Time-space variations of infrasound sources involving environmental dynamics around the Lützow-Holm Bay, East Antarctica

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Characteristic features of infrasound waves observed in the Antarctic reflect a physical interaction among the surface environment in the continental margin and surrounding Southern Ocean. Time-space variability of source location of the infrasound excitation during eight months in January –August, 2015 was investigated by using a combination of two arrays deployed along a coast of the Lützow-Holm Bay (LHB), East Antarctica. The infrasound arrays clearly detected temporal variations in frequency content and propagation direction during the period of eight months. A significant number of infrasound sources were determined and many of them were located approximately northward orientation from the arrays. Many of the events had predominant frequency content of few Hz, which were higher than the microbaroms from the ocean. On the basis of a comparison with the MODIS satellite data, these infrasound sources were considered to be the ice-quakes associated with calving of glaciers, discharge of sea-ice, collisions with icebergs around the LHB. Continuous measurements of infrasound in the Antarctic are the proxy for monitoring regional surface environment as well as temporal climate change in high southern latitude.

Keywords: infrasound, cryosphere dynmics, East Antarctica

Recurring LP-events within a tidewater greenlandic glacier

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Long-period (LP) events, with dominant frequencies below 5 Hz, have puzzled seismologists, volcanologists and glaciologists since their first detection more than 4 decades ago. Ever since, these seismic events have regularly resurfaced in the literature. Although a relationship between LP events and fluid presence in glaciers and volcanoes is often proposed, the debate surrounding the underlying source mechanism is ongoing. On the one hand, LP events are often explained as a fluid-filled cavity resonance excited by fracture-opening or rapid flow of water into a newly opened space. On the other hand, volcanologists have proposed an alternative interpretation in terms of a slow rupture combined with propagating effects through a layered material. As LP events on glaciated volcanoes demand seismologists to distinguish between ice-related signals and telltale eruption precursors, a better understanding of source mechanisms is also needed for volcanic hazard research.

In July 2015 and July 2016, we conducted two passive seismic experiments at Bowdoin Glacier, an iceberg calving glacier in northwest Greenland. Using 5 - 8 station networks installed directly on ice or rock near the glacier, we observed thousands of LP events occurring every 10 minutes or less. With 20-30-s-long, low-frequency (< 2 Hz) monochromatic coda tails, and broadband, high-frequency (up to 20 Hz) onsets.

To understand source mechanisms of LP events at Bowdoin Glacier, we detect them by pattern matching and locate them with frequency-wavenumber analysis performed at two seismic arrays. This yields source locations near the calving front of the glacier near an active subglacial discharge channel. We report LP-events features, present temporal variations, and compare them to other available time-series (GPS, borehole water pressure, AWS measurements, and time-lapse photography), which, at this point, suggest fluid-filled cracking as the most likely source mechanism.

Keywords: glacier, seismicity, Long-Period event

Seismological evidence for heterogeneous ice sheet basal conditions

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Basal conditions of the Greenland Ice Sheet (GrIS) are a key research topic in climate change studies. Recently, theoretical work provided impressive theoretical images of highly heterogeneous GrIS basal conditions, seemingly frozen in some areas, whereas it reaches pressure melting point in other areas (MacGregor et al., 2016; Rogozhina et al., 2016). An important next step in the research is to prove their theoretical work through observation.

The construction of a seismic network provides a new opportunity for direct, real-time, and continuous GrIS monitoring. Here we use ambient noise surface wave data from seismic stations all over Greenland for a 4.5-year period to detect seismic velocity changes beneath the inter-station lines. We observe clear seasonal/long-term velocity changes for many station pairs, and propose a plausible mechanism for the velocity changes. The dominant factors causing these changes might be pressurization of both the GrIS and underlying crust by seasonal/long-term snow accumulation, and depressurization by ice thinning due to GrIS flow and ice mass loss. However, heterogeneity in GrIS basal conditions might impose strong regionalities on the results.

An interesting feature is that, even at adjacent station pairs in the inland GrIS, both velocity decrease and increase can be caused by snow accumulations. The former pair might be located on a thawed bed that decreases velocity by increased meltwater due to pressure melting, whereas the latter pair might be located on a frozen bed that increases velocity by compaction of ice and bedrock. The results suggest that surface waves are very sensitive to the GrIS basal conditions.

Global warming enhances snowfall in the inland GrIS due to the moisture increase in warm air. The long-term velocity decrease at the inland areas of the GrIS may suggest that the warming climate enhances not only surface snowmelt, but also pressure melting of the GrIS basal ice. Seismological monitoring may contribute to the first real-time and continuous monitoring of the GrIS basal conditions which are indispensable to meltwater prediction in the Arctic region.

Related presentation: Progress of the GLISN field operations will be presented in this session, entitled "Seismic observations in Greenland by a joint USA and Japanese GLISN team (2011-2016)".

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Keywords: Greenland Ice Sheet (GrIS), Seismic interferometry, GLISN project

Moulins Detected as Ambient Noise Sources at the Kaskawulsh Glacier

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Hydrology is important for glacier dynamics, but it is difficult to monitor the subsurface drainage systems of glaciers by direct observations. Since meltwater drainage generates seismic signals, passive seismic analysis has the potential to be used to monitor these processes. To study continuous seismic radiation from the drainage, we analyze geophone data from six stations deployed at the Kaskawulsh Glacier in Yukon, Canada during the summer of 2014. The confluence of the north and central arms of the Kaskawulsh Glacier is an especially attractive place to study such phenomena not only because of the confluence but also because a nearby ice-dammed lake fills and drains rapidly every summer. We determine ambient noise source locations by back-projecting cross-correlated seismogram. Most of the ambient noise sequences are located in two clusters, with each cluster located in the vicinity of a moulin identified at the surface. Stronger seismic radiation is observed during the day, consistent with expected variability in melt rates. We interpret this ambient noise as being produced by meltwater drainage at moulins. We also found that precipitation controls the moulin activity at timescales longer than a day. The necessary condition of the observable seismic radiation at these moulins is that either the temperature is below its daily average or the precipitation is less than 1mm/day. We also suggest that significant rainfall may have changed the geometry of one of the moulins. Our result implies the potential of passive seismic observations to monitor water flow into subglacial channels through moulins with an affordable number of seismic stations, but quantification of the flow rate still remains a challenge. This cross-correlation back-projection technique is suitable for monitoring moulin activity, but it can potentially be applied to any localized source of ambient noise such as ocean noise, tectonic tremor, and volcanic tremor.

Keywords: Ambient noise interferometry, Subglacial drainage, Moulins

Reference seismic and thermal models for the crust and uppermost mantle beneath Antarctica from multiple datasets

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Since the last decade of the 20th Century, over 200 broad-band seismic stations have been deployed across the continent of Antarctica (e.g., temporary networks such as TAMSEIS, AGAP/GAMSEIS, POLENET/ANET, TAMNNET and RIS/DRIS by US geoscientists, as well as stations deployed by Japan, Britain, China, Norway, and other countries). In this presentation, we discuss our recent effort that builds a reference crustal and uppermost mantle shear velocity (Vs) model for continental Antarctica based on those seismic arrays. The data analysis for this effort consists of four steps. First, we compute ambient noise cross-correlations between all possible station pairs and use them to construct Rayleigh wave phase and group velocity maps at a continental scale. Coherence of the new maps with maps generated with teleseismic earthquake data from an earlier study (Heeszel et al., 2016) confirms the high quality of both maps, and the minor differences help quantify the map uncertainties. Second, we compute P receiver function waveforms for each station in Antarctica. Third, by combining all seismic measurements from the first two steps with the phase velocity maps by Heeszel et al., (2016) using a non-linear Monte Carlo (MC) inversion algorithm, a 3-D model is obtained for the crust and uppermost mantle beneath the central and western continental Antarctica and its periphery to a depth of ~ 200 km. Fourth and last, using the 3-D seismic model to provide constraints to the crustal structure, we re-invert for the upper mantle structure using the surface wave data within a thermodynamic framework, and construct a 3-D thermal model of the lithosphere of Antarctica. The resulting high resolution seismic/thermal model, that contains uncertainty estimates from the MC inversion, serves as a starting point for further development and geological interpretation. A variety of tectonic features, including a slower/hotter but highly heterogeneous West Antarctica and a much faster/colder East Antarctica, are present in the 3D model. The 3D seismic model, together with the surface heat flow map inferred from the 3-D thermal model, provide a basis for further investigation of the dynamic state of Antarctica's lithosphere and underlying asthenosphere, and provide key constraints on the interaction of the solid earth with the West Antarctic Ice Sheet.

Keywords: surface heat flow, lithosphere, antarctica, seismic tomography, thermodynamic inversion

Subglacial structure of the Whillans Ice Stream from inversion of Rayleigh wave velocities and H/V ratios

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The Whillans Ice Stream (WIS) is unique in that it represents the only place where large-scale ice stream stick-slip motion has been detected. Tidally controlled stick–slip events occur approximately twice daily, with slip propagating outward from one of two different initiation points [e.g. *Pratt et al.,* 2014]. The locations of the rupture initiation points and the slip characteristics are likely controlled by bed conditions. It is thought that the frictional properties of the WIS ice–bed interface are highly heterogeneous, including stick-spots of high friction, possibly as a result of compacted sediment or bedrock, and active subglacial lakes where frictional coefficients are effectively zero. Here we analyze Rayleigh waves from earthquakes and ambient noise correlograms recorded by 35 broadband seismic stations deployed for 50 days on the WIS during 2010–2011. Rayleigh wave phase and group velocities at 4–20 s period from ambient noise correlograms constrain the structure at crustal depths, and horizontal-to-vertical (H/V) ellipticity ratios of Rayleigh waves from both ambient noise and earthquakes at periods of 5–40 s constrain the shallow (< 5 km) velocity structure. H/V ratio modeling results suggest that ratios are highly sensitive to sedimentary layer thickness. The datasets are jointly inverted using a Bayesian Monte-Carlo formalism [*Shen and Ritzwoller,* 2016] to determine the best fitting shear velocity structure with depth. The results show a highly variable sedimentary layer beneath the WIS, with sediment thickness ranging from 1 km on the northeast side of the array to 5 km on the southwestern side, towards the Transantarctic Mountains. The rapid thickening may correspond to sedimentary infill of a rift structure just outboard of the similarly oriented Transantarctic Mountain Front. There is also evidence that the water content of the uppermost sediment layer immediately below the ice is highly variable, with low water contents inferred for the "sticky spot" where the high tide WIS slip events initiate. This study demonstrates that shallow (< 5 km depth) subice structure can be reliably retrieved from a passive broadband seismic deployment of less than two months duration.

Pratt, M. J., J. P. Winberry, D. A. Wiens, S. Anandakrishnan, and R. B. Alley, 2014. Seismic and geodetic evidence for grounding-line control of Whillans Ice Stream stick-slip events, *J. Geophys. Res., Earth Surf., 119,* pp. 333–348.

Shen, W. and Ritzwoller, M.H., 2016. Crustal and uppermost mantle structure beneath the United States. *J. Geophys. Res, Solid Earth, 121(6),* pp.4306-4342.

Keywords: West Antarctica, Ambient Noise Correlation, Subglacial material properties, Crustal Structure

