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Statistics of Seismic Tremors with Harmonic Overtones Recorded at Syowa Station, Antarctica: October 2014-March 2015

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Abstract

During the period from October 2014 to March 2015, a total number of 82 seismic tremors and 66 ice-quakes were identified in both three-component short-period seismographs (HES) and broadband seismographs (STS-1) at Syowa Station (SYO), Antarctica. Statistics of the number of these tremors indicated that many tremors were likely to occur when large increases in temperature and/or wind speed during the period. This implied that the rapid increase in temperature enhanced a melting speed of cryosphere environment with generating seismic energy; the tremors were also excited by stormy conditions, associated with interactive resonance between sea-ices and oceanic swells. The characteristic tremors of harmonic overtones with strong amplitudes were explained by repetitive sources, suggesting inter-glacial asperities such as the collision of icebergs and fast sea-ice, calving of glaciers/ice-streams at the coastal environment of Antarctica. These high amplitude tremors occurred independently from other majority types of events, characterized by non-linear, small amplitude and weak signals at the stormy condition and rapid increase in temperature.

Keywords

Seismic Tremors, Harmonic Overtones, Statistics, Syowa Station, Antarctica

1. Introduction

A various kinds of cryoseismic signals have been reported in many areas of Antarctica in the last decade [1]-[7]. The cyoseismic sources can be classified into several kinds: movements of ice sheets, sea-ice, oceanic tide-cracks, collition of icebergs and the calving fronts of ice caps. Recently, as well as in Antarctica, tide-modulated ice flow variations enhanced the seismicity near the calving front of Bowdoin Glacier, Greenland [8]. The cryoseismic dynamics could strongly be involved in surface environment, and their space-time variability provide a proxy for monitoring climate change in polar region.

Local seismicity including cryoseismic signals around Syowa Station (SYO; 69S, 39E), Antarctica (**Figure 1**) were previously determined along the coast of the continent as well as the edges of fast sea-ice near the station [9]. The seismic sources of these local events were estimated as the calving of glaciers, discharge of sea-ice, collision between icebergs, etc.. Sea-ice dynamics in offshore of SYO had generated predominant cryoseismic harmonic tremors. A large volume of fast sea-ice discharged in 1997 winter season, and the tremor signals was clearly recorded by seismographs at SYO [10] as a few tens of hour durations with non-linear harmonic overtones. Recently identifying tremors around SYO were also demonstrated in terms of surface envieronment in particular cryosphere evolution. A relationship with sea-ice conditions and iceberg dynamics were identified by comparison with the MODIS satellite images [11].

On the basis of these previous studies, we compare the statistic number of harmonic tremors with meteorological data at SYO for the six months' data from October 2014 to March 2015, in order to investigate details regarding the occurrence mechanism of the seismic tremors in terms of surface environment in the Antarctic.

2. Waveform Examples of Seismic Tremors

Some of the seiemic tremors attributed characteristics of strong harmonic overtones, in their frequency contents over 1 Hz, representing nonlinear features having upward and/or downward frequency contents with duration times from few minutes till few hours. These tremors occurred independently from the arrival times of teleseismic phases, moreover, they were recorded by both types of seismographs (short-period; HES and broadband; STS-1) simultaneously. In

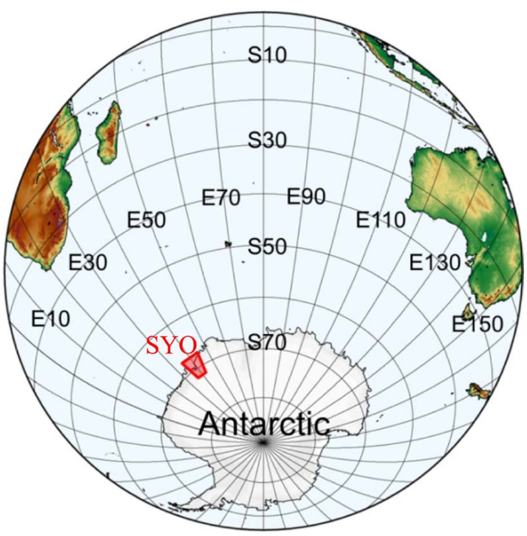


Figure 1. Location map of Syowa Station (SYO), Antarctica.

the regards, generating sources of the harmonic tremors were assumed to be local origins, presumably cryosphere dynamics. It is noticed that detail description and system configuration of seismic observation at SYO are given by [12] [13].

First example of recorded waveforms and their power spectral densities of seismic tremor at SYO are shown in **Figure 2(a)** and **Figure 2(b)** (18 - 24 UTC, 07 November, 2014). Both three-component short-period (HES) and broadband seismographs (STS-1) are indicated for comparison, however, all three-components of both seismographs clearly recorded the tremor event. Downward dipping frequency contents were significantly identified with duration about 60 min. beween 22:30 - 23:30 UTC. The high amplitude harmonic tremors with frequency overones (**Figure 2(a)** and **Figure 2(b)**) could presumably be related with the strong collision events between the iceberg and the northern edge of the fast sea-ice surrounging the station.

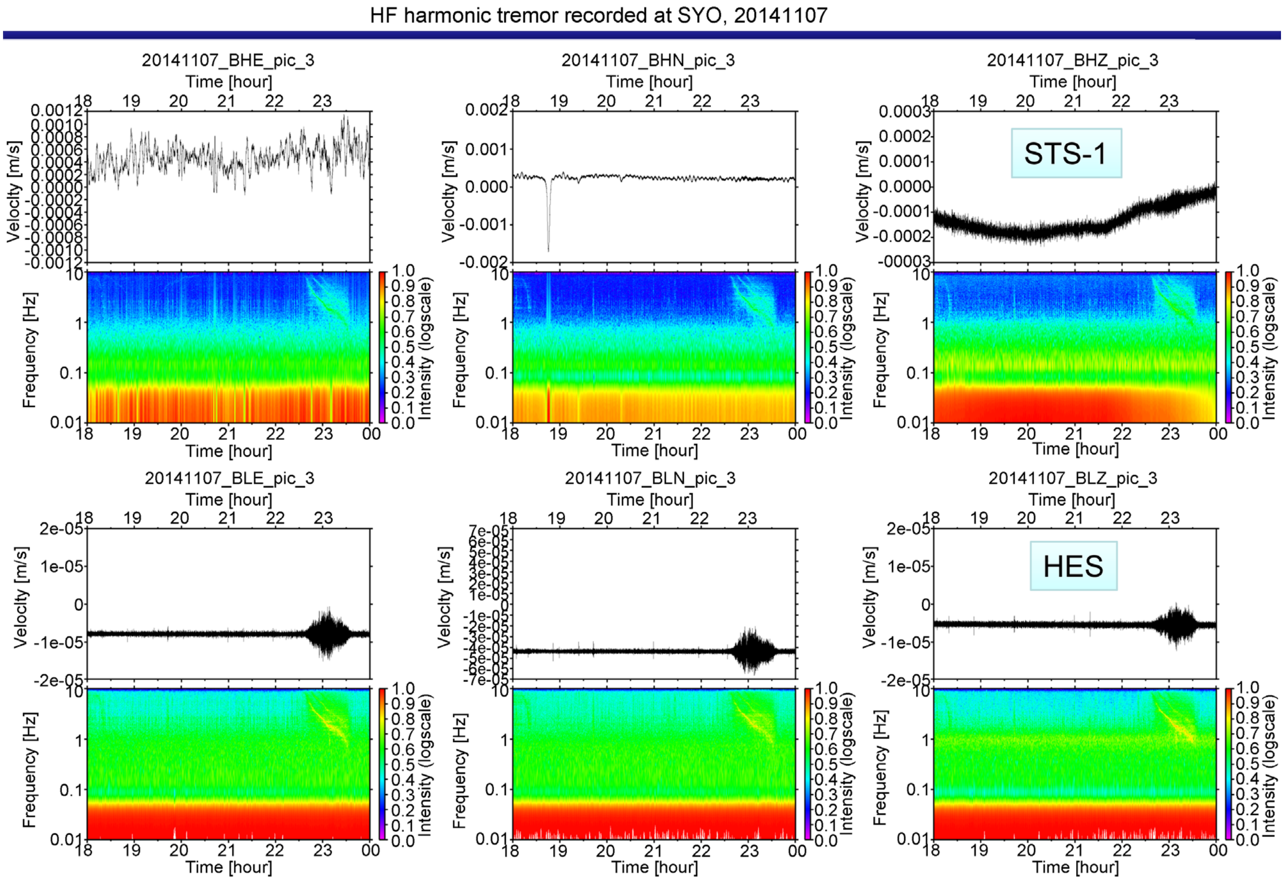
Second example is the tremor event on 20 November, 2014 (**Figure 3(a)** and **Figure 3(b)**) appeared for both kinds of seismographs. Long-duration and non-linear wavelets can be identified after 14 UTC until before 23 UTC of the day, with their frequency contents being from gliding down (*i.e.*, dowward dipping features) then turn to increasing (upward dipping features) within a range of few Hz. Time-variability in frequency contents demonstrated here are the similar pattern of the harmonic tremors caused by collisions of two tabular icebergs [3].

Third example is multiple and non-linear continous tremors on 30 March, 2015 (**Figure 4(a)** and **Figure 4(b)**). Complex features of frequency contents were recognized in the series of tremors, which reflected multiple collisions associated with cryosphere dynamics presumable by sea-ice movement/migration at offshore near the station. Tremor series for these small amplitude events were assumed to be increased when large storms visited to the local area around SYO, with arising oceanic swells amplitude in Southern Ocean [14]. Occurrence of crashing/collision phenomenon, afterthat, were increased among packed ices surrounding the bay nearby SYO.

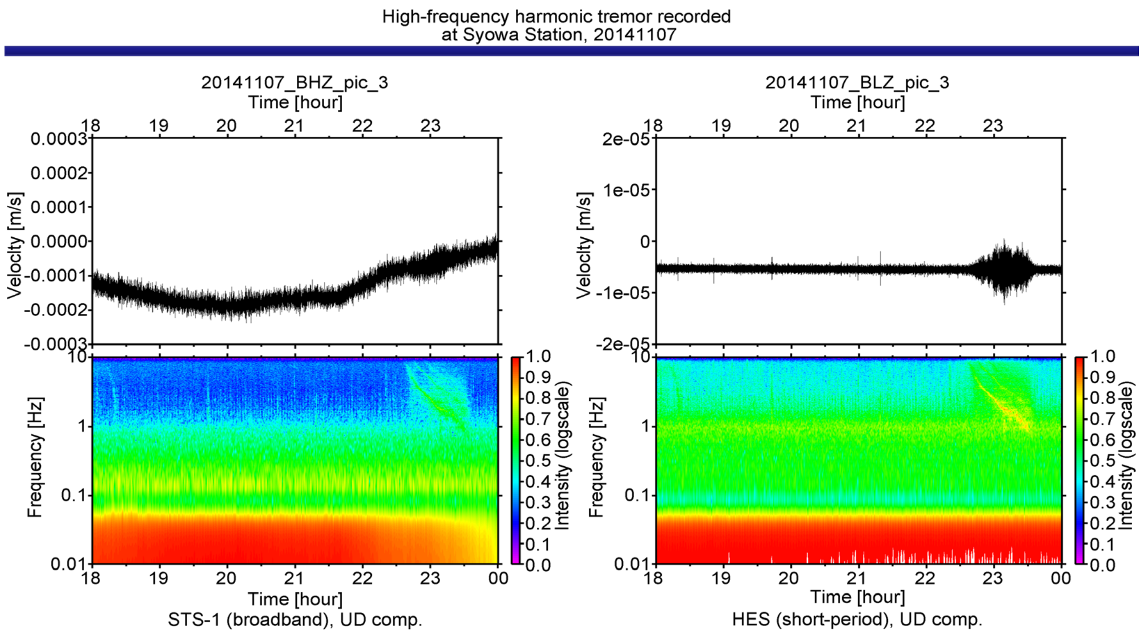
3. Statistics of Harmonic Tremors

During the period from October 2014 to March 2015, a lot of seismic tremors (N = 82) including short duration ice-quakes were identified in both short-period (HES) and broadband seismographs (STS-1) at SYO. **Figure 5(a)** shows statistics of the number of high-frequency tremors for six months of the studied period. A total number of 148 events including 66 ice-quakes were recognized. Definition for dividing harmonic tremors and ice-quakes were set as 15 minutes of their duration times, on the basis of experiences of the ice-quakes recorded at SYO [12] [13]. A couple of harmonic tremors were found in mid-October in 2014, mid-February and the late March 2015, respectively.

In order to investigate the occurrence mechanism in terms of surface environment, we compared the statistic number of harmonic tremors with meteorological data at SYO (**Figure 5(b)**). As the representative of meteorological data, we used air-temperature and wind speed, because these two parameters could



(a)



(b)

Figure 2. (a) Seismic waveforms and power spectral densities of seismic tremor with harmonic overtones recorded at SYO (18 - 24 UTC, 07 November, 2014) for both three-component short-period seismographs (HES; lower panels) and broadband seismographs (STS-1; upper panels). (b) Expanded waveforms and power spectral densities of seismic tremor recorded at SYO (18 - 24 UTC, 07 November, 2014; the same event in Figure 2(a) for vertical component (UD) of both short-period seismographs (HES; right panels) and broadband seismographs (STS-1; left panels).

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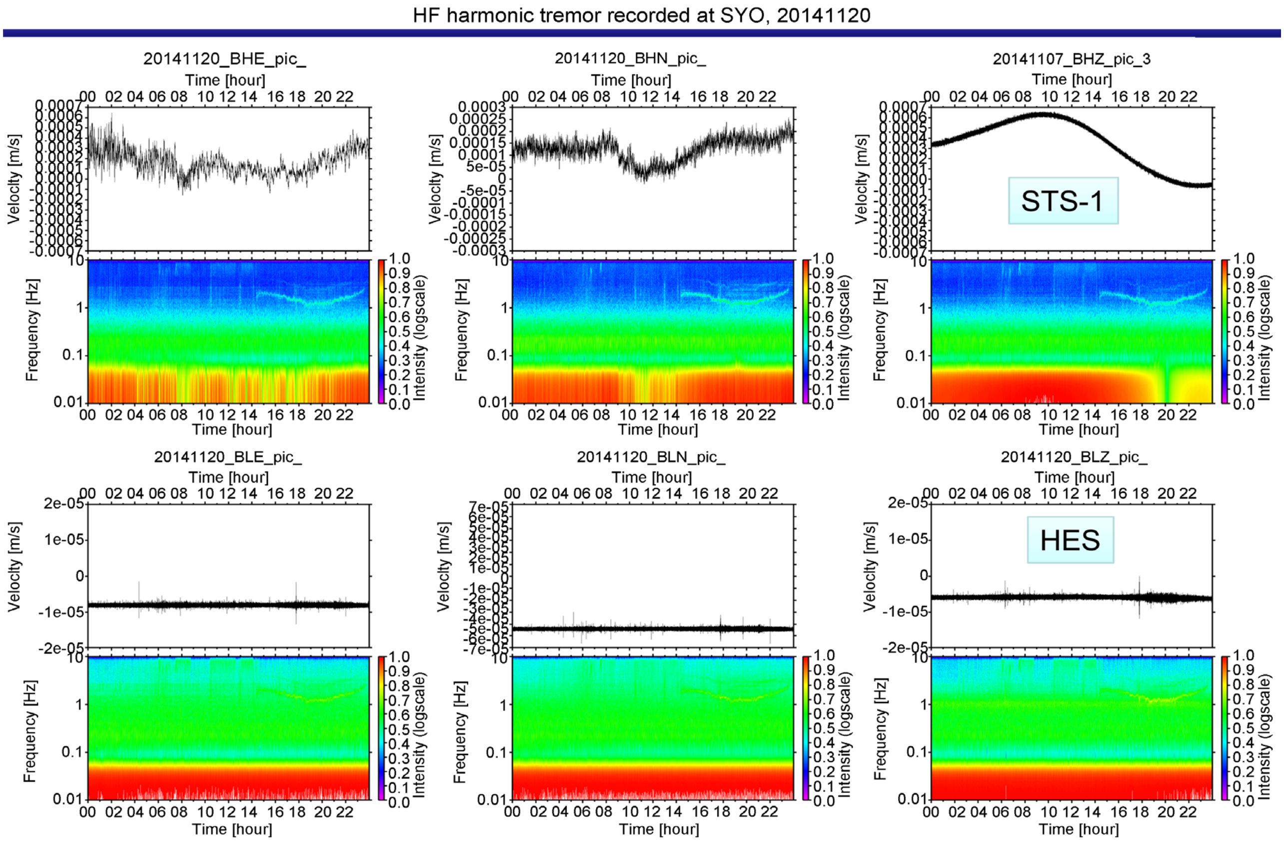
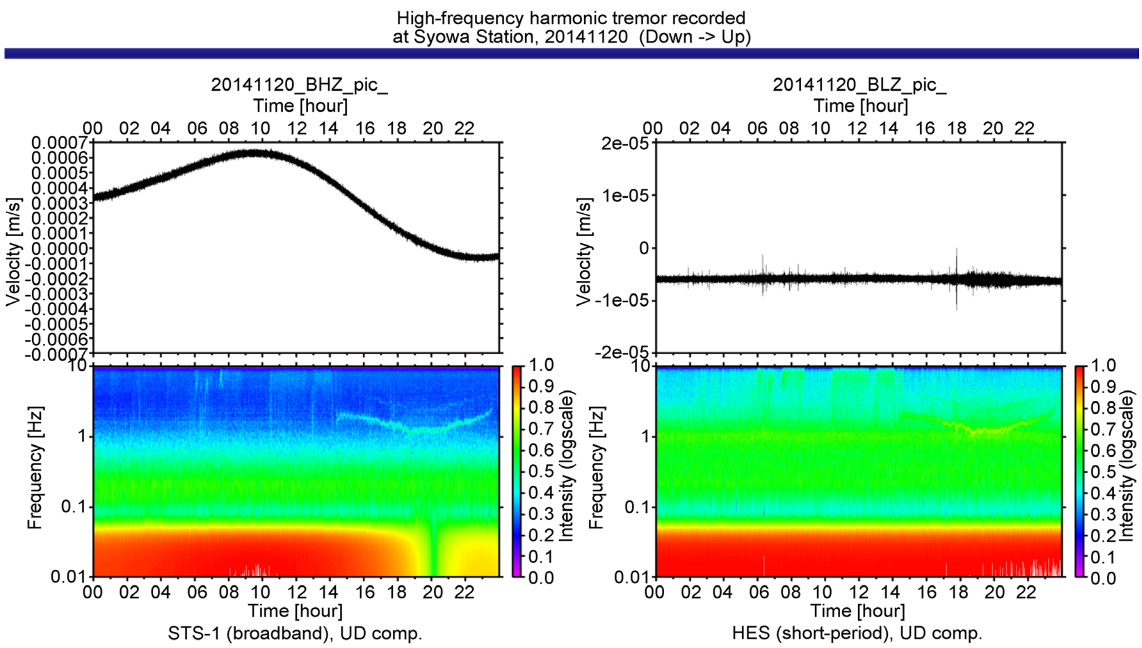
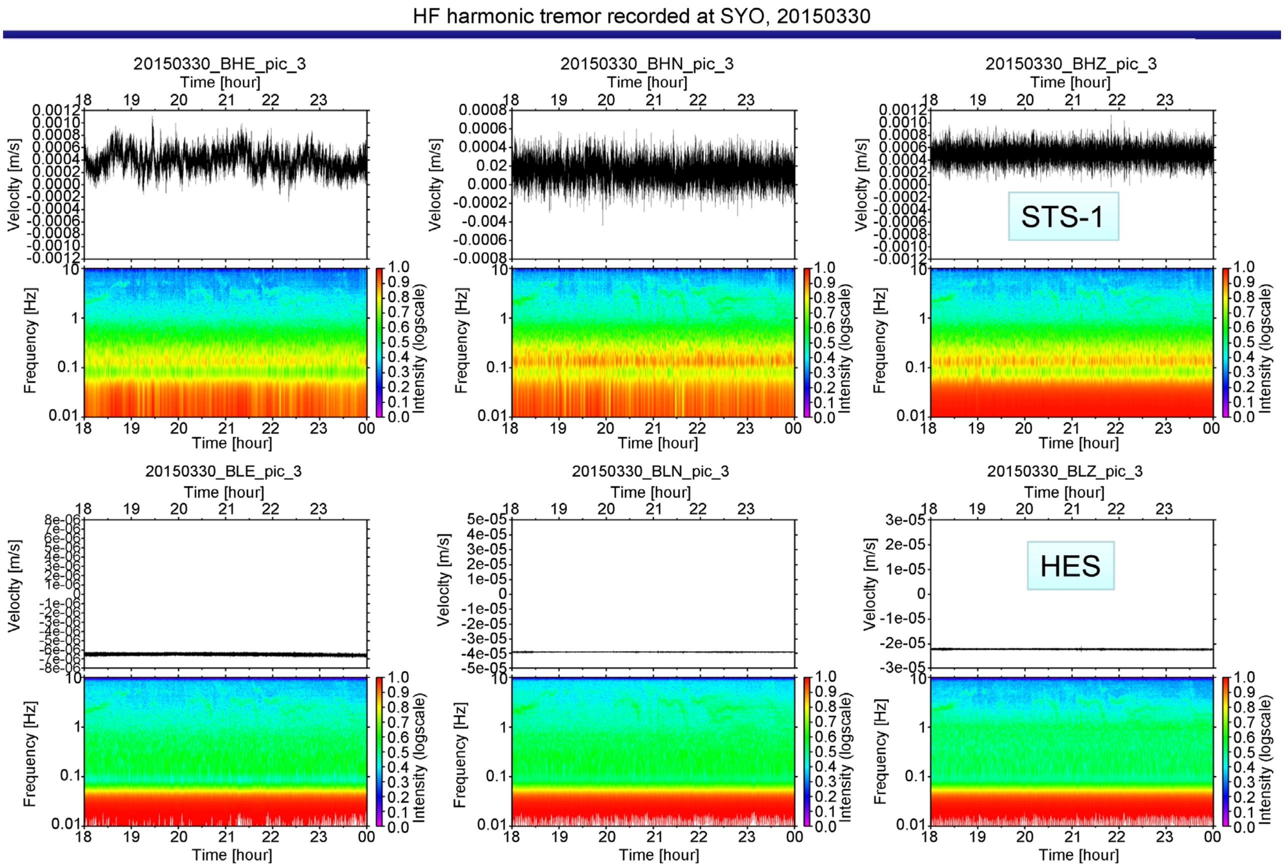


(a)

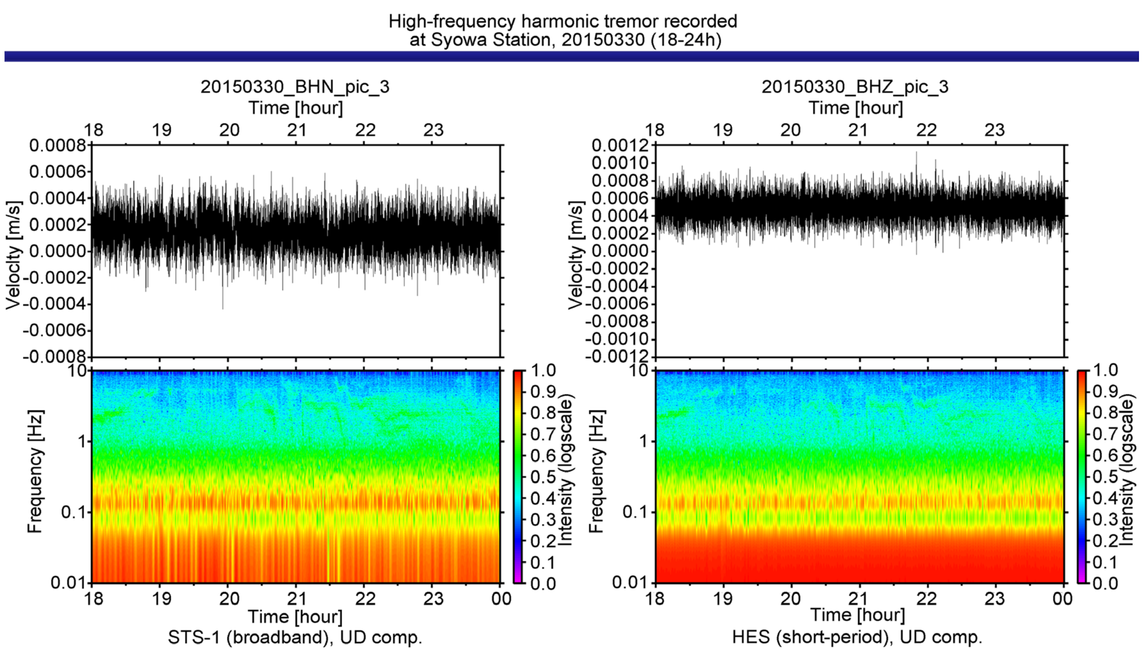


(b)

Figure 3. (a) Seismic waveforms and power spectral densities of seismic tremor with harmonic overtones recorded at SYO (00 - 24 UTC, 20 November, 2014) for both three-component short-period seismographs (HES; lower panels) and broadband seismographs (STS-1; upper panels). (b) Expanded waveforms and power spectral densities of seismic tremor recorded at SYO (00 - 24 UTC, 20 November, 2014; the same event in Figure 3(a) for vertical component (UD) of both short-period seismographs (HES; right panels) and broadband seismographs (STS-1; left panels). Non-linear wavelets are identified after 14 UTC from gliding down then turn into the upward frequency contents.



(a)



(b)

Figure 4. (a) Seismic waveforms and power spectral densities of seismic tremors with harmonic overtones recorded at SYO (18 - 24 UTC, 30 March, 2015) for both three-component short-period seismographs (HES; lower panels) and broadband seismographs (STS-1; upper panels). Complex features of frequency contents appear in the non-linear tremors. (b) Expanded waveforms and power spectral densities of seismic tremor recorded at SYO (18 - 24 UTC, 30 March, 2015; the same event in Figure 4(a) for horizontal component (NS; left panel) and vertical component (UD; right panel) of broadband seismographs (STS-1).

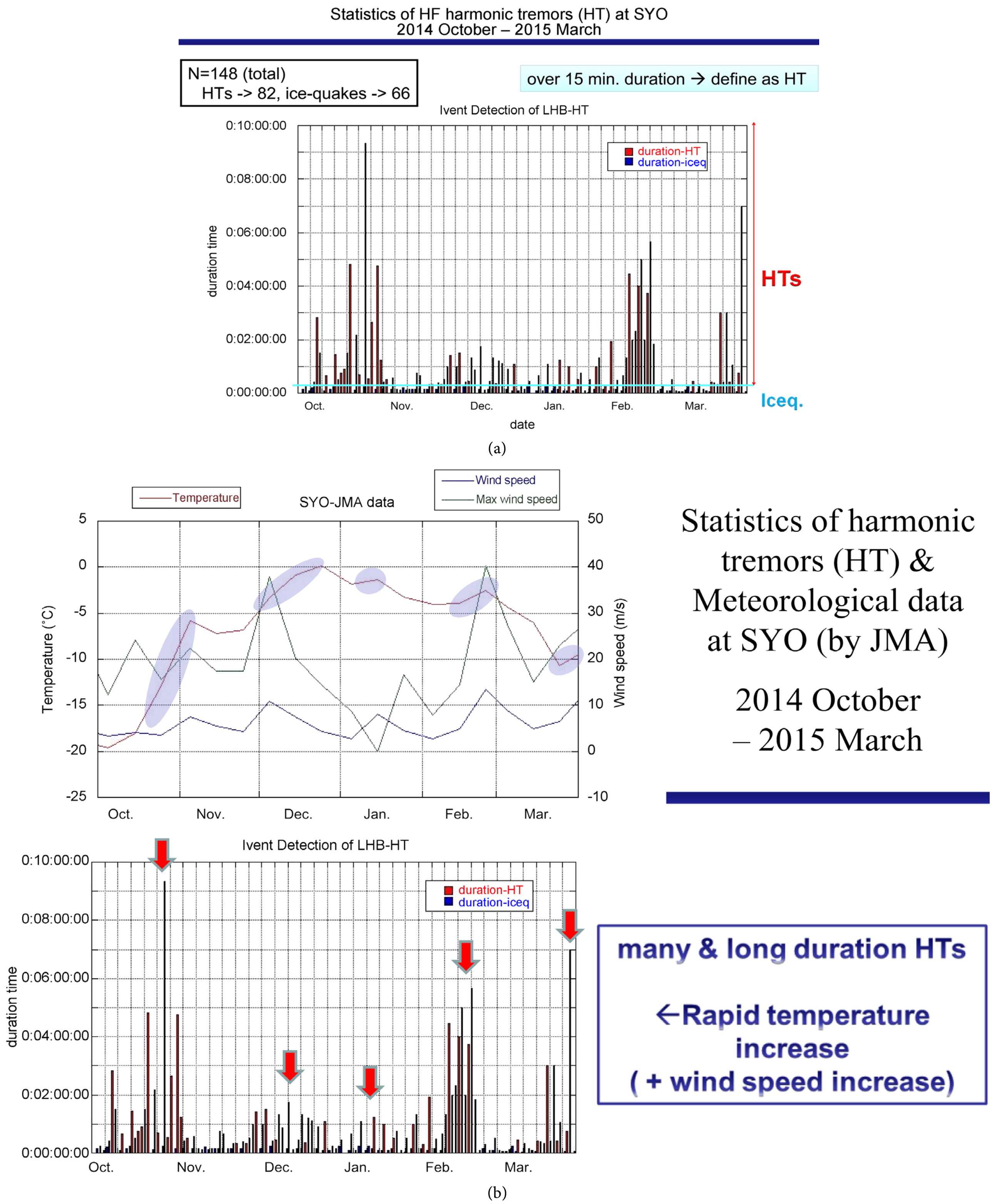


Figure 5. (a) Statistics of the number of high-frequency harmonic tremors recorded at SYO from October 2014 to March 2015. A total number of 148 events including 66 ice-quakes were recognized. Definition for dividing harmonic tremors and ice-quakes were set at 15 minutes of their duration times. (b) Statistics of the number of harmonic tremors from October 2014 to March 2015 (lower) and meteorological data (averaged and maximum wind speeds, air-temperature) at SYO (from Japanese Meteorological Agency). Periods when a large number of tremors occurred (shown by red arrows in lower panel) generally correspond to large increase in temperature and high wind speed periods (gray colored meshed area in air-temperature).

express most adequately the whether condition at the local area in particular the period of storms' visits.

The periods when a large number of tremors occurred (as shown by red arrows in lower panel of **Figure 5(b)**) generally correspond to large increases in air-temperature and wind speed (gray colored meshed area in "temperature" curvature). This implies that the harmonic tremors were easy to be excited by stormy conditions, such as by the visits of blizzards; these storms disturbed stable condition of sea-ice surroundings, glaciers and other cryospheric environment nearby, with making generation of seismic energy. Otherwise, the period of rapid increasing temperature might enhance the melting speed of the cryosphere environment, followed by the generation of seismic energy to be recorded as the tremors.

It is noticed that the high amplitude harmonic tremors with frequency overones as shown in **Figure 2(a)** and **Figure 2(b)** could presumably be related with the strong collision processes between icebergs, fast sea-ice surrounging the bay locating at SYO. These high amplitude tremor events occurred independently from the other major types of non-linear, small and weak signals as shown in **Figure 3(a)**, **Figure 3(b)**, **Figure 4(a)** and **Figure 4(b)**, which were generated by the stormy condition or the rapid temperature increase. It is required, eventually, to monitor longer duration of observation time over few years, so as to reveal detail relationship between whether condition, ocean circulation, and climate change in high southern latitude.

4. Discussion and Conclusions

Similar with seismic tremors treated in this paper, harmonic over-toned tremors caused by collision of two tabular icebergs were previously investigated [3]. Characteristic tremors were found to consist by extending episodes of stick-slip ice-quakes occurred when the ice-cliff edges of two tabular icebergs rubbed together during glancing. Characteristic frequency contents with being from the gliding down to the gliding up features (**Figure 3(a)** and **Figure 3(b)**) can be explained by the same occurring mechanism. Source mechanisms of such harmonic tremors provide useful information for the study of iceberg behavior, and a possible method for remotely monitoring of the iceberg activity and its evolving process. Similar nonlinear harmonic tremors involving glaciers were also reported at Whillans Ice Stream, West Antarctica [15] [16] [17]. The harmonic overtones of these tremors were explained by a repetitive source [18], suggesting existence of several inter-glacial asperities which generate the characteristic tremors. Quantitative evaluation of the annual variation in teleseismic detection capability at SYO was already reported accosiated with the meteological data such as temperature and wind speed [19]. The harmonic tremor events investigated in this paper could become one of the noise sources for the teleseismic phase detection.

In summary of this paper, a total of 148 seismic tremors including 66 ice-quakes were identified at Syowa Station, Antarctica during the period of six months from October 2014 to March 2015. Statistics of the number of these tremors represented that many of them occurred during large increase in temperature and/or high wind speed periods. On the contrary, characteristic tremors of harmonic overtones with strong amplitudes were explained by repetitive seismic sources, suggesting inter-glacial asperities such as the collision of icebergs and fast sea-ice, calving of glaciers or ice-streams at the coastal environment. These high amplitude tremors occurred independently from other majority types of tremor events, with characteristics of non-linear and relatively small amplitude at stormy condition and/or rapid increase in temperature period. These seismic tremors relating cryosphere dynamics are strongly involved in surface environmental change in the Antarctic, and their space-time variability provide a proxy for monitoring climate change among the global system.

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