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Water surface waves induced by calving events at Perito Moreno Glacier, southern Patagonia

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Abstract

In order to investigate characteristics of water surface waves, induced by calving events of Perito Moreno Glacier, a water pressure gauge was set at the shore of proglacial Lake Brazo Rico for a period from 2 to 13 December 1999. Continuous measurements of lake level show that the diurnal number of calving events is not related to temporal variations of air temperature, but that the hourly event number on the day weakly depends on the temperature rise. The spectral analysis for lake level revealed that surface waves are strong mostly at *ca.* 0.02 Hz and secondly at *ca.* 0.04 Hz. These frequencies probably correspond to inherent frequencies of surface seiche in the proglacial lake.

1. Introduction

In the Southern Patagonia Icefield, it is seen that, in recent decades, most glaciers have retreated, but a few of them have stagnated or even advanced (Aniya and Skvarca, 1992; Naruse *et al.*, 1995). The rate of terminus advance of calving glaciers is often expressed as a difference between the glacier flow rate and the calving rate. Warren (1994) stated that the terminus response does not directly relate to the regional climate trend, but can be controlled by the calving dynamics and topography. Hence, detailed studies on calving rate are important to understand the recent retreat of calving glaciers. An interesting issue in the study of calving is a difference in the calving mechanisms of freshwater and tidewater glaciers. According to Brown *et al.* (1983) the calving rate is proportional to mean water depth along the terminus for three tidewater calving glaciers in Alaska, which have rapidly been retreating.

This report presents a result of a reconnaissance study to investigate calving phenomena quantitatively and qualitatively, using a water pressure gauge in a proglacial lake. This method enables us to observe calving activities during both daytime and nighttime. Continuous observations and spectral analyses for water surface waves will provide statistical information for calving phenomena, *e.g.* hourly and daily variations in calving events and spectral features of water waves induced by the events.

2. Observation

The observation of calving events at Perito Moreno Glacier in southern Patagonia was carried out in proglacial Lake Brazo Rico for a period from 2 to 13 December 1999. A schematic map of the lower reaches of the glacier is shown in Fig. 1. The glacier is a temperate freshwater calving glacier, located on the eastern side of the Southern Patagonian Icefield. Skvarca *et al.* (2004) reported that the glacier tends to thicken with the stable terminus in the recent years.

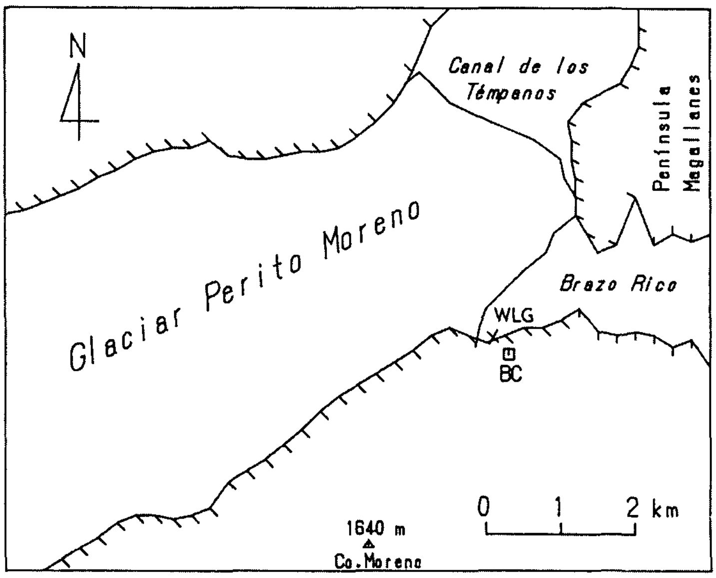

Fig. 1. Map of the terminal part of Perito Moreno Glacier. "WLG" indicates a gauging site of water level in proglacial Lake Brazo Rico. "BC" indicates base camp site.

A water pressure gauge, connected to a compact data logger, was set at about 0.6 m below the water surface at site WLG near the shore of Lake Brazo Rico, into which Perito Moreno Glacier calves (Fig. 1). The effect of dynamic pressure is considered as negligibly small because the sensor of the pressure gauge was covered with a number of stones of various sizes at the bottom of the lake. Figure 2 shows a sketch of the glacier terminus, the lake shore and site WLG (see Fig. 3). According to an optical topographic survey from two control points, α and β on the shore to six marked pinnacles, G1 to G5 and G7, on the lateral margin of the glacier terminus (Fig. 2; also see Fig. 1) the distance from the gauging site to the calving cliff is about 400 m - 1500 m, and the height of the ice cliff ranges from about 40 m to 70 m above the lake surface (Naruse *et al.*, 2001). The accuracy of the water pressure gauge is ± 20 mm with the resolution of 1 mm. The recording interval was 5 s for the early 9 days and 15 s for the residual 3 days because of battery shortage. The data at longer time intervals were not used for the spectral analysis.

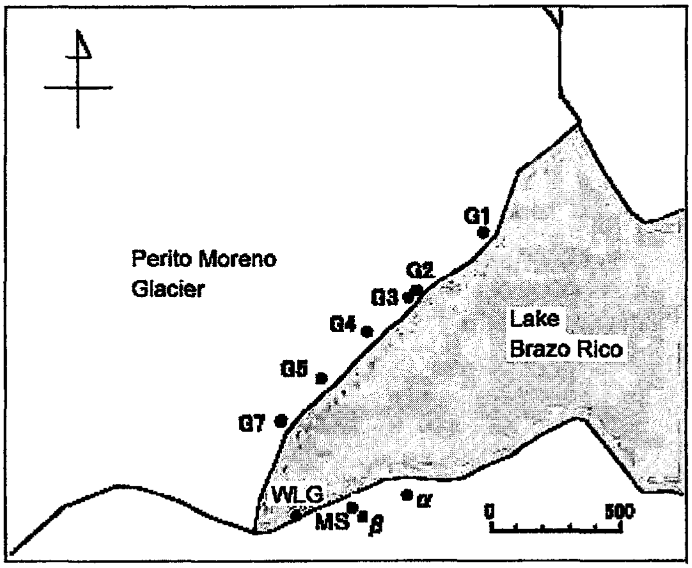

Fig. 2. Schematic picture of measuring points and the calving ice cliff near the glacier terminus. Solid circles on the glacier indicate marked pinnacles measured from the base line (α and β). The water level gauge was set near the shore of the lake Brazo Rico. "MS" indicates Meteorological Station, where the global radiation and Air temperature were measured.

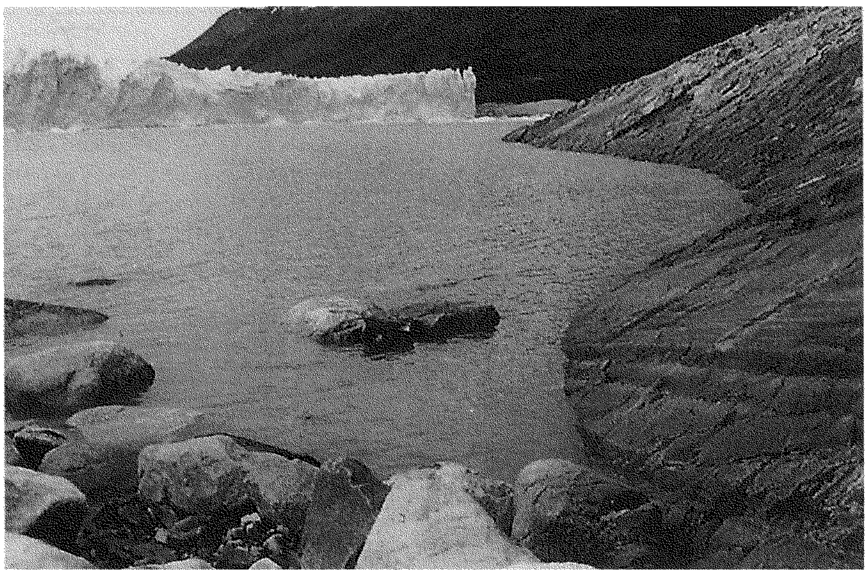

Fig. 3. Photograph of the measurement site. A water level gauge was set up beside the exposed small rock in the lake near the shore. The calving ice cliff can be seen behind the lake.

3. Results

The 12-day observation supplied data of 16 hours in total, and consequently 68 series of large calving waves were detected. The 68 series include 15 series recorded at 15 s intervals. Each series of large calving waves was compiled for the number, date, time, maximum amplitude and duration time. An example of this water level data on 2 and 3 December is shown in Fig.4. Generally, each series of calving wave shows the maximum amplitude at the beginning and lasts several tens of minutes with the amplitude decreasing towards the end. Some of the wave series exhibit complex patterns, when the next calving event occurrs before complete damping of the previous waves. Figure 5 shows an example of waves for a very large calving which occurred at 1152 h on 3 December. The maximum amplitude of the waves was 0.48 m, and this series continued for about 50 minutes.

4. Analysis and consideration

4.1. Daily and hourly numbers of events

To examine factors affecting calving activity using the data of the 68 series of lake level for large calving events, the daily number of the events is shown in Fig. 6. The event numbers were large for 6 to 9 December. The maximum amplitudes were also large on 7 and 8 December. Similarly, the number of calving events occurring each hour on all days is shown in Fig.7. During daytime hours of 1100 h to around 1800 h, the number of events was relatively high and the maximum amplitude was also large.

Global radiation and air temperature variations measured near the gauging site at Perito Moreno Glacier (marked as "MS" in Fig.2) are shown in Fig. 8. Monthly average temperature in December 1999 was 9.9°C and the maximum and minimum temperatures were 19.6 and 2.8°C, respectively. The variation of air

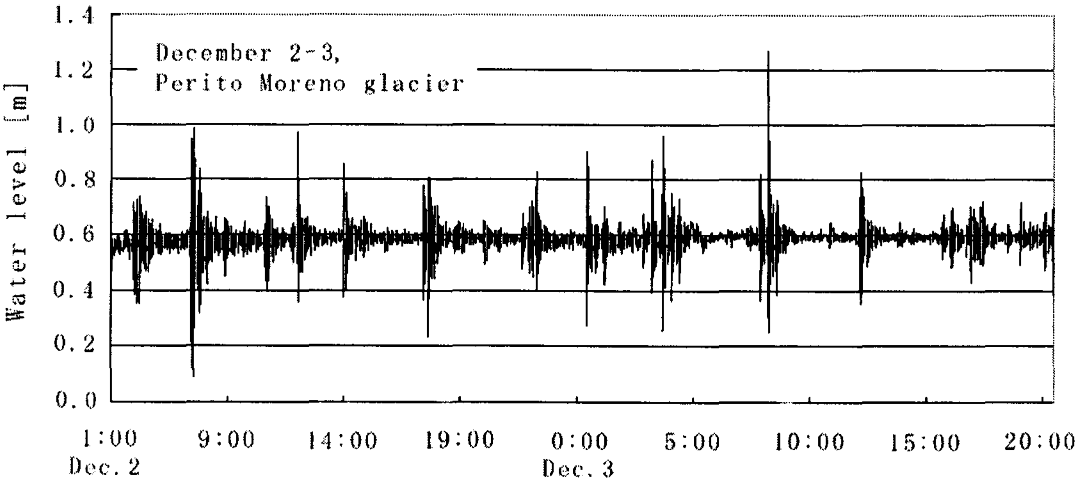

Fig. 4. Variations in water level on 2 and 3 December 1999. The horizontal axis shows the local time.

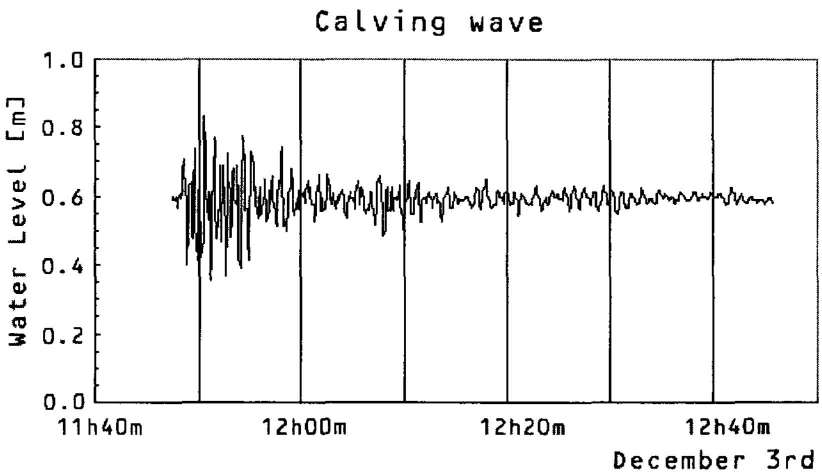

Fig. 5. An enlarged record of waves caused by a calving event on 3 December.

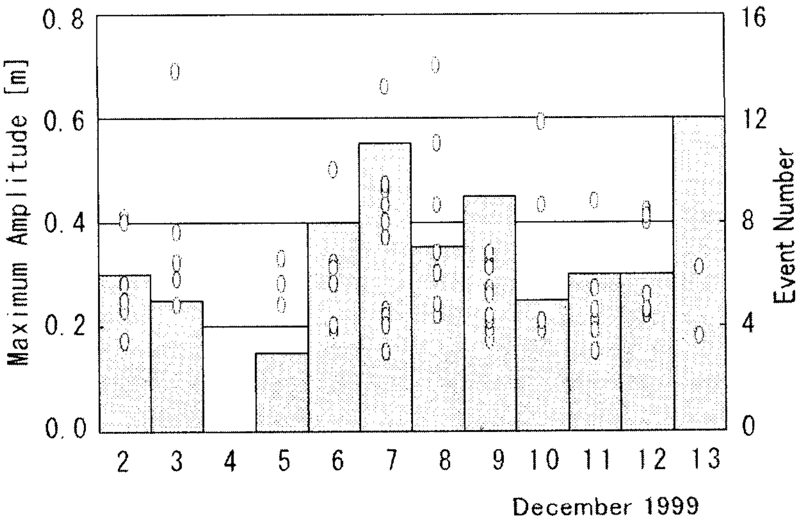

Fig. 6. Daily number of calving events (bars) and the maximum amplitudes of calving waves (open circles) for the observation period.

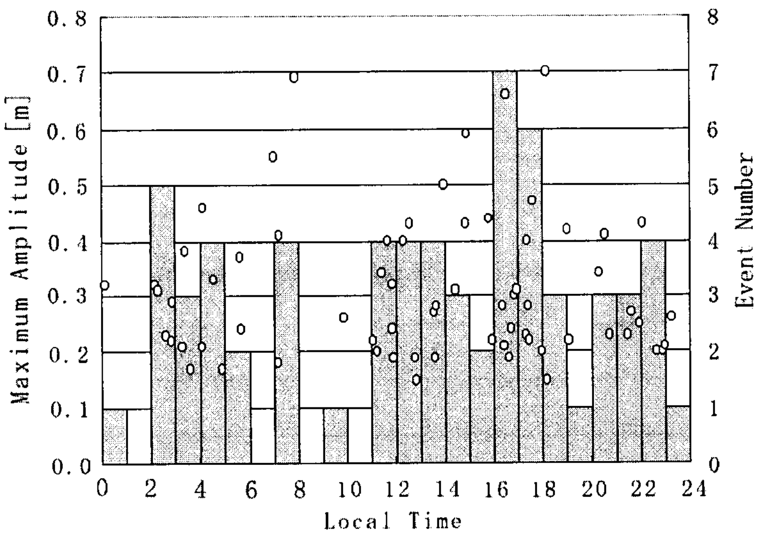

Fig. 7. Hourly number of calving events (bars) and the maximum amplitude of the calving waves (open circles) on the day for all the data.

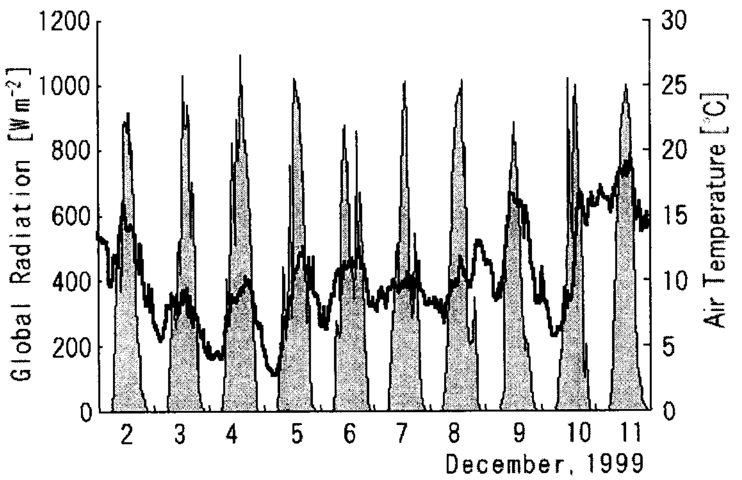

Fig. 8. Variations in global radiation (thin line) and air temperature (thick line) at Perito Moreno Glacier (measured by Helmut Rott).

temperature in Fig. 8 does not appear to be related to the daily number of calving events in Fig. 6. However, the hourly calving number in Fig. 7 is related to the temperature rise during the day; calving events may occur in response to daily temperature rise. These results suggest that the ice-melt by air temperature rise helps to fracture ice or enhances glacier flow to induce calving.

4.2. Spectral analysis

Using the Fourier Transform, power spectra of calving waves were calculated for each calving event. For the analysis, power spectra were calculated at a range of 0.001 to 0.1 Hz. An example of the analytical results is shown in Fig. 9. There are three definite power peaks at frequencies of 0.018 Hz, 0.023 Hz and 0.036 Hz. The spectral power of three dominant peaks for all the time series are plotted with the frequency in Fig. 10. The first dominant peak exists mostly at around 0.018 Hz and secondly at around 0.037 Hz, although the power values have a wide range. These peaks probably correspond to the inherent frequencies of surface seiche in the proglacial lake. The surface seiche is a free surface oscillation which occurs in response to the lake-basin scale (Horne and Goldman, 1994). If the lake depth and horizontal distance were given, the inherent frequency could be calculated. However the data are not accurate enough at this stage. Further investigations of the lake topography are needed.

5. Concluding remarks

Water level variations in proglacial Lake Brazo Rico of Perito Moreno Glacier show that surface waves, induced by calving events, commonly have a

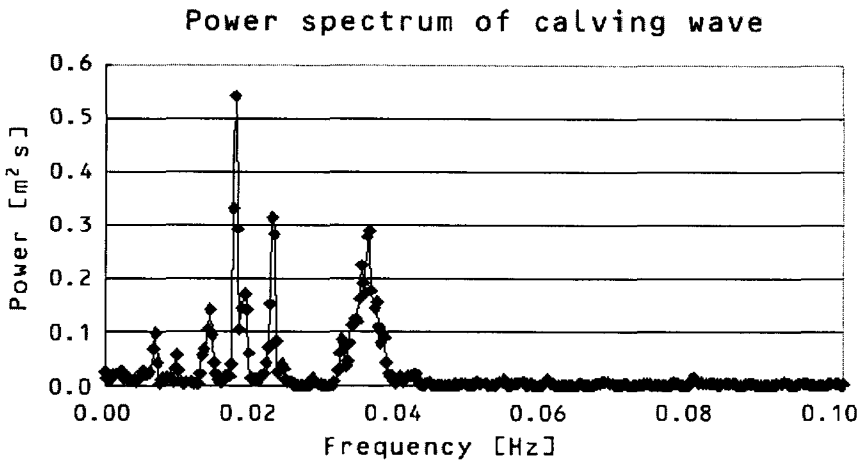

Fig. 9. An example of power spectra calculated for a calving event.

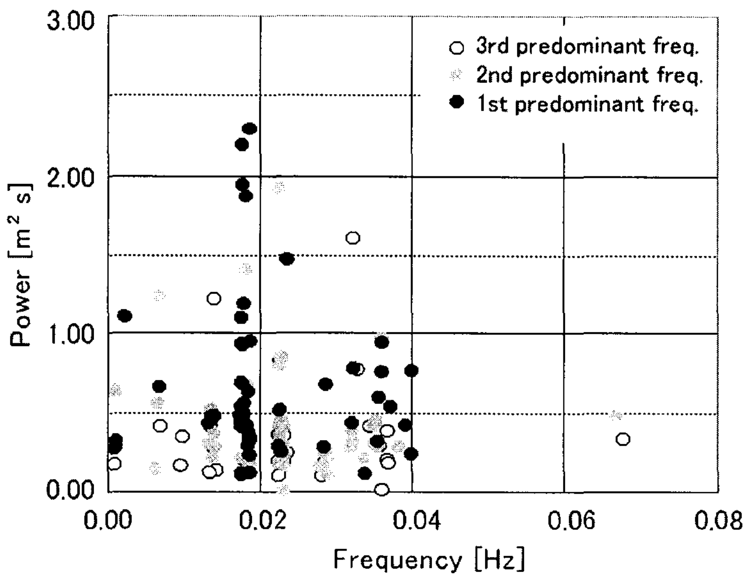

Fig. 10. Distributions of the three dominant spectral peaks on frequencies.

wave shape with an initial peak. There is no clear relationship between the air temperature and daily number of calving events, but the hourly number of events in the day is likely to be related to hourly air temperature rise. As a result of spectral analyses, the wave amplitude peaked around 0.02 Hz. It is possible that this frequency corresponds to the inherent frequency of surface seiche in the proglacial lake.

Acknowledgments

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References

Aniya, M. and Skvarca, P. (1992): Characteristics and variations of Upsala and Moreno glaciers, southern Patagonia. Bulletin of Glaciological Research, **10**, 39-53.

Brown, C. S., Meier, M. F. and Post, A. (1983): Calving speed of Alaska tidewater glaciers, with application to Columbia glacier. U. S. Geological Survey Professional Paper, **1258-C**, C1-C13.

Horne, A. J. and Goldman, C. R. (1994): Limnology. McGraw-Hill, Inc., Tokyo, 576pp.

Naruse, R., Aniya, M., Skvarca, P. and Casassa, G. (1995): Recent variation of calving glaciers in Patagonia, South America, revealed by ground surveys, satellite-data analyses and numerical experiments. Annals of Glaciology, **21**, 297-303.

Naruse, R., Skvarca, P. and Kobayashi, S. (2001): Measurements of surface height and flow velocity at the calving terminus of Perito Moreno Glacier, southern Patagonia, in December 1999. Glaciological and Geomorphological Studies in Patagonia 1998 and 1999, edited by Aniya, M. and Naruse, R., 141-144.

Skvarca, P., Naruse, R. and Angelis, H. (2004): Recent thickening trend of Glaciar Perito Moreno, southern Patagonia. Bull. Glac. Res., 21, 45-48.

Warren, C. R. (1994): Freshwater calving and anomalous glacier oscillations: recent behaviour of Moreno and Ameghino Glaciers, Patagonia. The Holocene 4, **4**, 422-429.