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Anomalous Signals Prior to Wenchuan Earthquake Detected by Superconducting Gravimeter and Broadband Seismometers Records

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ABSTRACT: Using 1 Hz sampling records at one superconducting gravimeter (SG) station and 11 broadband seismometer stations, we found anomalous signals prior to the 2008 Wenchuan (汶川) earthquake event. The tides are removed from the original SG records to obtain the gravity residuals. Applying the Hilbert-Huang transform (HHT) and the wavelet analysis to the SG gravity residuals leads to time-frequency spectra, which suggests that there is an anomalous signal series around 39 h prior to the event. The period and the magnitude of the anomalous signal series are about 8 s and 3×10^{-8} m/s^2 (3 μGal), respectively. In another aspect, applying HHT analysis technique to 11 records at broadband seismometer stations shows that most of them contain anomalous signals prior to the Wenchuan event, and the marginal spectra of 8 inland stations show an apparent characteristic of double peaks in anomalous days compared to the only one peak of the marginal spectra in quiet days. Preliminary investigations suggest that the anomalous signals prior to the earthquake are closely related to the low-frequency earthquake (LFE). We concluded that the SG data as well as the broadband seismometers records might be significant information sources in detecting the anomalous signals prior to large earthquakes.

KEY WORDS: superconducting gravimeters, broadband seismometers, anomalous signals, Wenchuan earthquake.

INTRODUCTION

Many studies (Afraimovich and Astafyeva, 2008; Dautermann et al., 2007; Shelly et al., 2006; Rogers and Dragert, 2003; Ihmle and Jordan, 1994) tried to detect different kinds of anomalous signals prior to large earthquakes. One or two kinds of anomalous signals could be sometimes observed by absolute gravimeters and broadband seismometers several hours to several days prior to certain large earthquakes (Hu and Hao, 2008). However, little attention was paid on detecting the anomalous signals prior to large earth-

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quakes based on superconducting gravimeters (SGs) records, which contain various temporal gravity signals (Crossley and Hindere, 2008; Goodkind, 1999). Previous studies on earthquakes using the data series recorded by SGs just focused on the coseismic and post-seismic gravity changes (Nawa et al., 2009; Imanishi et al., 2004; Furuya et al., 2003; Tanaka et al., 2001).

Here, we used both the Hilbert-Huang transform (HHT) technique (Huang et al., 1998) and the wavelet analysis technique (Daubechies, 1992) to analyze the SG records at Hsinchu (HS) station, Taiwan (see Fig. 1), to detect anomalous signals prior to the Wenchuan earthquake event, which, with a seismic magnitude M_W=7.9, on the Longmen Shan Fault zone with a length of about 300 km (Toda et al., 2008), occurred near Yingxiu Town (31.0ºN, 103.4ºE, D. 15 km) in the Wenchuan County, China, at 06:28:04, 12 May 2008 (UTC).

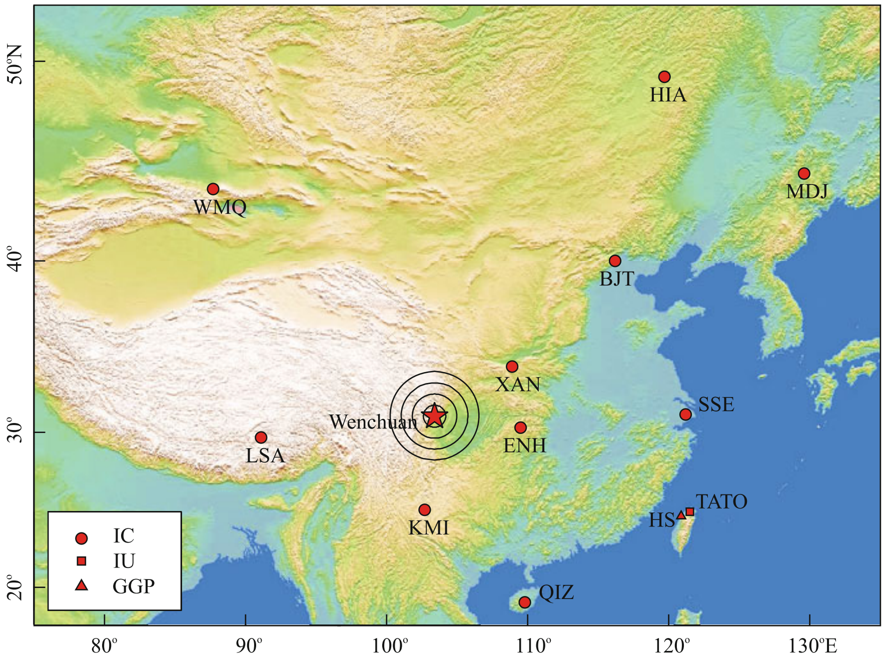

Figure 1. Distribution of 1 SG (denoted by a triangle), 11 broadband seismometers (denoted by 10 circular points located in mainland China and 1 square located in Taiwan), and the Wenchuan earthquake event (denoted by a star). IC. New China Digital Seismograph Network (NCDSN); IU. Global Seismograph Network (GSN-IRIS/USGS); GGP. Global Geodynamic Project. ENH. Enshi, Hubei Province; BJT. Baijiatuan, Beijing; HIA. Hailar, Inner Mongolia; KMI. Kunming, Yunnan Province; LSA. Lhasa, Tibet; MDJ. Mudanjiang, Heilongjiang Province; QIZ. Qiongzhong, Hainan Province; SSE. Shanghai; WMQ. Urumqi, Xinjiang; XAN. Xi'an, Shaanxi Province; TATO. Taipei, Taiwan; HS. Hsinchu, Taiwan.

The objective of this study is to use the SG data at the HS station and broadband seismometers records at 11 sites to investigate the anomalous signals prior to the Wenchuan earthquake. Similar studies using gravimeters and broadband seismometers observations were reported in a few studies (e.g., Hu et al., 2010; Hu and Hao, 2008). In this study, we selected SG and broadband seismometers records covering the time span (7–13 May 2008, UTC) before and after the Wenchuan earthquake. Preliminary geodetic and geophysical results of the HS SG data are given in Hwang et al. (2009). Currently, only the HS station makes available to the authors the 1 Hz SG data. For comparison, the data center of Global Geodynamic Project (GGP) provides only 1-min SG data, which only allow for resolving signals at frequencies <0.01 Hz. In addition, we chose seismic records at stations located in the range of the epicentral distances that are <3 000 km to detect the anomalous signals, and we noted that, in this case only, data at 11 broadband seismometer stations are accessible by the authors. Due to the relative short distances of these SG and broadband seismometer stations to the epicenter of the Wenchuan earthquake, the possibility of detecting the signals related to this event is higher compared to the case of using stations not in the region.

DATA SETS AND METHOD

Figure 1 shows the locations of the SG station HS and 11 broadband seismometer stations, including 10 sites of IC (Network Code for the New China Digital Seismograph Network) located in mainland China and 1 site of IU (Network Code for the Global Seismograph Network) located in Taiwan. All the 7-d records, sampled at 1-s interval, cover the period 7–13 May 2008. During this period, in addition to the Wenchuan earthquake, a typhoon event named RAMMASUN (http://agora.ex.nii.ac.jp/digital-typhoon/summary/wnp/l/200802.html.en) and at least 10 smaller earthquakes also occurred.

The HHT, consisting of empirical mode decomposition (EMD) and Hilbert spectral analysis, is a newly developed adaptive data analysis method and has been used extensively in geophysical studies (Huang and Wu, 2008). The EMD generates a collection of the intrinsic mode functions (IMFs), which may correspond to real physical processes. The theory and practice of HHT can be found in Huang et al. (1998).

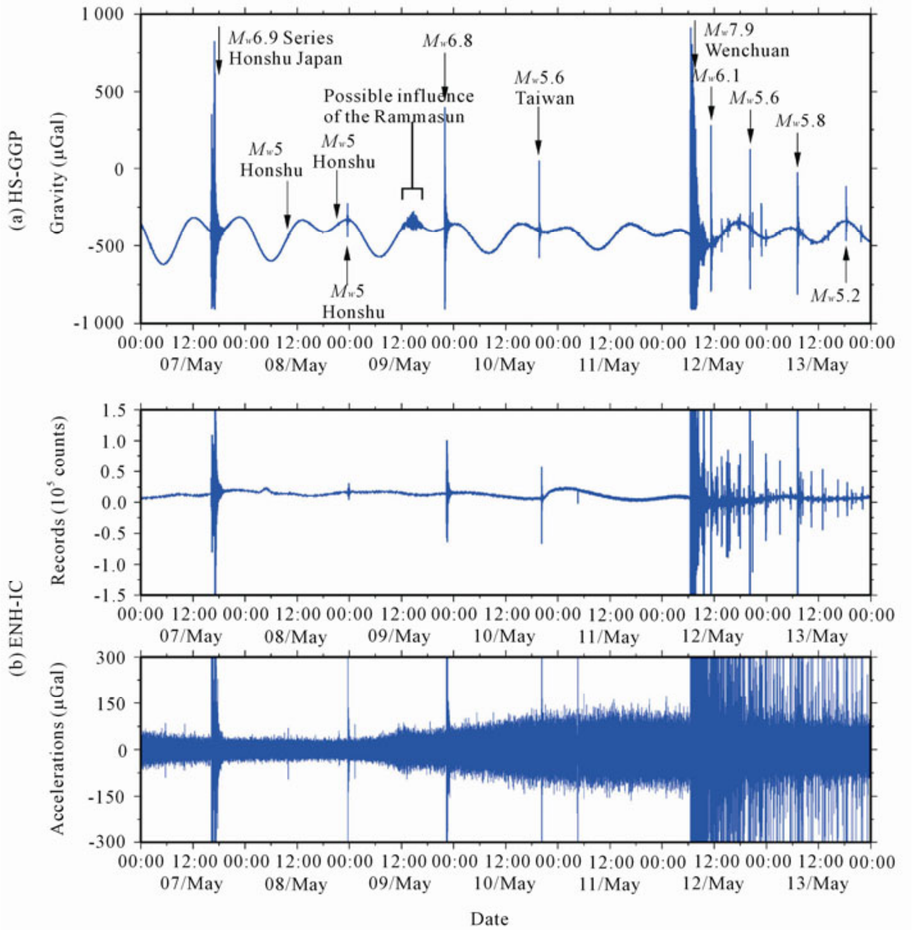

Figure 2. 1 Hz data series recorded during the period 7–13 May 2008 by the SG at HS station and a broadband seismometer as an example. (a) Original 1 Hz SG records at HS station; one spike (vertical line) corresponds to an earthquake event with the seismic moment magnitude larger than M_W=5.0 in the interested period. (b) STS-1 broadband seismometer records at ENH station; the top plot is original 1 Hz records of the LHZ channel, and the bottom is the acceleration derived from the original count records.

Anomalous signals are identified by the features that the amplitudes of some kinds of signals with certain frequencies or frequency bands become dominantly obvious with respect to those in the quiet days in time-frequency spectrum. The quiet days (or quiet periods) are defined as the days or period that are at least 3 or more days away from large earthquakes. On the contrary, the anomalous days (or anomalous periods) are defined as the days or period that are just several days or hours prior to large earthquakes. Obviously, the above definitions should not be taken in absolute sense but relative sense. This will become clear as the result of the signal analyses associated with the Wenchuan earthquake is presented in the sequel. The HHT method can obtain the high-resolution spectra in the frequency and time domains, making it possible to detect some anomalous signals prior to an earthquake without the influence of the earthquake itself. To verify the HHT result, the wavelet spectra of the data used in the HHT analyses will be computed. In this study, the wavelet analyses are based on the real part of the Morlet wavelet, which is also widely used in geophysical research, such as seismic data analysis. Properties of the Morlet wavelet in the time and frequency domains can be found in Foufoula-Georgiou and Kumar (1994).

Based on the estimated tide parameters (Hwang et al., 2009) with ETERNA3.4 (Wenzel, 1996), we first removed the tidal effects from the original data (the original data covering the period 7–13 May 2008 are shown in Fig. 2a) by using the software T-SOFT provided by the International Center for Earth Tides (ICET, http://www.astro.oma.be/ICET). The result is the residual gravity of SG over the 7 days under study. We then computed the HHT and wavelet spectra from the residual gravity series, which is shown in Fig. 3a.

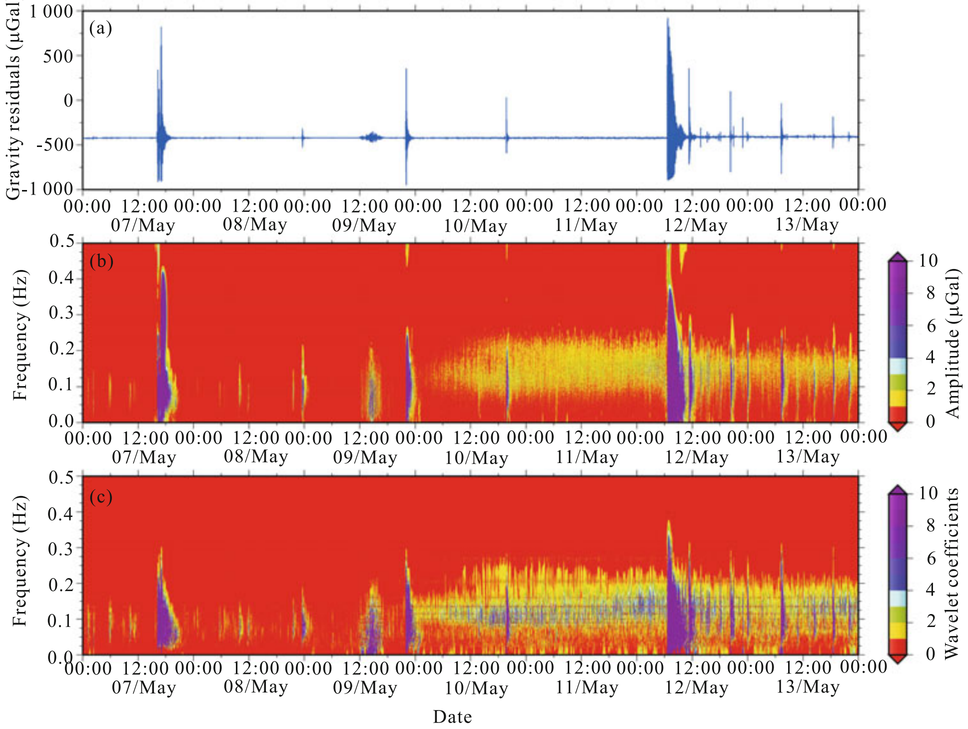

Figure 3. (a) Residual SG data series that covers the period 7–13 May 2008 recorded and sampled at 1-s interval at HS station after removing the tidal effects; (b) Hilbert-Huang spectrum of the data series (a); (c) Morlet wavelet spectrum of the data series (a). Both spectra show that some anomalous gravity signals prior to the Wenchuan earthquake have occurred since 15:00, May 10. The dominant period of the anomalous gravity signals is about 8 s (equivalent to frequency 0.13 Hz). Only the tidal influences were removed from the originally recorded data. Other influences, including atmosphere pressure and polar motion, were not removed. These influences have quite different frequencies, consequently, they will not affect the results here.

Concerning the 7-d-long broadband seismometer records at 11 stations, we mainly focused on the spectra analysis of the vertical component of the broadband seismometer records, except for the XAN station, for which we replaced the LHZ (long period, high gain, and vertical component) channel with the LHE (long period, high gain, and horizontal component) channel due to large noises in LHZ component. The seismic data sets were downloaded from Incorporated Research Institutions for Seismology (IRIS, http://www.iris.edu/data/). We first transferred the original count records, sampled at 1 s, to accelerations by removing the mean, trend, and instrument response and then applied HHT to the accelerations to obtain the HHT spectra and the averaged marginal spectrum. An example of seismometer data is shown in Figs. 2b.

RESULTS

Results of SG Data Analysis

The HHT and wavelet spectra of the SG records over the 7 d are shown in Figs. 3b and 3c. The anomalous signals associated with the HHT and wavelet spectra start at 3:00, 10 May and 23:00, 9 May, respectively, and lasted about 2 d before the Wenchuan earthquake. Both Figs. 3b and 3c show that, starting from about 15:00, May 10, the gravity variations are larger compared to the variations before 15:00, May 10. Such differences in gravity signatures suggest that, starting from 15:00, May 10, some anomalous gravity signals prior to the Wenchuan earthquake have occurred. The anomalous signals have an average period of 8 s (equivalent to frequency 0.13 Hz) and lasted about 39 h prior to the Wenchuan earthquake. The magnitude of the anomalous signals detected by using the SG records has an obvious increasing trend until the Wenchuan earthquake occurred, and the maximum magnitude is about 3 μGal.

To see whether the anomalous signals are caused by the very large coseismic gravity oscillations during the Wenchuan earthquake in the spectral analysis, we computed the HHT and wavelet spectra using only the SG data over the period from 0:00, 07 May to 06:27, 12 May, which is just before the Wenchuan earthquake event. Such HHT and wavelet spectra are given in Fig. 4. Comparison between the spectra in Fig. 3 (with data covering the Wenchuan earthquake event) and Fig. 4

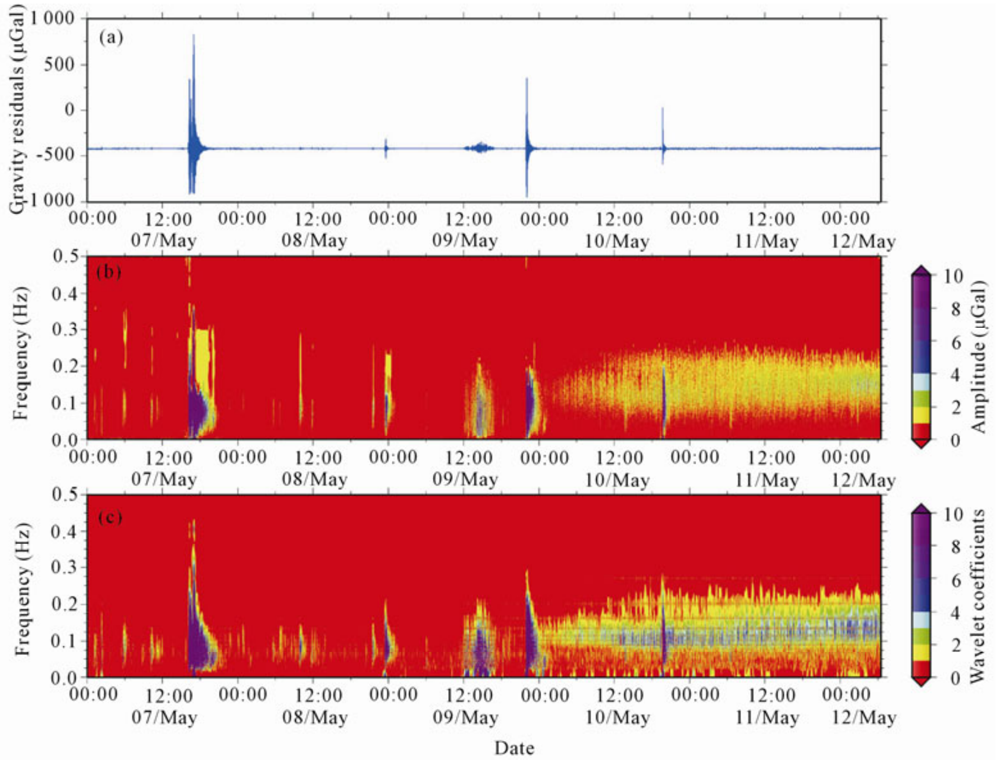

Figure 4. (a), (b), and (c) are the same as Fig. 3, but using SG data series covering the period between 0:00, 07 May and 06:27, 12 May, which does not include the "event spike" of the Wenchuan earthquake M_W=7.9 itself. The tidal effects have been removed.

(the data that do not cover the event) suggests that the anomalous signals are present in both cases. That is, the anomalous signals in Fig. 3 prior to the Wenchuan earthquake are not caused by the coseismic gravity oscillations.

One may argue that the anomalous signals provided in Fig. 3 may be caused by Typhoon RAMMASUN, which occurred during the period 7–13 May 2008. To resolve this argument, we examined another typhoon event NAKRI (http://agora.ex.nii.ac.jp/digital-typhoon/summary/wnp/l/200805.html.en) occurring from 27 May to 3 June 2008 and it is similar to typhoon RAMMASUN in many aspects. We used the de-tided 1 Hz SG data of HS over the period 27 May–3 June 2008 (UTC). These SG records are shown in Fig. 5a, which contain the possible influence of Typhoon NAKRI. Figures 5b and 5c show the HHT and Morlet wavelet spectra of the SG records, respectively. Comparison of the spectra in Figs. 5 and 3 suggests that the characteristic of the gravity effect of NAKRI is different from the characteristic of the anomalous gravity variation prior to the Wenchuan earthquake: the amplitude of the effects of Typhoon NAKRI is lower than the anomalous signals prior to Wenchuan earthquake, and the duration of the former as shown in the spectra of Fig. 5 is also much shorter than the latter as shown in Fig. 3.

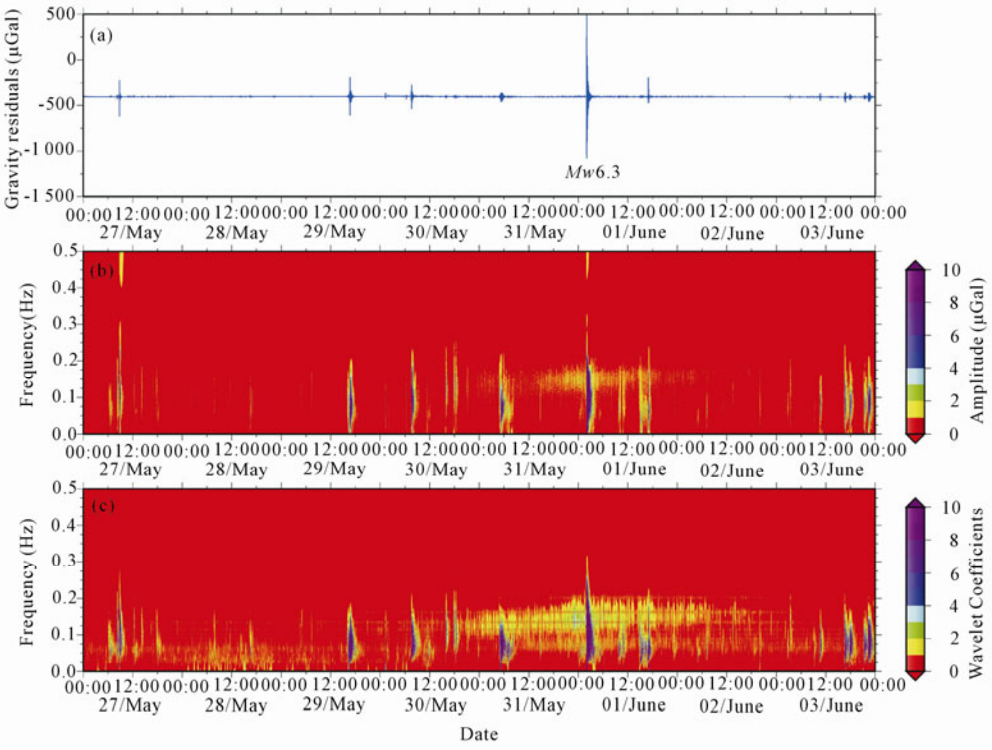

Figure 5. (a) 1 Hz SG records at HS station after removing the tidal effects, during the period 27 May to 3 June 2008, and in this period, Typhoon NAKRI occurred and an earthquake event M_W=6.3 occurred; (b) Hilbert-Huang spectrum of the data series; (c) Morlet wavelet spectrum of the data series.

Due to the close resemblance of RAMMASUN and NAKRI, the gravity effects of these two typhoons should be similar. Then, based on the investigations of the NAKRI, it is highly possible that RAMMASUN might not be the origin of the anomalous signals prior to Wenchuan earthquake as shown in Fig. 3. We noted that, during the period of NAKRI, an earthquake event M_W=6.3 occurred at 1:57:24, 1 June 2008 (UTC), located at (121.37ºE, 20.13ºN, D. 35 km) (see http://www.ncedc.org/anss) (see Fig. 5a). Hence, the gravity effect of NAKRI is largely contaminated by this earthquake. However, the combined gravity effect of NAKRI and this earthquake is not similar to the anomalous signals prior to the Wenchuan earthquake (Fig. 3). We found that the anomalous signals with about 8-s period in Figs. 5b and 5c just occurred ahead of the earthquake, so they might be the anomalous signals related to the M_W=6.3 earthquake. Hence, we may conclude that the comparison between Figs. 5 and 3 illustrates that the detected anomalous signals prior to Wenchuan earthquake are not due to the effects of the Typhoon RAMMASUN.

Results of Seismic Data Analysis

We divided the 11 broadband seismometer stations into two groups: Group I includes three coastal stations, i.e., QIZ in Qiongzhong, SSE in Shanghai, and TATO in Taiwan, and Group II includes eight inland stations, i.e., ENH in Enshi, KMI in Kunming, XAN in Xi’an, BJT in Beijing, MDJ in Mudanjiang, HIA in Haila’er, LSA in Lhasa, and WMQ in Urumqi.

Figure 6 shows the HHT spectra of the seismic data at the three coastal stations. We chose two time windows, one over the quiet days (between two vertical green solid lines as denoted in Fig. 6) and the other over the anomalous days (between two vertical blue lines that mark the period just prior to the earthquake event as shown in Fig. 6). The averaged marginal spectra in the two time windows were computed and are shown in the bottom plots in Fig. 6. The averaged marginal spectrum (called marginal spectrum hereafter) represents the averaged amplitude (energy) over the time span of the data, and it is a measure of the amplitude (or energy) contribution from each frequency value. The marginal spectrum of an HHT spectrum, being averaged over time, is time independent and is similar to the Fourier spectrum. It is noted that the starting times of the anomalous signals at the three coastal stations are not the same.

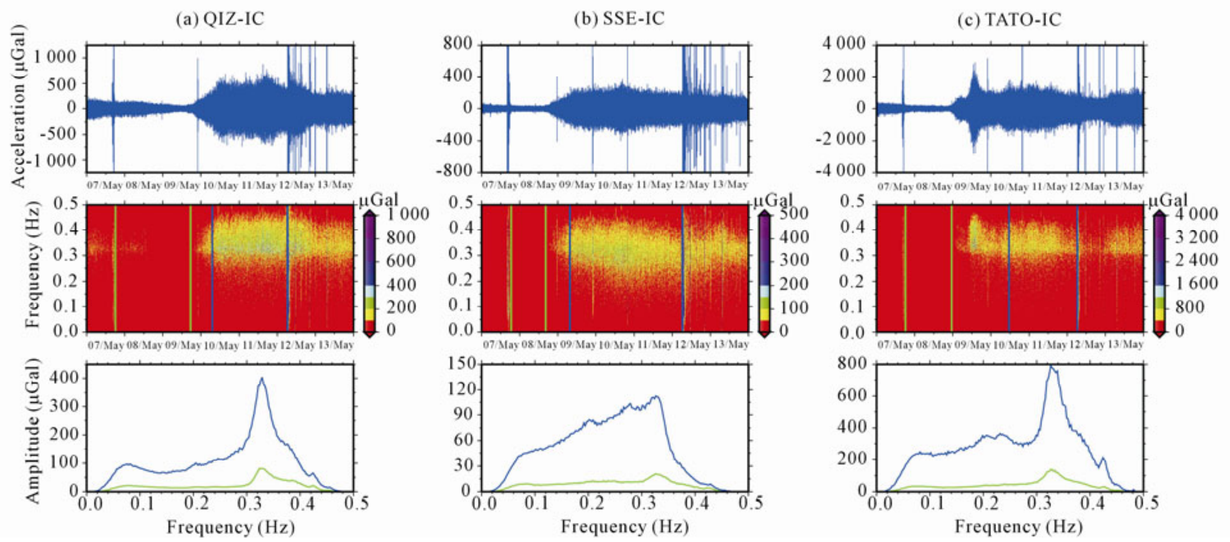

Figure 6. Broadband seismometer records (top) at three coastal stations, HHT spectra (middle) of the records, and the corresponding marginal spectra (bottom). In the middle row plots, anomalous days are indicated from the left-hand side vertical blue solid line to the right-hand side one that is located at the point just about 1 min before the earthquake occurrence, and the two green solid lines denote a time window for the quiet days. The quiet periods and anomalous periods chosen here are from 18:00, 07 May to 18:00, 09 May and from 07:10, 10 May to 06:27, 12 May for QIZ (a); from 18:35, 07 May to 16:15, 08 May and from 07:30, 9 May to 06:27, 12 May for SSE (b); and from 18:00, 07 May to 23:00, 08 May and from 11:20, 10 May to 06:27, 12 May for TATO (c), respectively. The anomalous periods are prior to the earthquake event, not including the data during the earthquake occurrence. The dominant frequency of the anomalous signals is 0.33 Hz. In the bottom row plots, green (lower) lines denote the marginal spectra of the records in quiet days, and blue (higher) lines denote the marginal spectra of the records in anomalous days.

Figure 7 shows the HHT result at the eight inland stations. The anomalous signals are evident at stations ENH, KMI, XAN, and BJT (see Figs. 7a–7d), the green circles denote the anomalous signals), especially

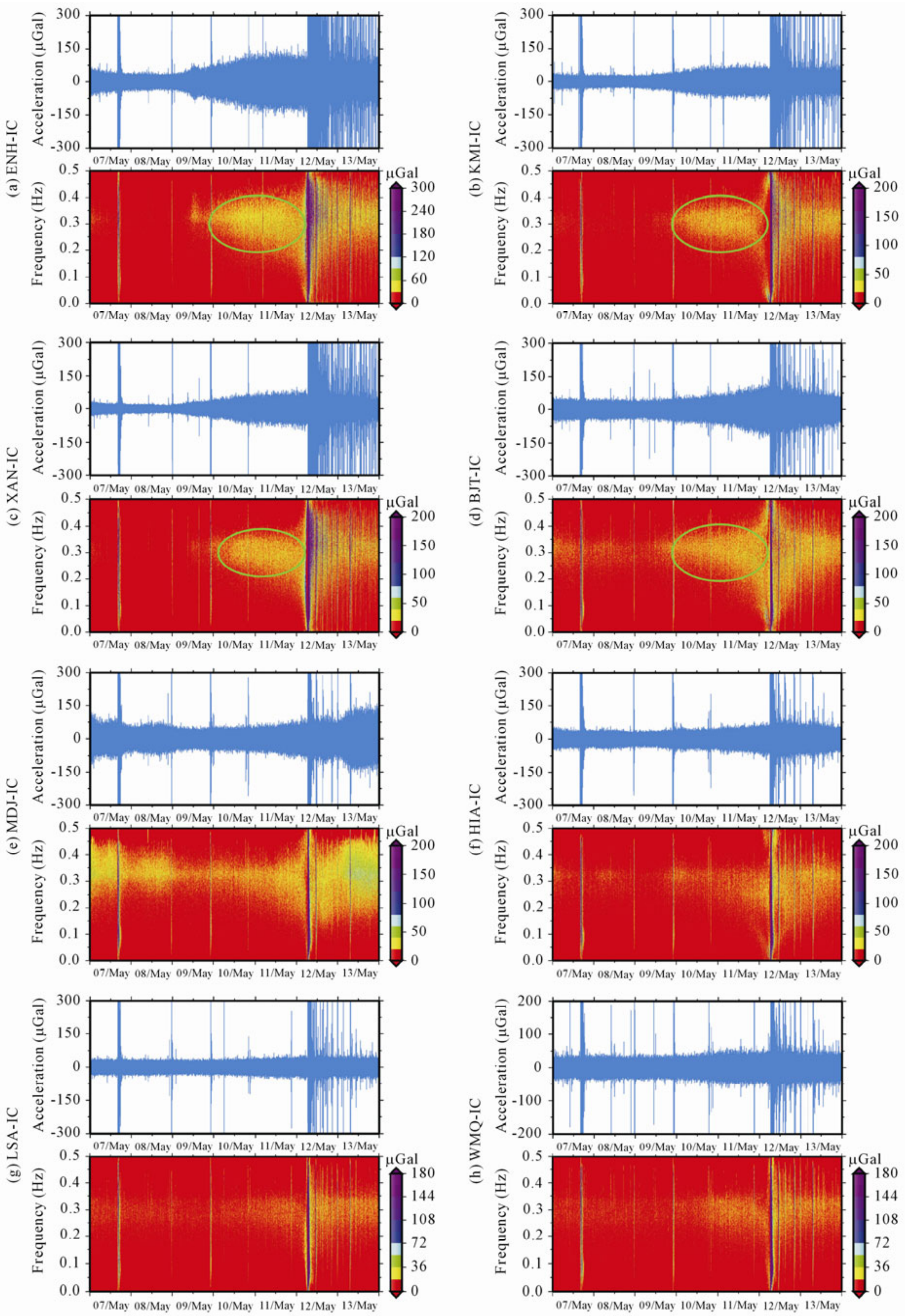

Figure 7. Broadband seismometer records (top) and their HHT spectra (bottom) at eight inland seismometer stations. (a) ENH, (b) KMI, (c) XAN, (d) BJT, (e) MDJ, (f) HIA, (g) LSA, and (h) WMQ. Green circles in (a) to (d) denote the anomalous signals recorded in relevant stations.

at the first three stations. Moreover, the starting times of the anomalous signals are consistent to 1 h. At the other four inland stations (Figs. 7e–7h), the anomalous signals are weak in amplitude. Two possible causes of the differences in amplitude are the distances and the orientations from these stations to the epicenter of the Wenchuan earthquake.

Further, we computed their marginal spectra (see Fig. 8) for quiet days and anomalous days at three coastal stations and eight inland stations. Figures 8a and 8b show the patterns of the marginal spectra for quiet days and anomalous days at three coastal stations, respectively. The average frequency of the dominant signals at the coastal stations is about 0.33 Hz, which is larger than the average frequency of the anomalous signals from the SG records. It is noted that the spectra of seismic records and gravity records are different. The reason is stated as follows. SGs directly sense acceleration (contributed by mass migration and ground vibration), and broadband seismometers directly sense velocity (generally caused by ground movement). These two kinds of physical quantities (acceleration and velocity) make the difference of the spectra of the two kinds of records (SG and seismic records). Another reason may be related to the eigen-frequency of the instruments. Different kinds of instruments (i.e., SG and broadband seismometer) dominantly sense different frequency bands due to the instruments' eigen-frequencies. This needs further investigations.

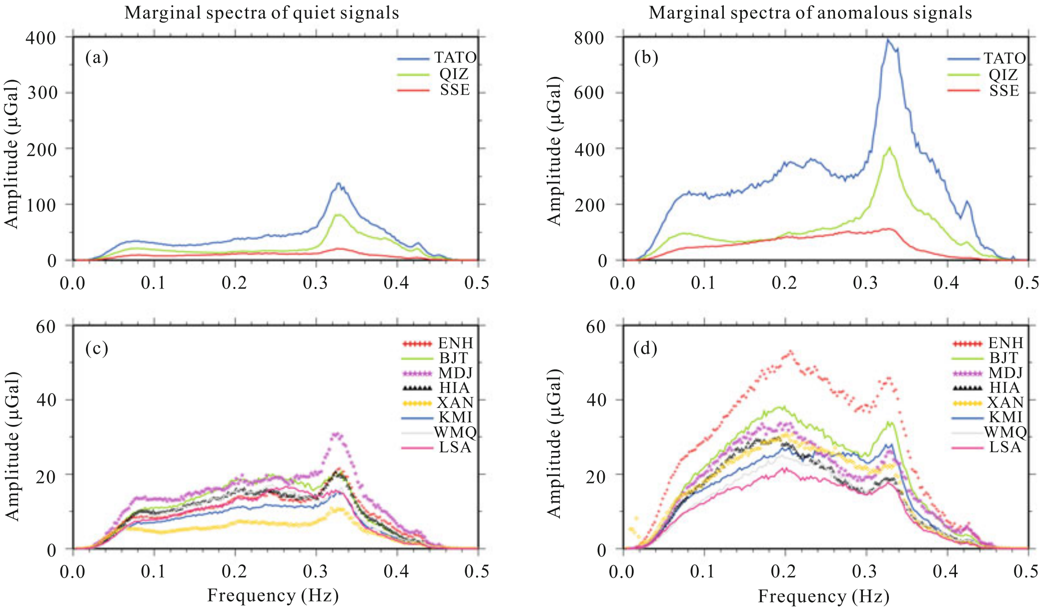

Figure 8. Marginal spectra of records at 11 broadband seismometer stations in quiet days (left-hand side column plots) and anomalous days (right-hand side column plots). (a) and (b) Comparison of marginal spectra of the records at three coastal stations in quiet days and anomalous days, respectively; the dominant frequency is 0.33 Hz. (c) and (d) Comparison of marginal spectra of the records at eight inland stations in quiet days and anomalous days, respectively; there are two frequency bands in the anomalous signals, around 0.2 and 0.33 Hz. Information of (quiet period; anomalous period) of the relevant stations is provided in the sequel (note that those of TATO, QIZ, and SSE are provided in Fig. 6): ENH (18:35, 07 May–07:30, 09 May; 07:10, 10 May–06:27, 12 May), KMI (18:35, 07 May–07:30, 09 May; 07:10, 10 May–06:27, 12 May), XAN (18:35, 07 May–07:30, 09 May; 07:10, 10 May–06:27, 12 May), BJT (18:35, 07 May–07:30, 09 May; 07:10, 10 May–06:27, 12 May), MDJ (00:10, 09 May–22:00, 09 May; 23:00, 10 May–06:27, 12 May), HIA (18:35, 07 May–18:00, 09 May; 23:00, 10 May–06:27, 12 May), LSA (18:35, 07 May–18:00, 09 May; 23:00, 10 May–06:27, 12 May), and WMQ (18:35, 07 May–18:00, 09 May; 23:00, 10 May–06:27, 12 May).

Figures 8c and 8d show the patterns of the marginal spectra for quiet days and anomalous days at eight inland stations, respectively. The marginal spectra in Fig. 8d show two dominant frequency bands at the eight inland stations: Band I, around 0.2 Hz, and Band II, around 0.33 Hz. The width of Band I is relatively wider than that of Band II. The marginal spectra in Fig. 8 suggest that Band II may be the intrinsic frequency band of the broadband seismic records, because there is always an obvious spectrum peak (corresponding to frequency 0.33 Hz) in Band II for both coastal and inland stations, no matter in the quiet days (see Figs. 8a and 8c) or anomalous days (see Figs. 8b and 8d). The amplitudes in Band II of the coastal stations are much larger than those of the inland stations in both quiet days and anomalous days, so this band might be mainly dominated by the ocean waves. In anomalous days, the amplitudes are enhanced in both Bands I and II. However, due to the dominant influences of the ocean waves on the coastal stations for Band II, the marginal spectra of three coastal stations do not show double peaks as the eight inland stations do. From Fig. 8, we see that the amplitudes of the marginal spectra in Band I are lower than those in Band II over the quiet days. However, during the period of the anomalous signals prior to the Wenchuan earthquake, the marginal spectra at the eight inland stations contain two peaks, and the amplitudes in Band I exceed the amplitudes in Band II.

Using the seismic data, we concluded that the main ocean wave-excited signals are concentrated over a frequency of 0.33 Hz (i.e., Band II), so the influence of the ocean waves is manifested as signals over Band II. The same conclusion can be drawn from Figs. 8a and 8b: the main peak of the marginal spectrum lies in Band II at every coastal station. This is due to the short distances from the ocean to the three coastal stations that result in strong effects. So it is hypothesized that the energy concentrated on Band I over the anomalous days might be related to the Wenchuan earthquake. We noted that Band I is similar to the frequency band of the anomalous gravity signals in the SG records.

As a remark, the amplitudes and the frequencies of the signals obtained by applying the Hilbert transformation to every IMF are instantaneous as function of time. Then, the determined average marginal spectrum represents the averaged amplitude over the time span of the data. Since the data we used to compute the averaged marginal spectra in the anomalous days do not cover the Wenchuan earthquake event (see Fig. 6), the marginal spectra of anomalous signals in Fig. 8 are not contributed by the Wenchuan earthquake itself. Recently, Hu et al. (2010) obtained the similar results as we did using more broadband seismometers records (but without SG data) and most likely showed that the position of the origin of the anomalous signals is quite close to the epicenter of the Wenchuan earthquake. This might suggest that the anomalous signals detected in this study are related to the Wenchuan earthquake. Definite confirmation needs further investigations.

DISCUSSION AND CONCLUSIONS

A possible mechanism of the anomalous gravity signals prior to a large earthquake might be due to the ground (or tectonic) vibration that is caused by the slow slip of fault several days to several hours (or several minutes) prior to the earthquake event. The ground vibration due to the slow slip then results in accelerations as well as seismic waves (or gravity waves) that can be detected by SGs and broadband seismometers. The dominant frequency of the anomalous signals we detected in this study ranges from 0.13 to 0.3 Hz**.** We may expect that the anomalous gravity signals are closely related to low-frequency earthquakes (LFEs, e.g., Ide et al., 2007a, b; Shelly et al., 2006), which could be frequently observed in a digital seismic network several minutes to several days prior to a large earthquake (Shelly et al., 2006; McGuire et al., 2005; Rogers and Dragert, 2003).

Generally, it is considered that the LFEs are different from ordinary earthquakes and represent the phenomena that are specific to the subduction zone and/or the deep part of crust in the active tectonic regions (Nakamula and Takeo, 2010). If the anomalous signals we detected in this article originate from an LFE series prior to Wenchuan earthquake, the spectral peaks around 0.2 Hz seem to suggest a harmonic oscillation in the source, but it is currently not clear what kind of physical process can excite such oscillation in the source zone. Nevertheless, such an investigation would be a useful tool for the purpose of obtaining the characteristic frequency of precursory waves, which might modulate slow earthquakes. So the SG records as well as the broadband seismometers records might be significant information sources in detecting the anomalous signals prior to large earthquakes.

In this study, the 1 Hz SG records show that there is a spectral band around 0.13 Hz, which is observed in the anomalous days (signals prior to Wenchuan earthquake) but not in the quiet days, and the marginal spectra of the records at eight inland seismometer stations have double peaks over the anomalous days compared to the single peaks over the quiet days. Hence, the spectral analyses at the HS SG station and about 10 broadband seismometer stations suggest that there are anomalous signals prior to the Wenchuan earthquake. However, the relationship between the source processes and the detected anomalous signals has not been yet established, which is beyond the scope of this study, and needs further exploration.

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