Surface manifestations of the waves in the ocean covered with ice

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This paper summarizes winter oceanographic measurements in the Spitsbergen fjords. The measurements allow us to analyze different processes that occur in the fjords covered with ice: semidiurnal tides, tsunami wave, wind waves, seiches, and high-frequency internal waves. Space and time scales of these processes were compared and the frequency spectra of the surface manifestations of these waves have been plotted on one graph. *KEYWORDS:* Tides; seiches; internal waves; ice; surface manifestations; tsunami; ice; wind waves.

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Introduction

This paper overviews our winter oceanographic measurements in the Spitsbergen fjords. We studied different wave processes in the ocean covered with ice. Our measurements allow us to analyze several processes that occur in the fjords covered with ice that include: semidiurnal tides, tsunami wave, wind waves, seiches, and high-frequency internal waves. We conducted our measurements in the Temple Fjord and Van Mijen Fjord near the Paula and Tuna glaciers. These classes of waves occupy different space and time scales; however, the frequency spectra of the surface manifestations of these waves can be plotted on one graph. The spectra occupy 14 orders of vertical displacement fluctuations versus five frequency orders of magnitude.

1. Tides

We performed measurements of tides every winter from 2008 to 2015. Usually the vertical displacements of the ocean surface covered with ice were recorded using SBE-39 pressure gauges deployed on the ocean bottom at the depths ranging from a few meters to 50 m [*Marchenko et al.*, 2015]. The maximum vertical displacements of the ice caused by the tidal motions are slightly less than two meters. The spring-neap differences are within 50 cm. The M2 tidal wave with a period of 12.4 h dominates near the coasts of Spitsbergen. The other tidal constituents are several times smaller. The spectrum was calculated from the data of two months duration in the Van Mijen Fjord. The sampling time was 10 s. The dominating spectral peak at the tidal frequency is clearly seen.

2. Seiches

We observed seiches in Lake Vallunden. This is a natural lagoon formed by the glacier. It is about 1.3 km long and 0.8 km wide. The maximum depth of the lagoon is 12 m. The lagoon is connected to the Van Mijen fjord by a shallow passage 10 m wide. Seiche oscillations in this lagoon are generated by meteorological forcing. In the periods of calm weather they are not observed. Usually, the duration of the time series was one day. The sampling time was 1 s. The ice fluctuations were measured by an SBE 39 pressure gauge located at the bottom at a depth of 8 m. The vertical displacements of the ice caused by seiches were approximately 2 cm, and the spectral peak is very sharp. The period of seiches is about 4–5 minutes, which corresponds to the theoretical period of these oscillations in a basin of the given size [*Rabinovich*, 2009].

3. Tsunami

We observed a landslide tsunami near the glacier front in the Temple Fjord (Spitsbergen) caused by the motion of the Tuna Glacier [*Marchenko et al.*, 2012]. An SBE-37 pressure recorder was deployed at the bottom approximately 300 m from the glacier front at a depth of 46 m. The sampling time was 10 s. The vertical displacement of the ice was ap-

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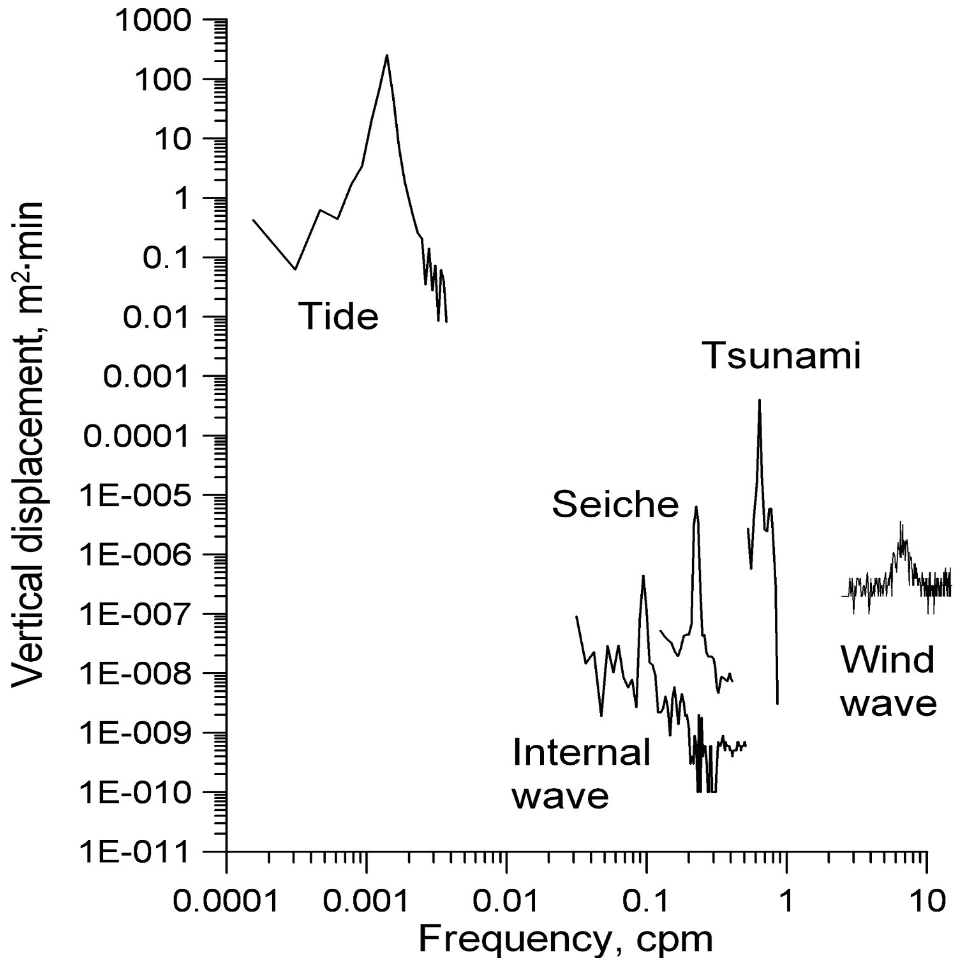

Figure 1. Combined spectra of the surface manifestation of five different wave processes measured under the ice cover in Spitsbergen fjords.

proximately 30 cm and the period of the tsunami wave was 90 s. The calculated wave length was 1850 m. The tsunami wave was generated at the low tide phase so that the water resistance to the glacier motion was minimal. This phase of the tide usually coincides with the landslide motions observed in the nature. We interpret the tsunami wave generation caused by the horizontal displacement of the glacier or probably a landslide of the moraine similarly to the landslide tsunami generated by the motion of a block of rocks down the sloping bottom. We consider that this was a glacier motion without ice fall. No new fallen ice blocks were found, but the ice cover was deformed. The initial pulse of the tsunami wave was followed by oscillations of smaller amplitude.

4. Wind Waves and Swell

The surface elevation of ice caused by wind waves and swell were measured in the Temple Fjord at a point located approximately at a distance of 1000 m from the ice edge. The measurements were made at a depth of 7 m. An SBE-39 pressure gauge was located on a sloping bottom at a distance of 300 m from the shore. The measurements were continuing for three days. The weather was very frosty and calm during the first two days. The wind increased on the third day reaching 15 m/s causing waves in the ice free part of the Temple Fjord. The ice fluctuations recorded by the instrument were approximately 2 cm, while the spectral peak was wide. The frequency of the spectral maximum corresponds to a period of 9 s. Compared to the ice displacements during the calm weather the spectral peak increased by two orders of magnitude. The frequency of the maximum spectral peak during the calm period corresponded to a period of 13 s.

5. Internal Waves

Usually, the “rigid lid” approximation is assumed in the theoretical studies of internal waves. The vertical velocity at the surface is assumed to be equal to zero; therefore, due to the kinematic condition, the internal waves cannot result in any vertical displacements of the ice cover. However, this is not absolutely true because this approximation filters off the surface mode. Even for the high frequency internal waves whose frequency is close to the Brunt-Väisälä frequency, the ice cover cannot be considered a rigid lid. Measurements of internal waves in a shallow fjord in Spitsbergen showed that fluctuations of temperature and velocity with a period of approximately 10 minutes and amplitude of internal waves about 1 m correlate with the fluctuations of the ice cover of the same period with an amplitude of a 5–8 millimeters [*Marchenko et al.*, 2011]. These results agree with the theory [*Muzylev*, 2008]. One can distinguish a spectral peak at a frequency corresponding to a period of 10 min on the spectrum of bottom pressure measured with an SBE-39 pressure gauge on a submarine slope at a depth of 8 m.

6. Summary

We consider that pressure measurements at the bottom reflect the vertical displacements of the ice surface in the frequency range from the semidiurnal frequency to a frequency corresponding to the periods of a few seconds. Figure 1 presents combined spectra of ice displacement caused by different wave classes. Surface manifestations of different waves in the ocean cover a spectral range of 14 orders of vertical displacement fluctuations versus five frequency orders of magnitude. Tidal displacements of the surface are, of course, the strongest among the wave classes considered in this study. Their frequency is the lowest in the spectral band of fluctuations presented in Figure 1. Tsunami wave generated by the motion of the Tuna Glacier has the second amplitude after the tide. Seiches, surface waves, and surface displacements induced by high-frequency internal waves are several orders of magnitude smaller. They cause vertical displacement of the ice of the order of one centimeter.

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