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TIDAL DISPLACEMENT OF SEA ICE OBSERVED AT NISI-NO-URA COVE ON EAST ONGUL ISLAND, ANTARCTICA

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Abstract: Vertical displacements of sea ice accompanied by the ocean tide were measured at Nisi-no-ura Cove on East Ongul Island, Antarctica, and compared with the ocean tide observed by pressure type tide gauge installed at the same cove. The displacements of sea ice were measured at two places which were respectively located at 20 m (P20M) and 60 m (P60M) offshore of bench mark BM No. 1040. The displacement at P20M, where the sea ice is close to the fast ice, showed strong non-linear behavior in both amplitude and phase compared with the ocean tide measured by the bottom-pressure gauge. On the other hand the displacement at P60M was very consistent with the observed ocean tide. According to the 6 measurements made at P60M in the 8 months from May to December, 1993, the differences in amplitude are less than 5% as represented by the ratio of the displacement of the sea ice to the ocean tide.

1. Introduction

As part of the five-year earth science program (1993-1998) in the Japanese Antarctic Research Expedition (JARE), observations of earth's free oscillation and earth tide are being carried out with a superconducting gravimeter at Syowa Station (SATO *et al*., 1993). One of the purposes of this observation is the detection of weak signals coming from earth's deep interior, which are considered to exist in wide frequency bands covering those of tide to free oscillation of the Earth. Although the gravimeter itself has the capability to detect weak signals at the magnitude of a few nano gal (1 ngal $= 10^{-11}$ m/s^2), the observed data include gravity changes far exceeding that magnitude, mainly due to the effects of ocean tide and atmospheric pressure change. For example, observations of the gravity tide at Syowa Station are known to be strongly affected by the ocean tide because the station is located very close to the sea (within 1 km). According to the study by OGAWA *et al.* (1991), the effect of the ocean tide at Syowa Station attains about 7 μgal as the sum of effects of the main eight diurnal and semidiurnal tidal constituents. Therefore, the expected signals to be detected are likely to be masked by an inaccurate correction for ocean tide. Since 1981, the Hydrographic Department, Maritime Safety Agency has carried out continuous observation of the ocean tide at Syowa Station by using bottom-pressure gauges (Odamaki *et al.*, 1991). We, therefore, have the opportunity to revise the ocean tide models around Syowa Station based on observed data.

The scale factor and drift of the bottom-pressure gauge are routinely calibrated by comparing with the actual water height change over one tidal cycle (Odamaki *et al.*, 1991). Due to growth of the sea ice, the above calibration could be carried out only for a limited period in summer when open sea surface appears in the packed sea ice. In order to examine the effect of the sea ice thickly covering the cove in winter, we have masured vertical displacements of the sea ice accompanied by the ocean tide and compared them with the bottom-pressure gauge data. We refer hereafter to the vertical displacement of the sea ice as the 'sea-ice tide'.

2. Observation

Figure 1 shows the sea-ice tide observation site. The site is located in Nisi-no-ura Cove on East Ongul Island, at 69.005°S and 39.587°E. At first, the measurement was carried out at the place 60 m from bench mark BM No. 1040 which has been set by the Geographical Survey Institute. We call this position P60M. Later, we also measured the displacement at a site 20 m (P20M) from the benchmark for comparison. The position of the bottom-pressure gauge is indicated in Fig. 1 as BPG.

We used a laser distance meter (hp3820a) for observations of the sea-ice tide. The

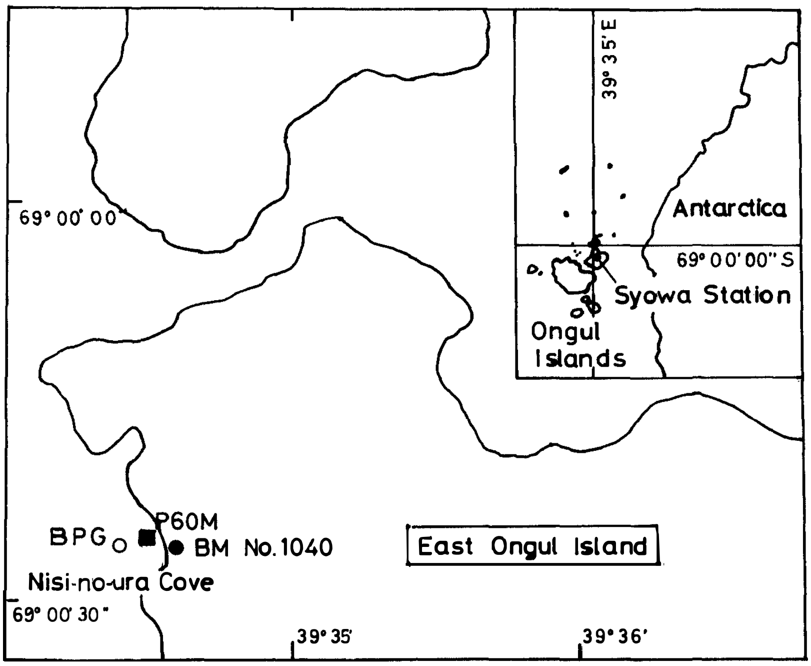

Fig. 1. The location of the observation sites. BM, P60M and BPG respectively show the location of the bench mark BM No. 1040, the observation site at 60 m from BM and the bottom pressure gauge. This figure is drawn based on Fig. 1 by Odamaki et al. (1991).

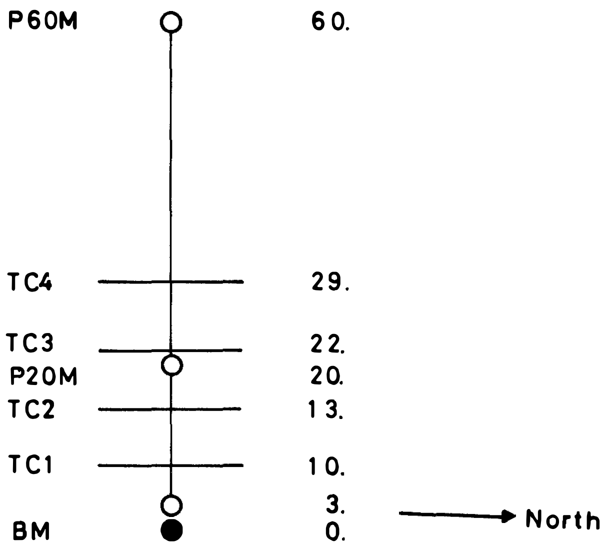

Fig. 2. The relation between the observation sites and tide cracks. P20M and P60M show the locations of the corner-cube reflectors which were set for the observations of sea ice tide. TC1, TC2, TC3 and TC4 are the relative locations tide cracks, where the major cracks are TC1 and TC2. The numbers shown in the right hand side represent the distance in meters measured from the bench mark.

arrangement of its main body and staves for the reflectors is shown in Fig. 2 with the positions of tide cracks. Due to automatic compensation mechanisms to correct for variations in the refraction index of air and in the level of the instrument itself, the distance meter is shown to have an accuracy of ±(5 mm+5 mm/km multiplied by the measuring distance in km). In order to avoid lowering the instrumental temperature (operational limit is −20°C), and also to protect the main body from wind, we constructed a temporal observation hut by covering a pipe frame with plastic sheets, and set the main body inside this hut.

Observations at P60M were made 6 times during May to December, 1993, while observations at P20M were carried out three times in June, July and September, 1993 (Table 1). In order to obtain a good signal to noise ratio, we tried to carry out observations on days when the tidal displacement was expected to reach its maximum in each month. For one complete tidal cycle, the displacements of corner-cube reflectors were read at an interval of 1 hour, twice each time.

In both the observations of November and December, the legs of the reflector staff were suspected to be unequally sunken, mainly due to heating by solar radiation. Therefore, we measured the three dimensional position of the reflector as referred to the surface of the ice with a hanging weight, and we covered the feet of the staff with snow. Figure 3 shows the relation between the time variation in height of the staff and that in the accumulated solar radiation, which was measured in the December observation. Because we had not measured it in the November observation, we performed a height correction for the November data by using the regression coefficients determined from the data shown in Fig. 3. The regression coefficients used here are 0.018±0.023 m and −0.0454±0.0014 m/(MJ/m^2) for the zero-th and first order terms, respectively.

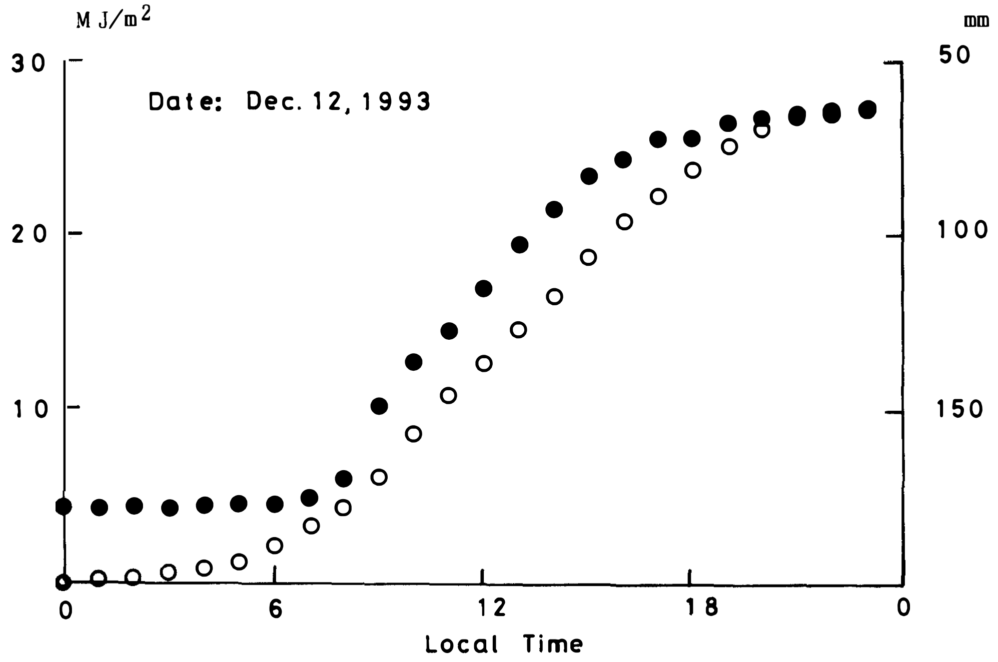

Fig. 3. The relation between the time variations in height of the staff and the accumulated solar radiation. The filled circles show the height change of staff (mm). The open circles show the accumulated solar radiation (MJ/m²). Note the sense of the height change of staff is reversed for comparison with the solar radiation.

3. Observation Results

The observation results are summarized in Table 1. For reference, the meteorological data, the sea ice thickness and the ocean tide amplitude on each observation day are shown in Table 2. Although it is necessary to know the time variation of sea water density to convert the output from the pressure gauge sensor into the sea surface height change, we use here the constant density 1025.0 kg/m^3.

In Table 1, 'Amp. ratio' shows the amplitude ratio of the sea-ice tide to the ocean tide, and 'Phase' shows the lag of the former behind the latter in minutes. A linear relation between the sea-ice tide and the ocean tide was assumed to determine these values. We searched for the best fit values for 'Amp. ratio' and 'Phase', so that they gave the minimum χ-square test value among those estimated from the data sets which were obtained by uniformly shifting the sea-ice tide reading times within the range of ± 40 min.

From Table 1, we see smaller amplitude ratios obtained at P20M as compared with those at P60M. This may be due to the complicated motion of sea ice near the shore line. As seen in Fig. 2, P20M is located at a position between the tide cracks, where the motion of sea ice is considered to be restricted by the strength of the ice itself. This was also confirmed from the evidence that the sea water welled out when a hole was dug to measure the ice thickness. The sea water depth at P20M is estimated to be a few meters or less. On the other hand, we did not observe welling out of water at P60M. From Fig. 3 of ODAMAKI *et al.* (1991), the sea depth at P60M is estimated to be 15 m or more. This depth is about 10 times the sea ice thickness. These suggest that the effect of fast ice on the

Table 1. Amplitude ratios of the sea-ice tide to the ocean tide measured by the pressure gauge and phase lags of the sea-ice tide.

Date		P60M			P20M		
M	D	Number of readings	Amp. ratio	Phase (min)	Number of readings	Amp. ratio	Phase (min)
5	21, 22	54	0.964±0.005	0.0			
6	18, 19	46	0.957±0.005	−1.0	56	0.552±0.015	8.0
7	18	17	1.038±0.024	0.0	16	0.774±0.030	8.0
9	9, 10	50	0.996±0.020	−8.0	54	0.576±0.013	31.0
11	23, 24	48	0.945±0.015	1.0			
12	12, 13	48	0.961±0.005	−1.0			
Simple mean			0.977±0.012	−1.5		0.634±0.019	15.7
Weighted mean*			0.967±0.008			0.605±0.017	
1	25, 26**	141	0.985±0.002	0.0			

*Mean value calculated by using the errors shown in the table as the weights.

**The result for these days shows the amplitude ratio of the ocean tide measured with a tide pole to that obtained by the pressure gauge.

Table 2. Meteorological data in each observation, the tidal change during the observation, and the thickness of sea ice.

Date		Air temperature max (°C)	Air temperature min (°C)	Maximum wind velocity (m/s)	Tidal change (m)	Thickness of sea ice P60M (m)	Thickness of sea ice P20M (m)
M	D						
5	21, 22	−17.2	−20.3	6.5	1.39		
6	18, 19	−17.5	−21.1	6.5	1.34	1.22	1.23
7	18	−34.2	−37.6	10.5	1.36	1.40	
9	9, 10	−24.9	−29.5	3.6	0.74	1.75	1.82
11	23, 24	+1.6	−3.4	14.9	0.61	1.88	
12	12, 13	−0.6	−3.1	13.5	1.59	1.75	

sea-ice tide rapidly decreases with increase of bottom depth.

The pressure gauge was calibrated by JARE-35 on the two days January 25 and 26, 1994. The open sea surface height changes were directly read at intervals of 10 min by using a tide pole. Using these data, we calculated the amplitude ratio of the sea surface height changes to the ocean tide measured by the pressure gauge. As listed in Table 1, we obtained 0.985±0.002 as the ratio. On the other hand we obtained 0.967±0.008 as the weighted mean value of the ratios of sea-ice tide to ocean tide. This difference in amplitude ratio suggests that the sea surface height changes are reduced by about 2% as compared with those expected without the effect of sea ice.

Our observation results are summarized as follows:

(1) The sea-ice tide amplitude can be measured with an error of 0.03 m or less. This error corresponds to 2% error in the ratio of the sea-ice tide to the ocean tide. If the environmental conditions are good, it may be possible to reduce the error to the order of 1%.

(2) When the pressure gauge is installed at a depth about 10 times the sea ice thickness, the amplitude difference between the sea-ice tide and the ocean tide observed by

the pressure gauge will be 5% at most.

(3) Due to the effect of sea ice, the height changes of the sea surface are reduced by about 2% as compared with those expected from the sea surface without the effect of sea ice.

4. Concluding Remarks

Because our observations of the sea-ice tide have not covered the complete one-year cycle, it is not certain whether there is clear seasonal variation in the amplitude ratio. However, at both P60M and P20M, the ratios in July and September were larger than in other months. ODAMAKI *et al.* (1991) also pointed out that, from analysis of monthly mean sea levels, the seasonal variation at Syowa Station attains 0.3 m as compared with the values obtained at other ports in the southern hemisphere where the amplitude is typically of 0.1 to 0.2 m. OGAWA *et al.* (1991) furthermore pointed out that the semidiurnal gravimetric tidal factors at Syowa Station after correcting for the ocean tide effects are very large compared with values expected from body tide theory, and the magnitude of the discrepancy far exceeds the observational errors.

How does the seasonal variation of the sea-ice tide affect observed amplitude of the ocean tide and/or the observed tidal gravimetric factors? In order to obtain a better ocean tide correction for the gravity tide at Syowa Station, we should study the effect of the sea-ice tide upon the seasonal variation of the ocean tide. By accumulating monthly sea-ice tide data, we might find physical mechanism of the seasonal variation in the ocean tide which is typical at Syowa Station. For detailed discussion, it is also necessary to measure the seasonal variation of sea water density around the pressure gauge.

Acknowledgments

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References

ODAMAKI, M., MICHIDA, Y., NOGUCHI, I, IWANAGA, Y., IKEDA, S. and IWAMOTO, K. (1991): Mean sea-level observed at Syowa Station, East Antarctica. Proc. NIPR Symp. Antarct. Geosci., **5**, 20–28.

OGAWA, F., FUKUDA, Y., AKAMATSU, J. and SHIBUYA, K. (1991): Nankyoku Syowa Kiti oyobi Asuka Kiti ni okeru jûryoku chôseki kansoku dêta no kaiseki (Analysis of tidal variation of gravity observed at Syowa and Asuka Stations). Sokuchi Gakkai Shi (J. Geod. Soc. Jpn.), **37**, 13–30.

SATO, T., SHIBUYA, K., OKANO, K., KAMINUMA, K. and OOE, M. (1993): Observation of earth tides and earth's free oscillations with a superconducting gravimeter at Syowa Station (status report). Proc. NIPR Symp. Antarct. Geosci., **6**, 17–25.

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