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Surface latent heat flux and nighttime LF anomalies prior to the M_w=8.3 Tokachi-Oki earthquake

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Abstract. Surface Latent Heat Flux (SLHF) is an atmospheric parameter proportional to the evaporation from the Earth's surface. SLHF has been found to exhibit an anomalous behavior in the epicentral region prior to several coastal earthquakes. Sub-ionospheric low frequency (LF) radio sounding measurements have shown its potentiality for the short-term earthquake forecasting since the last decade. The anomalous SLHF and nighttime LF sub-ionospheric signals are found to show complementary nature associated with the large Tokachi-Oki earthquake of 25 September 2003. Such complementary nature of parameters may prove to be potential in providing early warning information about an impending earthquake.

1 Introduction

Significant changes in the Earth, ocean, atmosphere and even ionosphere have been observed prior to earthquakes (Hayakawa et al., 1996; Singh et al., 2001a, b; Tramutoli et al., 2001; Hayakawa and Molchanov, 2002; Dey and Singh, 2003; Bello et al., 2004; Cervone et al., 2004; Hayakawa et al., 2004; Maekawa et al., 2004; Ouzounov and Freund, 2004; Pulinets, 2004; Pulinets and Boyarchuk, 2004; Cervone et al., 2005). Hayakawa et al. (2004) have discussed different mechanisms of lithosphere-atmosphere-ionosphere coupling as possible explanation of the observed ionosphere anomalies, and their relation to the earthquake preparatory process. The first mechanism is related to thermal anomaly, which in turns also responsible for enhancement in DC electric field that give rise to the changes in lower ionosphere (Pulinets and Boyarchuk, 2004). The second mechanism is based on the energy transmission in terms of atmospheric oscillations (gravity wave) (Molchanov et al., 2001; Shvets et al., 2004). Some promising results have been found to demonstrate anomalous deviations in the VLF phase or/and amplitude (Gokhberg et al., 1989; Hayakawa et al., 1996, 2004; Hayakawa, 1999).

Due to low spatial and temporal resolution of ground observation data, it was not possible to study the complementary nature of different precursory signals. However, with the availability of high resolution global remote sensing data, it has become possible to detect different types of anomalies, and study their complementary behavior. It is now believed that the routine monitoring of such changes can provide early warning information about impending earthquakes.

Changes in temperature at the epicentral have been studied in relation to large seismic events (Qiang, 1997; Tramutoli et al., 2001; Tronin et al., 2002). Thermal anomalies in the epicentral region prior to an earthquake are caused by the release of gases, movement and fluctuations of water and slow deformation (Glowacka and Nava, 1996). Several IR wavelength observations using MODIS data have shown an increase up to 5 K of the surface temperature in the epicentral region prior to earthquakes (Tramutoli et al., 2001; Ouzounov and Freund, 2004).

Recently, surface latent heat flux (SLHF), a key component of the Earth's energy budget, representing the heat flux from the Earth's surface to the atmosphere has been proposed as a possible precursor of coastal earthquakes. Dey and Singh (2003) and Cervone et al. (2004, 2005) have shown the consistent occurrence of anomalous SLHF peaks a few days prior to the main earthquake events. They have concluded that the routine measurements of SLHF can provide an early warning information of impending coastal earthquakes.

Several ground and satellite borne measurements have shown EM anomalies prior to earthquakes (Fujinawa and Takahashi 1994; Enomoto and Hashimoto, 1994; Hayakawa

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et al., 1996; Parrot, 2002; Valliantos and Tzanis, 2003; Liu et al., 2004; Maekawa and Hayakawa, 2004; Pulinets and Boyarchuk, 2004). Seismic zones are considered more conductive due to the high level of fracturing and micro-fracturing along the faults, caused by an increase in porosity and fluid content in the rocks (Madden and Mackie, 1996). The high stress field prior to earthquakes is responsible for surface and subsurface deformation in the epicentral region, which, in turn, is responsible for changes in the electrical and magnetic fields (Madden and Mackie, 1996; Pulinets and Boyarchuk, 2004). This phenomenon is often referred to as *dilatancy*, since the rocks either dilate or contract, and evidence of this phenomenon is likely to be associated with the large deformation that is sometimes observed prior to earthquakes. It is believed that electromagnetic fields associated with the earthquake preparation process can influence the lower ionosphere (Hayakawa, 2001; Pilipenko et al., 2001; Hayakawa et al., 2004).

In the present paper, we have discussed the retrospective analysis of SLHF and sub-ionospheric LF nighttime data, prior to the M_w=8.3 Tokachi-Oki earthquake of 25 September 2003. The SLHF and sub-ionosphere LF nighttime anomaly show a complementary nature, and may provide early warning information for coastal earthquakes.

2 SLHF and LF data

The SLHF data used in the present study have been taken from the NCEP/NCAR reanalysis data of the IRI/LDEO Climate Data Library (http://iridl.ldeo.columbia.edu/). The IRI/LDEO Climate Data Library contains over 300 datasets from a variety of Earth science disciplines and climate-related topics. All the datasets are distributed using a common netCDF format in gridded format, and can be downloaded using a simple and effective HTML based interface.

The NCEP/NCAR Reanalysis Project is a joint project between the National Centers for Environmental Prediction (NCEP) and the National Center for Atmospheric Research (NCAR). The goal of this project is to produce long time series for climate studies using new atmospheric analysis of historical data and current atmospheric data (Climate Data Assimilation System, CDAS). The reanalysis data consist of very long homogeneous time series with nearly global coverage, although historical data are less reliable because of the lack of satellite observations. The quality of the reanalysis data is high due to the use of state-of-the-art data assimilation based on both satellite and ground observations, quality control and modeling algorithms. The disadvantage is in the coarse resolution, which varies from 1.8 to 2.5° (∼200 km) depending on the parameter. The fluxes used in the operational weather forecast models are incorporated with in-situ observations through the assimilation process. The validation and detailed description of the reanalysis of NCEP SLHF data have been discussed by Kalnay et al. (1996, 2000). For the detailed analysis of SLHF, we have taken 5 years of data from 1 January 1999–31 December 2003.

The electromagnetic data has been acquired using a signal transmitted by Japanese Time Standard LF station (JJY, 40 kHz) located at the geographic coordinates (37.37° N, 140.85° E) in Fukushima prefecture, and retrieved at two locations; the Moshiri station in Hokkaido, Japan and the station at Petropavlovsk-Kamchatski, Russia. For receiving and logging of the VLF/LF signals, JAPAL system has been used (Shvets et al., 2004). The vertical electric component was received with a rod antenna installed on the roof of laboratory buildings at both locations. The different nature of the diurnal dependencies of the signal at these two receiving stations is connected with both the different orientation of the propagation paths to the terminator and their different propagation lengths. For the shorter path (JJY-Moshiri), we have observed stronger fluctuations during the nighttime period in comparison with the longer path (JJY-Kamchatski) possibly due to its proximity to the interference minimum as it is found from a comparison of average day-time and night-time levels. It is known that strong disturbances in VLF/LF signals occur during daytime due to additional ionization of the lower ionosphere by solar X-ray flares. The increase in the VLF/LF signal amplitudes is related to the increase in conductivity of the upper waveguide wall. Very strong (about 10 times over regular signal level, measured in decibels (db)) positive excursions of the signal amplitude observed at Moshiri during the daytime have a shape that is not typical for solar flare effects (fast growth and relatively slow decay), and seems to be unexplained in terms of waveguide propagation theory. It is likely that local disturbance also influence the VLF/LF signals.

3 Results and discussion

The Tokachi earthquake (M_w=8.3) occurred on 25 September 2003 near Hokkaido, Japan, with its epicenter located at the geographic coordinates (41.815° N and 143.910° E), and with a focal depth of 27 km. The epicenter is located in the same region where the earlier 1952 Tokachi-Oki earthquake M_w=8.1 occurred (Geist et al., 2003; Hirata et al., 2003). Figure 1 shows a map of the epicentral region with the plate boundaries and major fault lines, as well as the location of the epicenters of earthquakes that occurred within six months after the main earthquake of 25 September 2003.

This earthquake caused a large tsunami of about 1.5 m high on the Pacific coast, and that affected Hokkaido and Tohoku regions. Based on the observed seismicity the earthquake was forecasted using the M8 algorithm (Shebalin et al., 2004). Very low frequency (VLF) and low frequency (LF) sub-ionospheric radio wave data were also used to study the preparatory process of this earthquake using the nighttime LF signals (Shvets et al., 2004). The three-days average of LF signals collected from the two stations located in Hokkaido, Japan and in Kamchatka, Russia are found to show anomalous signals about a week prior to and a week after the main earthquake event. SLHF anomalies over the

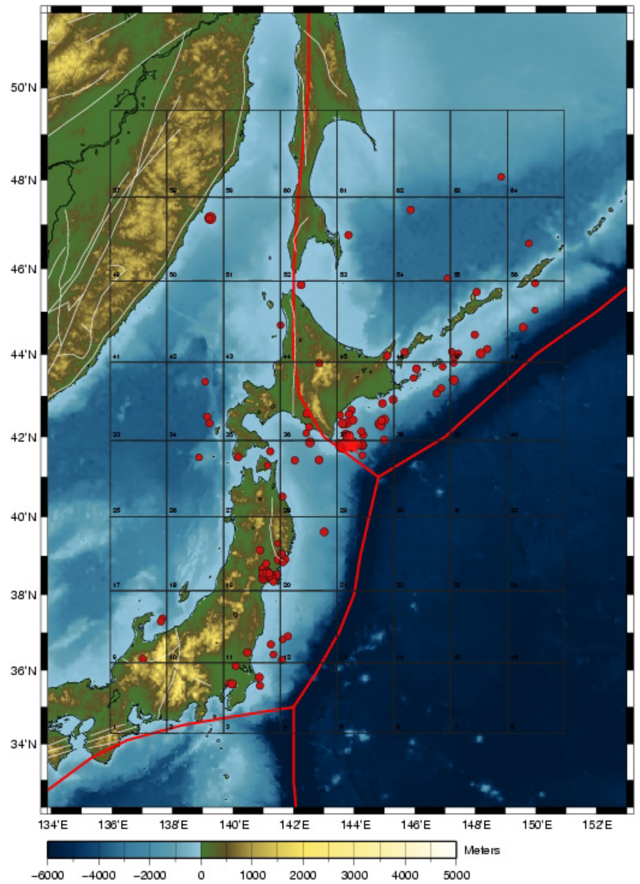

Fig. 1. Map of Japan showing the location of the epicenter (star) of earthquake (M_w=8.3) 25 September 2003. Plate boundaries, faults and their type are also shown. The grids represent the location for which experiments were performed.

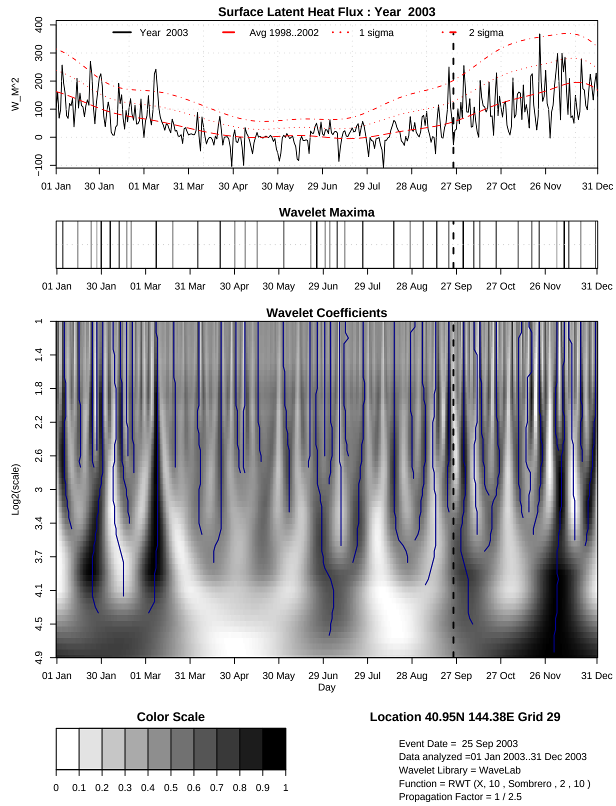

Fig. 2. Wavelet transformation of SLHF data over grid 29 (epicentral region).

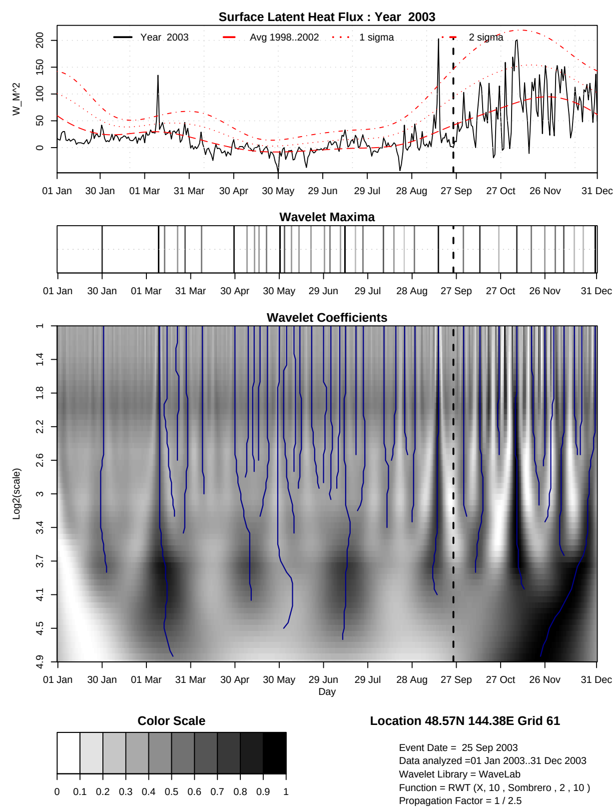

Fig. 3. Wavelet transformation of SLHF data over grid 61 (Kamchatka station).

epicentral area are also observed prior and after the earthquake event in the same time period.

Two strong SLHF anomalies are found at the epicenter, 11 and 3 days prior to the earthquake events, respectively. The SLHF anomalies occurred 11 days prior to the event is found to extend north of the epicenter, while anomaly observed 3 days prior to the event extent, south of the epicenter. These anomalies are found over the continental boundary extending for several hundred kilometers. Figure 2 shows the wavelet transformation and the generated maxima curves for the epicentral region of the earthquake. Prominent anomalies (more than two sigma) are found 3 days prior and 8 days after the earthquake, are the largest anomalies in the entire year. Figure 3 shows a second wavelet transformation and the generated maxima curves for a region 400 km north of the epicenter, closer to the Kamchatka station.

A prominent SLHF anomaly larger than 4 sigma is observed 10 days prior to the earthquake. Wavelet transformations for the adjoining region show similar large anomalies 10 days prior to the earthquake event. Due to the high values of SLHF for this region, the spatial analysis of the continuity generates several maxima curves and it is not possible to assert the significance of the signal.

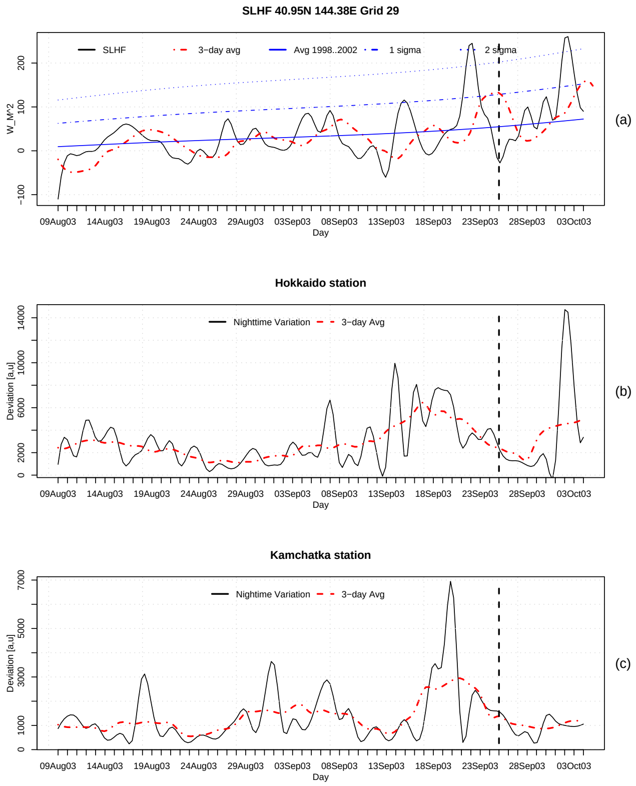

Fig. 4. **(a)** SLHF (solid line) for the region around 40.95° N and 144.38° E, its 3-day average (dot full line), the 5-year average (solid trend line) with 1 and 2 sigma. The LF signals observed at Moshiri, Japan (44° N, 142° E) **(b)** and Petropavlovsk-Kamchatski, Russia (53° N, 158° E) **(c)**, with their respective 3-day average for August to October 2003.

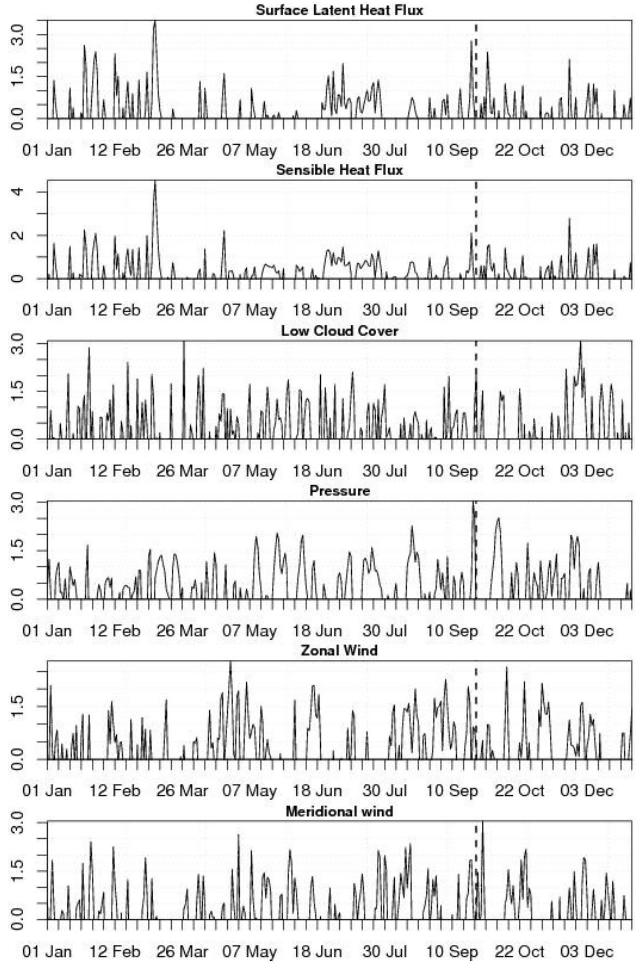

Fig. 5. Various atmospheric and EM anomalies detected prior to the Tokachi earthquake.

Figure 4 illustrates a comparison of both, SLHF and ionospheric anomalies associated with this earthquake. The first image shows the SLHF time series for the epicentral region from 9 August to 3 October 2003 over the epicentral region. The three-days average for the same time period (in dot-broken line), the 30-days average computed using the data from 1998 to 2002 (in full line), and the 1 and 2 sigma. The second and third images are generated using the nightime LF signals (Shvets et al., 2004). LF signals represent the observed time series from 9 August to 3 October 2003, and the three-day average observed from the Hokkaido (second panel) and Kamchatski (third panel) station, respectively. Anomalous signals are observed in all three time series prior to and after the earthquake event with very similar temporal evolutions. The SLHF time series show an extended anomaly during the period from 15–23 September, while the LF amplitude fluctuation at both Moshiri and Kamchatski shows anomalies during the period of 18–22 September. The LF propagation characteristics are known to be influenced by the ionospheric perturbation within a certain Fresnel zone of each great-circle path. Both SLHF anomaly and ionospheric perturbations are expected to be extremely large due to the magnitude of this earthquake. The most important point from Fig. 4 is the common period from 15–23 September, where several complementary anomalies in both the SLHF and ionospheric data are observed. SLHF anomalies are found to exhibit a 2/3 days delay with respect to the ionospheric anomalies, which is likely due to different speed of SLHF and LF signals.

In Fig. 5, we have shown anomaly variations of SLHF, Sensible Heat Flux, Low Cloud Cover, Pressure, Zonal and Meridional wind, all derived from NCEP-NCAR model data. All these parameters show complementary nature, exhibiting prominent peaks prior to the Tokachi-Oki main earthquake. Such peaks are thought not to be of atmospheric origin due to their persistence both in times and space over the epicentral area of the earthquake. The anomaly (y-axis) is defined by subtracting from the observed values the 5-years averaged mean, and divide the result by the standard deviation. Therefore the anomaly shows the number of standard deviations above the mean. Whereas atmospheric phenomena tend to quickly move across locations, anomalies due to earthquakes are usually found to be persistent over the epicenter. When the anomalies are observed, both meridional and zonal winds are not high, suggesting the absence of severe weather phenomena which might cause the observed anomalies. This plot shows that the SLHF is highly sensitive prior to the earthquake event whereas it is difficult to comment about meteorological parameters which are highly variable over the year.

4 Conclusions

This paper presents the first attempt to compare SLHF and ionospheric anomalies observed prior to a major earthquake. The observed anomalies show a complementary behavior both in terms of temporal and spatial distribution. Although it is difficult to say that the SLHF anomaly is the main driving force of the ionospheric perturbations, but it is certain that changes in the lithosphere are likely to be related to the observed ionospheric perturbations. The underlying coupling mechanism is not yet well understood, and requires detailed further studies. However, the combined use of different anomalies (as proposed in this paper) could build a much more robust forecasting system from the standpoint of short-term earthquake prediction.

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