Chapter 4

GREENLAND ICE SHEET DYNAMICS AND GLACIAL EARTHQUAKE ACTIVITIES

Masaki Kanao1, Seiji Tsuboi2, Rhett Butler3, Kent Anderson4, Trine Dahl-Jensen5, Tine Larsen5, Meredith Nettles6, Peter Voss5, Dean Childs4, John Clinton7, Eleonore Stutzmann8, Tetsuto Himeno1, Genti Toyokuni1, Satoru Tanaka2, and Yoko Tono2

1National Institute of Polar Research (NIPR), Tokyo, Japan
2Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Yokohama, Japan
3University of Hawaii, Honolulu, HI, US
4Incorporated Research Institutions for Seismology (IRIS), Washington, DC, US
5Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark
6Columbia University, New York, NY, US
7Eidgenössische Technische Hochschule (ETH), Zurich, Switzerland
8Institut de Physique du Globe de Paris (IPGP), Paris, France

ABSTRACT

The Greenland ice sheet and its response to climate change have potentially a great impact upon mankind, both through sea-level rise and modulation of fresh water input to the oceans. Monitoring a dynamic response of the Greenland ice sheet to climate change is a fundamental component of long-term observations in global science. “Glacial earthquakes” have been observed along the edges of Greenland with strong seasonality and increasing frequency in this 21st century by the data from Global Seismographic Network (GSN). During the period of 1993-2006, more than 200 glacial earthquakes were detected, but more than 95% have occurred on Greenland, with the remaining
events in Antarctica. Greenland glacial earthquakes are considered to be closely associated with major outlet glaciers at the margins of the continental ice sheet. Temporal patterns of these earthquakes indicate a clear seasonal change and a significant increase in frequency after 2002. These patterns are positively correlated with seasonal hydrologic variations, significantly increased flow speeds, calving-front retreat, and thinning at many outlet glaciers. These long-period surface waves generated by glacial earthquakes are incompatible with standard earthquake models for tectonic stress release, but the amplitude and phase of the radiated waves can be explained by a landslide source model.

The seismicity around Greenland including tectonic/volcanic events was investigated by applying a statistical model to the globally accumulated data. Calculated $b$ values, the Magnitude-frequency-dependence parameter, indicated a slight increase from 0.7 to 0.8 in 1968-2007, implying that the seismicity including glacial events around Greenland become slightly higher during the last four decades. The detection, enumeration, and characterization of smaller glacial earthquakes were limited by the propagation distance to globally distributed stations of the GSN. Glacial earthquakes have been observed at stations within Greenland, but the coverage has been very sparse. In order to define the fine structure and detailed mechanisms of glacial earthquakes, a broadband, real-time network needs to be established throughout the ice sheet and perimeter. The International Polar Year (IPY 2007-2008) was a good opportunity to initiate the program with international collaboration. Then, the “Greenland Ice Sheet Monitoring Network (GLISN)” was initiated for the purpose of identifying the dynamic response of the Greenland ice sheet to climate change.

INTRODUCTION

At the time of the International Geophysical Year (IGY; 1957-1958), it was generally understood by a majority of seismologists that no extreme earthquakes occurred in polar regions, particularly around Antarctica and Greenland. Despite the Arctic and Antarctic being classified as aseismic regions, significant earthquakes do occur both on the continent and in the surrounding oceans. Since IGY, an increasing number of seismic stations have been installed in the polar regions, and operate as part of the global network. The density of both permanent stations and temporary deployments has improved over time, and has recently permitted detailed studies of local seismicity (Kaminuma, 2000; Reading, 2002; 2006; Kanao et al., 2006).

Several kinds of natural seismic signals connected to the atmosphere - ocean - cryosphere system can be detected in polar regions. Ice-related seismic motions for small magnitude events are generally named ‘ice-quakes’ (or ‘ice-shocks’) and can be generated by glacially related dynamics (Deichmann et al., 1979; Tsuboi et al., 2000; Anandakrishnan et al., 2003; Kanao and Kaminuma, 2006). Such cryoseismic sources include the movements of ice sheets, sea-ice, oceanic tide-cracks, oceanic gravity waves, icebergs and the calving fronts of glaciers. At times, it can be hard to distinguish between the waveforms generated by local tectonic earthquakes and those of ice-related phenomena. Cryoseismic sources are likely to be influenced by environmental conditions, and the study of their temporal variation may provide indirect evidence of climate change.

In the Arctic, particularly in Greenland, the largest outlet glaciers draining the northern hemisphere’s major ice cap has suffered rapid and dramatic changes during the last decade (AMAP, 2009; Figure 1). They have lost kilometers of ice mass at their calving fronts,
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thinned by 15% or more in their lower reaches, accelerated by factors of 1.5 (Howat et al., 2005; Rignot and Kanagaratnam, 2006), and generated increasing numbers of large glacial earthquakes (Ekström et al., 2003; 2006). These significant changes, which have occurred as the climate has warmed and surface melting on Greenland has increased (Steffen et al., 2004), highlight the importance of dynamic processes operating within the polar ice sheet and at its outlet glaciers.

In this chapter, several characteristic features of cryoseismic activities are presented, particularly for the glacial earthquakes associated with the recent dynamics on the Greenland ice sheet in terms of climate change. Based on the unique seismic signals and their space-time activities associated with the ice-related phenomena, physical interaction mechanisms between the cryosphere – geosphere – ocean systems in the Arctic polar region are discussed. Moreover, the possible use as climate change indicators will be demonstrated involving the establishment of ice sheet monitoring network in Greenland.

New knowledge on the mass balance of the Greenland ice sheet

![Image](image.png)

New knowledge on the mass balance of the Greenland ice sheet.

Figure 1. A wide range of different approaches all indicate a decrease in the total mass balance of the ice sheet. The ‘boxes’ on the figure indicate the range of the mass loss estimate (vertical axis) and the time period for which the estimate is made (horizontal axis) (modified after AMAP, 2009).

CRYOSEISMIC SIGNALS IN POLAR REGION

Over the past few decades, more and more seismic observations in the polar regions by both temporary seismic networks and permanent stations have detected local seismicity. Bannister and Kennett (2002) found that the majority of the seismicity in the McMurdo
Station area was located along the coast, particularly near large glaciers. They suggested a few generation mechanisms for these events, distinguishable by their focal mechanism and depth: basal sliding of the continental ice sheet, movement of ice streams associated with several scales of glaciers, movement of sea-ice, and tectonic earthquakes. Müller and Eckstaller (2003) deployed a local seismic network around the Neumayer Station, and determined hypocenters of local tectonic events, located along the coast and the mid area of the surrounding bay. Seismic signals involving ice-related phenomena are called “ice-quakes” (ice-shocks for smaller ones), and are most frequently reported in association with glacially related mass movements of ice-sheets, or with the sea ice, tide-cracks and icebergs in the other polar areas (Wiens et al., 2008; Kanao and Kaminuma, 2006).

In West Antarctica, recent seismic and geodetic field experiments in the polar region have led to new discoveries related to the motion and deformation of ice sheets. For example, daily tidally modulated, rapid slip episodes of the Ice Stream in West Antarctica were discovered by microseismicity studies, and subsequently confirmed by GPS measurements (Anandakrishnan and Alley, 1997; Anandakrishnan et al., 2003; Bindschadler et al., 2003). Wiens et al. (2008) have more recently found that these slip events also radiate long-period surface waves, which allows additional constraints to be placed on the source mechanism. In the Antarctic Peninsula, moreover, the so-called “ice-micity” detected by a local network of hydrophone arrays in 2006-2007 illustrated the dynamic behavior of sea ice in the Bransfield Strait and Drake Passage (Dziak et al., 2009).

Local seismicity around the Lützow-Holm Bay (LHB), East Antarctica, from 1987 to 2003 was reported by Kanao and Kaminuma (2006). The seventeen events were only detected by local seismic network deployed around the LHB, except for the September 1996 m_b 4.6 earthquake in the southern Indian Ocean. Almost all the hypocenters were located along the coast, apart from a few on the northern edge of the continental shelf. Several of these events could be large ice-quakes associated with the sea-ice dynamics around the LHB or in the southern ocean. As an example of the sea-ice and iceberg dynamics affecting seismic signals, a large volume of sea ice was discharged from LHB during the 1997 austral winter, as clearly imaged by NOAA satellite (Ushio, 2003). The broadband seismographs at Syowa Station (SYO) significantly recorded characteristic waveforms associated with the discharge events (Kanao et al., 2011). The long-duration sea-ice tremors had very distinct spectral characteristics that distinguished them clearly from ordinary teleseismic and/or local tectonic events. Several sequences of harmonic over-toned signals, presumably associated with the merging of multiple ice volumes, appeared on the Power Spectrum Density (PSD).

Identification of the exact sources that produced these characteristic signals has not yet been completed, and theoretical modeling will most likely be required to explain the physical processes. Similar cryoseismic phenomena were also reported around the Ross Sea (MacAyeal et al., 2009), the marginal sea of the Antarctic Peninsula (Bohnenstiehl et al., 2005; Dziak et al., 2009), as well as the continental margin of Dronning Maud Land (Muller and Eckstaller, 2003). In particular, iceberg-originated harmonic tremor emanating from tabular icebergs was observed by both seismo-acoustic and local broadband seismic signals (MacAyeal et al., 2009). The tremor signals consisted of extended episodes of stick-slip ice-quakes generated when the ice-cliff edges of two tabular icebergs rubbed together during glancing, strike-slip iceberg collisions. Source mechanisms of such harmonic tremors might provide useful information for the study of iceberg behavior, and a possible method for remotely monitoring iceberg activity.
The processes that result in seismic events associated with glaciers (internal deformation, sliding at the base, disintegration at the calving front) are all integral to the overall dynamics of glaciers, and seismic observations of glaciers therefore provides a means of monitoring changes in their behavior over time. Because seismology detects processes internal to the ice and the Earth, the monitoring capability that it provides is complementary to that of other methods, such as satellite remote sensing and GPS geodesy. Nevertheless even with the development of local seismic networks during two decades (e.g., Kanao and Kaminuma, 2006; Muller and Eckstaller, 2003; Bannister and Kennett, 2002), we can hardly distinguish between the waveforms generated by local tectonic earthquakes and those of ice-related phenomena.

**ICE SHEET DYNAMICS IN GREENLAND**

The Greenland ice sheet and its response to climate change have potentially a great impact upon mankind, both through the long-term sea-level rise and through modulation of fresh water input to the oceans. The response of glaciers and ice sheets to climate change is critically important, but poorly understood. Ice sheets themselves affect climate, and ice discharged from major glaciers makes a significant contribution to sea-level change and ocean circulation patterns. The Intergovernmental Panel on Climate Change (IPCC, 2007) currently estimates that approximately half of Greenland’s contribution to sea-level rise comes from dynamic processes such as the discharge of ice from outlet glaciers, while the other half comes from melting (Figure 2). This assessment does not include possible effects from rapid changes in dynamic behavior of the ice sheet and glaciers, primarily because these changes, and their climatic drivers, are insufficiently understood.

In Greenland, the largest outlet glaciers draining the northern hemisphere’s major ice cap has suffered rapid and dramatic changes during the last few years. They have lost kilometers of ice at their calving fronts, thinned by 15% or more in their lower reaches, accelerated by factors of 1.5-2 (Howat et al., 2005; Rignot and Kanagaratnam, 2006), and generated increasing numbers of glacial earthquakes (Ekström et al., 2006). These changes, which have occurred as the climate has warmed and surface melting on Greenland has increased (Steffen et al., 2004), highlight the importance of dynamic processes operating within the Greenland ice sheet and at its outlet glaciers. Internationally monitoring the dynamic response of the Greenland ice sheet to climate change is a fundamental component of long-term observational efforts for monitoring climate change.

The spectrum of time scales over which significant velocity variations in outlet-glacier flow can occur now appears to be much broader than previously believed. In addition to interannual variations in flow speed at Greenland’s major outlet glaciers, seasonal variations in flow speed have been observed near the ice sheet equilibrium line (Zwally et al., 2002), and high-rate continuous GPS analyses have demonstrated sub-daily variations in glacier velocity, correlated with the ocean tides, at marine-terminating glaciers in both East Greenland (Hamilton et al., 2006; Davis et al., 2007; de Juan et al., 2008) and Antarctica (Anandakrishnan et al., 2003; Bindschadler et al., 2003). Significant variations in outlet-glacier velocity on time scales of a few minutes or less have been inferred from recordings of
glacial earthquakes (Ekström et al., 2003), and rapid variations in flow speed during the summer season have been documented from GPS observations (Nettles et al., 2008).

Variations in glacier flow speed lead to changes in strain patterns and strain rate in the glaciers and ice sheet, resulting in large internal deformations that include dynamic thinning of the ice. The observed velocity and strain variations are of particular interest because ice flow through outlet glaciers accounts for the majority of mass loss from the Greenland Ice Sheet over the last decade, with this mass loss leading to a doubling of Greenland’s contribution to sea-level rise (Rignot and Kanagaratnam, 2006).

Understanding what controls flow configuration at outlet glaciers, and the time scales over which they may respond to climatic forcing, is therefore of great importance for proper modeling of systems affected by the transfer of fresh water from the polar ice caps to the world’s oceans. However, the mechanisms that allow for, or drive, temporal variations in flow are currently poorly known. It is also unclear how variations in flow behavior at different timescales are related to one another.

Glaciers near Kangerlussuaq, southwestern Greenland, 2011 June


Figure 2. Photos of Glaciers near Kangerlussuaq city, southwestern Greenland, on June 2011, taken by G. Toyokuni.

Glacial related earthquakes have been observed along the edges of Greenland with strong seasonality and increasing frequency since 2002 (Ekström et al., 2003; 2006) by continuously monitoring data from the Global Seismographic Network (GSN; Figure 3). These glacial earthquakes in the magnitude range 4.6-5.1 may be modeled as a large glacial ice mass
accelerating and decelerating over a duration of 30 to 60 seconds. In general, recent experience now suggests that the glacial environment is richer in seismic sources than previously thought. The following sections describe several new types of seismic sources that have been detected on Greenland, and that are directly associated with the dynamic processes leading to ice loss from the Greenland ice sheet.


Figure 3. Location map of the broadband seismic stations deployed by the Greenland Ice Sheet Monitoring Network (GLISN) project. (proposed to NSF on 2007) Red symbols denote existing GSN/FDSN stations and green triangles indicate proposed GLISN sites, where station codes indicate existing or recently occupied GEUS sites.
GLACIAL EARTHQUAKES

In addition to the short-period cryoseismic signals mentioned in the previous section, a new class of seismic events associated with the Greenland ice sheet was discovered in 2003 (Ekström et al., 2003). Recently compiled data by the Geological Survey of Denmark and Greenland (GEUS) for all the glacial earthquakes recorded since 1958 represents the same location as by Ekström et al. (2003). These “glacial earthquakes” generate long-period (T>25 s) surface waves equivalent in strength to those radiated by standard magnitude-5 earthquakes and are observable globally. The glacial earthquakes radiate little high-frequency energy, which explains why they were not detected or located by the traditional earthquake-monitoring agencies, such as the National Earthquake Information Service (NEIS) or the International Seismological Centre (ISC). These events are two-magnitude units larger than previously reported seismic phenomena associated with glaciers (Tsai and Ekström, 2007), a size difference corresponding to a factor of 1,000 in seismic energy. Figure 4 represents the distribution of locations for glacial earthquakes around Greenland and vicinity, after the listed events by Tsai and Ekström (2007).

The long-period surface waves generated by glacial earthquakes are incompatible with standard earthquake models for tectonic stress release, but the amplitude and phase of the radiated waves can be explained well by a so-called landslide source model (Kawakatsu, 1989), which describes the forces exerted on the earth as a mass initially at rest on the Earth’s surface is accelerated downhill by gravity and is subsequently arrested by friction. With this model, the seismic data have been used to place constraints on the direction of sliding motion, and on the product of sliding mass and sliding distance (Tsai and Ekström, 2007), and there is
good agreement between the inferred sliding direction during the glacial earthquakes and overall glacier flow directions. The duration of this sudden motion is constrained by the seismic data to be 30-60 s. An example of waveforms for a recent glacial earthquake in Baffin Bay is shown in Figure 5. The predominant long period can be identified for all the traces of the recorded stations.

Most aspects of the mechanics and detailed nature of glacial earthquakes remain unclear, however, mainly as a result of the limited constraints provided by teleseismically observable long period seismic radiation. Uncertainties in the geographical locations of the events are of the order of 20 km, which originally made it unclear whether the earthquakes involved a very limited portion of the glacier or represented deformation over a large volume.

Recent work (Joughin et al., 2008; Nettles et al., 2008; Amundson et al., 2008; Nettles and Ekström, 2010) provides clear evidence that glacial earthquakes are temporally associated with major calving events at Greenland’s outlet glaciers. Several possible mechanisms have been explored theoretically (Johnston, 1987; Tsai et al., 2008). These mechanism models are characterized by (1) lost basal resistance coupled to viscoelastic deformation with extensive internal crevassing or with low effective elastic modulus and possibly low effective viscosity or (2) by non-equilibrium calving, such as having large icebergs capsize into the glacier front.

New observations from a continuous GPS network operating on Helheim glacier during a glacial earthquake there in the summer of 2007 have also placed new constraints on the source process (Nettles et al., 2008). Investigations of ice-front variation and tidewater behavior on the Helheim and Kangerdlugssuq glaciers by using satellite images (Joughin et al., 2008) then found that the relations of the large iceberg-calving episodes coincided with the occurrence of glacial earthquakes.

Figure 5. An example of waveform for glacial earthquake event on August 26, 2011, in Baffin Bay at 60.3 W, 75.8 N, (hypocentral information by Columbia University). The station codes are listed with the hypocentral distance and the data have been band-pass filtered from 0.01Hz to 0.1Hz. All the waveforms are provided by GEUS.
The timing of glacial earthquakes is very closely associated with abrupt increases in glacier speed, but no sudden displacements of the glacier surface are observed at the time of seismologically detected earthquakes. Although it is now understood that the “landslide” mass involved in the earthquakes is relatively small (approximately 1 cubic km) and confined to the newly calved ice mass, there remains a need for improvement in detailed physical models of the earthquake source process.

A second new class of seismic source that has recently been discovered on Greenland is a sustained seismic-wave radiation called a seismic “rumbling” (Rial et al., 2009). These events were detected and located using a temporary array of seismometers deployed approximately 50 km north of the Jakobshavn Isbrae glacier. The events appear as long-lasting (up to 40 minutes) sources of radiation and are associated with, and frequently culminate with, an impulsive burst of seismic radiation that has the characteristics of a regular double-couple earthquake. Whereas the onset of a rumbling frequently is associated with calving events at the front of the glacier, the culminating events are located 5–15 km upstream along the trunk of the glacier. More than 80 of these events have been recorded over two summer seasons. A few of the detected rumblings are coincident in time with detections of the long-period glacial earthquakes discussed above, strongly suggesting a common cause.

**STATISTICS ON SEISMICITY**

Over the fourteen-year period between 1993 and 2006, more than 200 glacial earthquakes were detected worldwide. More than 95% of these have occurred on Greenland, with the remaining events in Alaska and Antarctica. Greenland glacial earthquakes are closely associated geographically with major outlet glaciers of the Greenland Ice Sheet. Ekström et al. (2006), as well as Nettles and Ekström (2010), reported on the temporal patterns of the occurrence of events, finding (1) a clear seasonal signal and (2) a significant increase in the frequency of glacial earthquakes on Greenland in 2002-2005 (Figure 6). These patterns are positively correlated with seasonal hydrologic variations, recent observations of significantly increased flow speeds, calving-front retreat, and thinning at many outlet glaciers. Broadband seismic observations of recent large calving events from the Jakobshavn Isbrae glacier in the Ilulissat Icefjord in Western Greenland were discussed by Amundson et al. (2008). Figure 7 indicates the annual variations in detectability of all earthquakes in Greenland since 1958 compiled by GEUS. The number of earthquakes recorded per year represents the significant increase in the last decade.

The last four decades of seismicity in Greenland and surrounding regions were investigated by Kanao et al. (2010), as for the all tectonic and volcanic events plausibly include the glacial earthquakes (Figure 8). Here, we applied the statistical model of the Epidemic Type Aftershock Sequences (ETAS), on the basis of the Gutenberg–Richter’s magnitude frequency distribution. The ETAS model is a statistical tool for analyzing the occurrence times of earthquakes associated with magnitude, and has been used for the discrimination of seismicity patterns in many regions (Ogata, 1988). The model stochastically classifies earthquakes into aftershocks and background events. The background events are
Figure 6. (a) Histogram showing seasonality of glacial earthquakes in Greenland based on detections for 1993–2008. Bars show the number of earthquakes per month detected in Greenland. (b) Histogram showing the number of glacial earthquakes detected in Greenland each year since 1993 (after Nettles and Ekström, 2010).

Figure 7. A: Histogram showing the variations for detectability of all earthquakes on or near Greenland by GEUS. (left) Number of earthquakes recorded per year since February 1958. (right) Magnitude distribution of the total earthquakes recorded since February 1958.
Figure 8a.

Figure 8 (Continues)
Figure 8b.

Figure 8. Background seismicity and Magnitude–frequency-dependent $b'$-values for Greenland and the neighboring areas, on the basis of the statistic ETAS model using the hypocentral data collected at the International Seismological Centre (ISC). G: Greenland block; I: Iceland block; C: northern Canadian block. (a) 1968-1977; (b) 1978-1987; (c) 1988-1997; (d) 1998-2007.

Figure 9. Hypocentral map of the earthquake occurred at Svalbard with 6.2 magnitude in Richter scale on February 21, 2008 (left; main shock events, right; after shock events; hypocentral information by NEIC/USGS).
Figure 10. Top page of the web-site for the Greenland Ice Sheet Monitoring Network (GLISN; http://glisn.info).
obtained by stochastically removing clustered events or aftershocks. The same procedures were applied for the space-time analyses in seismicity around the Antarctic Plate, particularly in the vicinity of the Balleny Island region (Himeno et al., 2011).

Analysis of a seismic activity estimated by using the ETAS model applied to events in the region of Greenland compiled by the International Seismological Center (ISC) indicates a slight increase in magnitude-dependency b-values from 0.7 to 0.8 from 1968 to 2007 (Figure 8). This result implies that total seismicity in this Greenland area, including glacial earthquakes, has slightly increased in magnitude over the last four decades. However, before correlating this evidence to global climate change, this increase must be evaluate considering the large changes in this period in terms of instrumentation quality and seismic station density, both globally and specifically within the Arctic region.

Concluding this section, a strong earthquake reaching 6.2 on Richter scale hit Svalbard on 21 February 2008 (Figure 9). The epicenter was located in Storfjorden area, 10 km under the sea bed and 136 km from Longyearbyen city. Several smaller shakes were also registered both before and after the main one took place. There had been no damages reported from Longyearbyen during the events. The earthquake was well recorded by all NORSAR seismometers as well as by many other global stations, including the GSN. The most recent strong earthquake took place on 18th Jan 1976 and had a magnitude of 5.5. The hypocenter of this event is located on the margin of the European continental crust, and therefore, the events are plausibly associated with the crustal uplift after deglaciation (the post glacial rebound). Alternatively these large events could relate to ice-mass movement or calving of glaciers in the vicinity of Svalbard, however, the mechanisms consistent with a double-couple, in which case the glacier motion seems less likely.

ICE SHEET MONITORING NETWORK

Seismic activity on Greenland is dominated by sources associated with movement and deformation of the ice sheet. Large tectonic earthquakes are rare, which in part explains the paucity of permanent seismic instrumentation on Greenland. Recent changes are the increase in frequency of glacial earthquakes in 2001-2005, and spatial variation in glacial earthquake activity, including the recent initiation of glacial earthquake activity at high latitudes on Greenland’s west coast (Ekström et al., 2003; 2006). A network of seismic stations that covers the area of Greenland with relatively uniform inter-station spacing will allow several questions related to ice-related seismicity to be answered. For examples, are the unusual rumblings associated with Jakobshavn Isbrae unique to that location, or is this type of activity occurring at other glaciers and ice streams? Stations on the ice sheet will allow for monitoring of seismogenic deformation in the interior associated with variations in the rate of ice loss at the margins. These stations will also be very useful for constraining the locations of seismic events occurring in the upper reaches of ice streams.

Generally, a permanent monitoring network on Greenland would serve an analogous purpose to that of a network deployed to monitor a volcano. After an initial period of characterization of background seismicity, volcano networks become useful in documenting changes in the seismic activity of the volcano. Migration of seismicity, changes in the intensity of seismic activity, and the occurrence of different types of earthquakes are all
quantifiable changes that are used to inform the scientists of the state of the volcano and that can be used to predict its future behavior and potential for eruption. The detection, enumeration, and characterization of smaller glacial earthquakes has for a long time been limited by the propagation distance to globally distributed seismic stations of the GSN and Federation of Digital Seismograph Networks (FDSN). Although glacial earthquakes have been successfully observed at stations within Greenland in recent years (Larsen et al., 2006), the station coverage was too sparse for detailed studies.

In order to define the fine structure and detailed mechanisms of glacial earthquakes within the Greenland ice sheet, a broadband, real-time seismic network needed to be installed throughout Greenland and surrounding its perimeter (the Greenland Ice Sheet Monitoring Network; GLISN; Figure 10; Anderson et al., 2010; Dahl-Jensen et al., 2010; Kanao et al., 2008). This effort, led chiefly by the Incorporated Research Institutions for Seismology (IRIS) Consortium for the United States, is international in its scope and approach, and involves the participation of the GEUS, the GeoForschungsZentrum Network (GEOFON) of Germany, the Eidgenössische Technische Hochschule (ETH) Zurich of Switzerland, the Istituto Nazionale di Geofisica e Vulcanologia (INGV) of Italy, NORSAR of Norway, Natural Resources Canada, Institute of Geophysics of the Academy of Sciences of Poland, Institut de Physique du Globe de Paris of France (GEOSCOPE), the National Institute of Polar Research (NIPR) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) of Japan.

The open collaboration of these national groups creates a foundation welcoming other international interest and participation, not only for seismological monitoring Greenland’s Ice Sheet, but also for other observations using the infrastructure being developed. The International Polar Year (IPY 2007-2008) was an opportunity to initiate the new program by international collaboration. An example of this new international cooperation on the remote ice sheet is the GLISN station at Ice-S (69.1°N, 39.6°W, 2941 m above sea level), which initiated observations in June 2011 through the collaboration of IRIS, NIPR and JAMSTEC (Figure 11). An image of the fast data viewing system developed by IRIS/PASSCAL is shown in Figure 12. The data shown here for Ice-S station were transmitted by the Iridium satellite communication system from the field sites on Greenland.

Continuous digital records from the Global Seismographic Network (GSN; Butler and Anderson, 2008), the FDSN and their precursor networks extend back more than 40 years, and hence open up the possibility of using seismic data to investigate climate change. The new permanent network in Greenland (GLISN) significantly increases coverage of the surrounding Arctic region. The GLISN has also a significant role in the Sustaining Arctic Observing Network (SAON) of the International Arctic Scientific Committee (IASC) under the International Council for Science (ICSU). Additionally, another large IPY-endorsed program is the ‘Polar Earth Observing Network’ (POLENET; Figure 13; Wilson and Bell, 2011; http://www.polenet.org/) whose aim was to establish a geophysical network to cover the whole Antarctic continent as well as Greenland, and Lapland in the Arctic.

The seismic data obtained by the combined POLENET network are being used to clarify the heterogeneous structure of the Earth, particularly in the Antarctic region, by studying the crust and upper mantle and the Earth’s deep interior, including features such as the Core-Mantle-Boundary (CMB), the lowermost mantle layer (D” zone) and the inner core. Figure 14 represents the distribution of the permanent GSN/FDSN stations in the Arctic together with
Figure 11. (a) Location of the Ice-S station (39.6 W, 69.1 N, 2941 m above sea level) by open red circle. (b) Flight course from Kangerlussuaq (SFDJ) to Ice-S station. (c, d) photos of installation for the Ice-S station on June 2011, taken by G. Toyokuni.
Figure 12. An image of the fast data viewing system developed by PASSCAL applied for the GLISN stations (in case of Ice-S). http://xeos.passcal.nmt.edu/cgi-bin/sensordata.cgi?lstProjects=13. The data shown here were transmitted by the Iridium satellite communication from the field sites.
Figure 13. Continuously recording GPS (circles) and seismic stations (crosses) prior to IPY 2007-2008 (a, b) and deployed during the extended IPY period from 2006 to early 2010 (c, d). (Credit: POLENET database, maintained by T.J. Wilson; maps drafted by M. Berg and S. Konfal). All stations in Antarctica and Greenland contributed to the POLENET program.
Hypocenters and permanent stations.

Figure 14. (Continues)
Figure 14. (a) A distribution map of the permanent FDSN stations in the Arctic region (red color; data compiled from IRIS/DMS and PASSCAL). Hypocentral data in the northern hemisphere were collected in 1990-2004 (indicated by green color). (b) Distributions of the observable earthquake numbers for the individual epicenter distances of 40°-60° (upper left), 60°-90° (upper right), 145°-160° (lower left) and 160°-180° (lower right), respectively. Gray contour scales indicate the accumulated earthquake numbers that are counted at each location using an earthquake list for the period from 1990 to 2004.
hypocenters from ISC in northern hemisphere. Mapping of the observable earthquake seismicity for the individual epicenter distance groups indicates the good coverage to utilize the regional and teleseismic events for the study on deep interior of the Earth. In addition to conventional seismological targets (e.g. crust and lithosphere structure, inner core structure), the IPY seismic stations can be used to help monitor geographical variations in climate indicators, over the span of 2-3 years during IPY and longer using the legacy of seismic stations established. All data from IPY experiments will be distributed to the scientific community.

CONCLUSION

We have described several features of cryoseismic signals, particularly involved in the glacial earthquakes associated with the recent ice sheet dynamics in Greenland. Based on the characteristic cryoseismic signals and their time-space activities, physical interaction mechanisms between the cryosphere - geosphere - ocean systems in the Arctic polar regions were demonstrated. Moreover, the plausible utilization of climate-change indicators were presented involving an ice sheet monitoring network.

Most of the community agrees that the polar regions play a critical role in the Earth’s climate system. The Greenland ice sheet and its response to climate change potentially have a great impact upon mankind, both through long-term sea-level rise and through modulation of fresh water input to the oceans. Monitoring the dynamic response of the Greenland ice cap and the Antarctic ice sheet, are important components of a long-term effort to observe climate change on a global scale. Future directions in global monitoring targets will emerge from multidisciplinary projects combining the data of several global networks.

In Greenland, long-term seismic monitoring of the ice sheet was established as a baseline for detailing seismic activity in the Arctic polar region. Deviations from the baseline will be useful indicators of dynamic changes that could signal, for example, new mechanisms of dynamic collapse of the ice sheet. At least as importantly, the seismic data obtained by the GLISN network can provide, along with the monitoring capability, new constraints on the dynamics of ice sheet behavior and its potential role in the sea-level rise during the coming decades.

There is still a lot to be learned about the physical mechanisms of interaction between the cryosphere-geosphere-ocean systems in the polar regions. Continuous observation by a sufficiently large number of high-quality stations, as well as theoretical work, will be necessary to make progress in this field. Given the high cost and technical difficulties of continuous observation in the polar regions, such efforts will require strong international collaboration well beyond the end of the International Polar Year.

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