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Interactions among Multispheres of the Earth's System and Polar Regions

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Abstract

Among the environmental variations in the surface layers of the Earth, global warming and those involving multisphere interactions in the polar region are reviewed with scientific research funding. By focusing on the wavelet phenomena with various generating sources within the Earth's system, interdisciplinary research studies are conducted on the influences and responses to climate change in the polar region.

Keywords: multispheres, interaction, polar region, infrasound, microseisms/microbaroms, Earth's system

1. Introduction

Among the Earth's complex system, various kinds of temporal-spatial variations have been observed by the interactions among multispheres such as the atmosphere, ocean, cryosphere, and solid Earth. For example, seismographs deployed in the Antarctic by the Federation of Digital Seismographic Networks (FDSN) and the Polar Earth Observing Network (POLENET) could efficiently record microseismic noise (microseisms) generated from the Southern Ocean. The microseismic noise represents the characteristic wavelets originated by coupling the solid Earth and the ocean [1]. Moreover, microseisms with different intrinsic periods (the "first fundamental mode" came from the Southern Ocean and the "second fundamental mode" from the continental shelf) were identified to have a relationship with the seasonal evolution of sea ices, which are distributed surrounding the Antarctic continent. In addition, physical interactions between the solid Earth and other spheres (atmosphere, ocean, and cryosphere)

were investigated in detail by using both microseismic noise and newly deployed infrasound (microbarometric) data during the IPY [2].

In this chapter, as mentioned earlier, by focusing on the characteristics of wavelets propagating in the frequency bands between 0.001 Hz and few tens of Hz (subaudible bands) with various generating sources in the Earth's system, the recent seismological research, which comprises the surface environments in the polar region, involves the physical interactions among multispheres. Particularly, targeting temporal-spatial variations in "microseisms" and "microbaroms" detected by infrasound sensors, the response of shallow atmosphere, and the surface layer of the solid Earth from the oceanic swells and involved atmospheric variations in the polar region are examined in detail. By checking the relationship between amplitudes and frequency variabilities of these wavelets and meteorological data/sea-ice distribution, as well as computer modeling of the multisphere coupling, integrated information to evaluate the effects of global warming/climate change on the surface environment in the polar region is provided.

2. Ocean-solid Earth coupling

At the middle-high latitudes in the Southern Hemisphere, variations in temperature, air pressure, strong winds, and associated swells, "ocean disturbance," occurred when large storms passed through. Moreover, the co-oscillation ground noise occurred from a few to 30 s at the Earth's surface (the microseisms and microseismic noise) [3, 4]. The microseisms can be observed with large amplitudes at the coastal areas of the continents across the globe; these amplitudes including the origins from deep oceanic swells are predicted theoretically all over the Earth [5]. In this regard, the data from global seismographic networks, FDSN, are expected to be utilized for the microseismic studies.

From previous observations, "microseisms" are classified into two groups: the relatively long period (12–30 s; single-frequency microseism, SFM) originated from deep oceans and short period (4–10 s; double-frequency microseism, DFM) from continental shelves [3, 4]. In the Antarctic, however, there were no studies of the microseisms for long-term observations including the inland area before the IPY. Recently, by using the data from FDSN and POLENET deployed in the Antarctic, microseismic signals from the Southern Ocean have been clearly recognized with their frequency contents and time variations. For instance, seasonal variations in SFM and DFM can clearly be recognized with a strong correlation with seasonal changes in the surrounding sea-ice spreading areas (in particular the fast ices) by using the FDSN data [6, 7]. The seismic stations in East Antarctica such as the Dumont d'Urville (DRV) and Syowa (SYO; see **Figure 1** of Chapter 1) have recorded strong seasonal changes in sea-ice spreading areas and associated variations in microseismic amplitudes.

Following the development of the FDSN stations around the world including Antarctica, digital acquisition of the broadband seismograph data (type STS-1) started in 1989 at Syowa Station [8]. By using the long-term data from the seismographs, the dynamic power spectral density (PSD) represented the various scale of time variations in SFM and DFM [1, 7] (**Figure 1**). From data since 2001, DFM signals with smaller amplitudes in austral winters have been continuously recorded at Syowa Station. In contrast, variations in the periods from a few hours to a few days in PSD have been assumed to be the effects of large storms and

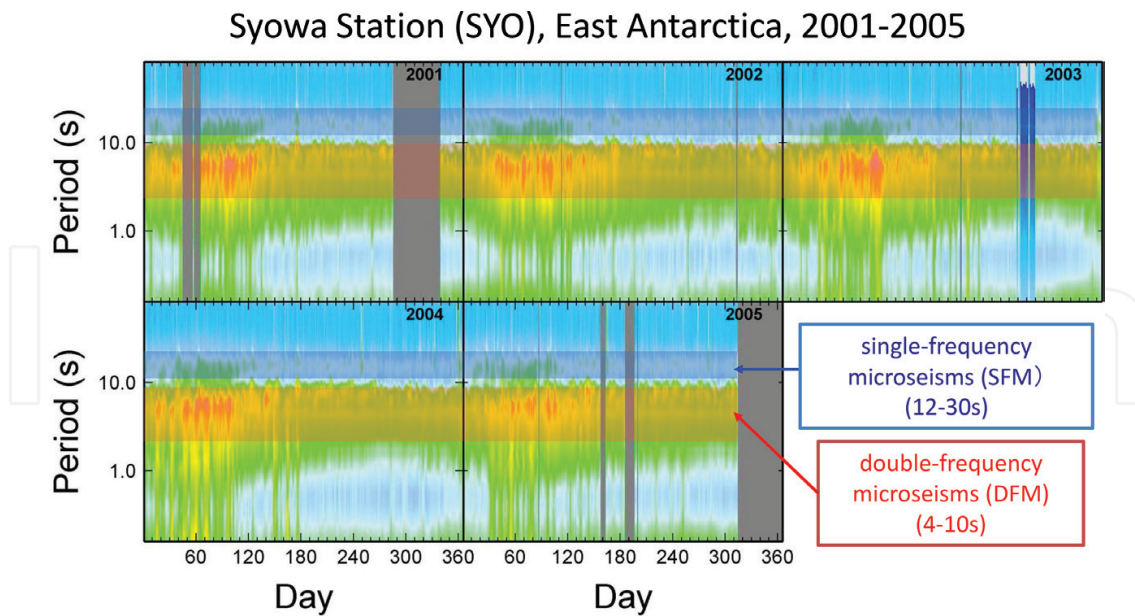


Figure 1. Power spectral densities of the broadband (STS-1 V) at SYO Station, East Antarctica, for the period of 2001–2005. Signals corresponding to SFM and DFM are indicated by blue and red arrows (modified after [1]). Open Access Journal (CC BY 3.0) (first author is M. Kanao).

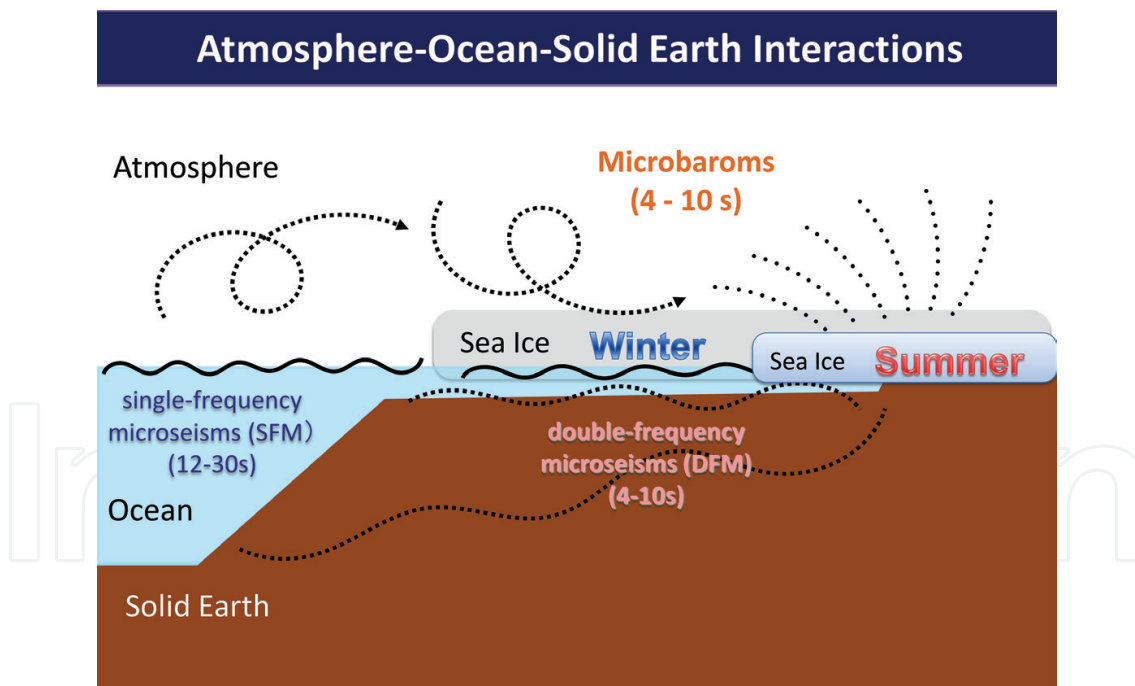


Figure 2. Schematic illustration of atmosphere-ocean-cryosphere-solid Earth environments in polar regions exemplified in the Antarctic. Infrasound signals (microbaroms) and seismic noise waves propagate from the source regions in the Southern Ocean SFM and the continental shelf area DFM to the margins of the Antarctic continent. Seasonal variations from the extending sea-ice spreading areas and the thickness effect on the arrival energy of the oceanic seismic noise at the coastal stations in the Antarctic. (Original figure prepared for this InTech Book.)

related swells in the Southern Indian Ocean. PSD of SFM, on the other hand, represented relatively small amplitudes compared with DFM and the largest in austral summers. In this regard, PSD amplitudes increase in the austral summers, which is opposite to the stations in

the Northern Hemisphere, such as in Japanese islands [6]. This is explained by the development of sea ices surrounding the Antarctic continent in winter seasons, which depresses the effects on the microseismic noise energy (**Figure 2**). Moreover, the microseismic noise from sea-ice spreading areas affected the teleseismic detection capability of the stations making observations of seasonal variations [9, 10].

Understanding the intrinsic features of seismic phenomena generated by oceanic swells under the coupling condition between the Antarctic ice sheet and the underlying solid Earth might involve the static and dynamic conditions of the adjacent Southern Ocean and shallow atmosphere. Future studies on ocean-solid Earth coupling are expected to be interdisciplinary, with research themes corresponding to topics on satellite altimeter, geoid model, ice-sheet evolution, mass balance, plate movement, regional tectonics, sea-level rise, precise gravity measurements such as by the Gravity Recovery and Climate Experiment (GRACE), satellite, and so on.

3. Atmosphere-solid Earth coupling

Of the interdisciplinary research studies on the coupling phenomenon at the boundary regions among the atmosphere, ionosphere, ocean, and solid Earth, a branch of research using “infrasound” (subaudible band frequency lower than 20 Hz) is currently underway in the polar region [11]. The “infrasound” has a medium frequency band between audible acoustic waves and planetary scaled gravity waves. Infrasound can propagate for long distances, more than few thousands of km, and is focused on the plausible sources of perturbation within the upper atmosphere. A global infrasound network has been established by the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO). At present, 60 stations including planning sites have been deployed; there are two existing CTBTO stations at Neumayer (NM; 127DE) and McMurdo (MCM; 155US) in addition to two planned ones in Antarctica. (For details of observations at NM, refer [12].)

The recent obtained infrasound data contained various kinds of natural sources in addition to the original targets by CTBTO—earthquakes, volcanic eruptions, tsunami waves, oceanic swells, rapid developing clouds, auroras, fireball and meteorite falls, ice quakes, and so on [13, 14]. The Japanese CTBTO site is located at the “Isumi” city of Chiba Prefecture, and the infrasound signals generated by tsunami waves of the huge Tohoku earthquakes on March 11, 2011, were clearly recorded [15]. Another example was the detection of shock waves by the reentry of the “Hayabusa” spacecraft on June 2010 inside the desert in Australia [16, 17]. Moreover, the Sumatra-Andaman earthquake on December 2006 generated tsunami waves and associated infrasound, which are propagated upward to create a coupling with the ionosphere and observed as the total electron content (TEC) perturbation [18, 19].

Characteristic features of infrasound waves observed in the Antarctic reflect the physical interactions between the surface environment in the continental margin and in the surrounding Southern Ocean. Infrasound observations have been started at Syowa Station, in the Lützow-Holm Bay (LHB) of East Antarctica, since April 2008 during the IPY by using a single sensor. The “microbaroms” were clearly detected, which corresponded to the same frequency range waves of DFM that originated from the Southern Indian Ocean [20, 21]. The infrasound

Occurrence rate (%) of detected predominant signals at SYO from February 10 to March 31, 2013

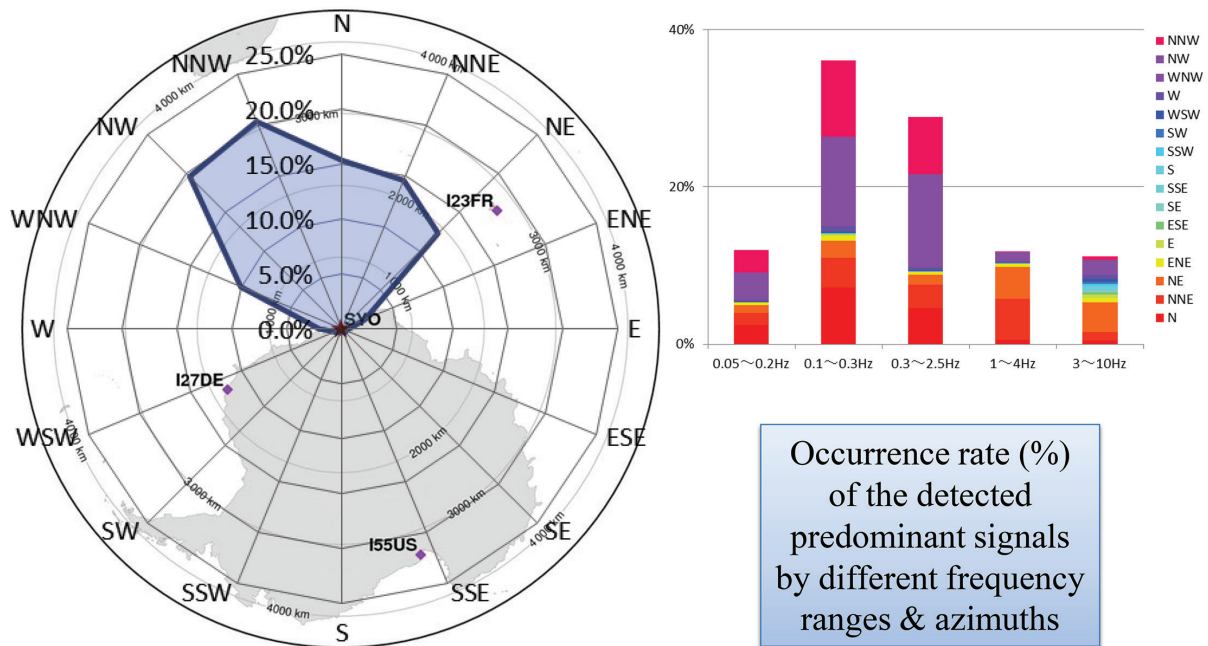


Figure 3. Occurrence rate (%) of the orientation for the detected infrasound signals at SYO Station from February 10 to March 31, 2013 (modified after [22]). Copyright Clearance Center (CCC, <http://www.copyright.com/>). License Number: 4282180930831, License date: February 04, 2018.

observation in the Antarctic could have a possibility to detect characteristic signals in addition to the troposphere-stratosphere phenomenon, shock waves from auroras and meteoroid falls, volcanic eruption in the Southern Hemisphere, oceanic swells and tsunami waves, vibrations by earthquakes, cryoseismic signals involving global warming, and so on. Moreover, since 2012, multiscaled infrasound array observations have been started at LHB to identify the orientation of the source locations on the origin of swell signals [22] (**Figure 3**). By continuing the long-term observations for more than few years, it would be possible to evaluate the effects of global warming/climate change on the Southern Ocean and coastal margins of the Antarctic. Infrasound observations in Antarctica, where there has been less noise by human activities, have a significance in terms of their long propagation distance; the physical interactions among multispheres in the polar region can be revealed by monitoring for decades.

4. Recent progress in infrasound research

Long-term infrasound data from the Syowa Station in LHB of East Antarctica were recently analyzed from 2008 to 2014 [23]. Seasonal variations in microbaroms and high-frequency harmonic overtone signals were especially investigated, and the data were strongly involved in local dynamics of the surface environments. The microbaroms have relatively low amplitudes in austral winters by an effect from the extending area of sea ice around LHB, with

decreasing oceanic swell loading effects. The other reasons of seasonal variations in microbarom amplitudes were caused by the effect of a number of storms during the whole year and snow accumulation over the porous hoses on the infrasound station at Syowa Station. In contrast, nonlinear high-frequency harmonic tremors were considered to be caused by the katabatic winds from the Antarctic continent flowing in the northeast dominant orientation. The high-frequency tremors had characteristics of daily variations, particularly the austral summers.

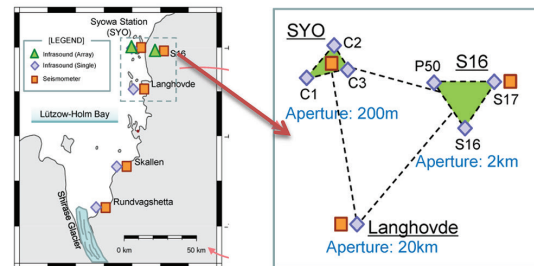
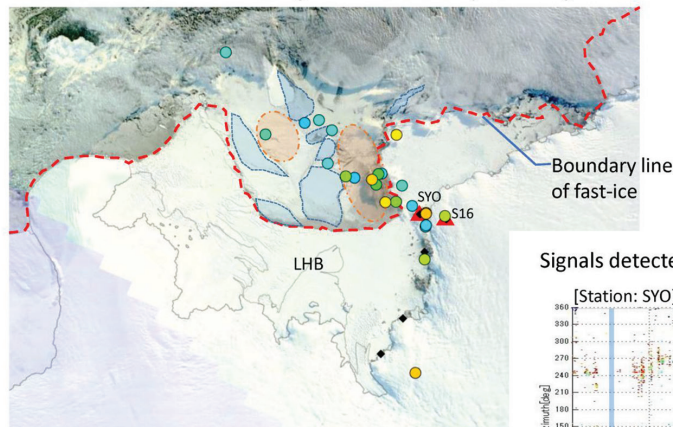
These infrasound arrays established in LHB [22] clearly revealed temporal variations in the frequency content and propagation direction of the identified events by using recent datasets. Time-space variability of the source location for the infrasound excitation from January to August 2015 was investigated by using a combination of two arrays deployed along the coast of the bay [24, 25]. The infrasound arrays clearly detected temporal variations in the frequency content and propagation direction during the period of 8 months (**Figure 4**). A significant number of infrasound sources were identified, and many of them were located in a northward direction from the arrays. Many of the events had a predominant frequency of a few Hz, which is higher than that of the microbaroms coming from the ocean. Many of these sources are assumed to have cryoseismic origins such as the ice quakes associated with the calving of glaciers, the discharge of sea ice, a collision between sea ices and icebergs around LHB, and so on. Comparing the moderate resolution imaging spectroradiometer (MODIS) satellite data, these infrasound sources were considered to be ice quakes associated with the calving of glaciers, discharge of sea ices, and collisions with icebergs.

Characteristic features of infrasound waves observed in West Antarctica-Transantarctic Mountains also revealed physical interactions involving surface environments around the continent and the Southern Ocean [26]. On December 2015, an infrasound array (100-m spacing) with three sensors (Chaparral Physics Model 25, with a detectable frequency range of 0.1–200 Hz), together with a broadband barometer (Digiquartz Nano-Resolution Model 6000-16B Barometer, with a detectable frequency range of 0–22 Hz), was installed at Jang Bogo Station, Terra Nova Bay of the Northern Victoria Land, by the Korea Arctic and Antarctic Research Program (KAARP). Initial data recorded by the broadband barometer contained the characteristic signals that originated from the surrounding environment, including local noise such as katabatic winds. Clear oceanic signals (microbaroms) were continuously recorded as the background noise with a predominant frequency of around 0.2 s during the austral summer in December. Variations in their frequency content and amplitude strength in power spectral density (PSD) had been affected by an evolution of sea ices surrounding Terra Nova Bay. Continuous infrasound observations in Terra Nova Bay attained a new proxy for monitoring environmental changes such as the climate change in West Antarctica, involving cryosphere dynamics, as well as the episodic volcanic eruptions appearing in the Northern Victoria Land.

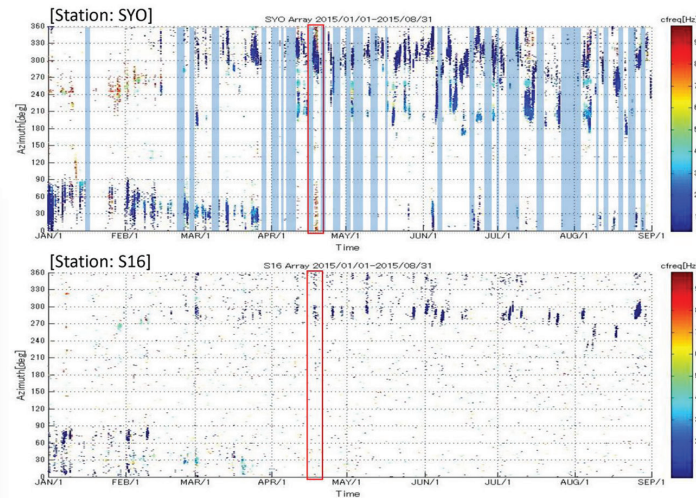
In addition to analyzing the observed data, numerical modeling of the microbarometric and microseismic oscillations due to ocean surface waves was applied [27]. Ocean surface waves (OSWs) shake the atmosphere on the sea surface and the top layer of the crust (the solid Earth) at the sea bottom. In order to estimate the amplitude and propagation directions of OSWs, (1) the amplitude and propagation directions of oscillations excited by OSWs and (2) variations in the amplitude after their propagation to observation points need to be quantified. To validate

MODIS satellite image around LHB, 20150419

Massive fast-ice discharged from LHB by iceberg collision



Signals detected by PMCC (2015/01/01-2015/08/31)



Light blue area for SYO corresponds to the time window over 15 m/s speed.

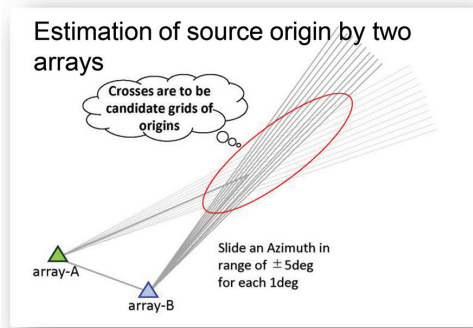


Figure 4. Time-space variations in infrasound sources involving the environmental dynamics around LHB (modified after [25]). (Upper right) Locations of array deployment in LHB. Array stations of infrasound (green triangles), single stations of infrasound (blue diamond), and broadband seismometers (orange squares) are shown, respectively. (Upper right) Array configuration of infrasound stations to localize the source signals. Tripartite arrays have been deployed by small size [at Syowa Station (SYO); an aperture of 200 m; C1, C2, C3], medium size (at S16, S17, P50; an aperture of 2 km), and large size (a combination of other outcrop stations such as Langhovde; an aperture of 20 km) have been deployed. (Lower right) Time sequence of azimuthal variation in arrival orientation and frequency contents of the detected infrasound signals (from January 01 to August 31, 2015). The vertical axis shows the back-azimuth (station-to-source) directions for the SYO array (upper) and the S16 array (lower), respectively. Colored bars on the right-hand side correspond to the central frequency (Hz) for each plotted event. Red open squared area corresponds to the date April 18, when a series of infrasound events were identified. Light blue areas for SYO correspond to the time window with over 15 m/s wind speed. (Upper left) MODIS satellite image around LHB on April 19, 2015. Massive fast ice had discharged from LHB associated with iceberg collision. The light blue-colored areas correspond to the location of the icebergs on the previous day. Orange-colored areas indicate the pack-ice regions where dynamic movements were considered to be generated in the last one day. In addition, estimated source locations of infrasound excitation are also overlapped with the MODIS image by using two arrays of SYO and S16. (Lower left) Flow chart of methodology for estimating source origins by two infrasound arrays [using the progressive multichannel correlation (PMCC) algorithm]. Copyright Clearance Center (CCC, <http://www.copyright.com/>). License Number: 4282180480777, License date: February 04, 2018.

these assumptions, two OSWs traveling in the opposite directions and having almost the same frequency and wavelength are imposed, and the resultant atmospheric and seismic oscillations are analyzed. The analysis results showed that the imposed OSWs excited acoustic waves in both the atmosphere and ocean. The frequency and the wave number of the acoustic waves were the sums of OSWs. The oceanic acoustic waves propagated to the ocean bottom to excite the seismic surface waves with the same frequency and wavelength. In the crustal depths, seismic body waves were also excited.

In several aspects introduced in the above new findings, infrasound studies of various kinds of natural phenomena in geophysics including the upper atmosphere, ocean, and cryosphere have greatly been advancing in the polar region. It is expected that the contribution from individual countries will be relatively small; therefore, the progress of scientific investigations in the polar region in addition to single national programs will be required to advance the studies of multisphere interactions among the same subaudible frequency bands [28].

5. Summary

The multidisciplinary study treated in this chapter aimed to understand the physical interactions among multispheres that compose the polar region in the Earth's system. Particularly, the infrasound could connect several spheres from the surface of the solid Earth to the ionosphere, giving a new idea for interdisciplinary research. Seasonal variations in the cryosphere are striking evidence appearing in the polar region and can also be investigated by using statistical analysis. Recently, a relationship between the climate change and sea-level rise and the dynamics of glaciers and ice sheets has been pointed out efficiently. By adding the approach from the view point of interaction with the solid Earth, it is possible that a new proxy for checking the progressing system of the climate change might emerge.

During the International Polar Year (IPY) and beyond, the characteristic solid Earth vibrations associated with the variations and dynamics of the ice sheets, sea ices, oceans, and atmosphere have been reported in the polar region. In order to realize the occurrence mechanism and activities of these wavelet phenomena, which the existing global networks cannot detect, understanding the interactions of the surface layer of the Earth and vicinity environments regarding global warming, such as the evolution of sea ices, the dynamics of ice sheets and glaciers, as well as the glacial earthquake activities, should be important. It is also expected that the succeeding interdisciplinary research studies use the long-period wavelets recorded by seismographs and infrasound and acoustic sensors in the polar region to achieve a deep understanding of the Earth's complex system.

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