Seismic Wave Interactions Between the Atmosphere - Ocean - Cryosphere System and the Geosphere in Polar Regions

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1. 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. Despite the Antarctic being classified as an aseismic region, several 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 (Fig. 1). Ice-related seismic motions for small magnitude events are generally named 'ice-quakes' (or 'ice-shocks') and can be generated by glacially related dynamics (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 ice caps. 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 have suffered rapid and dramatic changes during the last

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decade. They have lost kilometers of ice mass at their calving fronts, 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 features of seismic wave propagation in polar regions are illustrated, through discussion of travel time anomalies, wave amplitudes and the frequency content of power spectral densities (PSD). Characteristic seismic signals are classified into one of three main categories according to their origin: ice-related phenomena, oceanic loading effects and atmospheric perturbations. The physical interaction mechanisms between the atmosphere - ocean - cryosphere system and the geosphere (solid Earth) in polar regions are analyzed, and their possible use as climate change indicators is discussed.

Fig. 1. Photographs of atmosphere - ocean - cryosphere and geosphere environments in polar regions, particularly around the Lützow-Holm Bay (LHB) region, Antarctica. Left , from top to bottom: a glacier, tide-cracks, iceberg and sea ice. Middle: Syowa Station (SYO) in the Ongul Islands, surrounded by sea-ice and separated from the continent by the Ongul Channel. Right, from to to bottom: glacier and mountains, the 'spring river' between sea-ice and the coast, ice fall at the edge of a small glacier. All photos are provided by M. Kanao and NIPR

2. Seismic signals from the ocean

All seismic stations deployed on the Earth's surface record ubiquitous signals at periods between 4 and 25 s are commonly referred to as "microseisms". In the absence of earthquakes, microseismic waves are the strongest amplitude signals worldwide. Microseisms are considered to be dominated by Rayleigh waves that arise from gravity waves in the ocean that are forced by surface winds. The period ranges of microseisms are dictated by the physics of gravity wave generation, and are constrained by the speed and extent of Earth's surface winds (Aster et al., 2008; Aster, 2009; Bromiriski, 2009).

The microseism spectrum has a bimodal composition, caused by the existence of two distinct physical mechanisms that transfer ocean wave energy to seismic waves in geosphere

(Fig. 2). The first spectral peak between approximately 12 and 30 s, commonly called "primary" or single-frequency microseism (SFM), arises from the transfer of ocean gravity wave (swell) energy to seismic waves as oceanic waves shoal and break in the shallow waters. The highest amplitude and longest period swells are created by large and intense storms that generate strong sustained winds over a large area. Swell propagates dispersively across ocean basins, which results in longer period swell arriving at the coast before the shorter period swell. This period-dependent delay is readily measured in data recorded by seismic stations, ocean buoys, and seismographs, such as those deployed recently on a giant Antarctic iceberg (MacAyeal et al., 2009).

The second, more prominent, microseism peak between approximately 4 and 10 s, commonly called secondary or double-frequency microseism (DFM), arises from nonlinear interaction of interfering ocean wave components that produce a pressure pulse at double their frequency. This pressure pulse propagates with little or no attenuation to the sea floor where it generates seismic waves. The DFM is thought to be generated both near the coasts, where coastal swell reflection can provide the requisite opposing wave components, and in the deep southern ocean.
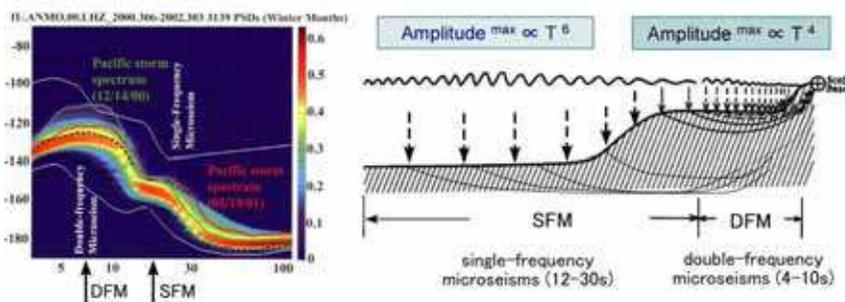
An example of PSD and the origin for microseisms

Fig. 2. Left: An example of a typical power spectral density plot (PSD) (modified after Aster, 2009). Right: An illustration of the origin of microseisms (modified after Hatherton, 1960)

3. Microseisms in polar regions

On a global scale, microseism amplitudes are generally highest during local winter, because nearby oceans are stormier in winter than in summer (Stutzmann et al., 2009). In polar regions, particularly from the evidence of Antarctic stations, the opposite observation is made: microseism amplitude is attenuated during local winter for both primary and secondary microseisms (Hatherton, 1960). The observation is explained by the presence of the sea-ice extent impeding both the direct ocean-to-continent coupling that generates the SFM and the coastal reflection which is an important component in the generation of the DFM (Grob et al., 2011).

In order to illustrate the variability of microseismic amplitude over time we have calculated power spectral densities (PSD) for data from the broadband seismometer (STS-1) at Syowa Station (SYO; 39E, 69S, Lützow-Holm Bay, East Antarctica). During time period shown, continuous STS-1 waveform data with 20 Hz sampling were automatically transmitted from

SYO to the National Institute of Polar Research (NIPR) by an Intersat telecommunication system (Aoyama and Kanao, 2010; Iwano and Kanao, 2009).

Figure 3 shows PSDs of the vertical broadband seismometer at SYO for a typical austral summer day in January, 2010, over the period band 0.1-100s. The DFM is clearly visible, as are several high-frequency dispersed signals that may be caused by variations of the ice environment in the vicinity of the station.
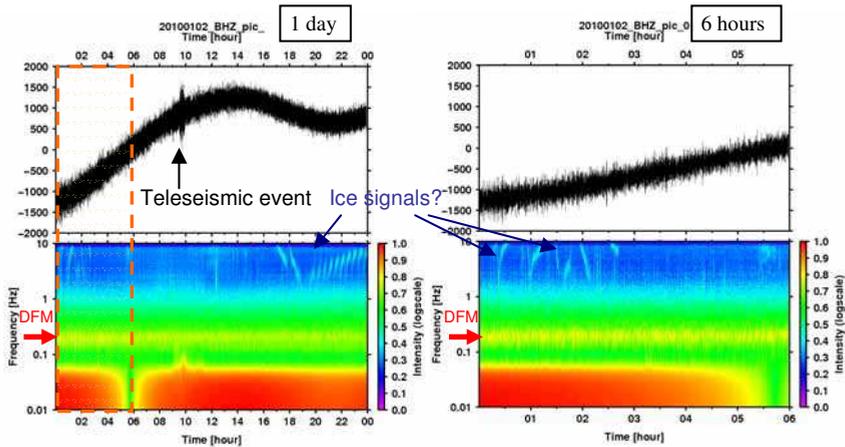

Fig. 3. The power spectral densities (PSD) of the vertical broadband seismometer (STS-1V) at SYO for January 02, 2010. Left: one day of data. Right: 6 hours of data, corresponding to the shadowed area of the left figure.
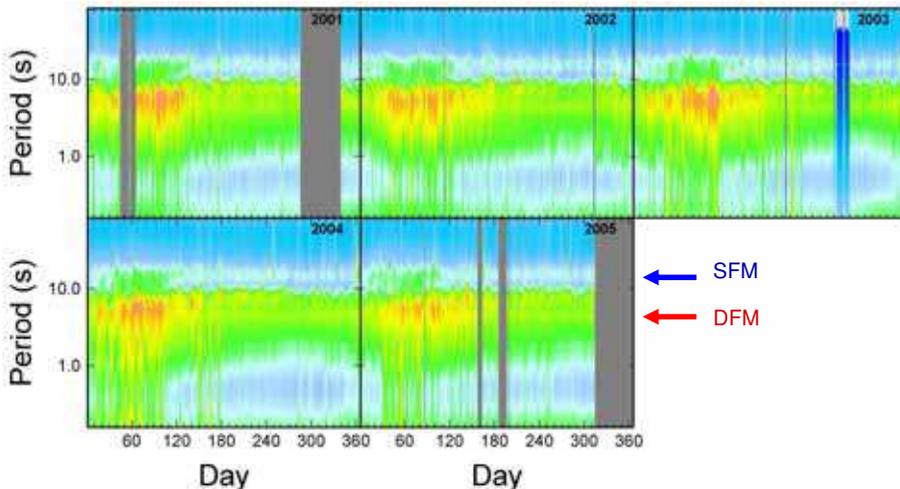

Fig. 4. Power spectral densities (PSD) of the broadband seismometer (STS-1V) at Syowa Station (SYO), Antarctica, for a period in 2001-2005. Signals corresponding to SFM and DFM are indicated by blue and red arrows (modified after Grob et al, 2011)

Figure 4 shows similar PSDs calculated for 5 consecutive years (2001-2005) over the period band 0.1-80 s. The DFM can be identified all year round, though with distinctly lower amplitude during the local winters (april-october). The relatively high degree of inter-annual variability presumably reflects the large influence of extratropical cyclonic storms that commonly affect both the northern and southern oceans. On the contrary, the SFM is observed only under excellent storm conditions during the austral local winter. The strength of both DFM and SFM are strongly related to the seasons, but presumably also to local ice conditions. For example, summers with lower amplitude microseisms at SYO correspond to residual sea-ice extension area near the Enderby Land coast (Grob et al, 2011).

In contrast, one-day PSD images for broadband seismograph at SYO clearly represent the continuous DFM; which was detectable in any time slots when storms or blizzards visited the station (Fig. 3). The DFM could probably be generated from the near southern oceans, including the vicinity of Lützow-Holm Bay.
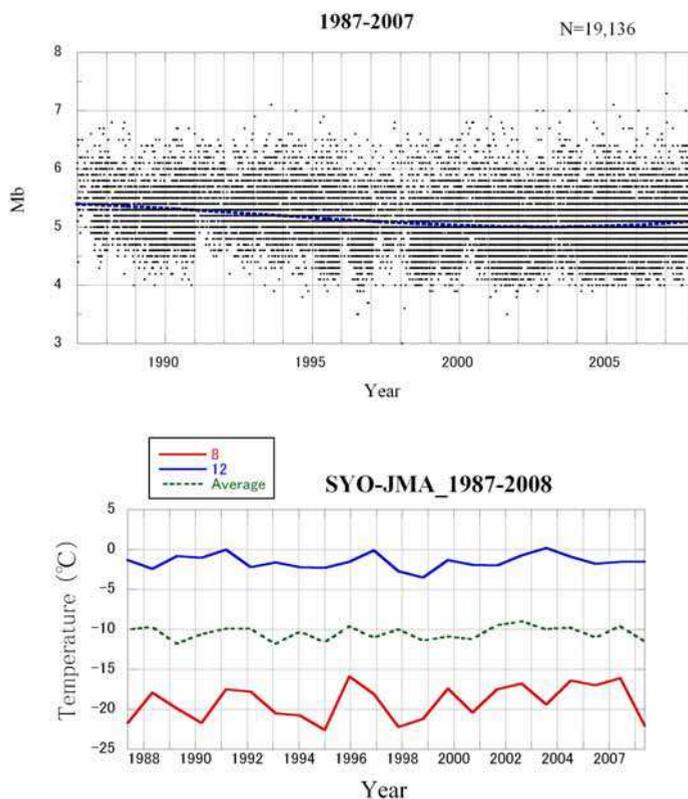

Fig. 5. Top: Teleseismic detectability at Syowa Station (SYO), Antarctica in 1987-2007 (modified after Kanao, 2010) as a function of Mb. Broken blue line indicates the smoothed average of Mb values for the whole period. Bottom: Temperature variations at SYO for the same years. Blue solid line: August (austral winter); red solid line: December (austral summer); green broken line: averaged values for a whole season

An important parameter for station operators is the teleseismic detectability, i.e. the capability of a station to detect a seismic event occurring at teleseismic distances (over 30° away). This parameter is strongly correlated to the noise level at the station. Temporal variations in teleseismic detectability at SYO were investigated for the period from 1987 to 2007 by Kanao, 2010. Figure 5 shows the body-wave magnitudes (Mb) for the events detected at SYO over the past two decades. The magnitudes of detected events range from a maximum of 6.5-7.0 to a minimum of 4.0-4.5. The average detected magnitude has decreased slightly over time, as the station quality has improved. During the austral summer, the station shows less teleseismic detectability (i.e. the station detects fewer low magnitude events) than during the austral winter, because of high noise level in the local summer due to both natural factors and human activity in the vicinity of the station.

The magnitude variations in teleseismic detectability imply strong relationship with the surrounding environment, such as meteorological events, sea-ice thickness and its spreading area (Ushio, 2003), and more particularly the amplitude of microseisms which is strongest during the austral summers.

4. Microbaroms and ice signals on infrasound

Infrasound is defined as sub-audible sound, i.e pressure waves with frequencies ranging from the cut-off frequency of sound for a 15°C isothermal atmosphere (3.21 mHz) to the lowest frequency of the human audible band (20 Hz). This frequency range is a new horizon for the remote sensing of the Earth's atmospheric physical environment. For example, the Sumatra-Andaman great earthquake of December 26th 2004 not only produced a tsunami that was recorded as far as Antarctica (Nawa et al., 2007), but also produced recordable infrasound waves in the atmosphere (Iyemori et al., 2005). Another example is given by the infrasound and seismic recording of the shock waves generated by a meteorite that overflew Japan (Ishihara et al, 2004).

Over the last few decades, in order to monitor the nuclear tests, a global infrasound network was constructed by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO; Fig. 6; Butler and Anderson, 2008). One objective of CTBTO is to estimate the detection and location capabilities of this network at regional and global distances, another is to explore ways to improve these capabilities and enhance the understanding of wave propagation through the atmosphere of the observed events. At this time, the CTBTO has sixty infrasound stations, each containing at least four sensors (arrayed stations), that can detect a several-kiloton TNT level explosion at a range of ~1000 km. Although the full capability of the global infrasonic network is yet to be established, it has been found to be adequate for monitoring nuclear tests, but too sparse for analyzing natural infrasound phenomena in detail.

In 2008, a Chaparral type sensor was installed on a rock outcrop at SYO station in East Antarctica as an International Polar Year (IPY 2007-2008) project (Ishihara et al., 2009). From the analysis of data recorded during the last two winter seasons in 2008-2010, we found continuous background infrasound noise (Fig. 7) that seem to correspond to co-oscillation of the DFM and SFM as observed by the seismometer at SYO. Time variations similar to those observed on seismic spectra are also observed in infrasound data, and also seem to correspond to storms that occur with intervals of a few days. These observations indicate physical interaction between the atmosphere – ocean system and the solid earth (geosphere) in the microseism/microbarom frequency ranges.

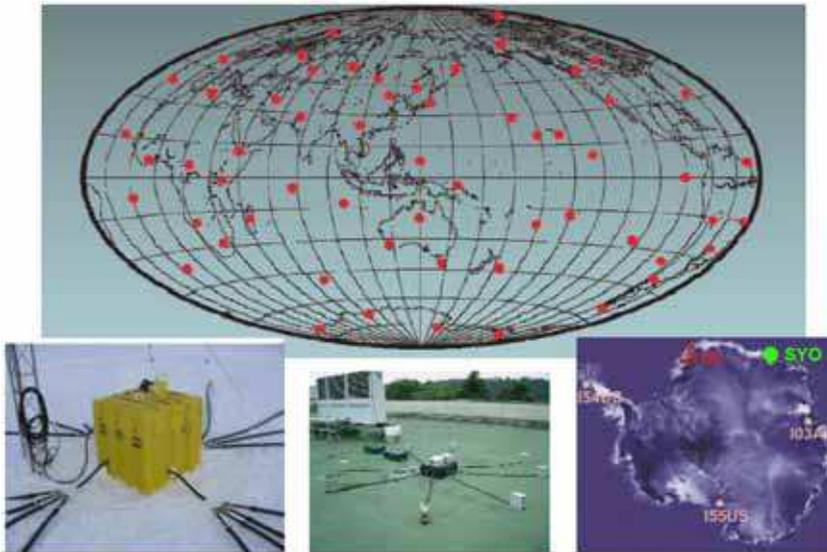## Comprehensive Nuclear Test-Ban Treaty Organization (CTBTO)

Fig. 6. Top: A global distribution map of the Comprehensive Nuclear Test-Ban Treaty Organization (CTBTO) infrasound network. Bottom, from left to right: infrasound station photo at 155US in West Antarctica; an observation test running at Tohoku University, Japan; infrasound station distribution in Antarctica
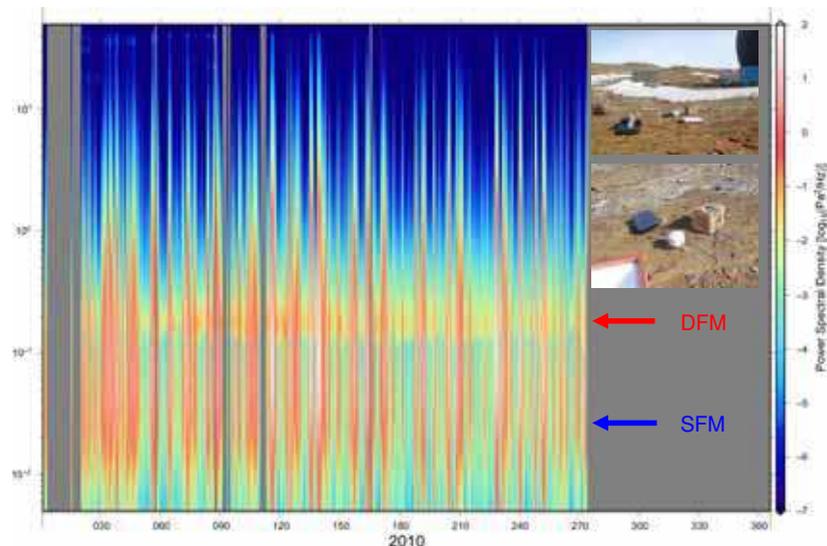

Fig. 7. Power spectral densities (PSD) of the infrasound signals at Syowa Station (SYO), Antarctica, during the period in January – October, 2010. Signals corresponding to SFM and DFM are indicated by blue and red arrows respectively

Figure 8 represents the PSD of infrasound signals at SYO during April 2009. The DFM is indicated by a red arrow, and varies significantly both in amplitude and frequency content over the month. These variations appear to correspond to the atmosphere variations tied to changes in weather conditions, as well as the spreading area and the thickness of sea ice in the surrounding bay. Also visible are the repeating signals with harmonic over-tones at a few tens of Hz (labeled 'ice sheet motion?' in Fig. 8), that may be related to ice dynamics caused by various environmental changes in cryosphere near the station (i.e. sea-ice movement, tide-crack opening shocks, ice-berg tremors, basal sliding of the ice-sheet, calving of glaciers etc.). Energy from storms sometimes extends to the low frequencies, below 0.1Hz.

A theoretical modeling approach would be required to determine the actual sources of several kinds of infrasound signals in the polar region. It would be also useful to compare these signals with other data, such as broadband seismograms that share sensitivity over part of the infrasound frequency range. The array alignment of the infrasound stations, moreover, could provide robust information about the arrival direction and epicentral distance from the infrasound sources.
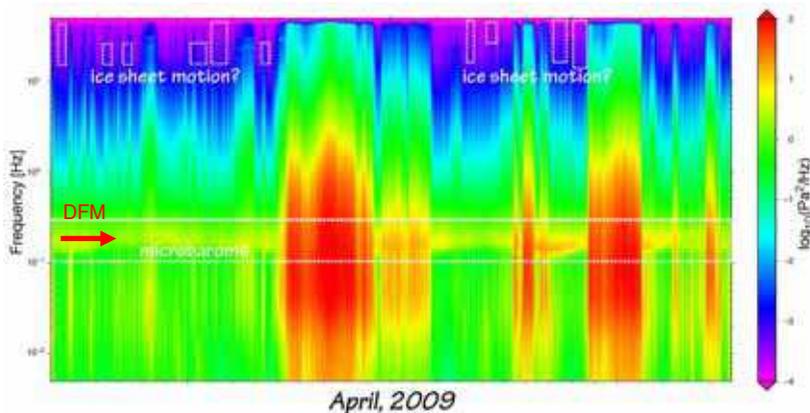

Fig. 8. Power spectral densities (PSD) of the infrasound signals at SYO during the period April 2009. The DFM is indicated by a red arrow. High frequency signals above 10Hz are also identified, and labeled as 'ice sheet motion?'

5. Glacial earthquakes in polar regions

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 sea-ice, tide-cracks and icebergs in the other polar areas (Wiens et al., 1990; Wiens, 2007; Anandakrishnan and Alley, 1997; Kanao and Kaminuma, 2006). The so-called «ice-micity» detected around the Bransfield Strait and Drake Passage by a local network of hydrophone arrays in 2006-2007 illustrate the dynamic behavior of sea ice in the Bransfield and Antarctic Peninsula regions(Dziak et al., 2009).

Local seismicity around the Lützow-Holm Bay (LHB) from 1987 to 2003 was reported by Kanao and Kaminuma (2006) (Fig. 9). The seventeen events were only detected by local seismic network deployed around the LHB, except for the September 1996 Mb=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.
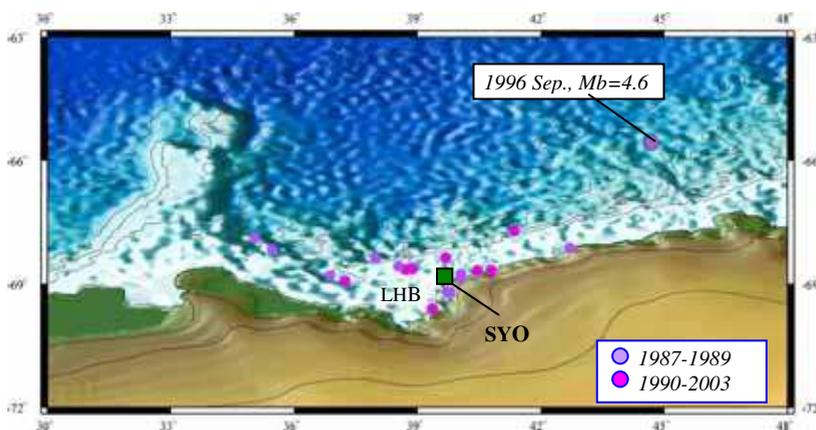

Fig. 9. Local seismicity around the LHB region from 1987 to 2003 (modified after Kanao and Kaminuma, 2006). These events, except for the September 1996 Mb=4.6 earthquake in the Indian Ocean, were detected by the local seismic network deployed at the LHB

Sea-ice dynamics and icebergs also affect seismic signals. A large volume of sea ice was discharged from LHB during the 1997 austral winter, and clearly imaged by the NOAA satellite (Ushio, 2003). The broadband seismographs at SYO recorded distinct waveforms associated with the discharge events (Fig. 10). 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 PSDs. The PSDs also showed surge events that seem more closely related to the break-up process of the sea-ice mass. Both kinds of cryoseismic waves occurred continuously for few hours, and repeated themselves several times within a few days during late July, 1997. 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 region (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.
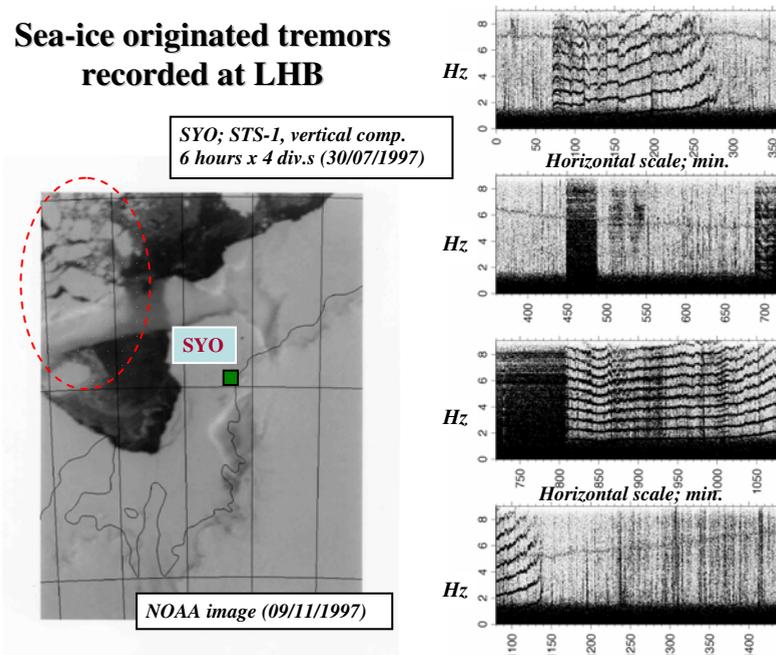

Fig. 10. A large volume of sea-ice discharge from the LHB occurred during the 1997 austral winter. Left : NOAA image in September 11, 1997. The broken red circle with light-blue shading highlights the estimated residuals of the discharged sea-ice volume. Right: PSDs of the broadband seismographs at SYO in July 30, 1997, in four successive time-periods of 6 hours each. Several characteristic signals with harmonic spectra were identified on the seismograms

Several kinds of natural signals were recorded by a seismic experiment with 161 temporary stations on the continental ice sheet (Mizuho Plateau in the LHB region) during the 2002 austral summer (Miyamachi et al., 2003). The experiment recorded chiefly the artificial waveforms originated by seven large explosions, but also detected tectonic earthquakes and ice related phenomena. The recorded signals have been classified into teleseismic events, local events assumed to be ice-quakes and the unidentified events (X-phases, Yamada et al., 2004). These ice-related phenomena are expected to be sensitive to climate change (Kanao et

al., 2007). The recordings display variations in frequency content and arrival-times along the seismic profile consistent with documented abrupt variations of the sub-ice topography.

The features of the X-phases were clearly different from those of the small local ice-quakes (Fig. 11). A possibility for the origin of the X-phases may be regional intra-plate earthquakes. Such regional events around Antarctica from 1900 to 1999 are compiled by Reading (2002). East Antarctica from 90ºE to 180ºE, particularly the areas of Wilkes Land, the Transantarctic Mountains, and the Ross Sea, was the region showing the highest seismicity in the Antarctic. From the comparison with the arrival data at SYO, the maximum amplitudes of seismic phases appear to arrive at SYO with the delay of several seconds. Therefore, the X-phases could possibly travel to the seismic observation line and then SYO from the relatively active, intraplate seismogenic region in Wilkes Land – Ross Sea area. The estimated origin of the unidentified X-phases might be an intraplate earthquake or possibly a large ice-quake (glacial earthquake) around East Antarctica.
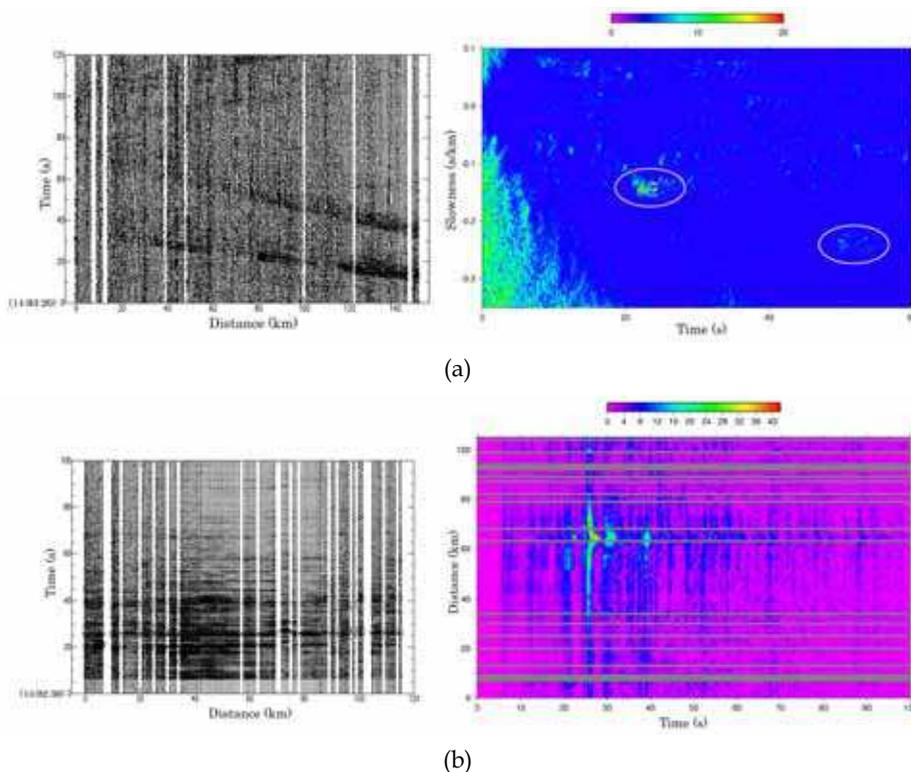

(a)

(b)

Fig. 11. Seismic signals recorded at a linear profile of stations deployed on ice sheet of the Mizuho Plateau (modified after Yamada et al., 2004). (a) Left: Record section showing seismic waves of ice-quakes. Vertical axis starts from Jan. 14, 2002, 14:03:20 (UTC). Right: Contour map of phase-weighted stacking (PWS) applied to the ice-quakes (two circled area). (b) Left: Record section showing seismic waves of «X-phases». Vertical axis starts from Jan. 27, 2002, 14:02:30 (UTC). Right: Contour map showing envelope amplitudes of band-pass filtered traces (1.0-2.0 Hz)

However, it should also be pointed out that several small to middle magnitude natural seismic events could not be located accurately, since they have ambiguous arrivals in the waveforms recorded by the present global network, particularly around Antarctica. In spite of the development of local networks in last two decades, we can hardly distinguish a difference between waveforms generated by local tectonic earthquakes and those of large ice-related phenomena.

In addition to the short-period cryoseismic signals mentioned above, a new class of seismic events associated with melting of large ice cap was discovered recently (Ekström et al., 2003 and 2006; Nettles et al., 2008; Fig. 12). These large events were called "glacial earthquakes", generated long-period (T>25 s) surface waves equivalent in strength to those radiated by standard magnitude five earthquakes, and were observable worldwide. The glacial earthquakes radiated little high-frequency energy, which explains why they were not detected or located by traditional earthquake-monitoring systems. These events are two magnitude units larger than previously reported seismic phenomena associated with glaciers, a size difference corresponding to a factor of 1,000 in a seismic moment.

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 by a landslide source model (Kawakatsu, 1989). 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 (Dahl-Jensen et al., 2010).
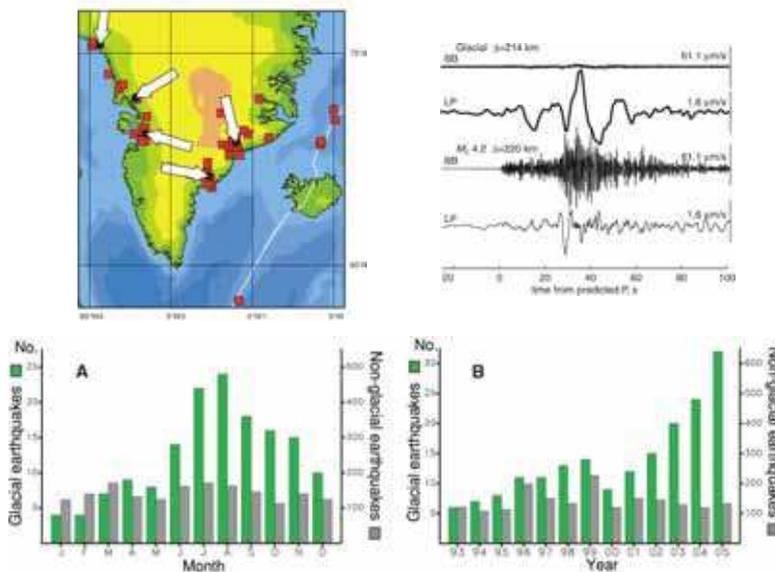

Fig. 12. (upper left) A distribution of the glacial earthquakes around Greenland. (upper right) An example of the comparison between a glacial earthquake and a tectonic crustal earthquake (after Ekström et al., 2003). (lower) Number of glacial and non-glacial earthquakes as a function of month (A) or year (B) (after Ekström et al., 2006)

6. Greenland ice sheet dynamics

Glacial earthquakes have been observed along the edges of Greenland with strong seasonality and increasing frequency from the beginning of this century (Ekstrom et al, 2003), by continuously monitoring data from the Global Seismographic Network (GSN). These glacial earthquakes in the magnitude range 4.6-5.1 may be modeled as a large glacial ice mass sliding downhill several meters on its basal surface over the duration of 30-60 s. Greenland glacial earthquakes were closely associated with major outlet glaciers of the ice sheet. Ekstrom et al. (2006) reported on the temporal patterns of the occurrence of events, finding a clear seasonal signal and a significant increase in the frequency of glacial earthquakes on Greenland after 2002. 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.

The last four decades of seismicity in Greenland and surrounding regions, including tectonic and volcanic events together with glacial earthquakes, have been investigated by Kanao et al. (2010). Statistically estimated seismic activity using data 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 (Fig. 13). This seems to indicate that the total seismicity in this area, including glacial earthquakes, has increased in magnitude over the last four decades. Before attributing this evidence to global warming, the other
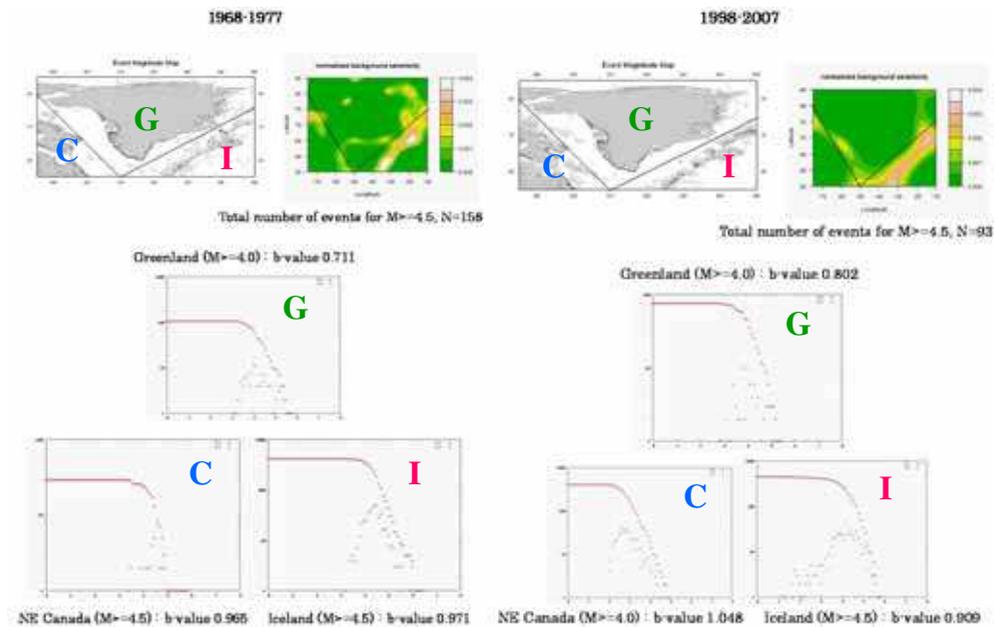

Fig. 13. Background seismicity and Magnitude–dependent 'b'-values for Greenland and the neighboring areas, on the basis of the statistic ETAS model using the hypocentral data collected at the International Seismological Centre (ISC). G: Greenland block; I: Iceland block; C: northern Canadian block. (left) 1968-1977; (right) 1998-2007

possibility for this increase are to be considered, such as of improvement of sensitivity of instrument over time and stations densities in the Arctic region.

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 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 onshore Greenland and around its perimeter (the Greenland Ice Sheet Monitoring Network; GLISN; Anderson et al., 2010; Kanao et al., 2008). The 2007-2008 IPY was an opportunity to initiate the new program by international collaboration.

In Greenland, long-term seismic monitoring of the ice sheet will be used to establish a baseline for the seismic activity in Arctic polar region. Deviations from the baseline would 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.

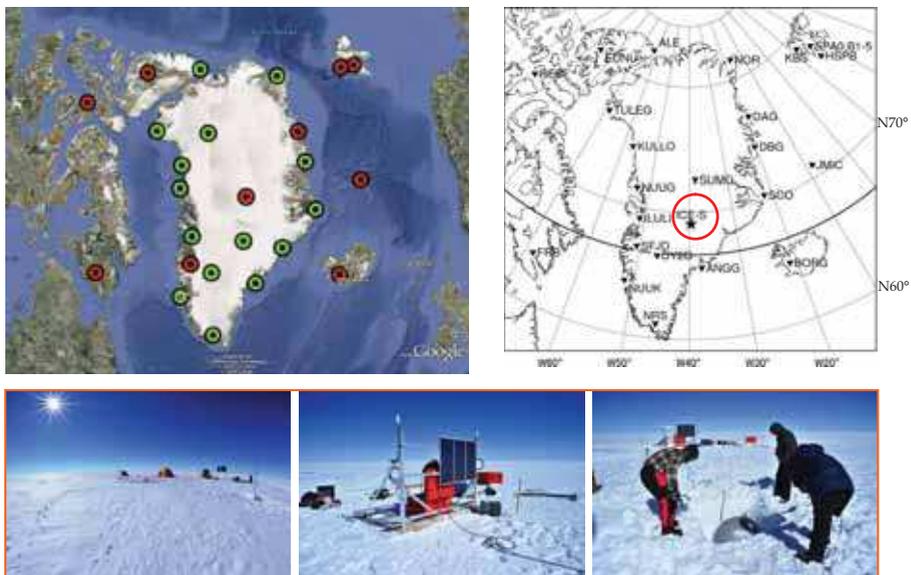**Greenland Ice Sheet Monitoring Network (GLISN)**

Fig. 14. (upper left) Location map of the broadband seismic stations deployed by the GLISN project. The solid red circles denote the existing FDSN stations and the solid green circles indicate the GLISN sites. (upper right) Location of the Ice-S station by open red circle. (lower) Installation of the Ice-S station on June 2011, taken by G. Toyokuni

7. Monitoring the atmosphere-ocean-cryosphere-geosphere system, the contribution of IPY and CTBTO

In the previous sections of this chapter, we have shown that seismic data contain significant information regarding wave activity, ice-dynamics and weather-related phenomena (e.g. storms). Microseism measurements in polar regions are a useful proxy for characterizing ocean wave climate and global storm intensity in the high latitudes, complementing other estimates such as marine surveys and satellite images. Individual stations respond most strongly to wave activities at regional shorelines, and the sensitivity of specific stations to ocean wave climate is controlled by factors such as storm tracks and coastal bathymetry. Continuous digital records from the Global Seismographic Network (GSN), the Federation of Digital Seismographic Network (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.

A program containing several field-campaigns was launched during the International Polar Year (IPY 2007-2008) and complements the networks of permanent stations at the high latitudes of the polar regions. In Antarctica, the most ambitious seismological field campaign conducted for the IPY was the «GAmburtsev Mountain SEISmic experiment» or GAMSEIS, an internationally coordinated deployment of more than 50 broadband seismographs over the crest of the Gambursev Mountains (Dome-A – Dome-F area) in East Antarctica. The aim of this experiment was to provide detailed information on the crustal thickness and mantle structure of the region and find key constraints on the origin of the Gamburtsev Mountains (Wiens, 2007; Hansen et al., 2010; An et al., 2010). GAMSEIS and many other seismological deployments, including a French deployment between Concordia and Vostok (CASE-IPY) and a Japanese deployment around the Lützow-Holm Bay (JARE-GARNET), were coordinated under a larger program called the 'Polar Earth Observing Network (POLENET; http://www.polenet.org/; Fig. 15)' whose aim was to establish a geophysical network to cover the whole Antarctic continent as well as Greenland for the duration of the IPY.

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. In addition to conventional seismological targets (e.g. crust and lithosphere structure, inner core structure), the IPY seismic stations could be used to help monitor geographical variations in climate indicators, over the span of 2-3 years. All data from IPY experiments will be distributed to the scientific community.

Together with the seismic networks, the infrasound stations in the Antarctic contribute to both CTBTO and the Pan-Antarctic Observations System (PAntOS) under the Scientific Committee on Antarctic Research (SCAR). The combination of seismic, infrasound and hydro-acoustic observations is required to understand in more detail the atmosphere-ocean-cryosphere-geosphere system and its variations. We are hopeful that the large quantity of data of these three types accumulated over the past decades by the CTBTO will one day be distributed to the scientific community.
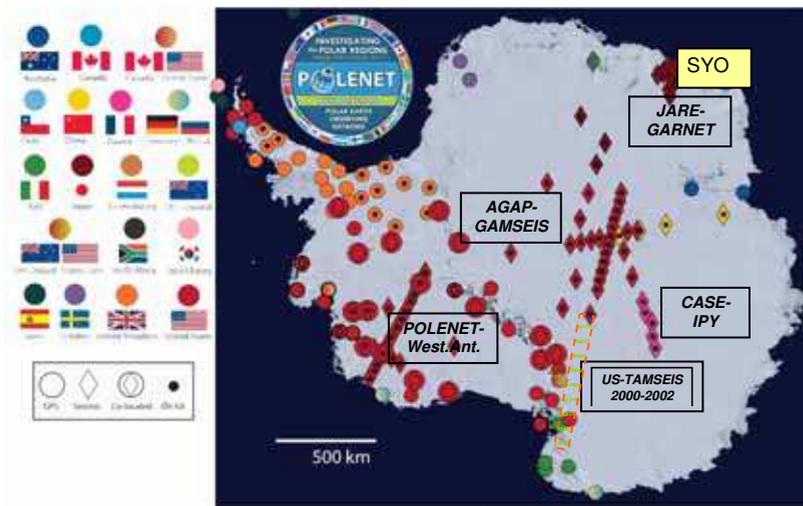
POLENET in IPY 2007-2008

Fig. 15. Distribution map of seismic and the other geophysical stations deployed during the IPY 2007-2008. The major project names are labeled as; JARE-GARNET, AGAP-GAMSEIS, CASE-IPY, POLENET-West.Ant. and US-TAMSEIS, respectively. All stations in Antarctic continent contributed to POLENET program

8. Conclusion

We have described several features of seismic waves, and how they are related to the atmosphere-ocean-cryosphere system. Microseisms and microbaroms from the southern ocean are clearly recorded by both broadband seismographs and infrasound sensors deployed at Antarctic stations, and are modulated by the presence of sea-ice. Microseism measurements were a useful proxy for characterizing ocean wave climate and global storm intensity, complementing other estimates by ocean buoys or satellite measurements. Using the infrasound data at SYO, we have detected long duration signals with harmonic over-tones that may be related to the ice dynamics near the station.

Most of the community agrees that the polar regions play a critical role in the Earth's 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, would be 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.

There are still a lot to be learned about the physical mechanisms of interaction between the atmosphere-ocean-cryosphere system and the geosphere in the polar regions. Continuous observation by a sufficiently large number of high quality stations, as well as theoretical work, will probably be necessary to make progress in this field. Given the high cost and

technical difficulties of continuous observation in the polar regions, such work would require strong international collaboration beyond the end of the International Polar Year.

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10. References

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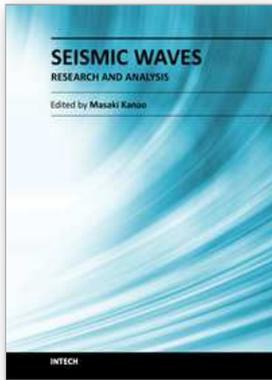
Seismic Waves - Research and Analysis

Edited by Dr. Masaki Kanao

The importance of seismic wave research lies not only in our ability to understand and predict earthquakes and tsunamis, it also reveals information on the Earth's composition and features in much the same way as it led to the discovery of Mohorovicic's discontinuity. As our theoretical understanding of the physics behind seismic waves has grown, physical and numerical modeling have greatly advanced and now augment applied seismology for better prediction and engineering practices. This has led to some novel applications such as using artificially-induced shocks for exploration of the Earth's subsurface and seismic stimulation for increasing the productivity of oil wells. This book demonstrates the latest techniques and advances in seismic wave analysis from theoretical approach, data acquisition and interpretation, to analyses and numerical simulations, as well as research applications. A review process was conducted in cooperation with sincere support by Drs. Hiroshi Takenaka, Yoshio Murai, Jun Matsushima, and Genti Toyokuni.

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