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Reanalysis of background free oscillations using recent SG data

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ABSTRACT

Background free oscillations (BFOs), observed even during seismically quiet periods, have been widely recognized. Although atmospheric or/and oceanic disturbances are suggested to be the possible excitation sources, there still exist some unknown uncertainties regarding their contribution. Note that most studies used seismometer records to explore the excitation mechanism of BFOs, while only a few used superconducting gravimeter (SG) records just for detection purposes. In view of the high precision, the wide measurement range and the increase of SGs distributed worldwide, this paper aims to further explore the excitation mechanism of BFOs by combining recent gravity records at several low-noise SG stations, rather than traditional seismometer records. We first analyzed gravity records at each station to ensure the detection of BFOs from spectrograms and averaged power spectra. On the basis of the BFOs detection, annual variations of the modal energy in the averaged spectrograms stacked over all stations and over different years were calculated. By comparing them with those derived from atmospheric/oceanic observations, we proved qualitatively that the atmospheric disturbance is the major excitation source of BFOs while the oceanic disturbance plays a relatively minor role below 5 mHz for the whole period considered; however, the excitation of BFOs could be mainly attributed to the oceanic disturbance for a certain period. It is necessary to further quantitatively estimate the modal energy excited by these disturbances, but as a supplementary means of seismic exploration, the results in this paper are expected to be helpful for understanding BFOs.

1. INTRODUCTION

Background free oscillations (BFOs), also called "hum" and different from free oscillations excited by earthquakes, have been early detected from analyses of gravimeter/seismometer records as continuous vertical lines corresponding to the fundamental spheroidal modes in the frequency-time spectrogram even during seismically quiet periods (Nawa et al. 1998; Suda et al. 1998a; Tanimoto et al. 1998). With more detailed studies carried out, the excitation source of this phenomenon has been suggested as a continuous random process near the whole Earth's surface (e.g., Nishida and Kobayashi 1999; Fukao et al. 2002). However, there still exist some unknown uncertainties about the possible excitation mechanisms—atmospheric or/and oceanic disturbances.

In earlier research, the atmospheric disturbance was a possible excitation source for BFOs. Kobayashi and Nishida (1998) proposed that the atmospheric disturbance could generate dynamic pressure onto the Earth's surface, thereby exciting continuous free oscillations. Tanimoto (1999) and Tanimoto and Um (1999) proved the possibility of the atmospheric excitation hypothesis by comparing the observed mode amplitudes with those derived from stochastic normal mode theory. Later, the oceanic excitation mechanism for BFOs was increasingly recognized due to the development of multiple station analysis. By utilizing records from two regional seismic networks, Rhie and Romanowicz (2004) considered that BFOs should be generated probably through the interaction between ocean infragravity waves and seafloor topography. Tanimoto (2005) also presented theoretical evidence of the oceanic excitation hypothesis based on

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normal mode formula. Note that only background spheroidal modes were intensely examined in these BFOs studies until Kurrle and Widmer-Schnidrig (2008) were the first to discover background toroidal modes. Then, Bromirski and Gerstoft (2009), Traer and Gerstoft (2014), and Ardhuin et al. (2015) demonstrated that BFOs may be excited by coastal infragravity waves generated by the interaction of ocean waves with the bottom slope or the nonlinear interaction of ocean waves. Nishida (2014), using records from 618 seismic stations, further concluded that topographic coupling between ocean infragravity waves and seismic surface waves could be the dominant excitation mechanism above 5 mHz, while below 5 mHz, both atmospheric and oceanic disturbances were possible mechanisms.

It is worth noting that most of previous studies used seismometer records to explore the excitation mechanism of BFOs while only a few (Nawa et al. 1998, 2000; Rosat et al. 2003) used superconducting gravimeter (SG) records just for the detection, on account of the establishment of dense seismic networks. However, there is no denying the fact that SGs of extremely high precision and wide measurement range (Goodkind 1991) surely have potential to explore the excitation mechanism of BFOs, especially with the increase and the upgrading of SGs distributed worldwide (Crossley and Hinderer 2009).

The aim of this paper is to further explore the excitation mechanism of BFOs by combining recent records at several low-noise SG stations rather than seismometer records. We first analyzed records at each station, with known gravitational effects removed, to ensure the detection of BFOs from spectrograms and averaged power spectra for seismically quiet periods. We then obtained annual variations of the modal energy in the averaged spectrograms stacked over all the stations and over different years. By comparing them with those derived from atmospheric and oceanic observations, we finally discussed the excitation mechanism of BFOs. As there exist no horizontal component data from SG, only background spheroidal modes or vertical BFO were considered in this study.

2. DATA ANALYSIS

2.1 Detection of BFOs

Since the intensity of BFOs is very weak (Nawa et al. 1998, 2000), 4 SG stations with quite low noise levels (Rosat and Hinderer 2011; Zhang et al. 2014), including Canberra (Australia), Bad Homburg (Germany), Kamioka (Japan), and Wuhan (China), were chosen to detect this phenomenon. The locations, instrument types and data spans of these stations are listed in Table 1. All of the original records were decimated to 1 minute and were corrected for spikes, gaps, steps, and large amplitude caused by earthquakes. Local tides determined from tidal analyses (Tamura 1987) were then removed from gravity records. To better identify low frequency modes (Zürn and Widmer 1995; Roult and Crawford 2000), we elaborately corrected for the atmospheric pressure effects on gravity variations by using time- and frequency-dependent atmospheric admittances obtained from wavelet filter analysis proposed by Hu et al. (2005), rather than a single admittance. In this wavelet method, both gravity and pressure data were decomposed into a finite number of narrow sub-bands through filter banks derived from a high-degree wavelet function, and then atmospheric admittances in these sub-bands were determined through a linear regression technique.

Figure 1 shows the averaged power spectra for seismically quiet periods (each of which is defined as a 3-day interval, not containing the day of or day immediately after any earthquakes with moment magnitude greater than 5.7 listed in the Global CMT catalogues, see Suda et al. 1998a) for gravity residuals at Canberra during 2012, the peaks of which correspond to BFOs. It is clear that using the wavelet method to correct for the atmospheric pressure effect indeed improves the resolution of BFOs to some extent. Furthermore, we stacked power spectra for all seismically quiet periods from 2010 - 2015 to ensure the detection of this phenomenon. Figure 2 plots averaged power spectra for gravity residuals at all of the stations from 2010 - 2015, with atmospheric correction using the wavelet method. The spectral levels are below the critical noise level of detection (10^{-17} m^2 s^{-3}) mentioned by Suda et al. (1998b). The comb-like spectral peaks correspond well to background fundamental spheroidal modes, though there exists an obvious descending tendency at Bad Homburg and Wuhan due to the influence of the decimation filter.

2.2 Annual Variations

On the basis of the above detection, it is possible to explore the excitation mechanism of BFOs by combining SG data at these stations. As many previous studies have inferred the excitation mechanism from investigation of the annual variation of this phenomenon based on a spectrogram (e.g., Tanimoto and Um 1999; Nishida et al. 2000), here we still follow this way of thinking. Figure 3 shows the averaged spectrogram (computed using 3-day time windows with a time lag of 1 day, see Suda et al. 1998a) stacked over all of the stations and over all of the years from 2010 - 2015. BFOs are clearly detected as continuous vertical lines parallel to the time axis and corresponding to the eigenfrequencies of fundamental spheroidal modes between 2 and 5 mHz. The annual variation of the averaged energy for modes from ${}_0S_{20}$ to ${}_0S_{33}$ in the spectrogram is plotted in Figs. 4a and d (red dashed line), with a maximum in July.

Furthermore, annual variations of the averaged modal energy stacked over all of the stations and over years from 2010 - 2012 and from 2013 - 2015 were calculated, as shown in Figs. 4b and e (black dashed line) and in Figs. 4c and f

Table 1. Information about the SG stations used in this study.

Station	Location	Instrument Type	Data Span
Canberra (Australia)	35.321°S, 149.008°E	C031	2010.01.01 - 2015.12.31
Bad Homburg (Germany)	50.229°N, 8.611°E	OSG-044	2010.01.01 - 2015.12.31
Kamioka (Japan)	36.425°N, 137.308°E	T016	2011.01.01 - 2012.12.31
Wuhan (China)	30.516°N, 114.490°E	OSG-065	2014.01.01 - 2015.12.31

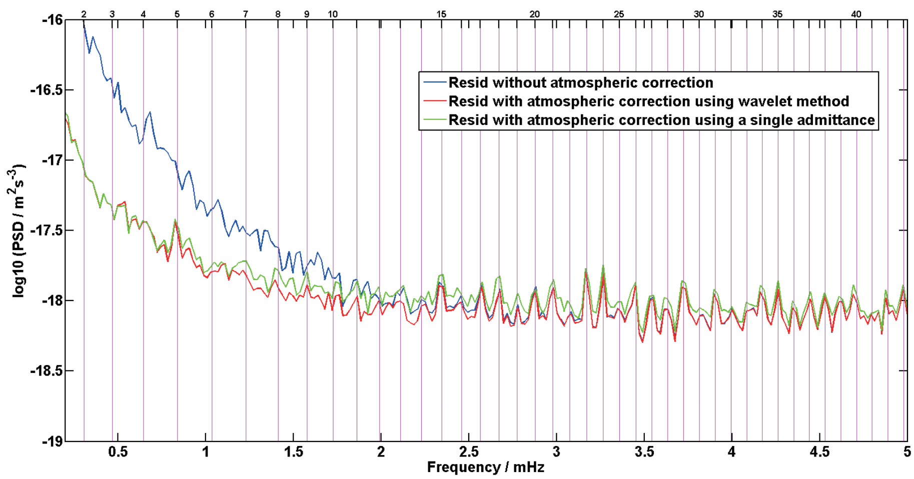

Fig. 1. Averaged power spectra for gravity residuals at Canberra during 2012 without atmospheric correction (blue), with atmospheric correction using the wavelet method (red) and a single admittance (green). Vertical magenta lines indicate theoretical eigenfrequencies of some spheroidal modes based on Earth Model PREM (Dziewonski and Anderson 1981), and numbers at the top frame represent angular orders of these modes.

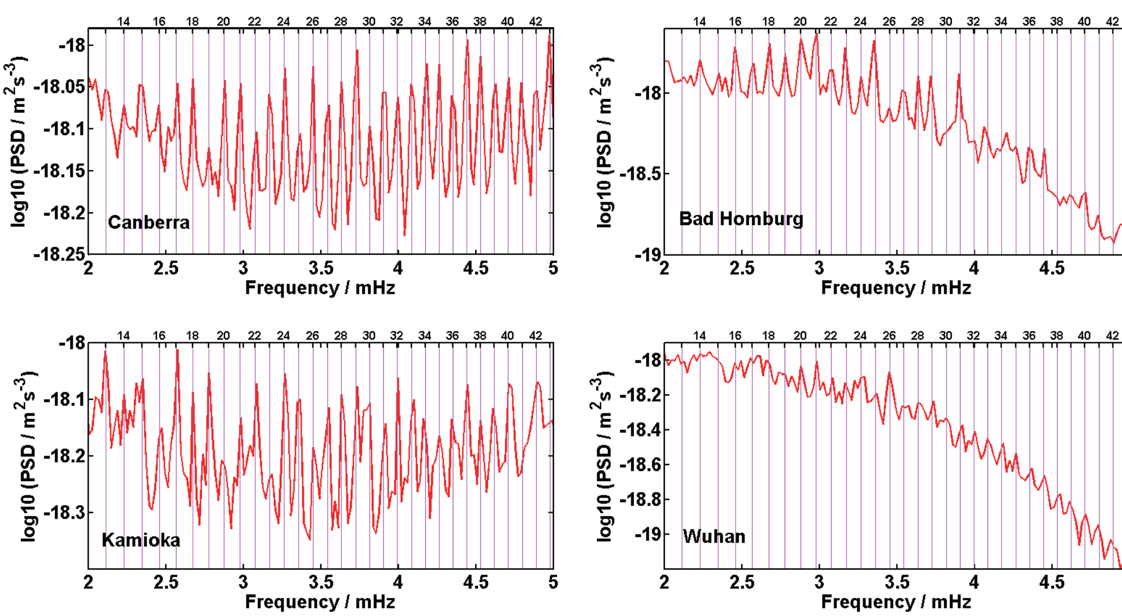

Fig. 2. Averaged power spectra for gravity residuals with atmospheric correction using the wavelet method at Canberra, Bad Homburg, Kamioka, and Wuhan from 2010 - 2015. Vertical magenta lines indicate theoretical eigenfrequencies of some spheroidal modes based on Earth Model PREM (Dziewonski and Anderson 1981), and numbers at the top frame represent angular orders of these modes.

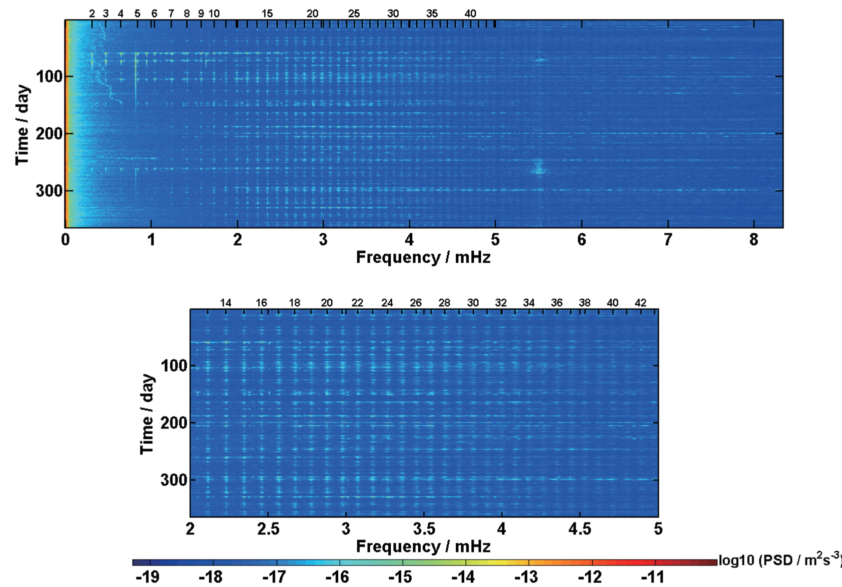

Fig. 3. Averaged spectrogram over all the stations and over all the years (2010 - 2015). The upper panel shows the whole spectrogram from 0 - 8.3 mHz (Nyquist frequency). The lower panel shows an enlargement of the upper panel from 2 - 5 mHz, where BFO are detected as continuous vertical lines parallel to the time axis and corresponding to the eigenfrequencies of fundamental spheroidal modes. Numbers at the top frame of each panel represent angular orders of fundamental spheroidal modes.

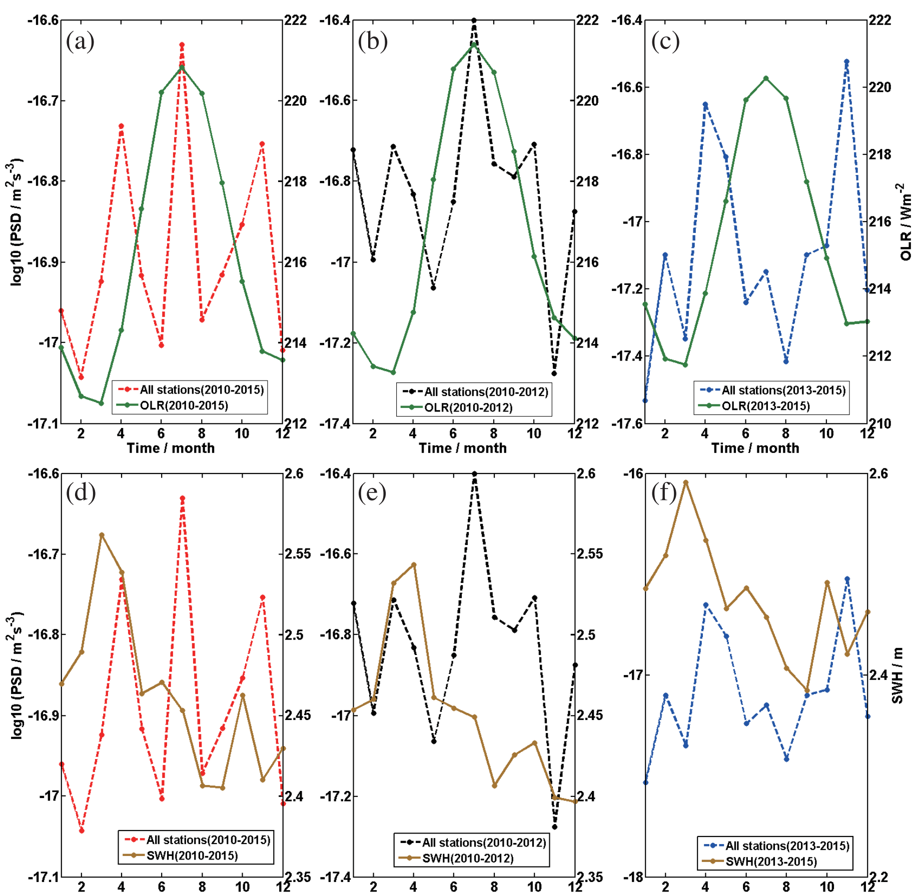

Fig. 4. Annual variations of the averaged energy for modes from ${}_0S_{20}$ to ${}_0S_{33}$ stacked over all the stations and over years from 2010 - 2015 [(a) (d): red dashed line], from 2010 - 2012 [(b) (e): black dashed line], and from 2013 - 2015 [(c) (f): blue dashed line]. Green solid lines in all the upper panels and brown solid lines in all the lower panels correspond to the global averaged outgoing longwave radiation (OLR) and significant wave height (SWH) stacked over the same years as the averaged modal energy.

(blue dashed line), respectively. It is surprising that, although the annual variation for the first three years is almost the same as that for the whole period from 2010 - 2015, it is quite different from and even opposite to that for the last three years. To underline this, annual variations of the averaged modal energy for each year and stacked over different years at a single station (Canberra and Bad Homburg) are plotted in Figs. 5 and 6, respectively. Likewise, there also exist contrasting trends in annual variations for the first three years (black dashed lines in Figs. 5 and 6) and the last three years (blue dashed lines in Figs. 5 and 6).

3. COMPARISONS WITH ATMOSPHERIC AND OCEANIC OBSERVATIONS

Similar to the results mentioned in previous studies (e.g., Nishida et al. 2000; Roult and Crawford 2000), we show evidence of an annual variation of BFOs with most energy in July for the whole period from 2010 - 2015 as well as for the years from 2010 - 2012. This evidence has been regarded as an indicator of the atmospheric excitation hypothesis. To further verify this hypothesis, here we compared the annual variation of the averaged modal energy with that of atmospheric data; referring to Nishida et al. (2000), atmospheric data are the global averaged outgoing longwave radiation (OLR; units: Wm^2) at the top of the atmosphere observed from the AVHRR instrument aboard the NOAA polar orbiting spacecraft, which is a measure of the intensity of convective activity. As shown in Figs. 4a - b, there is a good coincidence between the annual variation of the averaged modal energy and that of the global averaged OLR (green solid line) stacked over the whole period from 2010 - 2015 as well as over the years from 2010 - 2012, implying that atmospheric disturbance plays a major role

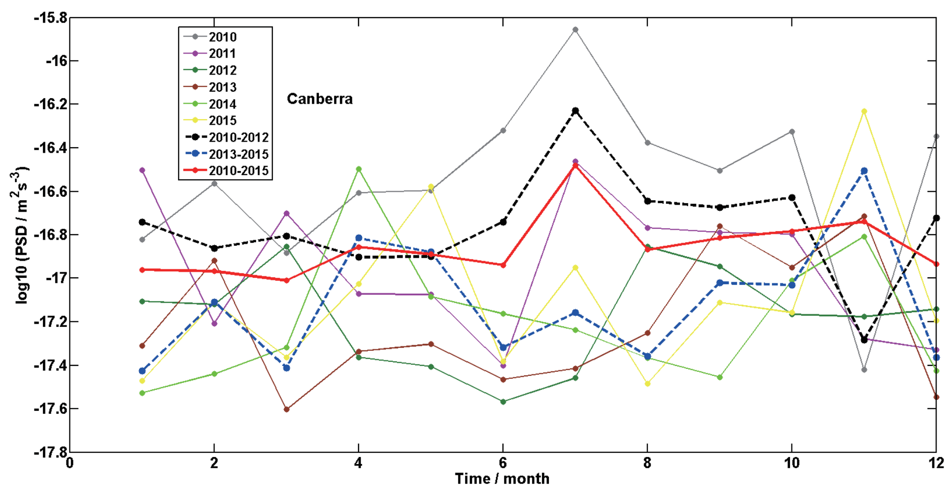

Fig. 5. Annual variations of the averaged energy for modes from $_0S_{20}$ to $_0S_{33}$ for each year from 2010 - 2015 and stacked over different years at Canberra.

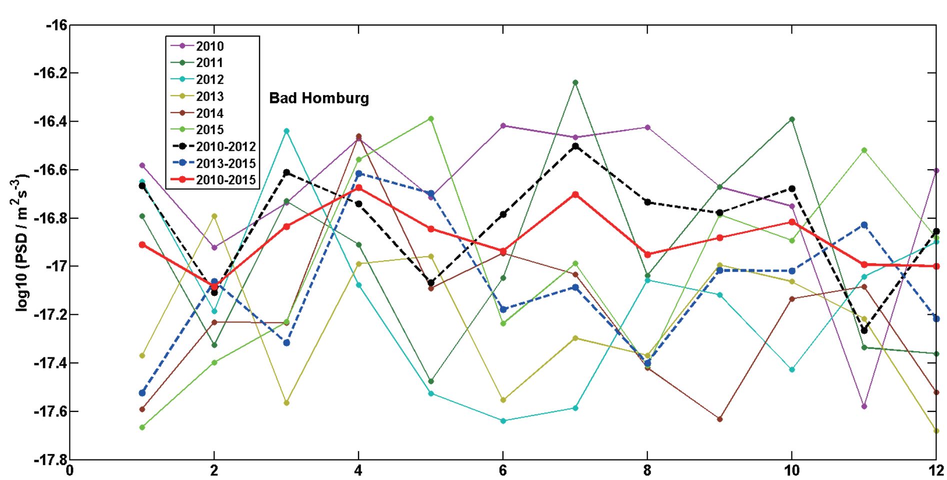

Fig. 6. Annual variations of the averaged energy for modes from $_0S_{20}$ to $_0S_{33}$ for each year from 2010 - 2015 and stacked over different years at Bad Homburg.

in the excitation of continuous free oscillations by generating dynamic pressure onto the Earth's surface. However, the annual variation of the averaged modal energy dose not match that of the global averaged OLR stacked over years from 2013 - 2015 (Fig. 4c).

To better understand the above mismatch and given that the oceanic disturbance is another possible candidate for the excitation of BFOs, we also compared the annual variation of the averaged modal energy with that of oceanic data; referring to Tanimoto (2005), oceanic data are the global averaged significant wave height (SWH; units: m) obtained from altimetry satellite Jason-2. Figures 4d - f show annual variations of the averaged modal energy stacked over different periods (just like those in Figs. 4a - c) as well as those of the global averaged SWH (brown solid lines). It is clearly observed that the annual variation of the averaged modal energy is generally consistent with that of the global averaged SWH for the period from 2013 - 2015. This result demonstrates the significance of the oceanic excitation hypothesis. In addition, for the periods from 2010 - 2015 and from 2010 - 2012, the oceanic disturbance could well explain smaller peaks appearing in the averaged modal energy, thereby compensating for the deficiency of above atmospheric excitation hypothesis. However, it may be worth noting that there exists some phase delay between annual variations of the averaged modal energy and those of the global averaged SWH, probably due to complex propagation processes occurring in the Earth.

From these comparisons, we argue that the atmospheric disturbance is the major excitation source of BFOs while the oceanic disturbance plays only a relatively minor role for the whole period considered in this study. However, the excitation of this phenomenon could be mainly attributed to the oceanic disturbance for a certain short period. We need to pay attention to this argument, however, that only qualitative comparisons are carried out. More quantitative comparisons will require estimating the modal energy excited by atmospheric and oceanic disturbances based on the normal mode theory (e.g., Tanimoto and Um 1999; Fukao et al. 2002; Tanimoto 2005). As the generation of BFOs depends on how close the resonant frequencies are between the Earth and the atmosphere/ocean, the inconformity and the correlation between the frequencies of OLR/SWH and those of BFOs are still critical problems that need to be discussed.

Some recent papers have discussed the oceanic excitation hypothesis above 5 mHz by using records from many seismic stations (Nishida and Fukao 2007; Nishida 2014), and through the cross-spectra method, which claimed that BFOs may be caused by coupling between ocean infragravity waves and seismic surface waves. Limited by the availability of 1 second sampled data, however, here, we do not focus on the excitation mechanism at higher frequencies (above 5 mHz). To fully explain this phenomenon, it is necessary to combine records of a higher sampling rate at more low-noise SG stations in the future.

4. CONCLUSIONS

We have reanalyzed BFOs and re-explored the excitation mechanism of this phenomenon by combining recent records at 4 low-noise SG stations rather than seismometer records. On the basis of qualitative comparisons between annual variations of averaged modal energy and those of atmospheric and oceanic observations, it is proven that both atmospheric and oceanic disturbances are the excitation mechanisms below 5 mHz. Different from previous studies, however, it is found that the oceanic disturbance could play different roles in different periods. For the whole period from 2010 - 2015 considered in this study, the atmospheric disturbance is the major excitation source of BFOs while the oceanic disturbance plays only a relatively minor role; but for the period from 2013 - 2015, the oceanic disturbance plays a leading role. Observationally, these results could constrain the contribution from atmospheric or/and oceanic disturbances at lower frequencies. At the same time, although there exists a good agreement between the trend of the annual variation of BFOs and that of the annual variation of atmospheric or oceanic data, more quantitative comparisons with atmospheric and oceanic observations, through estimating the modal energy excited by them, should be made.

Since there still exist some unknown uncertainties about the contribution from atmospheric or/and oceanic disturbances, it is important to continue to explore the excitation mechanism of BFOs by utilizing multiple observation means. The work in this paper, as a supplementary means of seismic exploration, is expected to be helpful for further understanding this phenomenon.

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