Longitudinal Seismic Waves in the Ross Ice Shelf Excited by Whillans Ice Stream Stick-Slip Events

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Rapid variations in the flow rate of upstream glaciers and ice streams may cause significant deformation of ice shelves. The Whillans Ice Stream (WIS) represents an extreme example of rapid variations in velocity, with motions near the grounding line consisting almost entirely of once or twice-daily stick-slip events with a displacement of up to 0.7 m (Winberry et al, 2014). Here we report observations of longitudinal waves from the WIS slip events propagating hundreds of kilometers across the Ross Ice Shelf (RIS) detected by more than 20 broadband seismographs deployed on the ice. The WIS slip events consist of rapid basal slip concentrated at three high friction regions (often termed sticky-spots or asperities) within a period of about 25 minutes (Pratt et al, 2014). Compressional displacement pulses from all three sticky spots are detected across most of the RIS up to about 600 km away from the source. The largest pulse results from the third sticky spot, located along the northwestern grounding line of the WIS. The best fitting propagation velocity, estimated using least squares and assuming the known location of the 2nd sticky spot, is 2.8 km/s. This agrees well with the predicted velocity derived by Press and Ewing (1951) for longitudinal wave propagation in a floating ice shelf. Particle motions are within the horizontal plane and roughly radial with respect to the WIS sticky-spots, but show significant complexity, presumably due to differences in ice velocity, thickness, and the thickness of water and sediment beneath. Strains within the ice shelf during wave passage are on the order of 10^{-6} s^{-1}, which is similar to strains from the surface waves of M_w ~ 9 earthquakes, which are known to trigger icequakes in continental ice sheets (Peng et al., 2014). Study of this phenomenon should lead to greater understanding of how the ice shelf responds to sudden forcing around the periphery.

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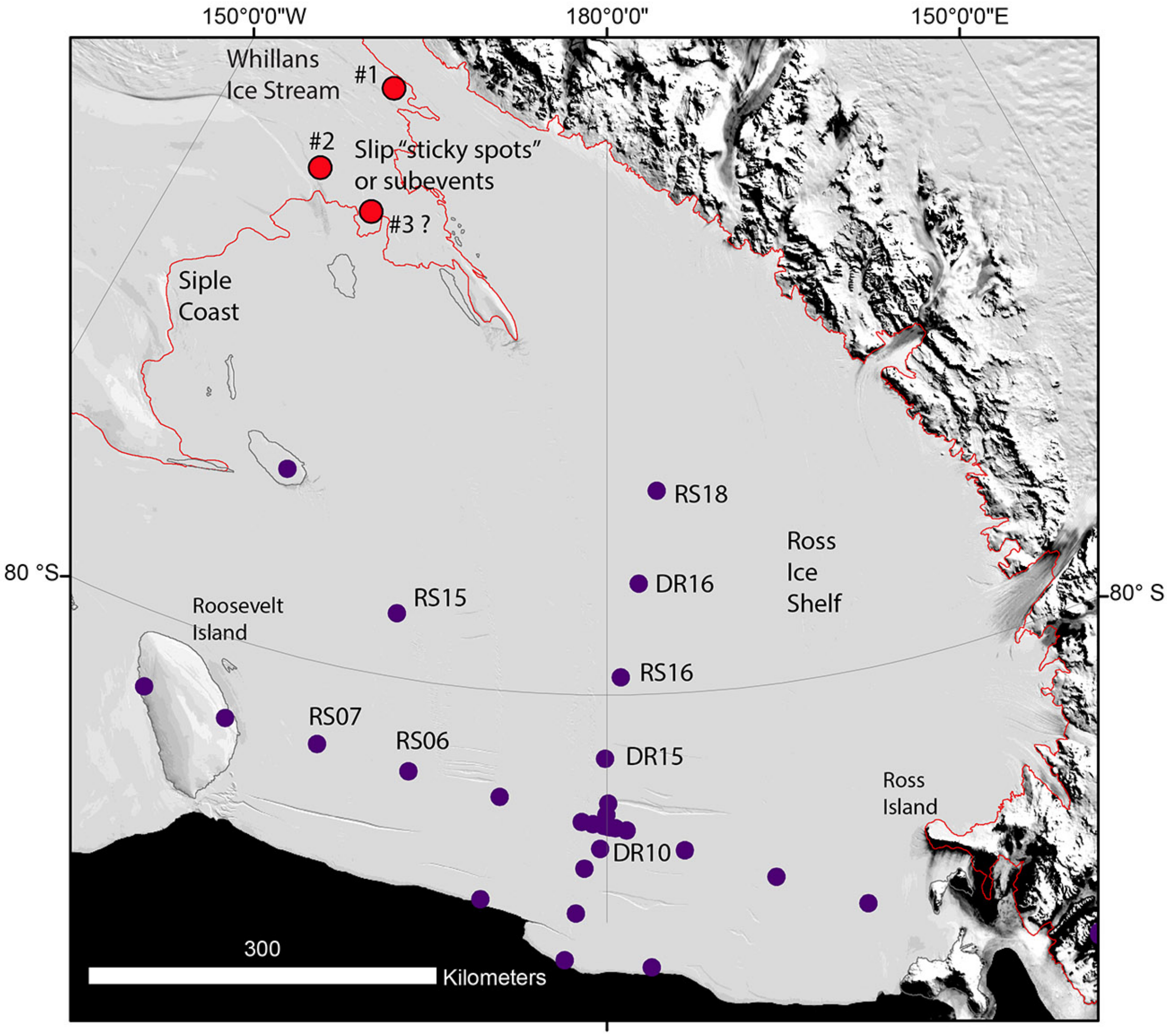
Keywords: glaciers, fault mechanics, Antarctica


150°0'0"W
180°0'0"
150°0'0"E
Whillans
Ice Stream
#1
#2
Slip "sticky spots"
or subevents
#3 ?
Siple
Coast
RS18
Ross
Ice
Shelf
80 °S
80° S
Roosevelt
Island
RS15
DR16
RS16
RS07
RS06
DR15
Ross
Island
DR10
300
Kilometers

Repeating Glacial Earthquakes Reveal Migration of Subglacial Sticky-spots.

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Many glaciers primarily dissipate their gravitational potential energy by sliding along the ice-bedrock interface. In such cases, a glacier’s driving stress is often balanced by regions of enhanced basal traction known as sticky-spots. While the role of sticky-spots in the force budget of glaciers and ice streams has long been recognized, their formation remains less well understood. In this presentation, we leverage recent advances in seismograph coverage in the Transantarctic Mountains (TAM) to study relatively large glacial seismic events (> M2) that can be observed at regional distances. We report on 5 newly discovered and one previously studied sequences of repeating glacial earthquakes. These new sequences reveal that families can remain active for up to 7 years. Additionally, by tracking subtle changes in relative arrival times as well as waveform similarity, we deduce that these sticky-spots originate from migrating bands of basal debris.

Keywords: ice sheet, repeating earthquake, glacier

東南極リュツォ・ホルム湾の多重共鳴地震微動の特徴：2014-2015
Characteristic seismic tremors with harmonic overtones in the Lützow-Holm Bay, East Antarctica: 2014-2015

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At the International Polar Year (IPY2007-2008), the 'Polar Earth Observing Network (POLENET)' was the largest contributions in establishing seismic network in the Antarctic. Several kinds of seismic signals associated with environmental variations within the atmosphere - ocean –cryosphere - solid earth system had been detected in continental margins and surrounding Southern Ocean. Ice-related seismic motions for small magnitude events are generally named ice-quakes (ice-shocks) and can be generated by glacially related dynamics. Such kinds of cryoseismic sources are classified into several kinds; movements of ice sheets, sea-ice, oceanic tide-cracks, oceanic gravity waves, icebergs and the calving fronts of ice caps. Hypocenters of these local events nearby Syowa Station were identified as their location along the coast and edges of the fast-ice in the Lützow-Holm Bay (LHB) region.
In this study, characteristic features of seismic tremors observed around LHB are demonstrated, by taking into consideration a relationship between surface environmental changes in vicinity of the area. 121 seismic tremors are recognized in both the three-component short-period seismographs (HES) and broadband seismographs (STS-1) deploying at Syowa Station, during the period from October 2014 to April 2015. Many of the tremors hold characteristics of strong harmonic overtones, in their frequency content over the 1 Hz, representing nonlinear features (upward and/or downward frequency contents) with duration times from few minutes till few hours. These tremors occur independently with the arrivals of teleseismic phases, as well as are recorded by both the type of sensors (HES and STS-1) simultaneously. The harmonic overtones can be explained by a repetitive source (Powell and Neuberg, 2003), suggesting existence of several inter-glacial asperities which generate the characteristic tremors. It implies the tremor signals might be involved in the local origins, presumably the cryosphere dynamics; discharge of fast-ice from the Bay, collision of icebergs and fast-ices, calving of glaciers.
In the austral winter in 1997, actually, a few tens of hours duration tremor of harmonic overtones were strikingly observed involving the discharge of a large volume of sea-ice (fast-ice) from LHB (Kanao et al., 2012). The similar nonlinear harmonic tremors associated with the glacial earthquakes have been reported at Whillans Ice Stream, West Antarctica (Winberry et al., 2011, 2013), with the colliding icebergs in the Ross Sea (MacAyeal et al., 2008) and nearby the Neumayer Station of Dronning Maud Land (Eckstaller et al., 2007), respectively. In contrast, relatively small tremor signals are estimated to have very local origins, such as ice-shocks in relation to the sea-ice revel changes in relation to oceanic tide variation in LHB. It is noticed that the laming signals by an ice-breaker ship "Shirase" are clearly identified around 11-13 January 2015, when the ship approach nearby Syowa Station. The laming signals hold frequency contents over few Hz with 10-15 min. intervals.
In summary, seismic tremors in terms of cryosphere dynamics are likely to be involved with variations in surface environments, and continuous monitoring of their time-space variability provides indirect evidence of climate change in the Antarctic.

キーワード：地震微動、多重共鳴、雪氷圏変動
Keywords: seismic tremors, harmonic overtones, cryosphere dynamics

グリーンランドICESG観測点で記録した2015年小笠原諸島西方沖深発地震

May 30, 2015 Bonin Islands, Japan deep earthquake (Mw7.8) recorded by broadband seismographic station on Greenland ice sheet

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May 30, 2015 Bonin Islands, Japan earthquake (Mw 7.8, depth 679.9km GCMT) was one of the deepest earthquakes ever recorded. We apply the waveform inversion technique (Kikuchi & Kanamori, 1991) to obtain slip distribution in the source fault of this earthquake in the same manner as our previous work (Nakamura et al., 2010). We use 60 broadband seismograms of IRIS GSN seismic stations with epicentral distance between 30 and 90 degrees. The broadband original data are integrated into ground displacement and band-pass filtered in the frequency band 0.002-1 Hz. We use the velocity structure model IASP91 to calculate the wavefield near source and stations. We assume that the fault is squared with the length 50 km. We obtain source rupture model for both nodal planes with high dip angle (74 degree) and low dip angle (26 degree) and compare the synthetic seismograms with the observations to determine which source rupture model would explain the observations better. We calculate broadband synthetic seismograms with these source propagation models using the spectral-element method (Komatitsch & Tromp, 2001). We use new Earth Simulator system in JAMSTEC to compute synthetic seismograms using the spectral-element method. The simulations are performed on 7,776 processors, which require 1,944 nodes of the Earth Simulator. On this number of nodes, a simulation of 50 minutes of wave propagation accurate at periods of 3.8 seconds and longer requires about 5 hours of CPU time. Comparisons of the synthetic waveforms with the observation at Greenland ice sheet station, ICESG (epicentral distance 83.4 degree), show that the arrival time of pP wave calculated for depth 679km matches well with the observation, which demonstrates that the earthquake really happened below the 660 km discontinuity. In our present forward simulations, the source rupture model with the low-angle fault dipping is likely to better explain the observations.

キーワード：深発地震、グリーンランド氷床、理論地震波形
Keywords: deep earthquake, Greenland icesheet, theoretical seismograms

Array detection of Antarctic microseisms: The effect of sea ice and Southern Ocean storms

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Antarctica is ideally situated for microseism studies because it is surrounded by the Southern Ocean where storm systems are relatively uninhibited by landmasses. Furthermore, the seasonal advancement of sea ice over the surrounding continental shelf has the effect of damping microseism generation in coastal waters. Until recently, ocean-sourced microseism studies in Antarctica have been limited to single station investigations leading to unconstrained microseism source locations. We present results from a 60 km aperture array deployed for two months on the Whillans Ice Stream, West Antarctica. We beamform month- and day-long stacks of noise correlograms to determine the prevailing noise source direction and the velocity of propagating waves for several frequency bands. Single-frequency (~15 s) Rayleigh wave microseisms are located to three coastal source areas of strong microseism generation around the continent with their intensity heavily modulated by the local sea ice extent. Long-period double-frequency (9–11 s) Rayleigh wave microseisms are generated in the deep ocean and correlate with ocean wave hindcast modeling. These deep ocean-sourced microseisms remain strong throughout the year and are relatively independent of sea ice variations. Short-period double-frequency microseisms (5–7 s) are found to contain both coastal-sourced microseisms and deep ocean-sourced body wave microseisms. The strongest arrival in this band is often observed to propagate faster than the predicted fundamental mode Rayleigh wave, slower than potential body waves, and so is interpreted to be an *Lg* phase propagating through Antarctic continental crust. *Lg* sources are likely Rayleigh wave conversions at the ocean-continent transition and body waves are modeled to be sourced in the deep ocean. *Lg* phase generation is switched on only as sea ice retreats over the continental shelves, potentially leaving only deep ocean, body wave sources throughout the winter months.

Keywords: Antarctica, Microseisms, Storms

グリーンランド氷床における広帯域連続地震波形記録を用いた地震波干渉法解析
Seismic interferometry using broadband continuous seismic waveform data from the Greenland ice sheet

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The GLISN (GreenLand Ice Sheet monitoring Network) is an international project to seismologically monitor changes in the Greenland ice sheet, by deploying a large broadband seismograph network in and around Greenland. This project is currently managed through joint collaboration by 11 countries for operating 32 seismic stations, although only four of them are on the ice sheet. Japan is a partner country from when the project was launched, and has been sending a field team every year since 2011. A joint USA and Japanese GLISN team has ever serviced three stations on ice sheet (station code: ICESG, DY2G, and NEEM) and also three stations on bedrock at the coastal area (NUUK, SOEG, and DBG), which indicates a great effort of this team among the whole GLISN committee. Especially in 2015, the joint team succeeded in relocating a seismometer at ICESG station, by excavation from 5 m depth below the snow surface.

The GLISN broad-band seismic data (20 sps) is available in realtime via the Iridium satellite network. The data is also open to the public at the IRIS Data Management Center (http://www.iris.edu/ds/nodes/dmc/). In this work, we detected the Rayleigh wave by the ambient noise cross-correlation analysis of the GLISN data, to investigate shallow structure including both ice sheet and bedrock in Greenland.

We used the vertical-component records during Jan. 1, 2015 –Apr. 20, 2015 from four GLISN stations on ice sheet (ICESG, DY2G, NEEM, SUMG). Daily cross-correlation functions (CCFs) for all possible pairs of stations are computed by the following procedure. First, we divide the continuous records into 600-s-long segments with 450-s overlap. Second, we correct the instrument response, eliminate segments with event data or error values, and apply the whitening in frequency domain and banalization in time domain. After that we calculate the daily CCFs by stacking CCFs for each segment (e.g., Shapiro & Campillo, 2004; Takagi & Okada, 2012). The final CCFs can be obtained by stacking all daily CCFs for the whole analysis range.

We found, for example, nearly constant Rayleigh wave group velocity of 2.8 km/s, for the period range of 2-14 s, on the CCF of the NEEM-SUMG pair. We also found that the ambient-noise source is well corresponded to a known source of microseisms at the southern tip of Greenland. In the presentation, we will show results for the other station pairs.

キーワード：グリーンランド、地震波干渉法、氷床、GLISN
Keywords: Greenland, Seismic interferometry, Ice sheet, GLISN

Seismic-infrasound monitoring of a tidewater calving glacier (Bowdoin, Greenland)

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Greenland is the second largest ice-covered area worldwide, where recent dramatic recession of outlet glaciers is known to be a key driver for accelerated ice-sheet mass loss. Bowdoin Glacier in northwestern Greenland (~120 km from Thule) is a grounded tidewater calving glacier that has been rapidly retreating since 2008. An observational seismic-infrasound network was installed in July 2015 near the 3-km-wide calving front of the glacier to enable near-source monitoring of frontal dynamics.
One Güralp CMG40T triaxial broadband seismometer was installed on the rocky coast in advance of the calving front, together with a time-lapse camera and a water pressure sensor in the fjord (for recording micro-tsunamis generated by calving). Four Lennartz LE-3D short- and long-period seismometers were arranged on the glacier ice in a triangle-shaped array, ~250 m from the marginal ice cliff, where icebergs are discharged into the fjord. An infrasound array comprising four pressure sensors was installed on a hill located ~3 km behind the calving front. Another two infrasound sensors were collocated with the central station of the on-ice seismic array and the broadband station. The aperture of both arrays was ~150 m. Additionally, three GPS on-ice stations with an on-rock reference station were established along the longitudinal profile of the Bowdoin Glacier to record ice-flow speed. Finally, an automatic weather station was used to record meteorological parameters near a base camp east of the glacier.
Multiple seismic and infrasound events were recorded and linked to surface crevassing, calving, presumably hydrofracturing, iceberg rotations, teleseismic earthquakes, helicopter-induced tremors, etc. Using classic seismological and array approaches (i.e., “Short Term Averaging / Long Term Averaging” and “f-k” analysis), as well as image processing, we explore and inter-compare this unique dataset. The most striking feature of the records is the temporal variability of microseismic events, which were continuously recorded over a period of two-weeks. The results show a double-peak diurnal oscillation in the number of events (up to 600 events per hour). Using high-resolution surface displacement GPS measurements, we show that the correlation between the number of events and tides is relayed through strain-rate variation. The strain rate corresponds to local extensional stretching of the glacial surface, mainly in response to increases in air temperature and falling tide velocity, which reduces back-pressure on the ice cliff.

Keywords: Greenland, tidewater glacier, icequake, seismic, infrasound, calving

多圏相互作用の一例としてのインフラサウンドと地震波の関係について
Relationship between infrasonic and seismic waves as an example of multi-sphere interaction

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Infrasound is known as lower frequency pressure waves than the hearable sound by human ears, thus the frequency range is below 20 Hz. The pressure waves can usually be generated by moving surfaces in the atmosphere with a kind of *resonance* situation with a huge moving membrane. In the earth's atmosphere, it can be realized by moving massive geophysical surfaces such as landslides, earthquakes, and tsunamis, for example. Thus, the infrasonic wave is one of the important waves in nature to be continuously and carefully monitored, if we intend to develop disaster prevention system with any kinds of sensor networks. The infrasound can be understood generally being coupled with long scale seismic waves as well as sea waves, atmospheric gravity waves, and planetary scale tidal waves.
The pressure waves can propagate in the atmosphere not only for horizontal direction but also for vertical orientations. When the waves propagate upward from the ground, the waves can enhance their amplitude as the background atmospheric pressure comes to rarefied situation in upper atmosphere, decreasing with “scale height” basis. Thus, such pressure waves with a fixed frequency can collapse themselves in a fixed atmospheric density level, thus at a fixed altitude. At an altitude of collapsing waves, the energy can be released into the molecules there and the remained energy can be thought as a source of another waves. In the mesosphere and thermosphere, many kinds of wave patterns have been found as many remote-sensing methodologies, those are, imaging of airglows and mapping of total electron contents (TEC) by analyzing the GNSS satellites receiving waves, for example.
On the other hand, at a time of meteorites encountering into the earth's atmosphere, the hypersonic entry from the outer space can generate intense pressure waves as shock waves and then propagates vertically to the ground. At the special case of Hayabusa's artificial reentry in 2010, we conducted an experiment on ground to expand many seismic and infrasonic sensors in the desert area of Australia, measuring precise infrasonic waves and its coupling into the ground motion. Such coupling phenomena can usually be detected by seismometers and sea waves monitoring stations on/near the ocean. Coupling between the infrasound in the atmosphere and the seismic waves on ground, sea waves in the ocean, or the sea ice motion on the polar sea, is usually understood as the both directing interaction as the inter-sphere couplings. Here we will introduce some interesting case studies for the inter-sphere coupling processes, showing possibilities to conduct a new disaster prevention technique for tsunami and any other geophysical destructive events and/or a new monitoring proxy for the global warming.

キーワード：インフラサウンド、地震波、相互作用
Keywords: Infrasound, Seismic waves, Interaction

海洋波浪による大気・地殻の微小振動の数値シミュレーション
Numerical modeling of microbarometric and microseismic oscillations due to ocean surface waves

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Ocean surface waves (OSWs) shake the atmosphere on sea surface and the crust on sea bottom. In order to estimate the amplitude and the propagation directions of the OSWs from the observes oscillations, we need to quantify (1) the amplitude and the propagation directions of the oscillations excited by the OSWs, and (2) the variation of the amplitude after their propagation to observation points. The quantification of (1) have been almost completed by previous mathematical studies: The excited oscillation amplitude is in proportion to the product of two OSWs' and the frequency and wavenumber are the sum of the OSWs’. Here the OSWs need to propagate in the nearly opposite directions, to have nearly the same wavelengths, and to interact nonlinearly. A recent study showed that ocean compressibility is needed for seismic body wave excitation [Ardhuin and Herbers, 2013 (AH2013)]. The quantification of (2) by mathematical approaches are, however, not so easy because it deals with many inhomogeneous and uncertain parameters such as atmospheric wind and temperature, and crust density. In such complicated conditions numerical approaches are more useful. In this paper, we develop a numerical model to quantify both (1) and (2), and validate the model. In our model, the atmosphere, ocean and crust are treated as as a single continuum and described by nonlinear and compressible equations. As the validation we impose two OSWs traveling in the opposite directions and having almost the same frequency and wavelength, analyze the resultant atmospheric and seismic oscillations, and compare them with AH2013. Our analysis shows that the imposed OSWs excite acoustic waves in the atmosphere and in the ocean. The frequency and the wavenumber of the acoustic waves are the sum of the OSWs’. The oceanic acoustic waves propagate to the ocean bottom to excite seismic surface waves with the same frequency and wavelength. In the crust seismic body waves are also excited. The excited amplitudes are consistent with AH2013.

キーワード：脈動地震、マイクロバロム、波浪
Keywords: microseisms, microbaroms, ocean surface waves

