ of latitude to the north. A "prediction" was computed for the Argentine Islands tide for the same 15 days, and the lake data correlated with it as outlined in Cartwright and others (1969). The results appeared reasonable and their leading harmonic constants are included in Table III.

The relationship was fairly simple for the diurnal tides, with amplitudes multiplied by a factor of 0·5–0·6 and very little change in phase. It was less simple for the semi-diurnal tides, with a variable amplitude response which suppressed the lunar tides even more than at the Argentine Islands, so that for the lake M_2 had an amplitude even smaller than S_2, while N_2 and lower frequency tidal components were apparently completely negligible. These relationships will be discussed more meaningfully in connection with the longer and more reliable data from Ablation Lake. The other remaining factor which should be mentioned here is that the standard errors estimated from the noise level of the Moutonnée Lake data are (0.14×amplitude, 8°) for semi-diurnal constituents. This noise level is much higher than is encountered in normal tide-gauge records.

To investigate the consistency of the remaining data, a tidal synthesis was computed from the 15 day analysis for the whole period for which data were supplied. In Fig. 5a, successive

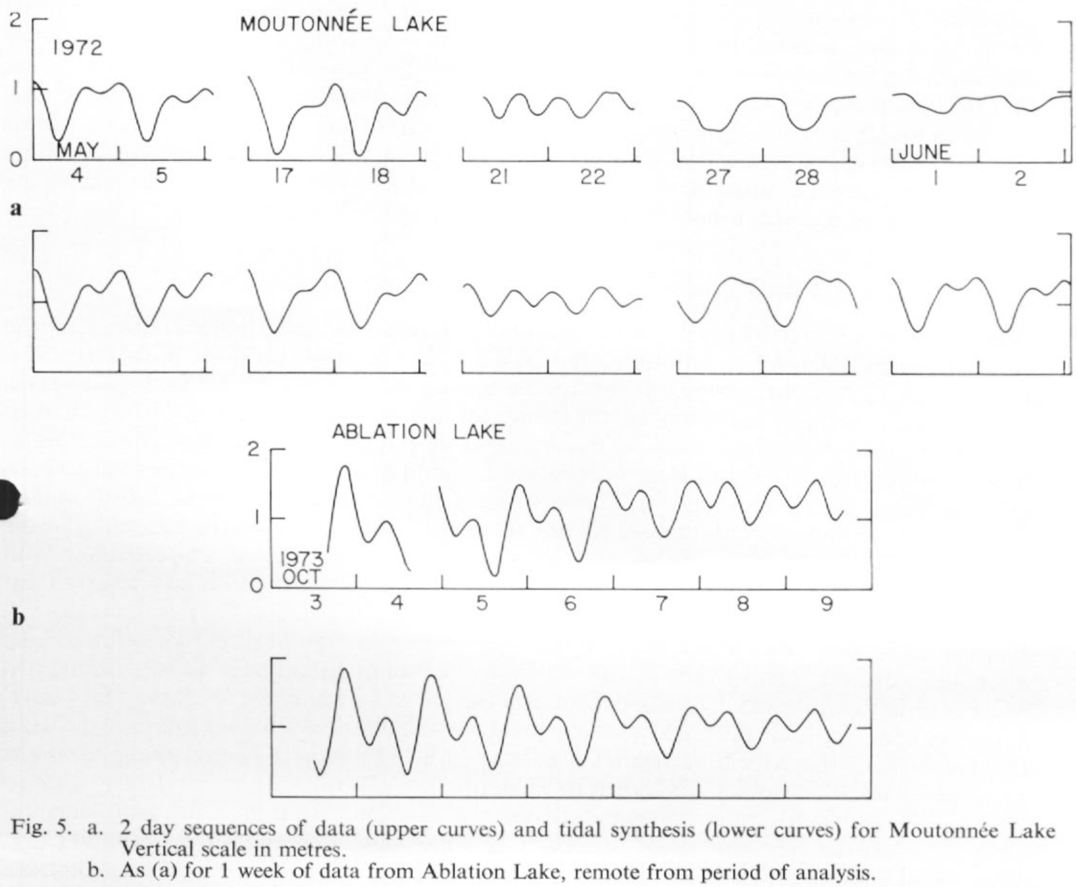

Fig. 5. a. 2 day sequences of data (upper curves) and tidal synthesis (lower curves) for Moutonnée Lake Vertical scale in metres.
b. As (a) for 1 week of data from Ablation Lake, remote from period of analysis.

2 day portions of the Moutonnée Lake data (upper curves) are compared with the tidal synthesis (lower curves). The first two portions cover, respectively, the first and last 2 days of the 15 days analysed, so the comparison is reasonably good, as one should expect. (A small difference in mean level is immaterial.) The third 2 day portion follows after 3 days of freezing. Again the comparison in amplitude is plausible, although close inspection shows that the turning points of the data occur an hour or so later than the synthesis. Another period of freezing preceded the fourth portion, and here we see marked differences between data and synthesis. The turning points in the data are about 5 h late and the amplitude is noticeably reduced. The data continued from here to the end without serious interruption but, by the last portion shown in Fig. 5a, it is evidently reduced to about a quarter of the amplitude of the synthesis with several hours' delay.

In case it should be suspected that the tidal synthesis is seriously at fault 15 days after the analysis period, it should be observed that the last day shown, 2 June, is just 29 days after the first, 4 May. In every normal tidal regime the wave form will roughly speaking repeat itself after 29 or 30 days with relatively slight variation. This is evidently the case with the synthesis, but the data bear no resemblance to their initial form. Physically, the motion appears to have been subjected to a damping mechanism with steadily increasing reaction. Without having studied the site in any detail, I cannot make any reliable suggestion as to the cause of this phenomenon, but one might suspect a gradual blockage of some subglacial water channel by which the lake is effectively connected to George VI Sound.

As a further test of the analysis, some data for high and low culminations from the same and neighbouring sites in 1973 were supplied. These were compared with tidal syntheses based on the same constants as above. The results, briefly, were that where amplitudes were given (for Moutonnée Lake only) they were in fair agreement with the synthesis, but the recorded times of culmination were all roughly an hour later than the synthesis. This confirms that the 15 day period of analysed data was fairly typical in amplitude but the time lag which is the most persistent feature in Fig. 5a is liable to apply at other times. On the whole, the tidal behaviour of the Moutonnée Lake ice is evidently rather variable.

Tidal Record from Ablation Lake (lat. 70°04′S, long. 68°25′W)

Ablation Lake, about 10 km north of Moutonnée Lake, provided a much more successful series of records, effectively continuous for 54 days, 21 December 1973–12 February 1974. Owing to the way the tide gauge was set up, the records were inverted, that is they increased for downward movement of the ice, but allowance for this is a trivial matter. Arbitrary changes in datum every week, sometimes by as much as 0.5 m, required more serious consideration. We adjusted the series to a quasi-uniform datum by adding or subtracting a constant to each weekly block of hourly readings, estimated to keep the mean level close to 1.0 m and to eliminate any obvious discontinuities between the end of one block and the beginning of the next. Only a few hours of recording were lost through freezing and we replaced these with interpolations. An additional week of data supplied from October 1973 was reserved for testing tidal syntheses derived by analysis of the main series.

54 days' data allow one considerably more scope in analysis than 15 days but, before taking the whole record on trust in view of the variability shown at Moutonnée Lake, I thought it advisable to test consistency by independent analyses of its first and last 29 days. The 4 days' overlap between the two portions is of no great consequence. As with Moutonée Lake, a tidal synthesis for the Argentine Islands was used as a "reference". The resulting constants for the major tidal harmonics are shown in Table II.

The amplitudes (mm) are as consistent as one should expect from uniform data, with less than $\pm 2\%$ variation. The equivalent variability of phase should be about 0.02 rad, or 1 deg, but the actual phases vary by about ± 3 deg for the largest amplitudes. This is still an acceptable

TABLE II. CONSTANTS FROM TWO 29 DAY PORTIONS FROM ABLATION LAKE AND FROM BARRY ISLAND

Harmonic constituent		O_1	K_1	M_2	S_2
21 December–18 January	H	257	312	169	238
	G	71	87	280	75
15 January–12 February	H	253	311	174	230
	G	78	91	271	79
Barry Island	H	247	329	156	192
	G	73	93	266	62

noise level, but suggests, as at Moutonnée Lake, that phases are liable to be more erratic than amplitudes. At any rate, there is no suggestion of a consistent phase or time shift between the two periods of data.

Table II also shows the constants for Barry Island (Debenham Islands) (lat. 68°08′S, long. 67°05′W) taken with change of unit and time zone from Table III of Roberts and Corkan (1941). Being in Marguerite Bay off the northern entrance of George VI Sound, one would expect a close relationship between the tides at Barry Island and in George VI Sound and, allowing for the sampling errors in both sets of data (Roberts and Corkan also showed results from two 29 day analyses), this appears to be so. Diurnal constants are roughly the same; semi-diurnals show about 15% increase in amplitude and about 10 deg increase in phase lag in George VI Sound. This contrasts with the consistent differences in amplitudes noted for the two records from the Argentine Islands site but in the present case both records are of ice movement.

On the other hand, Table III shows that the Ablation Lake amplitudes are very much

TABLE III. HARMONIC CONSTANTS (mm, deg)

Constituent symbol	*Argentine Islands* H	*Argentine Islands* G	*Moutonnée Lake* H	*Moutonnée Lake* G	*Ablation Lake* H	*Ablation Lake* G	*Hobbs Pool* H	*Hobbs Pool* G
σ_1	12	52.1	–	–	–	–	–	–
$2Q_1$	10	53.0	–	–	–	–	–	–
Q_1	65	61.1	31	59	58	82	60	91
O_1	289	69.8	148	68	258	73	267	81
M_1*	20	76.5	11	76	21	67	22	76
P_1	104	80.6	58	82	105	82	109	91
K_1	315	81.8	178	84	303	88	314	96
J_1	15	87.3	9	93	18	135	19	144
$2N_2$	8	106.9	3	–	21	120	22	126
μ_2	9	126.1	3	–	24	125	25	131
N_2	26	163.7	3	–	82	154	86	160
M_2	199	287.3	70	262	152	269	159	275
L_2	9	338.0	6	337	7	40	7	46
T_2	13	24.5	10	39	17	72	18	78
S_2	180	30.6	152	45	239	77	249	83
K_2	50	33.9	44	41	67	78	70	84
M_3	–	–	(15)	–	11	353	(24	355)
SK_3	–	–	(10)	–	13	211	28	213

* The constants for M_1 refer to the second-degree potential, not the true sub-harmonic lunar tide described in Cartwright (1975).

greater than those of Moutonnée Lake, only a few kilometres away. This confirms the general peculiarity of the records from the latter site and suggests considerable lateral variation in the tidal movements of sea-ice sheets.

The harmonic constants for Ablation Lake listed in Table III are derived not from those of Table II but from a separate analysis of the 54 day records as a whole. The period is long enough to forego using the Argentine Islands as a reference, so the record was referred directly to the gravitational and radiational potentials, as for the Argentine Islands record itself. The "response" or "admittance" functions are plotted as broken lines in Fig. 4. The phase curves (lower) refer to the raw inverted data. They could be easily transposed by adding π but the artificial separation aids clarity. The Argand diagram (right) is strictly plotted for $(-X, -Y)$ instead of (X, Y) for similar reasons.

Some waviness in the admittances for Ablation Lake, especially near the extremes of the tidal frequency bands, is due to the relative shortness of the record. Apart from this, the diurnal curves for Ablation Lake and the Argentine Islands are fairly similar, confirming the uniform behaviour of the diurnal tides throughout the region. In the semi-diurnal admittance, we see that the dip in R and rapid phase change are shifted to a slightly higher frequency and somewhat broadened. It is this shift in frequency which accounts for the further reduction in the amplitude of M_2. Otherwise, the depth of the trough and the amplitude response as a whole is somewhat raised, yielding larger amplitudes for S_2 and the lower-frequency lunar tides. It would be idle to speculate further here on the possible mechanics of the system, but clearly the semi-diurnal tides of this area of the Southern Ocean are very interesting and would repay a wider experimental and theoretical study.

Two ter-diurnal constituents are shown in Table III for Ablation Lake. These were unexpected but they showed up significantly in spectral analyses of both Ablation and Moutonnée Lakes, although the latter record was too short for adequate resolution. Ter-diurnal tides were practically absent from the more oceanic Argentine Islands record. The M_3 term is probably a normal oceanic tide from the third-degree harmonic of the gravitational potential but SK_3 can only arise from a non-linear interaction between the diurnal and semi-diurnal tides. It is certainly not the result of friction which causes triple interactions (e.g. S_6, quite negligible), and it is not likely to be caused by tidal propagation through the shallow water of George VI Sound, since the sound is relatively deep and the tidal amplitude small. It could be caused by an asymmetric response of the ice surface to rising and falling water pressures, or by the drag of tidal currents in the sea on the vertical recorder wire under the ice. (If the latter, then of course it has no geophysical interest.) Response analysis gives the average "interaction coefficient" as $(173 \times 10^{-6}\ \text{mm}^{-1}, 313^\circ)$.

Fig. 5b gives a general impression of the accuracy of a tidal synthesis for Ablation Lake based on the 54 day analysis, computed for the short period of data in October 1973. The steady rise in mean level of the recorded data (upper curve) cannot of course be accommodated in the synthesis (lower curve) but the times of culmination agree reasonably well.

Tidal Records from Hobbs Pool (lat. 71°18′S, long. 67°35′W)

This site is on the eastern side of George VI Sound, about 60 km south-east of Ablation Lake. The record was said to be of better quality than the previous ones described but was only a few hours longer than the 15 day period 12–26 August 1975.

Having now a respectable set of tidal constants for Ablation Lake, a synthesis for Ablation Lake was computed for the same 15 day period, and the new series correlated with it, as in the case of Moutonnée Lake. The correlation proved to be very close, with a few per cent increase in amplitude and a few degrees increase in phase lag relative to Ablation Lake for the principal tidal species. Allowance for variation of the relative admittance within the species bands gave insignificant change. The best constants were:

(1.038 × amplitude, 8.6° + phase lag) for diurnal tides.
(1.043 × amplitude, 6.0° + phase lag) for semi-diurnal tides.

The amplitude factors, which are practically the same in both species, may well reflect small differences in the tidal yielding of the ice cover at the two sites. The phase lags indicate a predominantly southward propagation of the tidal waves of both species along George VI Sound. Simple long-wave propagation along 50 km of the sound in a mean depth of 500 m would give a time lag of 0.20 h, corresponding to 3° phase lag for diurnal frequencies, 6° for semi-diurnals. Our diurnal phase lag is thus rather higher than one might expect but differences could easily be accounted for in terms of a combination of the south-bound wave with a north-bound wave from the southern entrance to George VI Sound.

A ter-diurnal component at Ablation Lake has already been noted. At the Hobbs Pool site, the ter-diurnal component appeared even stronger (amplitude factor 2.159) with 1.6° relative phase lag. This has no relationship to simple laws of wave propagation and confirms that the ter-diurnal effect is a non-linear one of local origin, due possibly to some non-linear properties of ice movement or possibly to some peculiarity of the recording mechanism, as suggested earlier.

Tidal constants corresponding to all the above conversion factors are listed in the last two columns of Table III. The only uncertainty is in applying the amplitude factor to M_3, since this is primarily a "linear" tide where the above argument suggests the ter-diurnal effect is non-linear. However, it is impossible to be more precise with only 15 days' record, and with such a small term any error is unlikely to be serious.

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