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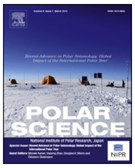

Numerical modeling of seismic waves for estimating the influence of the Greenland ice sheet on observed seismograms

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Abstract

We calculate regional synthetic seismograms for a realistic structure model beneath Greenland, including surface topography and ice sheet thickness, for observations of the multinational GreenLand Ice Sheet monitoring Network (GLISN). The thick and heterogeneous Greenland ice sheet can cause distortion of the seismic waveforms observed at the GLISN stations on ice. We developed a numerical technique that calculates accurate regional seismic wavefields with low computational requirements. Here, we calculate the elastic wave propagation up to 2 Hz for four structural models of the Greenland ice sheet from a seismic source at various depths and with different mechanisms. Our computations for a realistic ice sheet model, the near-surface seismic source produced a very characteristic wave train with a group velocity smaller than the *S*-wavespeed in the ice, considered to be an ice-sheet guided *S* wave, developed by the superposition of post-critical reflections between the free surface and the ice bed. We named this wave "*Le*", analogous to the *Lg* wave, a crustally guided *S* wave. Furthermore, computation for a deeper seismic source resulted in reinforcement of the crustal *Sg*-coda wave with a group velocity range of ~3.1–2.6 km/s, which agrees with the characteristic waveform observed on the Greenland ice sheet.

Keywords: Greenland ice sheet; seismic waveform; guided wave; finite-difference method (FDM); GLISN project

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1. Introduction

The Greenland and Antarctic ice sheets and surrounding rock areas are known as the remaining seismological frontiers for many reasons. For example, they are the setting of various seismological phenomena related to glacial movement and ice sheet dynamics, such as ice quakes, glacial earthquakes, calving events, and glacial rumblings. They also extend over a wide region, which enables the detection of various seismic phases related to the deep Earth. Seismic waves observed in these areas arrive after crossing regions within the Earth that had been poorly sampled in the past.

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Among the various cryo-seismic phenomena, the number of glacial earthquakes has increased in Greenland in recent years (e.g., Ekström et al., 2003, 2006; Nettles and Ekström, 2010). Glacial earthquakes occur mainly at the edge of the ice sheet with surface-wave magnitudes of ~5, characterized by an absence of high-frequency signals, compared with standard tectonic earthquakes of similar magnitudes. Ekström et al. (2003) discovered this new class of earthquakes and suggested that these events could be excited by large and sudden sliding motions of glaciers, as the radiation patterns show a better fit with landslide mechanisms than with standard faulting mechanisms. Ekström et al. (2006) further detected strong seasonality in the patterns of the Greenland glacial earthquakes, with fewer events during the winter, leading them to propose that such events are induced by summer surface melting followed by transport of meltwater to the base of the glacier. The frequency of glacial earthquake events on the Greenland ice sheet has doubled over the past 5 years, which is considered to be a dynamic response of the ice sheet to recent climate change.

In 2009, the GreenLand Ice Sheet monitoring Network (GLISN) was initiated as an international project to monitor changes in the ice sheet by deploying a large broad-band seismological network in and around Greenland (Dahl-Jensen et al., 2010; Clinton et al., 2014). This project is currently managed through the collaboration of 11 countries that operate 33 seismic stations, although only four stations are on the ice sheet. Four of the authors (GT, MK, ST, and YT) are members of the Japanese GLISN committee, which has been sending a field team to Greenland every year since 2011, to install and maintain the GLISN stations. In 2011, a joint USA and Japanese team established a dual seismic-GPS station (station code: ICESG-GLS2; ICESG for seismic, and GLS2 for GPS) in the middle of the Greenland ice sheet. Over the following three years (2012–2014), the team contributed to the maintenance of three ice stations (ICESG-GLS2, DY2G-GLS1, and NEEM-GLS3) and three stations on bedrock (NUUK, SOEG, and DBG), demonstrating the strong commitment of the team to support the ice stations as part of the GLISN committee. Our field activities for the years 2011–2012 are summarized by Toyokuni et al. (2014).

When analyzing seismic waveforms recorded at these ice stations we should take into account the effects of the Greenland ice sheet. Bamber (2001) published a Digital Elevation Model (DEM), ice thickness grid, and bedrock elevation grid of Greenland at a 5-km grid spacing in a polar stereographic projection (Fig. 1, see Bamber et al., 2001a,b, for details). That data indicates that the average thickness of the Greenland ice sheet is ~2 km, exceeding 3 km at its thickest point. Furthermore, substantial lateral changes in ice thickness can be observed along the E–W direction because of the rapid increase in bedrock elevation around East Greenland.

Such a thick and heterogeneous ice sheet is considered to have a strong effect on the observed waveforms. For example, Fig. 2 shows the UD component seismograms from three stations for the February 19, 2013 earthquake that occurred at the southern tip of Greenland (61.366° N, 42.538° W, 10 km deep, $m_b = 4.8$, from the ISC catalog). Compared to the waveform obtained at the bedrock station (NRS), the traces from the two ice stations (DY2G and ICESG) have a characteristic *S*-coda phase with a group velocity range of 3.1–2.6 km/s, as marked by the thick line under the traces, which is considered to be the effect of the Greenland ice sheet.

Seismic waveforms affected by the polar ice have been reported in only one paper (Robinson, 1968), which analyzed seismograms from seismic exploration of the Antarctic ice sheet and the Ross Ice Shelf. He reported characteristic *P*-coda waves recorded on the Ross Ice Shelf, and theoretically explained that these waves were formed by successive *P*-wave multiples inside the ice. He also analyzed surface wave dispersion to investigate the anisotropy of the ice. However, the work was based on geophone data of very high frequency (20–150 Hz), digitized from paper recordings; therefore, the broad-band feature of the body-wave propagation could not be well revealed.

In this paper, we conduct numerical simulations of the regional seismic wavefield on the Greenland ice sheet up to 2 Hz to investigate the generation and propagation of seismic phases affected by the ice sheet.

2. Methods

We apply a numerical technique called "cylindrical 2.5-D modeling" for computation of realistic regional synthetic seismograms up to high frequency. We use cylindrical coordinates (z,r,ϕ) where the z axis is positive downward through the seismic source, the r axis is positive in the radial direction from source to receiver, and the ϕ axis is in the transverse direction. We solve the 3-D wave equations on a z-r structural cross section under the assumption that the structures have rotational symmetry in the ϕ direction. Such an assumption enables to simulate the 3-D geometrical