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Variability of the Tide at Some Sites in the Canadian Arctic

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ABSTRACT. Various techniques are used to detect the possible distortion of the tide by the presence of an ice cover at some gauging sites in the Canadian Arctic. Some stations are apparently unaffected, while those around the periphery of Amundsen Gulf and Hudson Bay experience larger tides during the annual period of open water and the time of arrival of the tide is altered.

RÉSUMÉ. On a utilisé des techniques variées pour detecter des variations possibles de marée, dues à la présence d'une couverture de banquise en quelques sites, equipés de jauges, dans l'arctique canadien. Il n'y a pas de modification constatée en quelques stations mais dans la région du golfe d'Amundsen et de la baie d'Hudson, on a constaté des modifications de marée, dans l'amplitude des marées plus grandes pendant la periode annuelle d'eau libre et dans le temps d'arrivée de cette marée.
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INTRODUCTION

Zubov (1943) stated that the tide may be altered by an ice cover; he noted that the range becomes smaller and that high (or low) water occurs later during the winter months in two rivers (Kamenka and Pya) emptying into the White Sea. Laktionov (1960) reviewed some of the considerable Russian experience and provided several empirical formulae for the modification of amplitude and phase of the tide due to an ice cover. Henry and Foreman (1977) described marked changes in the tide observed at Tuktoyaktuk and an inspection of tidal records in Canadian waters revealed that the tide may exhibit irregularities at any time and at any site for variety of reasons (Godin, 1977). In an examination of the influence of ice cover on long waves Murty and Polavarapu (1978) concluded that " . . . the evidence . . . is not clear enough to draw . . . definite conclusion." Our object is to provide the result of an application of several relevant techniques to data from sites in Canada in a search for the existence of variability in the tide linked with the formation or breakup of an ice cover.

TECHNIQUES TO DETECT VARIABILITY

Zubov and other Russian investigators used the range and the time of high water as indicators of variability, while Henry and Foreman (1977) carried out a harmonic analysis for each month of data for 1963. Short harmonic analyses

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FIG. 1. Some place names in the Canadian Arctic and approximate locations of some sites of water level gauges.

give notoriously unstable results, especially when a significant variation of sea level occurs due to factors other than the tide, i.e. when the noise background is large. Ranges, even in an undisturbed record, may vary seasonally, reflecting the change in intensity of the tidal forces, while power spectra ignore the phase which determines the time of high (or low) water. Furthermore, whatever approach is taken one will always be faced with the task of extracting the mean signal and its variations from the signal itself.

Zetler *et al.* (1970) suggested the calculation of the admittance between two sets of observations to obtain some insight into the spectrum of the subsidiary set because admittance estimates can be quite stable and reliable for rather short series (Godin, 1976). An extension of this approach is to calculate the admittance between the observed water level for a given site and the predicted tide: the predicted tide is a constant signal and any variabilty in the computed admittance can be attributed to the observations. However, these estimates of the admittances are biased by the fact that the predictions are based on an analysis of the observations themselves using a least-square fit; the resulting set of constituents will reproduce some of the variability if it is present. Computed monthly admittances between the observed water level and the predicted tide may therefore tend to more readily reveal fluctuations in the signal for a given month rather than net seasonal trends, unless the latter are quite intense. A more empirical approach is to compute values of the mean lunitidal interval and of the range (the lunitidal interval is the time elapsed between the lunar transit and the occurrence of high (or low) water, and the range is the height difference between high and low water). We can also compute the power spectra over bands separated at an interval of 1 cycle/day (cpd) and so separate the contribution of the semidiurnal and diurnal tides as well as the longer period variations in water level.

Table 1 lists the stations used in the investigation, with the intervals of observation, and our conclusions about the existence, or absence, of variability. The sampling interval is one month, since the variability we are after has a period of one year and since we have here no interest in the shorter term irregularities due, for instance, to storm surges. Information on the date of formation and breakup of an ice cover for the stations investigated has been supplied by the Ice Climatology and the Applications Division, Environment Canada, who advised that for the stations in the high arctic, breakup occurs between the beginning and end of July and ice reforms by the 1st of October. For stations in Hudson Strait and Hudson Bay, breakup occurs in Mid-June and by November ice forms again.

ADMITTANCE

The admittance between the observed water level and the predicted tide has been calculated over bandwidths of 1 cpd for monthly segments of observations and we have inspected most closely the semidiurnal band over which the tidal energy is largest. These indicate no systematic deviation in the tide signal at Alert, Resolute, Lake Harbour, Frobisher and Rae Point. However, Churchill, which has open water between mid-June to mid or late November, did reveal larger amplitudes during this period. The noise at these stations was small and the admittance estimates were sharp and unequivocal. Noise increases by an order of magnitude at Cape Parry but the admittance indicated no clear trend. The noise increase is even larger at Tuktoyaktuk, but marked variations in the amplitude and phase of the admittance stand well above the noise. We show in Table 2 admittance values in the semidiurnal band for the extreme cases of Alert and Tuktoyaktuk. An amplitude and

TABLE 1. Arctic stations whose tidal records were searched for a variability induced by the formation and breakup of an ice cover.

Station	Sets of Observations Utilized	Variability
Resolute	1971; 1973 (May missing); 1975	Not detectable
Alert	1971; Jan.-Mar., Sept.-Dec. 1972; Jan.-Jan., Sept.-Nov. 1974	Not detectable
Frobisher (submerged gauge)	Aug. 2976 - Sept. 1977	Not detectable
Rae Point (submerged gauge)	Aug. 1975 - Aug. 1976	Not detectable
Lake Harbour	1972 (Mar. missing); 1973 (Jul. and Aug. missing); 1974	Not detectable
Coral Harbour	Jan.-Oct. 1972	Increased ranges and tide *later* during open water
Churchill	1971; 1972; 1973; 1974 (Nov.-Dec. missing); 1975	Increased ranges and tide *later* during open water
Cambridge Bay	1971; 1972; 1973	Increased ranges and tide *later* during open water
Cape Parry	Jan.-Oct. 1971; Jan.-Sept., Nov.-Dec. 1973; Jan.-Apr., Jul.-Sept. 1975 (data inadequate to calculate the lunitidal intervals for Nov.-Dec.)	Slight increase in ranges during open water; no noticeable difference in the time of arrival of the tide
Tuktoyaktuk	Jan.-Apr., Jul.-Dec. 1971; Jan.-June, Aug.-Dec. 1973; Jan.-May, Jul.-Nov. 1975	Marked irregularities, ranges larger and tide *earlier* during open water

phase of the admittance of 1.00 and 0° respectively would indicate that the semidiurnal tide was constant during the month examined. Keeping in mind that the predictions are based on the observations themselves and are therefore biased, we can still see that the admittance stays very close to 1,0° for Alert while it oscillates appreciably at Tuktoyaktuk. An admittance amplitude less than 1 implies that the observed tide is less than the predicted tide and vice versa for an amplitude larger than 1. A negative phase indicates that the observed tide occurs earlier than the predicted tide. Had we restricted the analyses exclusively to months with ice, the admittance values in Table 2 would have been quite different for Tuktoyaktuk; they would cluster around 1,0° for such months and would be $>1,<0°$ for the open water season with possibly more abrupt changes in the admittance, but the results would lead to an identical interpretation.

TABLE 2. Computed monthly admittance between the observed water levels and the predicted tide in the semidiurnal band (2 cpd) at Alert and Tuktoyaktuk (the number of significant figures is determined by the coherence). Mean difference in phase of ±2° amount to some ±4 minutes in time , an interval which is barely measurable by the standard tide gauge. The amplitude of the admittance is the ratio between the amplitude of the observed level and predicted tide: a ±2% deviation in the admittance amplitude implies a fluctuation in range of 12 to 15 cm where the tide is large, e.g. at Frobisher, and 1 to 2 cm at Alert and Tuktoyaktuk; the limit of resolution in height of the gauges is ±1 cm.

Month	Alert (1973)		Tuktoyaktuk (average from data available)	
	Amplitude	Phase (deg)	Amplitude	Phase (deg)
J	1.00	0	0.9	4
F	1.00	0.8	0.95	7
M	1.00	0.8	0.96	6
A	1.01	0.2	0.97	3
M	1.00	0.4	0.98	1
J	1.00	0.2	1.03	0
J	1.01	0	1.3	-13
A	1.00	-1	1.0	-12
S	0.99	0	1.1	1
O	1.00	-1	1.0	-4
N	1.00	0	0.9	-0
D	0.99	0	0.9	-1

POWER SPECTRA, MEAN RANGES AND LUNITIDAL INTERVALS

The indications of the admittance are corroborated by the results of an analysis of each of the power spectrum, the mean range and the mean lunitidal interval for the locations and data of Table 1 (only the results for Cape Parry and Churchill are shown). At Resolute and Alert the semidiurnal power exhibits maxima in the spring and autumn, which are a normal feature of the astronomical tide at this frequency and can be duplicated for any southern station such as Halifax or Pointe au Pere. The lunitidal intervals show a slight tendency to decrease during the latter part of the year (the tide is earlier) by about 0.1 hour (6 minutes) at Resolute and 0.2 hours at Alert, but this lies at the threshold of time resolution of the standard maregraphs. We therefore conclude that the annual change of the ice cover does not affect the tide recorded at these two sites. At Frobisher and Rae Point (where the data were obtained from submerged gauges) and at Lake Harbour, no appreciable influence due to the ice could be discerned. At Coral Harbour and Churchill (Fig. 2), however, the semidiurnal power was seen to increase perceptibly from June to October (the diurnal power is too weak to show anything). The range reflects the increase in semidiurnal power during these months and the

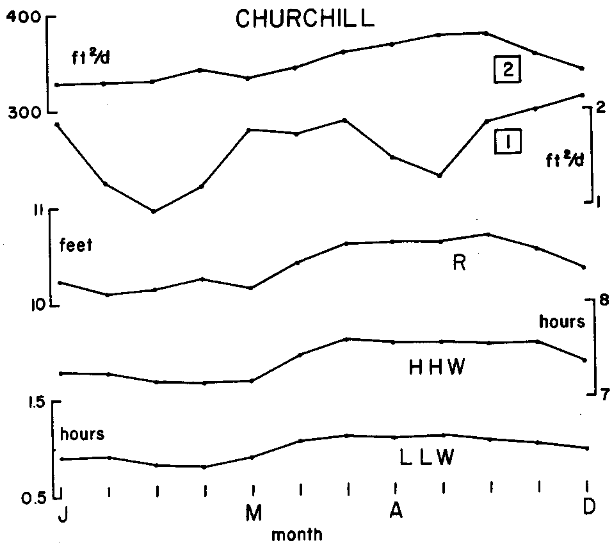

FIG. 2. Monthly values for Churchill of the spectral intensity (ft²/d) in the semidiurnal band at 2 cpd (denoted by 2), the diurnal band at 1 cpd (denoted by 1); the mean range (R) in feet and the mean lunitidal intervals in hours for higher high water (HHW) and lower low water (LLW).

lunitidal intervals indicate quite clearly that the tide reaches these sites later during intervals of open water (we have only 10 months of good observations for Coral Harbour whereas we have nearly five complete years for Churchill). The delay in the tide during the season of open water is of the order of 20 minutes for both stations.

Cape Parry (Table 3) exhibits no strong variation, but a slight increase in the semidiurnal power and range can be noticed during August and

TABLE 3. A listing for Cape Parry of the spectral intensity (ft²/d) in the two bands of interest, namely the semidiurnal at 2 cpd (denoted by 2), the diurnal at 1 cpd (denoted by 1); the mean montly range (R) in feet; the mean lunitidal intervals (hours) for higher high water (HHW) and lower low water (LLW).

Month	2	1	R	HHW	LLW
J	1.3	0.9	0.78	6.68	1.00
F	1.6	0.6	0.79	6.68	0.89
M	1.6	0.4	0.79	6.63	0.86
A	1.7	0.5	0.74	6.69	0.93
M	1.9	0.7	0.80	6.64	0.85
J	2.0	1.0	0.82	6.81	1.14
J	2.0	0.7	0.81	6.49	0.94
A	2.0	0.6	0.88	6.70	1.03
S	2.1	0.3	0.84	6.55	0.79
O	1.9	0.5	0.80	7.0	0.92
N	1.8	0.9	—	—	—
D	1.2	1.0	—	—	—

September. Cambridge Bay exhibits increased power in the diurnal and semidiurnal in August and September and the tide is later. During the period of open water Tuktoyaktuk exhibits marked increases in the diurnal and semidiurnal power as well as in the range. Interestingly the lunitidal intervals indicate that the tide there is earlier during these months and by as much as 1.5 to 2 hours.

The portion of the data at Tuktoyaktuk shown in the form of overlapping segments (Fig. 3) clearly indicates the diurnal peak (0.04 cph), the semidiurnal peak (0.08 cph), and the increase in power in the peaks, nearly double for the semidiurnal, in the absence of ice. The diurnal power is overcome frequently during the ice-free period by noise apparently contributed by strong winds at the surface, but the semidiurnal maintains its regularity. Our estimate is that the amplitude of the semidiurnal, specifically of the M_2 constituent, is about 50% greater in summer than in winter at Tuktoyaktuk.

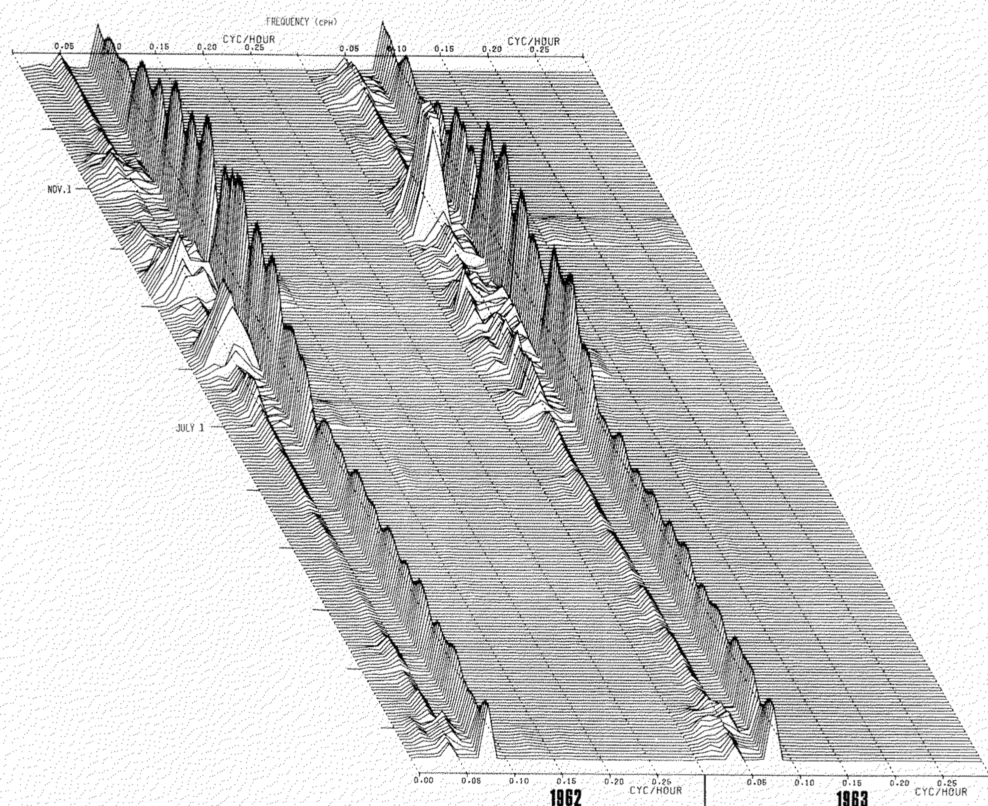

FIG. 3. Power spectra (ft²/h) over 50 frequency bands (cph) in the observed hourly values of water level at Tuktoyaktuk for the years 1962 (left) and 1963 presented in the form of overlapping segments. Each segment comprises 15 days of data and each is advanced by 1.5 days from January 15 to December 31, i.e. from the bottom toward the top.

INTERPRETATION OF THE RESULTS

There can be little doubt then that in some parts of the Canadian Arctic the tide is strongly influenced by the ice cover, and while we cannot now positively identify the nature of the influence, it may be useful to indicate our present belief, although it is speculative. Briefly, we theorize that two water bodies, Hudson Bay and Amundsen Gulf, exhibit slight resonance at frequencies close to tidal and that the frequency of resonance is altered by ice cover. For both Hudson Bay and Amundsen Gulf the amplification is reduced by the ice cover so that at the sites at the periphery, tidal amplitudes are less in winter. The phase is also altered but not in a particular direction, i.e. the tide may be earlier or later. I. V. Maksimov, as reported by Laktionov (1960), seems to have been the first to suggest such an influence, while Murty and Polavarapu (1978) suggested that increased amplitude in some storm surge data may have occurred because "resonance amplification may be somehow greater during the ice cover period." The influence likely occurs through alteration by the ice cover of the physical characteristics of a water body (depth, surface area, dimensions of openings or ports to adjacent seas) and as these may be varied appropriately in a numerical model, we are applying this additional technique to study of the variation in the Hudson Bay system.

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