Research Square

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Large air pressure changes triggered by P-SV ground motion in a cave in northern Taiwan

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Abstract

Barometers in the cave of the SBCB station observe a novel phenomenon of larger pressure changes inside than that at the Xinwu station (outside). Accordingly, the comparison between the observation data inside and outside the cave can drive investigations of potential sources of the novel phenomenon. Analysis of phase angle differences reveal that the air pressure outside the cave often lead air pressure changes inside. However, the larger pressure changes at frequencies $> 2 \times 10^{-4}$ Hz inside the cave lead smaller changes outside. To expose causal mechanism of the novel phenomenon, continuous seismic waveforms recorded inside the cave are further conducted for examination. When the horizontal and vertical ground velocities of ground motion yield difference in the phase angle close to 90°, air pressure inside the cave increases accordingly. This suggests that the pressure-shear vertical ground motion can drive air pressure changes. Meanwhile, the results shed light on investigating the existence of acoustic waves near the Earth's surface using a partially confined space underground due to that the assumptions of the waves can propagate upward in the atmosphere driving changes in the ionosphere.

Introduction

A barometer is one of scientific instruments that is generally installed above the Earth's surface and is utilized to monitor variations of atmospheric pressure in a particular environment (Kenneth, 2013). The monitoring collects useful information (i.e., atmospheric pressure) to help weather analysis and to forecast short-term changes in the weather for further evaluating impacts on human life (Rasouli et al., 2012; Gutierrez-Lopez et al., 2019). Alternatively, the observation exhibits low-noise characteristics in caves and/or tunnels with rare artificial activities due to that the environment inside can mitigate influence from weather and artificial activities outside. The recorded data can be utilized as references for correcting responses of air pressure on distinct geophysical measurements (Huang et al., 2009) and detecting an unlike change in deep tunnels that is resulted from the weather through a comparison with outside (Wasilewski, 2014; Tan et al., 2008).

Previous studies (Liu et al., 2006, 2011a, 2011b, 2016, 2019; Otsuka et al., 2009; Astafyeva et al., 2011; Sun et al., 2011, 2016; Astafyeva 2019; Chou et al., 2020) reported that acoustic wavs can propagate from the ground upward the atmosphere and drives changes in electron density in the ionosphere. However, acoustic wavs originate from ground vibrations that is obscured and difficult to be identified. The difficulty is mainly due to that seismic waves generally comprises distinct types of ground vibrations. Meanwhile, the acoustic wavs disperse in an open area (i.e., near the Earth's surface) and become weak, accordingly.

A cave of the SBCB station is located at (24.79°N, 120.98°E) with the altitude of 141.5 meters beneath the 18-peaks mountain in the northeastern Taiwan. The cave was built for bomb shelter in 1941 (https://gps.moi.gov.tw/SSCenter/Introduce/IntroducePage.aspx?Page=Gravity4). Aisles inside the cave exhibit as a "U" sharp. The cave wall is rocks covered by calcium silicate boards and tiles. The width and the height of the cave is about 1.2–1.5 meters and 1.8 meters, respectively. The cave is under overburden soils with a thickness of about 40 meters that causes the stable temperature and structural integrity (Huang, et al., 2009). Meanwhile, the influence from the groundwater is relative-small due to that the groundwater is static and its level is about 23 meters lower than the cave. Doors were set up in the both entrances of the cave to avoid the interference from artificial activities. A broadband seismometer was installed at the innermost of the cave, where is about 38 meters away from the entrances. All the efforts are benefit to high-quality data (Huang, et al., 2009).

A barometer was installed a few meters above the Earth's surface at the Xinwu (operated by the Central Weather Bureau in Taiwan code 467050) weather station (25.00°N, 121.05°E; Fig. 1a) with an altitude of about 20 meters, which routinely monitors changes in air pressure dominated by the weather. The other barometer was installed approximately 25 km away inside the cave (Fig. S1-S4) at the SBCB station for comparison due to the interior of the cave can eliminate the effects of the artificial activity and severe weather outside the cave. Note that the barometer was also installed with a broadband seismometer for correcting unwanted influence from air pressure changes on seismic data (Beauduin et al., 1996; Zurn et al., 2007).

Figure 1b shows air pressure changes inside and outside the cave from February 1 to 5 2016. The air pressure outside the cave is mainly ranged from 1016 mb to 1024 mb. Alternatively, the air pressure inside the cave is ranged from 1004 mb to 1012 mb. Air pressure inside and outside the cave roughly shows a discrepancy of about 12 mb. The discrepancy is considered to be contributed by difference of altitudes (120 = 141 – 20 meters) between these two barometers based on the decrease rate (1 mb / 9 meters) close to the Earth's surface. Meanwhile, both air pressure data show perturbations with an amplitude < 1 mb lie on semidiurnal variations. These suggest the air pressure outside and inside the cave has in-phase changes and the air can circulate through aisles. According to the comparison, the amplitudes of the pressure perturbations inside the cave are roughly comparable from February 1 to 3 in 2016. In contrast, the amplitudes are 0.5 mb greater than those outside the cave particularly from February 4 to 5 in 2016 (red arrows in Fig. 1b as examples). The great amplitude inside the cave is a novel phenomenon due to that artificial activities are rare and weather influence from outside is small, which leads us to investigate a causal mechanism of the large pressure changes inside.

Methodology And Analytical Results

To examine the causal mechanism of the characteristics including the amplitude and the frequency, we transformed both air pressure datasets into the frequency domain using the Fourier transform. We also assessed the coherence of the amplitude within a particular frequency band using the Magnitude-Square Coherence (MSC) index (Stoica & Randolph 2005). The MSC was computed from the bivariate time series using a subroutine called "mscohere" in MATLAB. The MSC can identify significant frequency-domain correlations between two time series datasets. Meanwhile, phase angle estimates in the cross spectrum are useful for understanding where significant frequency-domain correlations exist. The differences in the phase angles of a particular frequency band were computed to understand the leading (or lagging) of air pressure changes inside or outside the cave.

The air pressure data at the Xinwu and SBCB stations have coherence values close to 1 near a frequency of 3×10^{-5} Hz (~ semi-diurnal; Fig. 1c). The differences in the phase angles reveal that variations in air pressure outside the cave occurred before (leaded) variations in air pressure inside the cave. Note that, under typical conditions, the barometer takes time to respond to weather changes outside the cave.

The coherence rapidly decreases at frequencies > 2×10^{-4} Hz (Fig. 1c). Variations in air pressure outside lags behind the changes inside, that exhibits the coherences > 0.4. However, perturbations inside the cave sometimes lead perturbations outside it, which is entirely different from our common senses of that the pressure variations should be relatively-small and quiet inside, if the variations inside are due to weather and human activity outside.

The odds ratio (Holcomb, 2001; Viera, 2008, Szumilas, 2010) is defined as $p/(1-p)$ where p is the probability of success and is used in this study to show if the leading events were statistically significant. Notably, with an odds ratio near one, a success (i.e., an enhancement in this study) was more likely than a failure. We calculated the odds ratios by dividing the number of the leading events by the number of the lagging ones within a moving window of 5 events. The odds ratios are obviously larger than one in particular frequency bands (e.g., close to 1×10^{-4} Hz, 4×10^{-4}–7×10^{-4} Hz, 1×10^{-3} Hz, 1.7×10^{-3}, 4×10^{-3} Hz, 6×10^{-3} and 8×10^{-3} Hz in Fig. 1d). This suggests that those promising leading events can pass the statistical test (i.e., the odds ratio > 1) and exist in the observation data in particular frequency bands. In short, we found that air pressure with an amplitude of approximately 0.5 mb inside the cave is larger than it outside. Variations of the air pressure inside the cave is mainly dominated by them outside for the relatively-low frequency band (< 2×10^{-4} Hz). In contrast, for the relatively-high frequency band (> 2×10^{-4} Hz), variations of the air pressure inside the cave can leads them outside. The large amplitude inside the cave is mainly limited within the relatively-high frequency band.

Discussions

Wasilewski (2014) and Tan et al. (2008) reported that the amplification effect of air pressure changes in deep mines can be caused by variations of the environments on the Earth's surface due to the partially confined interior of tunnels. However, the large air pressure reported in this study is observed in the shallow cave with short aisles. The large air pressure is mainly limited within the relatively-high frequency band of > 2×10^{-4} Hz. Those are significantly different with the reports in Wasilewski (2014) and Tan et al. (2008). This suggests that variations of the environments outside the caves are not the major factor of the large air pressure observed inside in this study. Otherwise, the air can be squeezed out from the cave. However, the pressure variations caused by air blowing are hardly monitored at the Xinwu station about 25 km away due to that the difference of 0.5 mb becomes smaller with the propagation via dispersion.

Previous studies (Artru et al. 2004; Hao et al. 2013; Liu et al. 2016) reported that changes in air pressure can be triggered by the arrival of propagating Rayleigh-like (Pressure-Shear vertical; P-SV) waves. Thus, beside the air blowing in the atmosphere, large-scale ground motion forces the ground and perturbs the air that can be one of the candidates for resulting the lags. The large-scale ground motion amplifies variations in air pressure changes inside the cave due to the confinement of the surrounding rocks and influence surface air pressure. In other words, relatively-large variations should result from activities inside the cave or beneath the ground that shows the possible connection between changes in ground motion and air pressure changes.

To examine the connection, continuous seismic waveforms (i.e., seismic data) were also analyzed in this study to understand how ground motion triggers air pressure variations. We computed the coherence and the phase angle difference varying with frequencies between the vertical ground velocity (Fig. 2a) and the air pressure inside the cave (i.e., both at the SBCB and Xinwu stations). A low coherence close to 0.2 in most of the frequency bands (Fig. 2b) suggests that, in typical condition, changes in air pressure are generally uncorrelated to ground motion. However, ground motion leads to changes in air pressure inside the cave (red circles in Fig. 2b), which can be observed in the frequency bands (e.g., close to 4×10^{-4}–7×10^{-4} Hz, 1.5×10^{-3}–4×10^{-3} Hz, 6×10^{-3}–7×10^{-3} Hz in Fig. 2d) that exhibits the higher coherences (> 0.35). This finding suggests that ground motion can drive changes in air pressure in the cave. Meanwhile, the changes in the cave were amplified due to the surrounding materials. We thus investigate whether air pressure at the Xinwu station changes accordingly or dissipates due to dispersion.

We distinguished changes in air pressure outside the cave that are driven by ground motion using the same method (i.e., coherence and phase angle differences). Similarly, changes in air pressure outside the cave are almost uncorrelated with ground motion, except for several specific frequencies close to 3×10^{-4}–9×10^{-4} Hz, 1.5×10^{-3}–4×10^{-3} Hz, and 6×10^{-3}–7×10^{-3} Hz (Figs. 2c and 2e). In these frequency bands, we can find that ground motion leads changes in air pressure outside the cave exhibiting the higher coherence (> 0.35).

One of the characteristics associated with P-SV waves is the 90° phase angle difference between the horizontal and vertical components. We computed the maximum horizontal amplitude as the horizontal component (Fig. 2a) by using the East-West and North-South ground velocities utilizing the method proposed by Tanimoto *et al.* (2006). We determine the ground motion with the differences of the phase angle between the horizontal and the vertical component are from 75° to 105° and from − 105° to -75° as P-SV waves. We integrated coherences that were larger than distinct thresholds ranging from 0 to 0.35 and counted the numbers associated with the P-SV waves for the different criteria. The P-SV motion ratios (number of the P-SV waves at each frequency grid / total number of the frequency grids) are proportional to the coherence, and increase to double the average (i.e., 0.017 = 60/360) for a threshold of 0.35 (Fig. 2f). In short, both air pressure and ground motion share frequencies that are dominated by the existence of the P-SV ground motion.

We try to evaluate air pressure changes dominated by variations of the volume of the cave through the ideal gas law (Clapeyron, 1834). We assumed that a total number of moles and temperature of air inside the cave are constant, while ground vibrations trigger changes in air pressure without break and/or damage. The volume of the cave in this study is approximately 270.00 (= 1.5 in width x 1.8 in height x 100 in length) m^3. If the P-SV ground vibrations contribute changes of 0.5 mb in air pressure, the volume reduces to approximately 269.87 m^3, accordingly, for maintaining the product of the air pressure and the volume. If the reduction of the volume is mainly contributed by the vertical component of the vibrations, the ground in the cave uplifts about 10^{-3} meters. The comparable results between the observation and the model suggest the large air pressure changes in a cave can be attributed to the P-SV-type ground vibrations.

If the P-SV ground motion can drive changes in air pressure, the question is how often the interaction can be detected. The interaction of events by using both the P-SV ground motion and a coherence value > 0.35 at each particular frequency can be determined. The total number of interaction events was generally maintained at 20 during the study period of 930 days (from January 1, 2015 to July 19, 2018; in Fig. 3). This finding suggests that interactions permanently occur every day. These interactions can be dominated by the P-SV microseisms triggered by the interaction between oceanic waves and land (e.g., Cessaro 1994; Kimman *et al*. 2012).

Conclusion

This study proposes an efficient method to document the physical evidence of the P-SV types ground motion triggering changes in air pressure near the Earth's surface. When the ground motion with the P-SV types is related to microseisms, the air pressure can change accordingly. The air pressure in caves can be amplified by the existence of the P-SV type motion due to the interior space being partially confined (similar to press a rubber air ball). Thus, the air pressure retrieved from a barometer inside a cave are sensitive to the P-SV type motion.

The novel observation sheds light on extension of the use of a cave and/or a tunnel. The amplified air pressure triggered by the P-SV type motion creates an excellent opportunity to study the origin of acoustic waves from ground motion. Air pressure data observed in a cave and/or a tunnel can become treasure, while scientists want to prove existence of acoustic waves that propagate upward and drive changes in the atmosphere. On the other hand, the P-SV type ground motion can be often observed in microseisms and surface waves after earthquake occurrence. When stable environments of air pressure are seriously concerned in a cave, the effects of the P-SV types ground motion have to be taken into consideration.

Declarations

Availability of data and materials

Seismic waveform data and air pressure data at SBCB station were provided by the Institute of Earth Sciences, Academia Sinica, Taiwan. The air pressure data at Xinwu station were provided by the Central Weather Bureau, Taiwan. Those data can be downloaded at the website of https://doi.org/10.5061/dryad.05qfttdzh.

Competing interests

The authors declare that they have no known competing interests that could have appeared to influence the work reported in this paper

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Author contribution

Y.Y.S. contributed discussion and revision; L.C.L. contributed discussion and revision; P.H. contributed discussion; H.Z.Y. contributed discussion; X.Z. contributed discussion; C.C.T. contributed data collection; C.R.C. contributed data collection and discussion; H.Y.Y contributed data collection and discussion; C.H.L. contributed data collection, discussion and revision; J.Y.L. contributed discussion and revision; L.C.R. contributed data collection.

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Figures

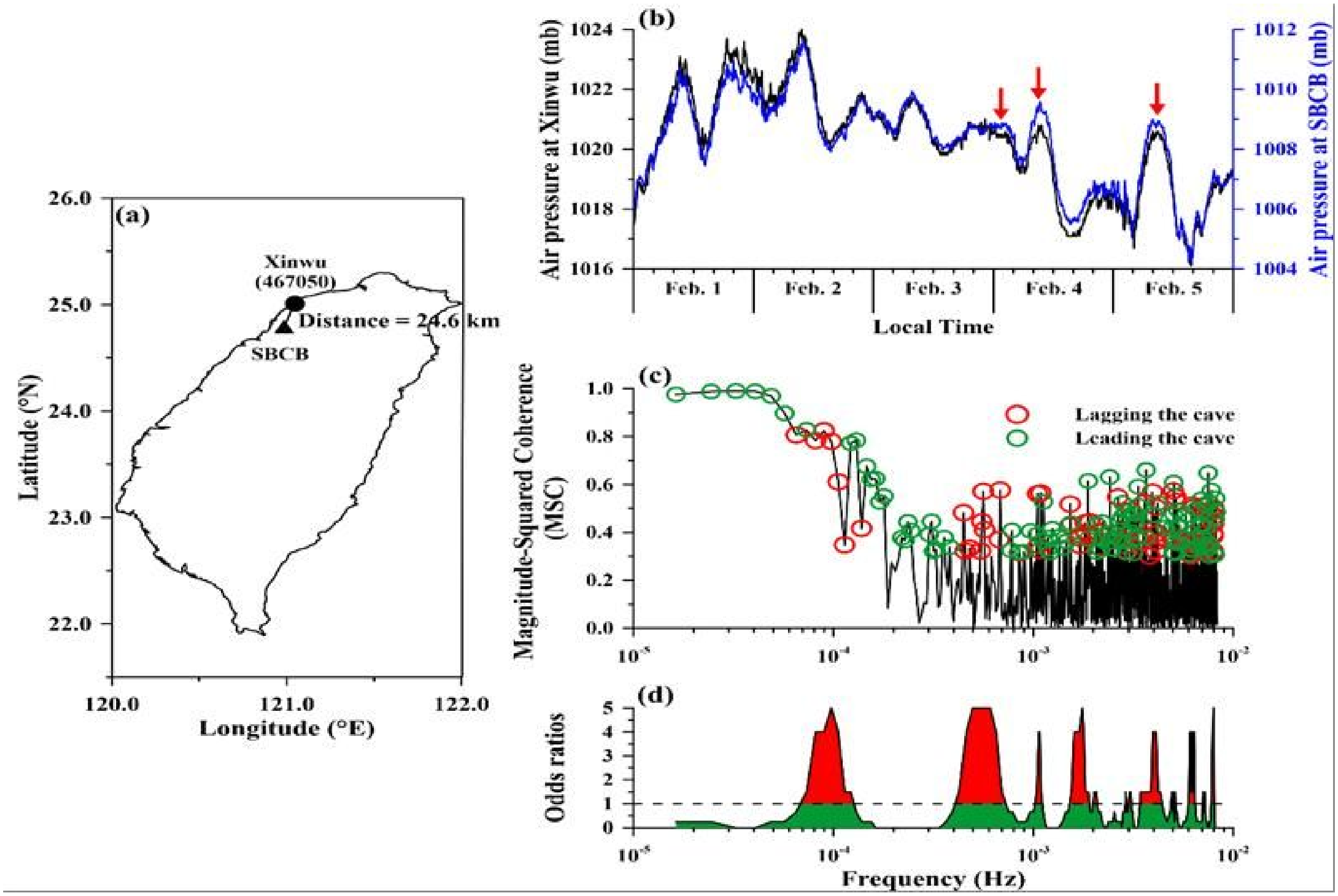

Figure 1

Locations and analytical results of air pressure data at Xinwu and SBCB stations. The locations of the two stations are shown in (a). The variations in air pressure during Feb. 1–5, 2016, are shown in (b). Black and blue lines denote the variations in air pressure at Xinwu and SBCB stations, respectively. Red arrows indicate the amplified variations in air pressure in the cave at SBCB station. The Magnitude-Square Coherence (MSC) varied with frequency thatis shown in (c). Red (green) open circles denote changes in air pressure at SBCB station that lead (lag) to variations at Xinwu station by utilizing the phase angle at each frequency. (d) The statistical results of the leading values with a coherence > 0.35 determined by the Odds test with a moving window of 5 events.

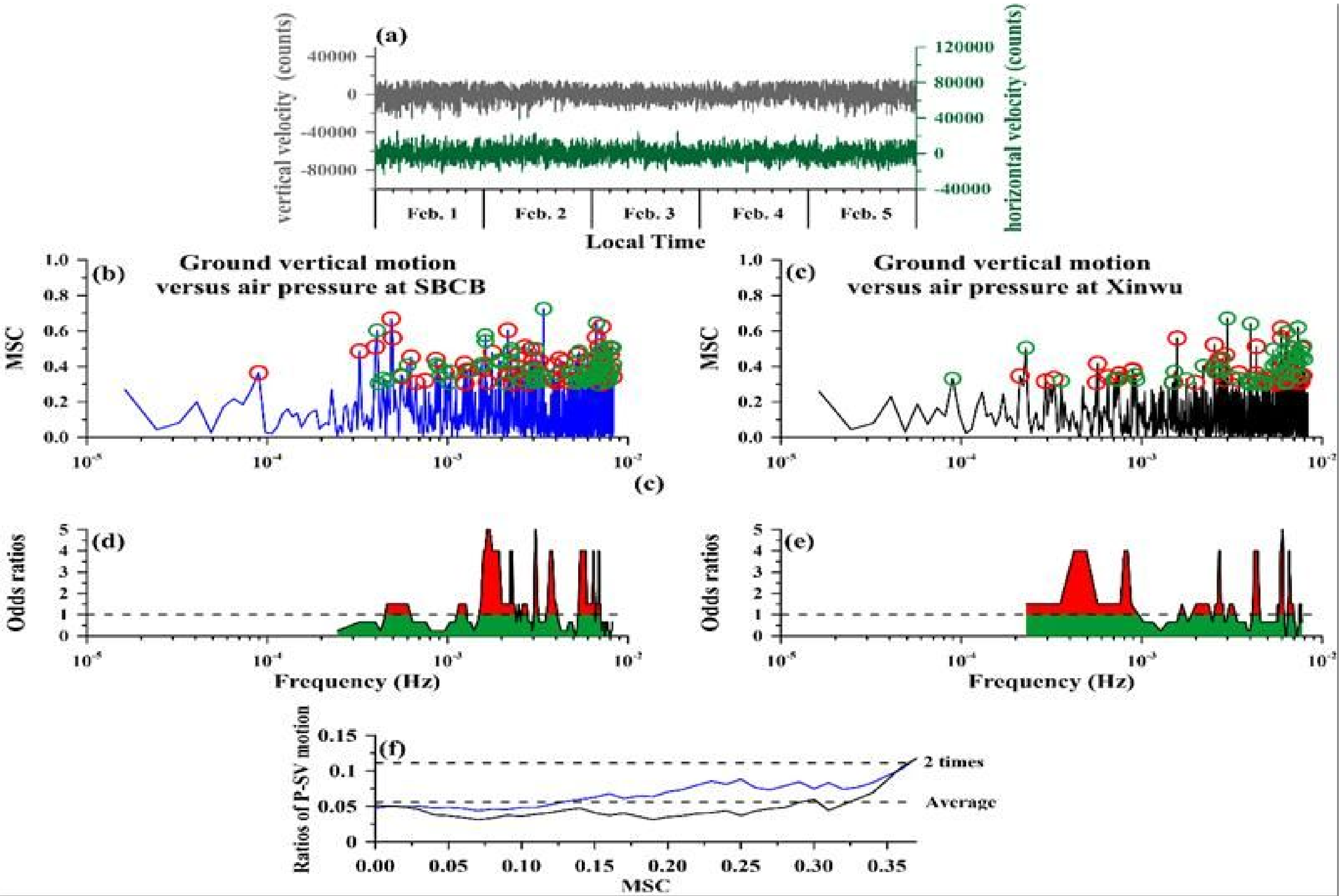

Figure 2

Variations in horizontal and vertical ground velocities and their comparison to air pressure data at Xinwu and SBCB stations. The variations in horizontal and vertical ground velocities are shown in (a). The coherence between the vertical ground velocity and air pressure at SBCB and Xinwu stations is shown in (b) and (c), respectively. Red (green) open circles denote that changes in ground velocity lead (lag) variations in air pressure. (d) and (e) The statistical results of the leading values for a coherence > 0.35 in (b) and (c) determined by the Odds test using a moving window of 5 events. The Odds test reveals that the leading values are clustered at a few particular frequency bands. (f) The ratio of P-SV motion to the total coherence greater than the set criteria.

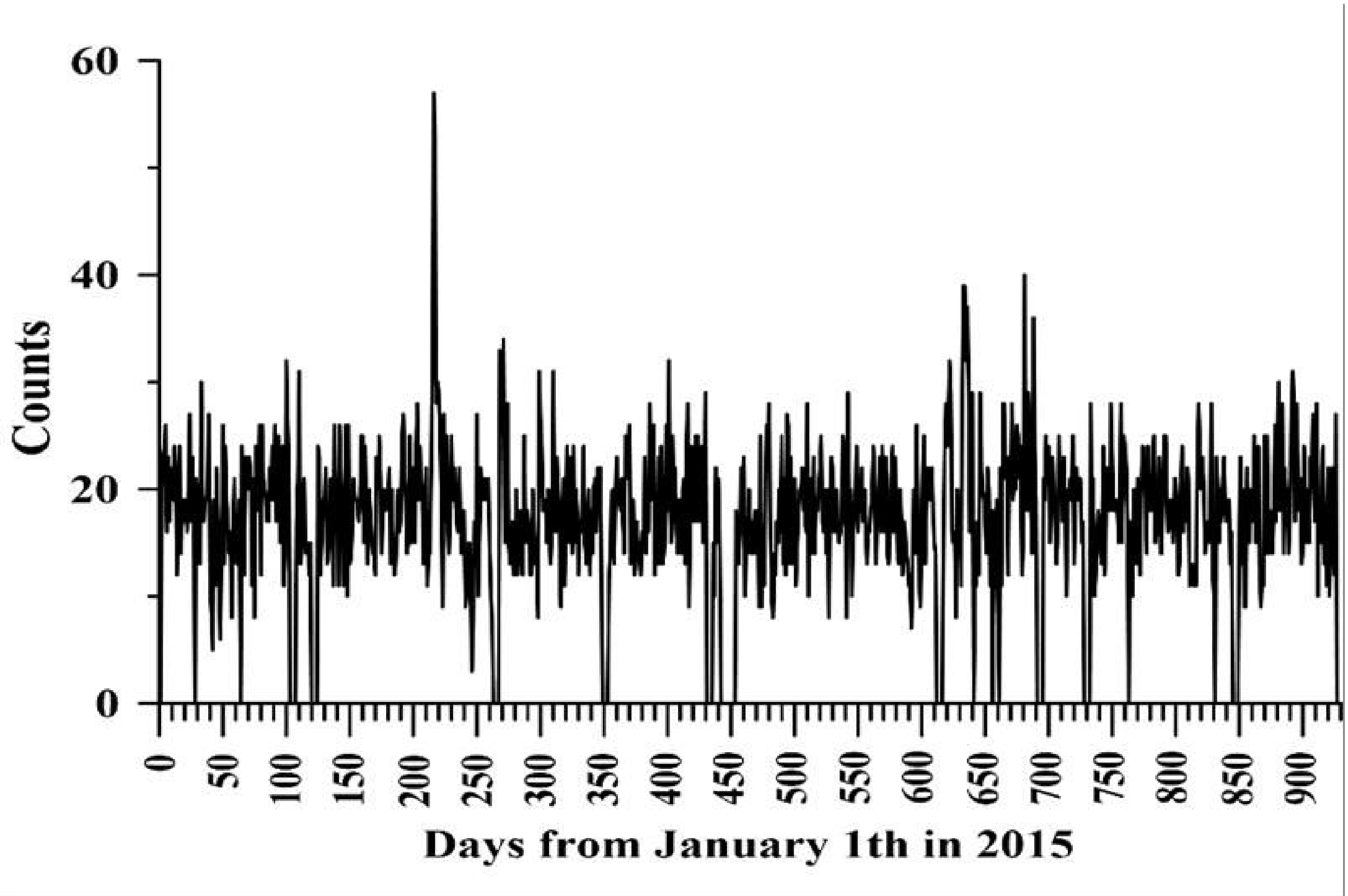

Figure 3

Daily counts of P-SV ground motion driving air pressure. The black line denotes the number of the P-SV waves at each frequency grid.

Supplementary Files

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- Supplementary.docx