Surface Latent Heat Flux Associated with Indian Coastal Earthquakes

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Abstract

Detailed analysis of surface latent heat flux (SLHF) over the epicentral and adjoining region of numerous recent coastal earthquakes have shown anomalous SLHF prior to the earthquakes. Such anomalous behavior of SLHF is not found with the earthquakes occurring far away from the coastal earthquakes. The surface latent heat flux retrieved from the NOAA satellites over the epicentral region of coastal earthquakes show anomalous SLHF few days prior to the main earthquakes. The analysis of SLHF associated with recent coastal earthquakes have shown that the anomalous peaks prior to earthquakes depend on the distance of the epicenter of the earthquake from the coast, season in which earthquakes occur, ocean depth and magnitude of the earthquakes. Detailed analysis of SLHF deduced from various satellites data have been analyzed and also using signal – noise decomposition of time series using continuous wavelet transformation. The use of SLHF over the ocean and land will be discussed in the Early Warning of impending coastal earthquakes.

Introduction

Soon after the Gujarat earthquake (January 26, 2001), efforts have been made to analyze multi sensor data, which are available from the optical and microwave sensors onboard satellites. Using Indian Remote Sensing Satellite (IRS) data prior and after the earthquake, the significant changes in the chlorophyll concentrations in adjacent ocean, emergence of land along the coast, emergence of water in the epicentral region, changes in vegetation cover, changes in lineaments, changes in atmospheric aerosols and atmospheric water vapor have been observed. The changes in the infrared thermal temperature have also been observed prior to the Gujarat earthquake (Singh et al., 2001a, b, c, 2002, Dey and Singh, 2003). The thermal anomaly prior to the China and Japan earthquakes was found from the thermal satellite imageries (Tronin et al., 2002) which was not found to be common with other earthquakes.

The analysis of IRS-P4 Multi-spectral Scanning Microwave Radiometer (MSMR) data has shown significant changes in water vapor over adjacent ocean, soil moisture and brightness temperature in the epicentral region of Gujarat. Singh et al. (2003) and Chandra and Sharma (2003) have also found ionospheric anomalies prior to Gujarat earthquake. The analysis of TOPEX-POSEIDON data has also shown anomalous variations in total electron content (TEC) prior to the Gujarat earthquake (Parrot and Trigunait, 2003).

The Indian sub-continent have experienced large earthquakes ($M > 5$) quite frequently in the last two centuries. Large earthquakes have frequently occurred in the Himalayan region (interplate earthquakes) whereas few disastrous earthquakes have occurred in Indian shield (intraplate) (Figure 1). In India, the earthquake precursor studies are limited to the intermediate and long-term using only geophysical and geochemical anomalies. Some attempts have been made towards understanding the behavior of the short-term precursors, but limited only to the geochemical parameters: mainly radon and helium anomalies which is difficult to monitored continuously (Virk 1993, Virk and Singh 1993, Singh et al., 1999). In this paper, we present surface latent heat flux (SLHF) as a new short-term precursor parameter, which can be monitored using satellite data. Using SLHF data of few recent coastal earthquakes in India, we have demonstrated the use of SLHF data in providing early information about an impending earthquakes.

Land-ocean-atmosphere interaction during an earthquake

The physics of changes in surface manifestations associated prior and after the earthquake is common and well understood, whereas the changes in chlorophyll concentrations, water vapor in the atmosphere, electric and magnetic fields in the atmosphere, changes in ionospheric and gravity wave are not fully understood. Numerous claims of these parameters associated as precursors of earthquakes have been made in the past but due to insufficient justifications of such changes with other parameters, lack of quantitative effort of these parameters and lack of consistency of such changes, these precursors have been doubted recently (Geller, 1997, Geller et al., 1997). The availability of satellite data allows us to monitor the changes in surface and atmospheric parameters in response to the earthquake in spatio-temporal domain and leads to consider the land-ocean-atmosphere coupling in seismological processes. Studies regarding the role of fluid in triggering of intraplate earthquakes especially in Indian shield region have been discussed by Singh et al. (1995). Prior to the intraplate earthquakes, the movement of subsurface fluids cause changes in the chemical composition of ground water and escape of gases in the atmosphere. Land-ocean-atmosphere interaction involves changes in surface temperature; changes in water level and soil moisture leading to the changes in the physical properties of soil and changes in the atmospheric parameters (Dey et al., 2004). The epicenter of Gujarat earthquake (January 26, 2001) lies close (100 km) to ocean. The Gujarat earthquake was felt over 70% parts of India.

Freund and Ouzounov (2001) have experimentally proved that thermal infrared emission occurs at the surface of the rock masses due to the accumulation of stress prior to the earthquake. This is manifested in terms of increased surface temperature observed in the low-stress zones prior to the earthquake. In the marine environment, thermal energy dissipates while traveling through the water column up to the surface and so the movement of the thermal anomaly is difficult to interpret in terms of the tectonics of the region. In the tropical oceans, SST has been found to be strongly influenced by seasonal variations, hence, it is very difficult to fix the threshold of the background noise. This prompted us to look for SLHF in addition to SST for the coastal and marine earthquakes.

Surface Latent Heat Flux (SLHF) Data

The SLHF is related to the energy exchange from the ocean to the land through atmosphere which is considered as major energy source for atmospheric circulation, which can be accurately monitored using satellite data. Singh et al. (2001d) have calculated SLHF over the Indian Ocean and the Bay of Bengal from the IRS-P4 MSMR data for the limited time period and suggested that in the high SLHF regions (> 300 W/m^2), the sensors get saturated leading to the underestimation of SLHF. The SLHF data is found to show seasonal and inter-annual variability. The magnitude of the SLHF is higher near the ocean and decreases away from the ocean over the land. Using the optical and microwave sensors onboard satellites, now it is possible to monitor SLHF globally. The National Center for Environmental Prediction (NCEP) retrieves SLHF globally and the global data set is available through NCEP web site (http://iridl.ldeo.columbia.edu/). The data set is represented by the Gaussian grid of 94 lines from equator to pole with a regular 1.8^0 longitudinal spacing. The data set is projected into 2^0 latitude by 2^0 longitude grid. Global database of various meteorological and ground parameters are maintained at NCEP, where the database are generated taking into consideration the measured values at various worldwide stations. The validation and upgrading of the database at NCEP have been discussed by Kalnay et al. (1996). The SLHF is found to be accurate to 10-30 W/m^2 as described by Smith et al. (1999). Singh et al. (2001d) have analyzed NCEP SLHF and in situ observed SLHF during the period June- August 1999 have found RMS errors of the order of 34 W/m^2.

In this paper, we have used NCEP derived SLHF data prior and after the earthquake to study the behavior of these parameters in response to the earthquakes. The spatial distribution of SLHF prior to the earthquake has been studied over the epicenter and adjoining areas. Monthly average of 5 years data has been subtracted from the daily data to minimize the monthly and seasonal effect (termed as background noise). The standard deviation of SLHF for each day has been calculated using 5 years data to fix the threshold values of the background noise and to differentiate the earthquake signal. This background noise may be attributed to tidal effects, high wind speed and atmospheric perturbations. The standard deviation (σ - sigma) of each data set and average value (μ) of five years of daily data are shown in figures. The SLHF values beyond two sigma are considered as anomalous peaks, which corresponds to the occurrence of main earthquake. In Indian region, during monsoon period, the anomalous SLHF peaks are commonly found. Such anomalous peaks are difficult to distinguish with the anomalous SLHF peaks associated with an impending earthquake. Recently, Cervone et al. (2004) have developed a technique which can be used to distinguish SLHF peaks associated with earthquakes and with monsoon disturbances.

Results and Discussion

In the present study, we have considered four major earthquakes occurred in India during the last few years (Table 1 and Figure 1). Experiments were performed using five

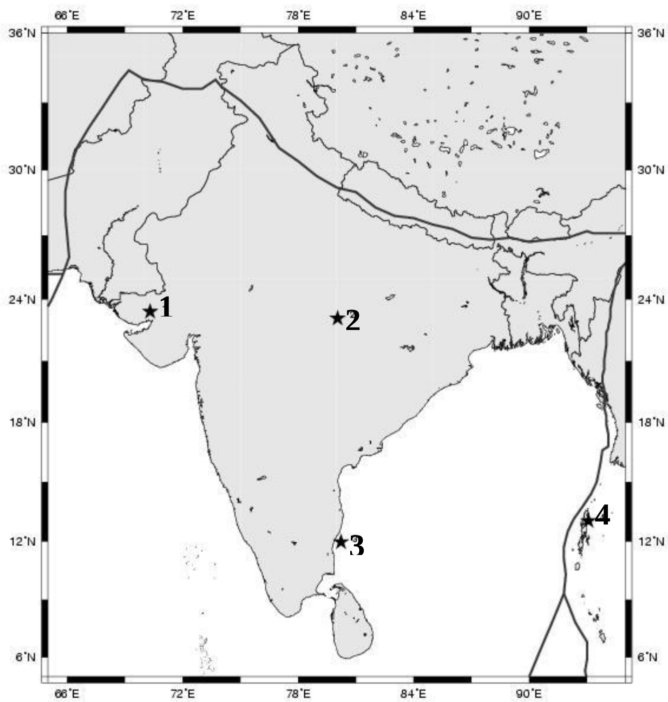

Figure 1 shows the epicenter of earthquakes considered in the present study. Details of these earthquakes are given in Table 1. The solid thick line shows the plate boundary. All the four earthquakes are far away from the plate boundary.

years of daily SLHF data from the reanalysis project maintained by NCAR and NCEP. The time-series for the year of the earthquake event was used for the wavelet transformation, while the remaining five years were used to calculate simple statistics. The monthly average and standard deviation for the five years have been used to minimize the effect of background noise, which may be attributed to tidal effects, monsoon and atmospheric perturbations. The wavelet transformations were performed using Wavelab, a wavelet library developed at Stanford University, using the second derivative of the Gaussian function as mother wavelet (often called 'sombrero' because of its resemblance to a Mexican hat). The wavelet transformations were used to identify the singularities in the data, or abrupt changes in the first derivative, which in turns correspond to SLHF anomalies. The singularities were detected interpolating the wavelet maxima of different scales, and considering those maxima which propagate from the finest to the coarser scale. The propagation depth is the minimum length that a maxima curve must have in order to be considered, and it is usually fixed to ½ of the wavelet scales. In order to reduce the complexity of the problem and increase the statistical significance of the results, only singularities corresponding to peaks above the average are considered. The significance of the peaks is computed by comparing their magnitude to the standard deviation.

Table 1. Details of the earthquakes (Source: http://www.asc-india.org)

No.	**Earthquake**	**Date**	**Longitude**	**Latitude**	**Ms**	**Depth (km)**
1	Gujarat	Jan 26, 2001	70.32 E	23.33 N	7.8	23.6
2	Jabalpur	May 22, 1997	80.04 E	23.08 N	5.8	36
3	Pondicherry	Sep 25, 2001	80.23 E	11.95 N	5.4	19
4	Andeman	Sep 14, 2002	93.11 E	13.09 N	6.5	33

The results of the wavelet analysis for four earthquakes occurred in India are shown in figures 2a,b,c,d; three earthquakes (Gujarat, Pondicherry and Andeman) are very close to the coast whereas Jabalpur earthquake is far away from the coast. The results shown in Figures 2a – 2d contain three parts:

1. The first part shows the time series for the original signal, the 30-days average for the previous five years 1998-2002, and the 1 and 2 sigma line (standard deviation of SLHF) five years of daily average of SLHF.
2. The second part is a graphical representation of a characteristic vector which shows the time when significant wavelet maxima are detected.
3. The third and last part consists of a graphical representation of the wavelet coefficients, and the corresponding maxima lines. It is possible to notice how the maxima lines converge to the lines indicated in the previous part.

In all cases except for Jabalpur (4 in Figure 1), a prominent SLHF peak few days before the earthquake is seen (Figures 2a – 2c), and this is also indicated with a wavelet maxima. In case of Jabalpur earthquake, the maxima SLHF peak is seen after few days occurrence of the earthquake (Figure 2d).

The magnitude of the SLHF is found to be lowest in the case of Gujarat earthquake (January 26, 2001). Since the SLHF is related to the energy exchange between ocean-land-atmosphere, this interaction is enhanced during the earthquake due to the accumulation and release of stress. The ocean adjacent to Gujarat is rather shallow compared to elsewhere, the average ocean depth in the western coast of India is about 200 m deep up to 400 km near Gujarat. The SLHF at the epicenter of Gujarat earthquake is of low magnitude due to its distance from the open ocean.

The SLHF for one year for the year 2001 over the epicenter of Gujarat earthquake (January 26, 2001) is shown in Figure 2a. A maxima peak of the SLHF is found to occur on January 24, 2 days prior to the main earthquake event of magnitude (Ms = 7.8) occurred on January 26, 2001, and it is also identified by the wavelet maxima. After the earthquake occurrence, few peaks of SLHF are seen which may be attributed to the occurrence of series of aftershocks recorded by India Meteorological Department (IMD) (more than magnitude 5.0), however their intensity is not large enough to corresponds to a wavelet maxima curve. The main earthquake event is shown with a vertical dotted line (Figure 2a). Similar behavior of SLHF peaks are seen for the Pondicherry and Andeman earthquakes. The maxima peaks of SLHF is seen few days well in advance which is found to depend on many factors. Detailed analysis is underway to study various parameters controlling the occurrence of peaks prior to the main earthquake events.

Further, we have carried out analysis of SLHF for more than 40 coastal earthquakes throughout the globe and we have found the maxima SLHF peak about 1 - 20 days prior earthquakes greater than magnitude 5 and above with focal depth less than 35 km. The SLHF shows a great promise for providing an early warning information about a disastrous earthquake occurring close to the ocean coast. The improved spatial and temporal resolution of the future sensors will provide more accurate SLHF information over the seismic coastal prone areas.

Conclusion

The present results show the association of prominent SLHF peak with three coastal earthquakes occurred in Indian region which are close to the ocean coast. Such maxima peak is not seen in the case of Jabalpur earthquake since the location of this earthquake is far away from the ocean. In such cases the SLHF maxima peak is seen after

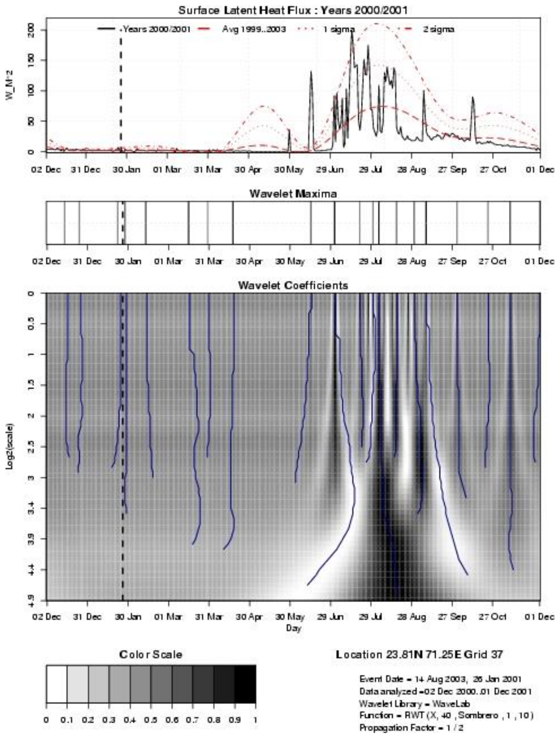

Figure 2a Gujarat

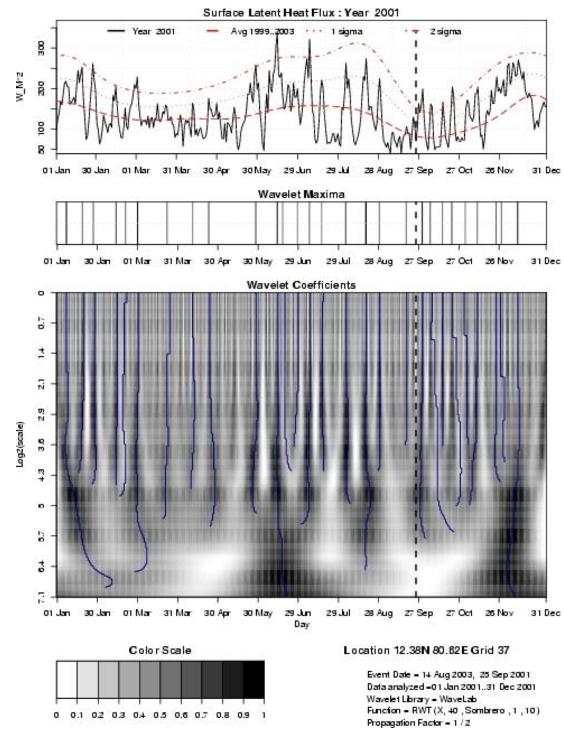

Figure 2b Pondicherry

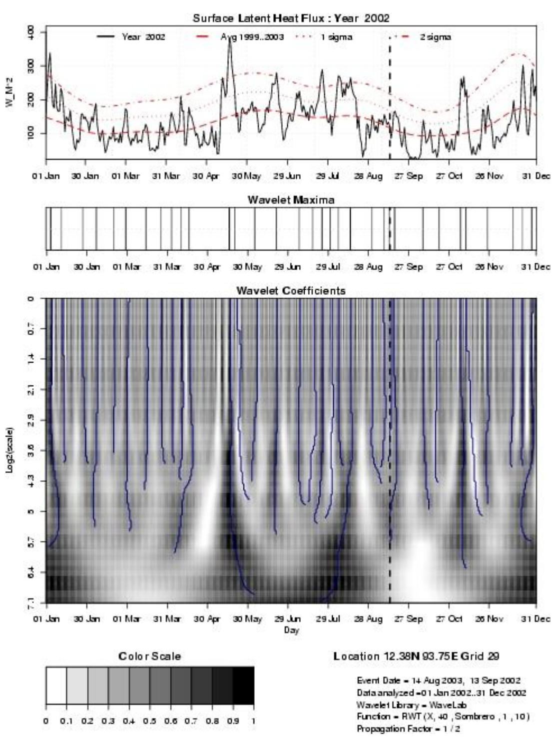

Figure 2c Andeman

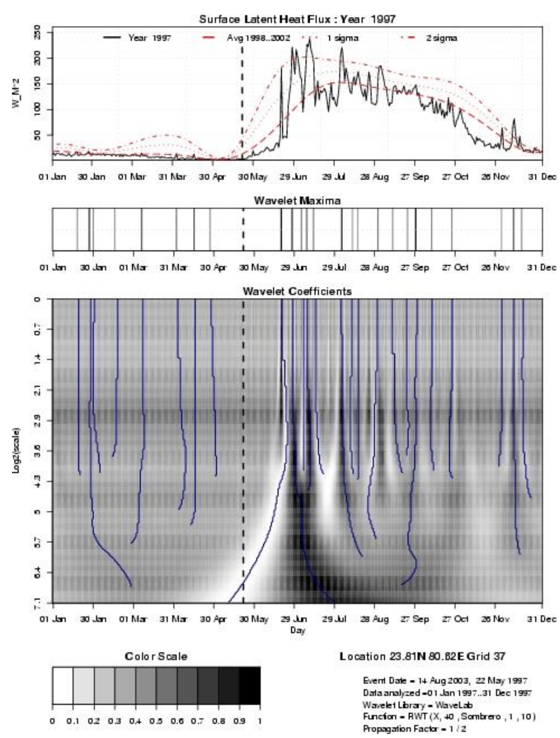

Figure 2d Jabalpur

Figure 2 shows yearly SLHF variations and wavelet maxima curves for (a) Gujarat, (b) Pondicherry, (c) Andeman and (d) Jabalpur earthquakes.

the main earthquake events, this may be due to the weak coupling between the ocean-atmosphere-land. From the detailed analysis of these four earthquakes and few other costal earthquakes occurred around the globe, it has been found that the SLHF peak is associated with the coastal earthquakes of magnitude greater than 5.0 and focal depths smaller than 35 km. The magnitude of SLHF peaks is observed to be related to magnitude of the earthquake, distance from the ocean and season in which the earthquake occurs. The present results show that the SLHF may act as a potential precursor for earthquakes occurring near the coastal regions. The migration of the SLHF may provide the probable location of the epicenter of the earthquake, which requires further detailed analysis with data of higher spatial resolution. The monitoring of SLHF globally is possible due to availability of optical and microwave sensors onboard satellites, which may provide early information about an impending coastal earthquake.

Acknowledgement

The surface latent heat flux (SLHF) has been downloaded from the National Center for Environmental Prediction (NCEP) website (http://iridl.ldeo.columbia.edu/). The data has been downloaded from the Scientific Computing Division of the National Center for Atmospheric Research (NCAR) website (http://ingrid.ldeo.columbia.edu/SOURCES/NOAA/NCEP-NCAR/).

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