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Low frequency signal spectrum analysis for strong earthquakes

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ABSTRACT

We examined changes in the spectral composition of the low frequency (LF) subionospheric signals from the NRK transmitter (37.5 kHz) in Iceland that were received in Bari (Italy) relative to the earthquake that occurred in L'Aquila on April 6, 2009. In our previous studies, we have reported the occurrence of preseismic night-time anomalies using observations from three receivers located in Bari, Graz (Austria) and Moscow (Russia). The strongest anomalies in the signals were observed in the NRK-Bari propagation path during the period 5-6 days before the L'Aquila earthquake, as well as during the series of aftershocks. During this period, similar very low frequency (VLF)/LF amplitude anomalies were also observed along several other propagation paths that crossed the L'Aquila seismogenic zone. Spectral analysis of the LF signals filtered in the frequency range 0.28 mHz to 15 mHz shows differences in the spectra for seismo-disturbed days when compared to those for either quiet or geomagnetically disturbed days. These spectral anomalies, which are only observed in the propagation path between NRK and Bari, contain signals with periods of about 10 min to 20 min. These periodic signals are absent both in the spectra of the undisturbed signals for the control paths, and in the spectra of the signals received during geomagnetic storms. The same changes in the spectral composition were observed in the analysis of LF (40 kHz) signals from the JJY transmitter in Japan that were received in Petropavlovsk-Kamchatsky (Russia) during the occurrence of three strong earthquakes with M ≥7.0. The results of this study support the theoretical prediction that the possible mechanism for energy penetration from the origin of an earthquake through the atmosphere and into the ionosphere is based on the excitation and upward propagation of internal gravity waves.

1. Introduction

European research into very low frequency (VLF)/low frequency (LF) (20-50 kHz) signals associated with earthquakes began in 2002 with the installation of an OmniPal receiver at the Department of Physics, University of Bari, in southern Italy. A second receiver that operates in the VLF frequency range was installed in Graz (Austria) at the end of 2007. During 2008, a new type of receiver that operates in both the VLF and LF bands was developed at the factory of the Italian company Elettronika (Palo del Colle, Bari). At the beginning of 2009, these new receivers were installed in central and southern Italy, Greece, Turkey and Romania. In 2010, an Elettronika receiver was also installed in Portugal. This European network of receivers also includes an UltraMSK receiver that operates in Moscow.

Regular signal monitoring by the Bari receiver revealed preseismic and postseismic effects in the VLF/LF radio signals when the wave propagation path passed close enough to the epicentres of earthquakes [Biagi et al. 2004, 2007, 2008, Rozhnoi et al. 2005]. The most significant results were obtained from observation by the Russian and two of the European VLF/LF stations, namely those in Moscow, Bari and Graz, for the earthquake that occurred in L'Aquila (Italy) on April 6, 2009 [Rozhnoi et al. 2009]. Strong night-time anomalies for long propagation paths, together with a shift in the evening terminator for short paths, were shown to have occurred 5-6 days before this earthquake. Direction finding studies have shown excellent coincidence with the actual position of the earthquake epicenter.

In this study, we examined the spectral modifications of a LF subionospheric signal from the NRK transmitter (37.5 kHz) in Iceland hat was received at Bari during the period around the time of this earthquake in L'Aquila, and also the spectral changes that were observed during three strong earthquakes with M ≥7.0 in the Far East.

2. Results of the analysis

The signals from the NRK transmitter that were recorded in Russia and at two European stations (Moscow, Bari and Graz) were compared to investigate any differences in their spectra that might have originated from seismic effects. The NRK-Bari propagation path passes in close proximity to the seismically active region around L'Aquila, while the NRK-Moscow and NRK-Graz signals were used as control paths. Strong night-time anomalies that are similar to those that result from strong geomagnetic activity were found up to 5-6 days before the L'Aquila earthquake, and also during the series of aftershocks. Figure 1 shows the details regarding the reception of these signals at Bari, Graz and Moscow. The top panel in Figure 1 shows the Dst index. During the period immediately before the earthquake there was no significant geomagnetic activity. The second panel shows when the foreshock, the earthquake, and its aftershocks occurred, together with their magnitudes. The third panel shows the amplitudes of the NRK signals recorded at Bari. The peaks represent the day-time amplitudes and the troughs were recorded during the night-time. It can clearly be seen that in the period leading up to the earthquake, the amplitudes of the day-time maxima decreased, while the night-time amplitudes increased. These changes began around 5-6 days before the main earthquake occurred. Finally, the lower panel compares the changes in the amplitudes recorded at Bari, Graz and Moscow. During the period up to the end of March, 2009, the changes in amplitude measured at all three of these stations were very similar. However, at the beginning of April, large changes

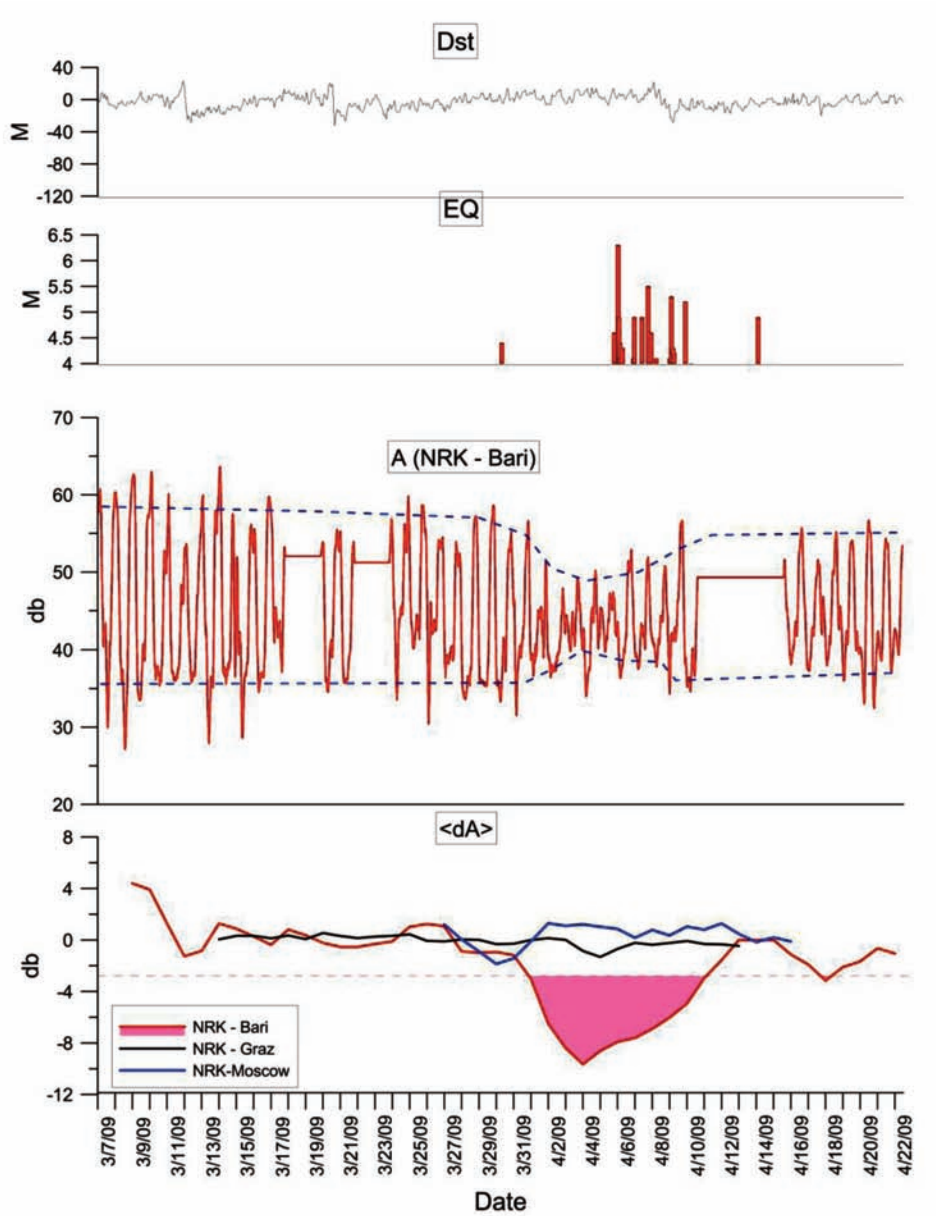

Figure 1. Variations in the amplitudes of the LF signals in NRK-Bari wave path during the period of the earthquake in L'Aquila. Upper panels: Dst index of geomagnetic activity and magnitudes of the main earthquakes between March 30 and April 9, 2009. Middle panel: Signal amplitudes (A) of the NRK signals recorded at Bari in the period March 7 to April 22, 2009. Bottom panel: Night-time residual amplitude (dA) for the NRK-Bari, NRK-Moscow and NRK-Graz paths. Colored region, period in which the residual amplitude exceeded the 2 level (horizontal dotted line) for the NRK-Bari path.

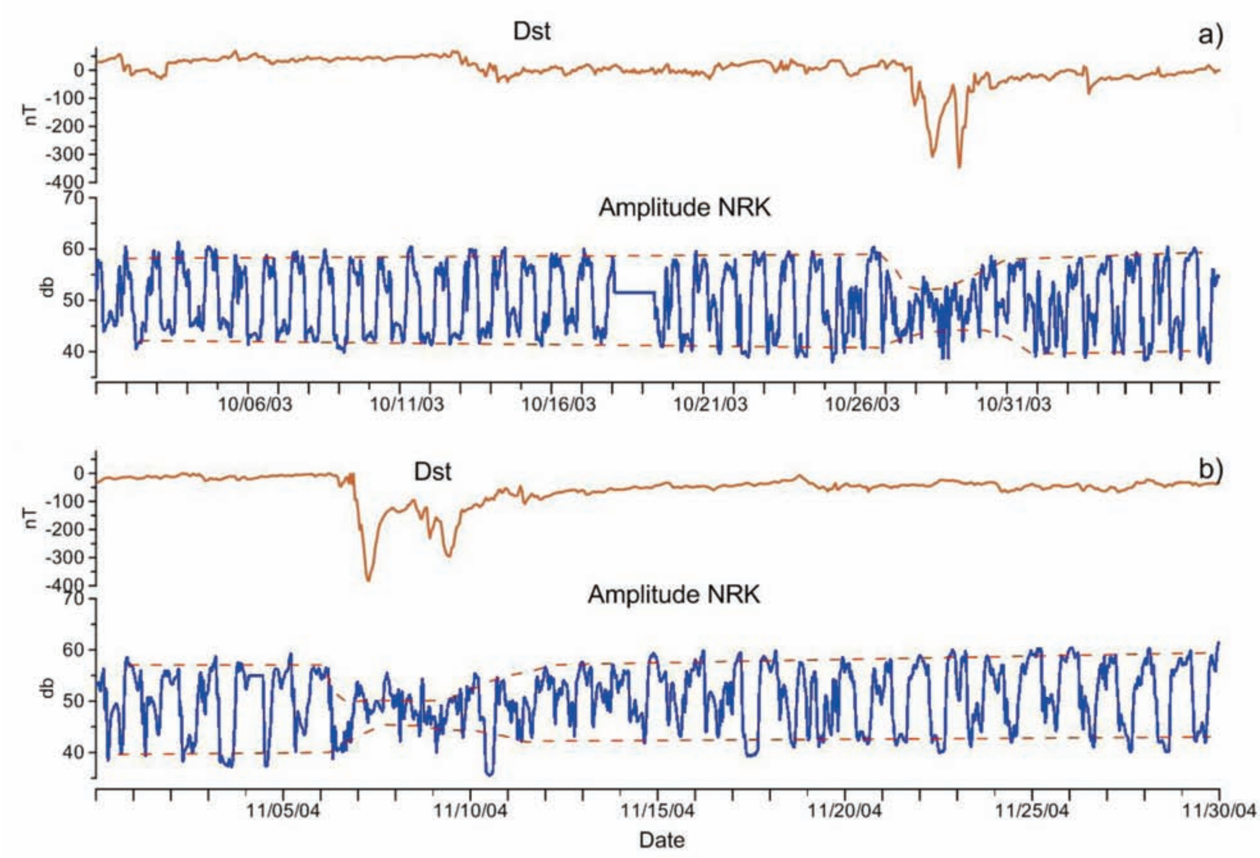

Figure 2. Variations in the amplitudes of the LF signals in the NRK-Bari wave path during periods of strong magnetic activity. (a) A magnetic storm from October 28-31, 2003. (b) A magnetic storm from November 8-10, 2004.

were observed in the amplitudes measured by the Bari station, when compared to those measured in Graz and Moscow. These anomalies corresponded to the anomalies revealed at the same time in the amplitudes of VLF/LF signals in several other seismic paths of the network that crossed the L'Aquila seismogenic zone.

Figure 2 shows variations in the amplitudes of the NRK signal received at Bari during periods of strong geomagnetic activity. The top trace in each panel in Figure 2 shows the Dst index. Periods when the Dst index dipped below –400 nT during strong geomagnetic activity can clearly be seen for the periods of October 28-31, 2003 (Figure 2a) and November 8-10, 2004 (Figure 2b). The lower traces in each panel in Figure 2 show the amplitudes of the NRK signals measured at Bari. During the main and recovery phases of these strong geomagnetic storms, the LF signals showed large changes in the signal amplitudes in comparison to the regular daily variations observed before and after these events. The signal levels during the night-time increased considerably, while the day-time signal levels decreased. The result of these changes is that the variations in the signal amplitudes are around half of the normal daily peak-to-peak values. These effects in the propagation of a LF signal that were observed during strong geomagnetic activity have been explained through a number of studies [e.g. Beloglazov and Remenez 1982]. However, the precise mechanisms responsible for these observed variations in the intensities of the radio signals in connection with earthquakes still remain elusive.

Although the characteristics of the waveform of the NRK signal anomalies appear identical during the L'Aquila earthquake and during periods of strong geomagnetic activity, the resulting spectra are different.

We applied spectral analysis to signals recorded on quiet days and compared these to similar results for days on which geomagnetic-induced and seismo-induced anomalies were observed. For this analysis, we used the night-time amplitudes of the NRK signals filtered in the frequency band 0.28 mHz to 15 mHz, which corresponds to wave periods in the range T from 1 min to 60 min. In this frequency range, atmosphere gravity waves with periods that would typically be expected to be T >6 min were observed, in agreement with theoretical estimations. Figure 3 shows the spectra of these filtered LF signals received at the Bari, Graz and Moscow stations for quiet days long before the earthquake (Figure 3, top row), for possible seismo-induced anomalous days in the NRK-Bari wave path just before the L'Aquila earthquake (Figure 3, middle row), and for days after the main aftershocks (Figure 3, bottom row). Note that for the last period we have data only for the Bari station. The spectra

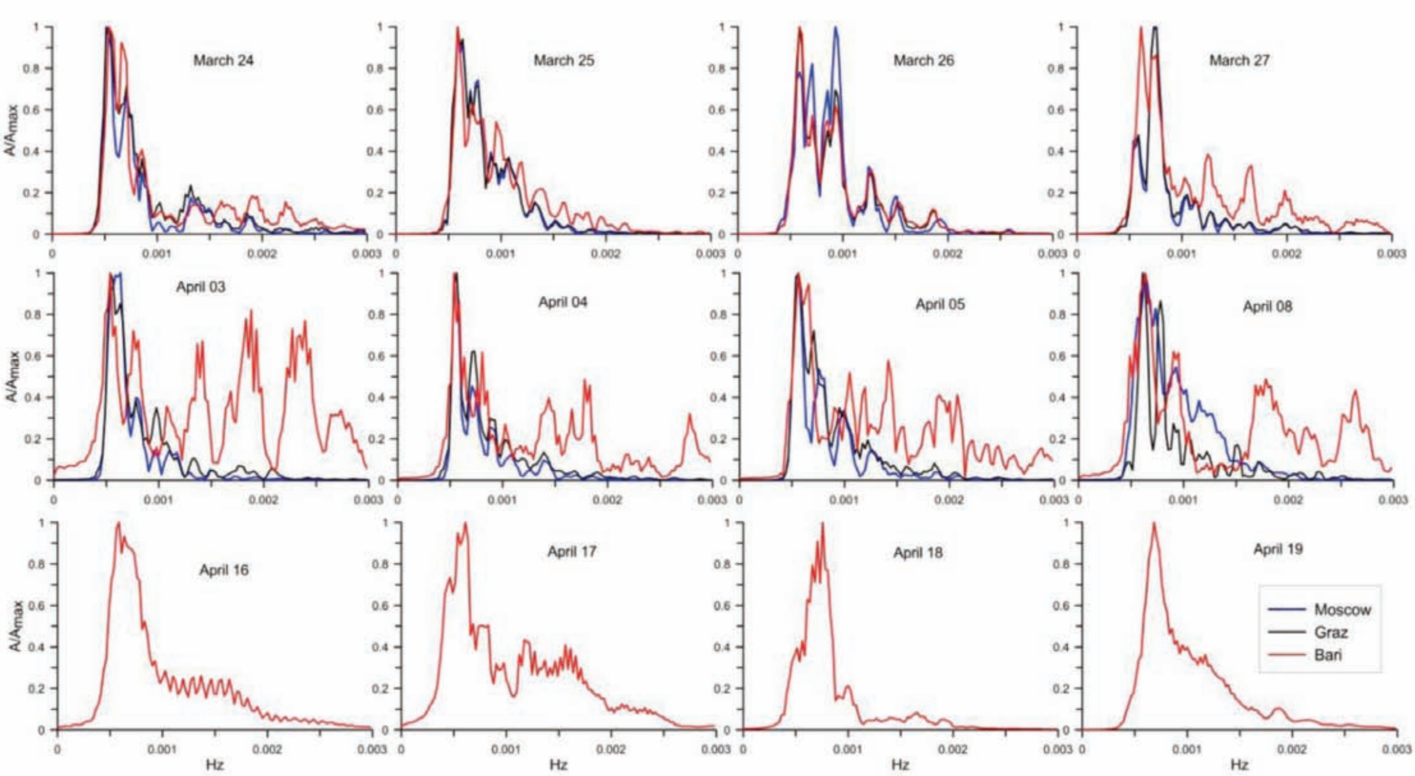

Figure 3. Normalized spectra of the filtered (0.28-15 mHz) amplitudes of the NRK signals. Upper panels: Spectra for Bari, Graz and Moscow for quiet days at the end of March, 2009, well before the occurrence of the earthquakes. Middle panels: Spectra for Bari, Graz and Moscow for days when the seismo-induced anomalies were observed in the NRK-Bari propagation path. Bottom panels: Spectra for Bari for the quiet days after the earthquake.

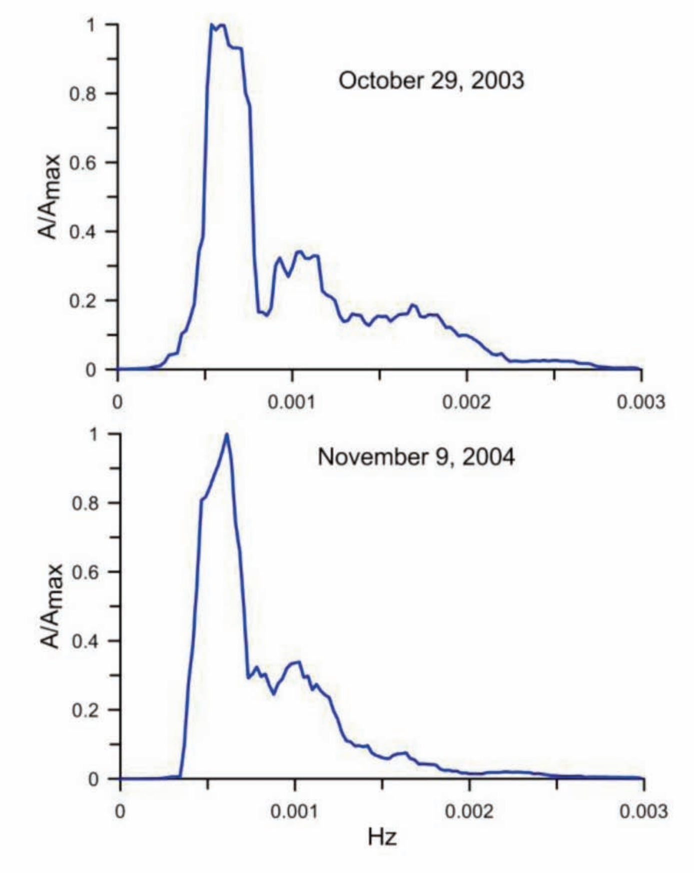

Figure 4. Normalized spectra of the filtered (0.28-15 mHz) amplitudes of the NRK signals registered at the Bari station during strong magnetic activity in October 2003 and November 2004.

were very similar for all three of these stations during the quiet periods. This contrasts with the differences seen in the spectra of the seismo-disturbed days. Only the spectra of the signal propagating along the NRK-Bari seismic path exhibited wave activity, with periods of the order of 10 min to 20 min. These periods were absent in the spectra of the undisturbed signals and of the signals used as the control paths, and in the spectra resulting of magnetic-induced anomalous signals (Figure 4). This result reinforces previous results in which spectral peaks in the range of T = 10 min to 25 min were observed for several strong earthquakes [Rozhnoi et al. 2007].

The same spectral changes were observed in the analysis of LF (40 kHz) signals from the JJY transmitter in Japan that were recorded in Petropavlovsk-Kamchatsky (Russia) for strong earthquakes (M 6.1-8.3) which occurred in the sensitivity zone of this wave path in November 2004, November 2005 and November 2006. The results of these analyses are shown in Figure 5. For comparison, the variations in the amplitude of the JJY signals for the quiet November month in 2002 are also shown. Night-time disturbances of the amplitudes of the LF signals (Figure 5, yellow-brown color) were conspicuous 2-10 days before the earthquakes and during strong aftershocks (M 5-6.5) activity in November 2006. The spectra of the seismo-induced anomalous days show a main maximum that corresponds to wave periods of T ~30 min, and they also

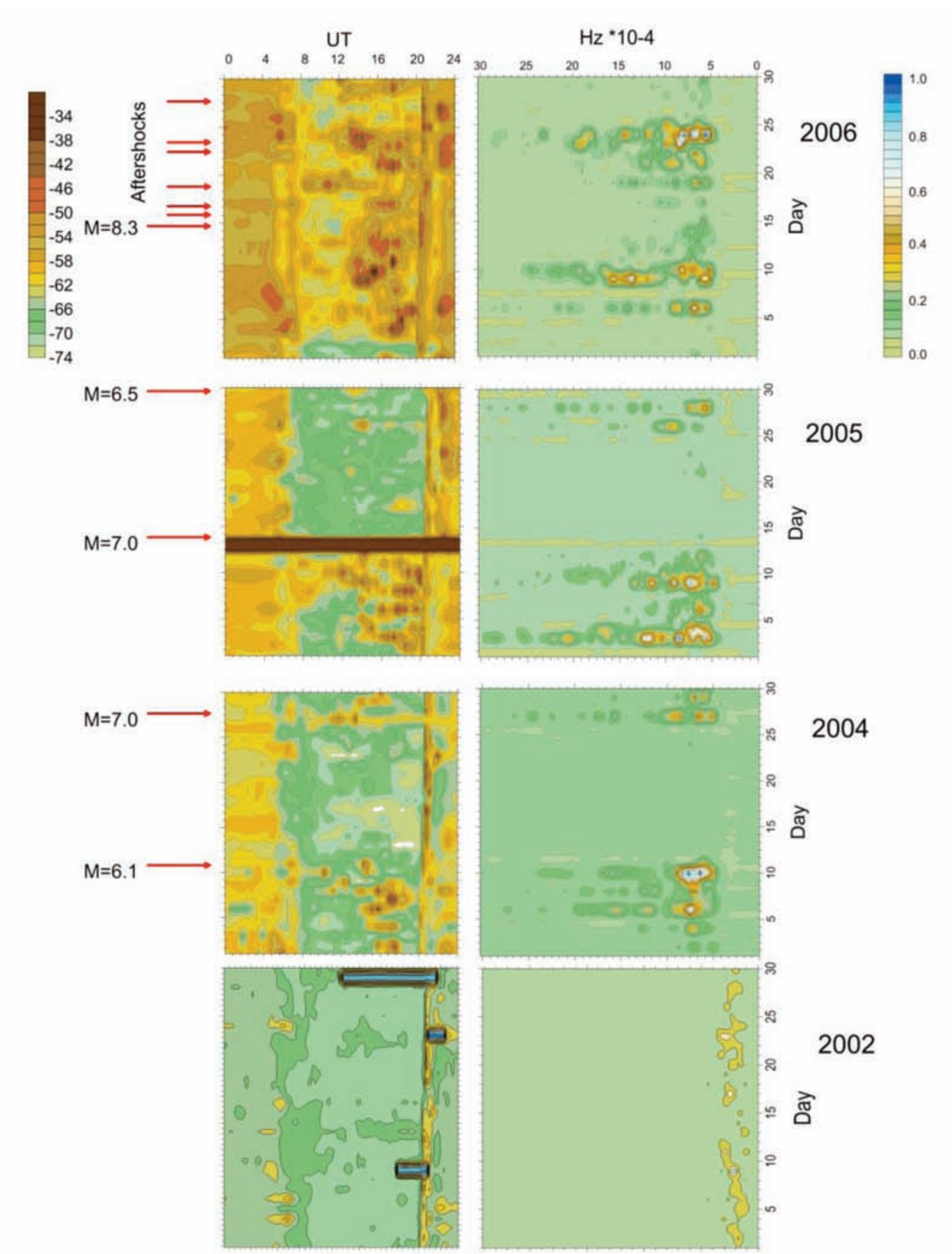

Figure 5. Time-and-frequency analysis of JJY signals received at Petropavlovsk-Kamchatsky in November 2002, 2004, 2005 and 2006. Left panels: Contour maps of the amplitudes of the JJY signal variations as a function of time of day (X-axis) and day of month (Y-axis). Right panels: Spectrograms of the filtered amplitudes of the signals as a function of frequency (X-axis) and day of month (Y-axis). Arrows indicate earthquakes with M >6.

contain waves with shorter periods, in the range of 10 min to 20 min.

3. Discussion and conclusions

We have presented here a spectral comparison of the amplitudes of LF signals received during periods of strong seismic and geomagnetic activities. Although the effects on the LF signals induced by the seismic and geomagnetic activities were very similar, the scale of resulting inhomogeneities in the ionosphere was very different. Magnetic storms are global processes, while seismo-induced disturbances in the ionosphere have a local character. This difference can be seen from the spectral compositions of the signals. In the spectra of the seismo-induced LF signals, waves with periods in the range of 8 min to 20 min were clearly observed. These periods were absent in the spectra of geomagnetic-induced anomalous days.

These results confirm that the observed effects in the case of the L'Aquila earthquake can be produced by the penetration of atmosphere gravity waves into the ionosphere. This penetration leads to perturbations in the plasma in the lower ionosphere [Molchanov and Hayakawa 2007]. The energy flux of the atmosphere gravity waves originates from the release of gas-water from within the earthquake preparatory zone. There are indications that such a release took place before the L'Aquila earthquake [Grant and Halliday 2010]. A secondary effect of this release was the dramatic change in behavior that was observed for the toads in the San Ruffino Lake area (74 km from the epicenter) 5 days before the earthquake, and some days after the event. The reduced toad activity precisely coincided with the preseismic perturbations in the ionosphere that were detected by VLF/LF radio sounding. Changes in the weather or air composition might have affected these toads; however, a detailed analysis of the local weather conditions (e.g. temperatures, humidity, wind and rainfall) at this time did not reveal any perceptible changes. We have every reason to believe that this abnormal behavior of the toads was caused by changes in the air composition due to the release of gases in this area.

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Data and sharing resources

The earthquake catalog used in this study can be found at the site: http://neic.usgs.gov/neis/epic/epic_global.html

The Dst data were taken from the site: http://wdc.kugi.kyoto-u.ac.jp/dstdir/index.html

References

Beloglazov, M.I. and G.F. Remenez (1982). Propagation of VLF radio waves in high latitudes, Leningrad, Nauka, 240 pp. (in Russian).

Biagi, P.F., R. Piccolo, L. Castellana, T. Maggipinto, A. Ermini, S. Martellucci, C. Bellecci, G. Perna, V. Capozzi, O. Molchanov, M. Hayakawa and K. Ohta (2004). VLF-LF radio signals collected at Bari (south Italy): a preliminary analysis on signal anomalies associated with earthquakes, Nat. Hazards Earth Sys., 4, 685-689.

Biagi, P.F., L. Castellana, T. Maggipinto, G. Maggipinto, A. Minafra, A. Ermini, V. Capozzi, G. Perna, M. Solovieva, A. Rozhnoi, O. Molchanov and M. Hayakawa (2007). Decrease in the electric intensity of VLF/LF radio signals and possible connections, Nat. Hazards Earth Sys., 7, 423-430.

Biagi, P.F., L. Castellana, T. Maggipinto, D. Loiacono, V. Augelli, L. Schiavulli, A. Ermini, V. Capozzi, M.S. Solovieva, A.A. Rozhnoi, O.A. Molchanov and M. Hayakawa (2008). Disturbances in a VLF radio signal prior the M=4.7 offshore Anzio (central Italy) earthquake on 22 August 2005, Nat. Hazards Earth Sys., 8, 1041-1048.

Grant, R.A. and T. Halliday (2010). Predicting the unpredictable; evidence of pre-seismic anticipatory behaviour in the common toad, J. Zool., 281, 263-271.

Molchanov, O.A. and M. Hayakawa (2007). Seismo-electromagnetics and related phenomena: History and latest results, Terra Sci. Pub. Co., 432 pp.

Rozhnoi, A.A., M.S. Solovieva, O.A. Molchanov, P.F. Biagi, M. Hayakawa and Sh. Maekawa (2005). Disturbances in VLF/LF signals correlated with earthquakes in the Europe station and Asia network, IWSE-2005, Abstracts, 428-431.

Rozhnoi, A., M. Solovieva, O. Molchanov, P.F. Biagi and M. Hayakawa (2007). Observation evidences of atmospheric gravity waves induced by seismic activity from analysis of subionospheric LF signal spectra, Nat. Hazard Earth Sys., 7, 625-628.

Rozhnoi, A., M. Solovieva, O. Molchanov, K. Schwingenschuh, M. Boudjada, P.F. Biagi, T. Maggipinto, L. Castellana, A. Ermini and M. Hayakawa (2009). Anomalies in VLF radio signals prior the Abruzzo earthquake (M=6.3) on 6 April 2009, Nat. Hazards Earth Sys., 9, 1727-1732.

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