# Surface Anomalies Prior to Earthquakes

**Habibeh VALIZADEH ALVAN; Shattri MANSOR; Husaini OMAR; and Farid HAYDARI AZAD, Malaysia**

**Key words**: Earthquake, Heat flux, Chlorophyll, Upwelling, Remote sensing, Early warning


## SUMMARY

Seismic activities prior to earthquakes cause the deformations of surface and rise in temperature. In case of oceanic and coastal earthquakes, with thinner crust, these pre-earthquake activities may be detected through secondary oceanic and atmospheric phenomenon. Water is a better media to transfer the earthquake related heat to the top. So anomalies in the sea surface temperature (SST) or sea surface Chlorophyll-a (Chl-a) concentration may be warning signs of the seismic activities in the ocean floor or nearby coastal area. The main purpose of this study is to explore and demonstrate possibility of any changes in SST or surface latent heat flux (SLHF) before, during and after the earthquakes occurred near the western coast of the United States, California. We expect that variations in these factors are accompanied with the increase of Chl-a concentration on the sea surface and upwelling events prior to the earthquakes. Our detailed analyses reveal significant increase of SLHF from one month before the earthquakes in epicenter areas and upwelling of nutrient-rich water prior to the main events which is attributed to the raise in SST and Chl-a concentration at that time. One problem in continuous monitoring of these factors is the cloud coverage which has made impossible to get surface data for all pixels in the scene. However, relative higher concentration of Chl-a in adjacent oceanic regions is obvious.

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## 1. INTRODUCTION

Earthquakes occur when the accumulated stress in the earth's crust suddenly releases. The process of build-up of this energy is associated with some chemical and physical interactions which, in turn, lead to some on and above surface phenomena. Seismic activities prior to earthquakes cause the formation of micro-cracks in rocks, the deformations of surface and rise in thermal signs. The amount of energy exchange between oceanic region and atmosphere in the form of humidity rate would show rises at the preparation stage of an impending earthquake.

Recent devastating earthquakes in the world that caused thousands of deaths and millions of dollars in property loss and impacts on strategic and scientific planning has stirred stronger interest among researchers to work on the possibility of developing local earthquake prediction models by detecting anomalies in atmospheric and surface factors related to the underground activities before impending earthquakes (Ryabinin et al. 2011). Many researchers reported that large seimic activites can be revealed through the changes of surface temperature in land (e.g., Wang and Shi 1984; Gorny et al. 1988; Saraf and Choudhury 2005; Ghoudhury et al. 2006; Ma et al. 2008; Marchesew et al. 2010) and in ocean (e.g., Nosov 1998; Ouzounov and Freund 2003; Dey and Singh 2003-2006).

Some researches revealed that abnormal SLHF in the epicentral regions is found to appear prior to several earthquakes in the world (Freund and Ouzounov 2001). The SLHF anomaly mostly occured a few days to weeks before the main earthquake event in the epicenter or its surrounding area, especially along the local active faults, and disappeared right after the main quake. Early warming message for earthquakes is posssible with continius remote sensing monitoring of tectonic activity in the world (Cervone et al. 2004; Qin et al. 2009). Increase in chl-a concentration along coasts near earthquake epicenters have been proved during seismic events (Singh et al. 2006).

Space monitoring of changes in plankton population which is the indicator of the primary productivity of phytoplankton biomass in the ocean, is possible by ocean color sensors (Sathyendranath et al. 1991; Yoder et al. 1993; Tang et al. 2002; Dey and Singh 2004). Changes in the climate, precipitation, winds, solar irradiance, light availability and sea surface temperature (SST) can result in distributions of the chl-a in the ocean. However, the concentration of chl-a in the ocean surface may also changes with the supply of nutrients from land run off (Bissett et al. 2001; Wang et al. 2002; Chaturvdi and Narain 2003). Changes in these parameters cause changes in thermal structure of water followed by occurence of upwelling and ocean water mixing (Singh et al. 2006).

In the present paper, we have carried out detailed analyses of spatio-temporal distributions of SST, Chl-a concentration due to upwelling in ocean and SLHF around the epicenters. In order to find relationships between the appearance of precursory signs in places of epicenters and impending earthquakes, we examined the time series variations of these four precursory factors on epicentral area together with chl-a concentration patterns over a wide area covering nearby oceanic area before, during and after the earthquakes.

Two earthquakes of magnitudes 6.5 and 6 occurred on December 22nd, 2003 and September 28th, 2004 in Central California. Table-1 presents the locations, magnitudes and depths of main earthquake events.

Table-1 Details of the earthquakes (source: http://earthquake.usgs.gov)

| No. | Place | Date | Longitude | Latitude | Magnitude | Focal Depth (km) |
|---|---|---|---|---|---|---|
| 1 | Central California | December 22, 2003 | 121.10W | 35.71N | 6.5 | 7.6 |
| 2 | Central California | September 28, 2004 | 120.37W | 35.81N | 6.0 | 7.9 |

## 2. DATA

For monitoring the changes in surface temperature we used Advanced Very High Resolution Radiometer (AVHRR) products with 1.25 km resolution were downloded from Ocean Watch North Pacific Demonstration Project Live Access Server (http://las.pfeg.noaa.gov/oceanWatch) and Advanced Microwave Scanning Radiometer (AMSR-E) /Aqua datasets provided by the National Space Development Agency of Japan (NASDA), which is capable of seeing through clouds and providing uninterrupted view of global.

SLHF data are provided by National Centers for Environmental Prediction (NCEP) Reanalysis Project of the IRI/LDEO Climate Data Library (http://iridl.ldeo.columbia.edu). The datasets are in resolution of global grid 1.9° by 1.9° and generated by taking into consideration the measured values at various worldwide stations and also those retrieved from satellite data. The daily values of the SLHF for three-month period prior to and after the earthquakes have been studied in a 14° by 14° area with the pixel covering the epicenter.

For Chlorophyll-a concentration and upwelling indices, Moderate Resolution Imaging

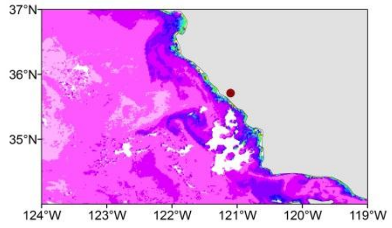
Spectroradiometer (MODIS) and Pacific Fisheries Environmental Laboratory (PFEL) datasets have been used respectively.

Variations of SST and SLHF near the epicenters are plotted from several weeks before the events together with the spatial distributions of Chl-a concentration on the sea surface. Over the oceanic regions, the averaged upwelling index is also analyzed to realise the blooming of chl-a is related to the earthquake.

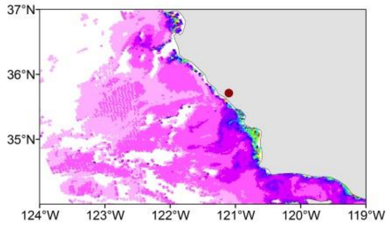
## 3. RESULT AND DISCUSSION

Two major coastal earthquakes (Table 1) in central California with magnitudes >6 were chosen to be studied for the pre-earthquake signs detection. Therefore the nearest points to the epicenters on the ocean are selected for chlorophyll and upwelling studies.

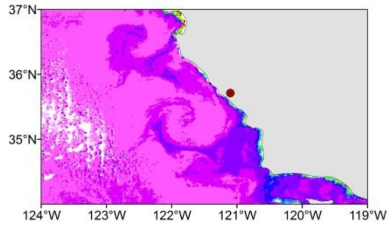
Chl-a concentration in the Pacific Ocean near the epicenter of the Central California earthquake during Nov-Dec, 2003 are shown in Fig. 1a. In general, the north-eastern part of the Pacific Ocean, which is characterized by vast gyre that is a high-nutrient, low-chlorophyll region has not been found to be a productive area regarding low cumulative upwelling index from October to January. However low light levels and/or cloud during November–January prevent examination of winter patterns. The Chl-a concentration in this part is generally blow 0.5 $mg.m^{-3}$for much of the year (Bograd et al. 2007; Brickley & Thomas 2004). This phenomenon is noticeable in our images with a narrow high chl-a belt along the coast. The chl-a concentration in offshore water near the epicenter is found between 2 and 3 $mg.m^{-3}$, greater than normal value on some occasions; December 3, 8 and 17-18. Meanwhile the peak value of chl-a is more than 10 $mg.m^{-3}$ in the coastal water on June 3, 8, 13 and 18 (four days before the main event). Chl-a time series (Fig. 1b) reaches the highest chl-a values of the pixel near the epicentre about a month before the earthquake with a sudden fall immediately after the event, which is in correspondence of the upwelling of 21$^{st}$ - 23$^{rd}$ Nov, 2003 and downwelling of Dec 23. The upwelling, triggered by seismic activities in ocean floor, has a cumulative effect on ecosystem productivity and structure, so we focus on the daily average coastal upwelling indices in this region (Fig. 1c) to confirm that chl-a increases due to upwelling of nutrient-rich water. It seems the upwelling is enhanced prior to the earthquake; it reaches its maximum value about a month before the main event. Another high upwelling event has also been detected on Dec 26, 2003, well in agreement with the rise of chl-a concentration on the near-shore water that can be the effect of aftershocks.



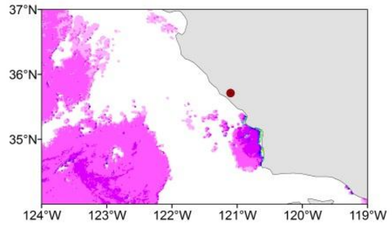

10-Nov-2003



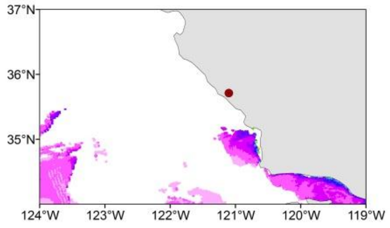

16-Nov-2003



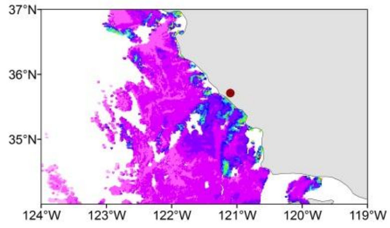

22-Nov-2003



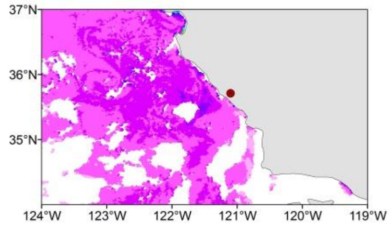

1-Dec-2003



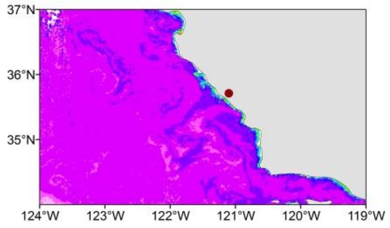

2-Dec-2003



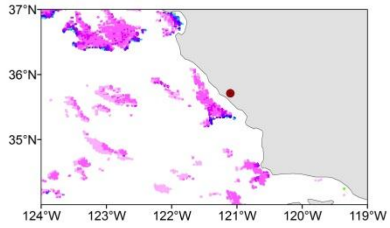

3-Dec-2003



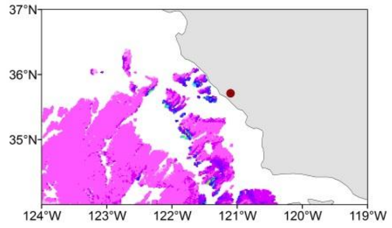

7-Dec-2003



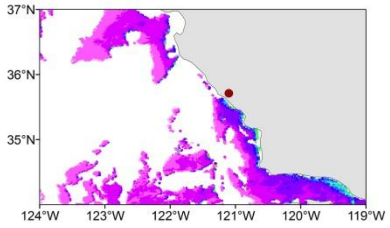

8-Dec-2003



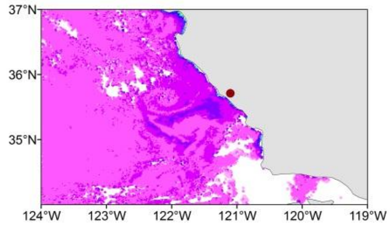

11-Dec-2003



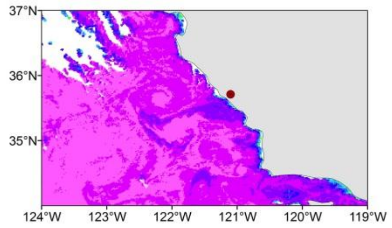

12-Dec-2003



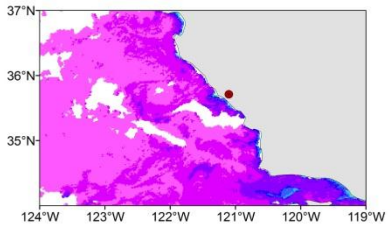

13-Dec-2003



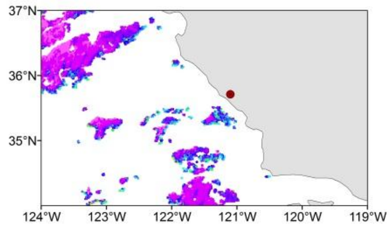

14-Dec-2003




15-Dec-2003




16-Dec-2003




17-Dec-2003

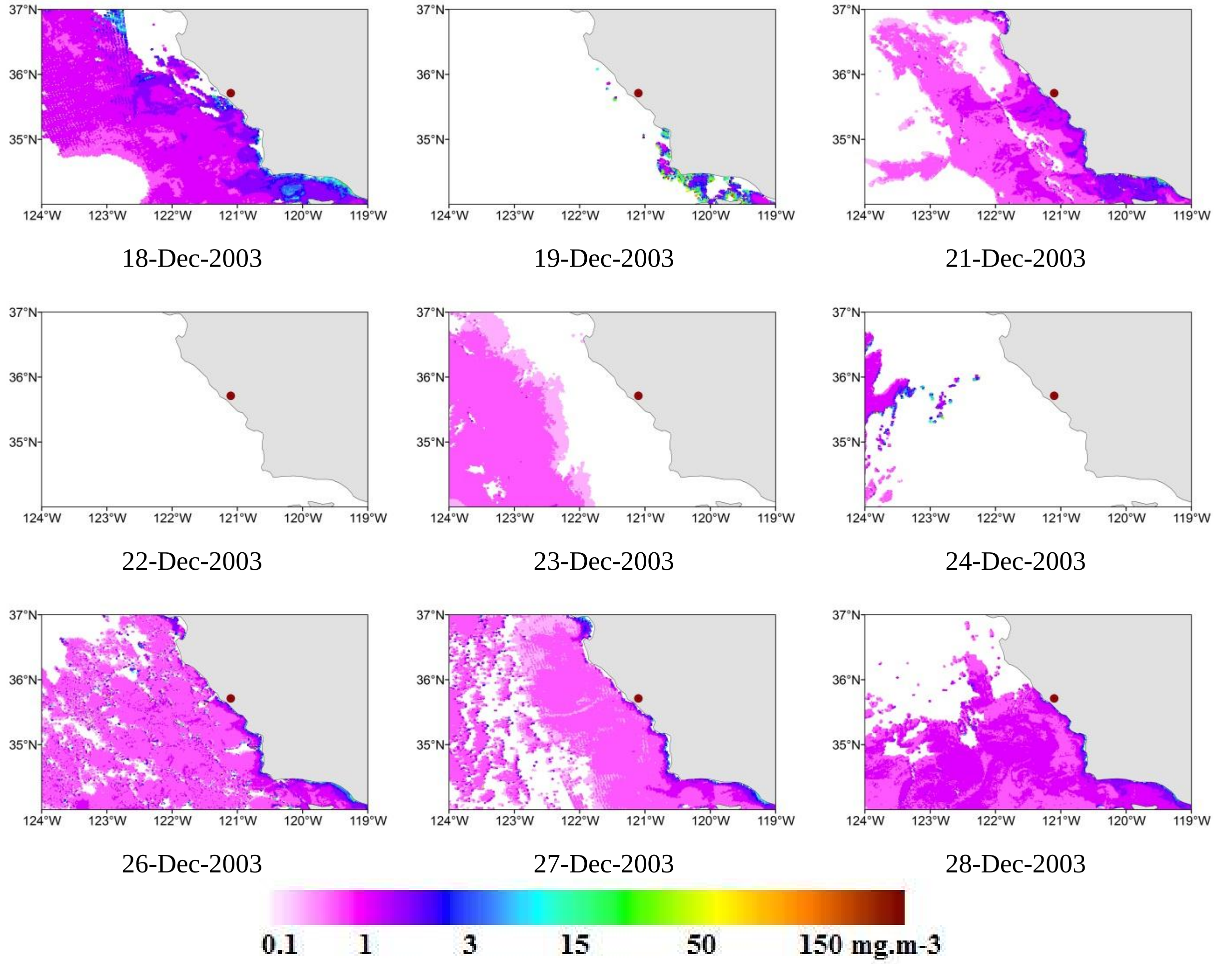



Figure 1a – Temporal distribution of Chl-a concentration retrieved from MODIS in the Pacific Ocean during the central California earthquake of December 22, 2003.

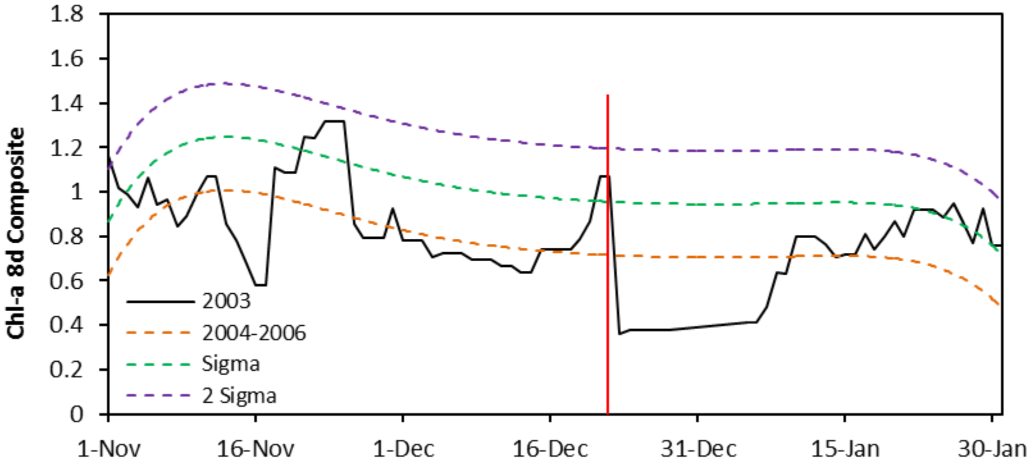



Figure 1b– 8-day composite Chlorophyll-a time series for Central California earthquake of December 22, 2003 showing anomalies in some occasions from one month before the main event followed by a sudden decrease immediately after that.

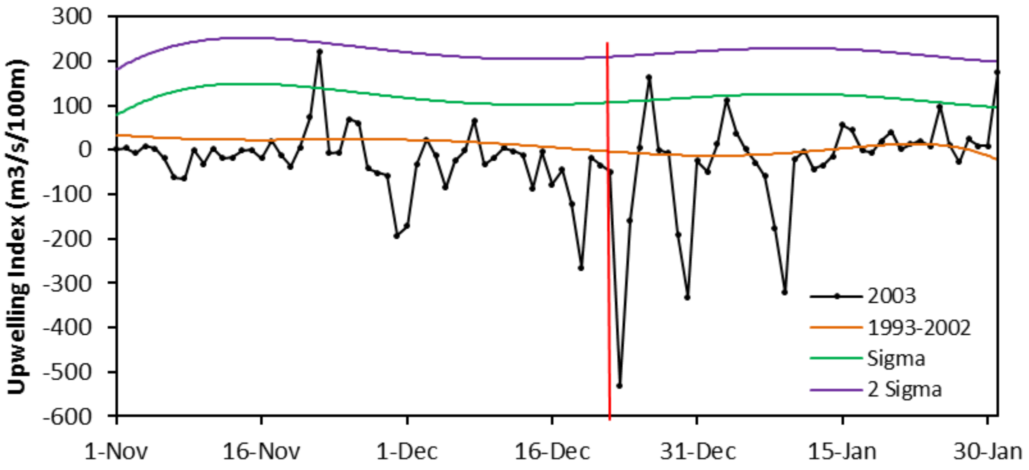



Figure 1c– Daily averaged upwelling index for Central California earthquake of December 22, 2003 showing maximum rise a month before the main event; trend lines are the 10-year average of upwelling indices, 1 and 2 sigma; the red bar indicates the day of earthquake.

Variations in SLHF are controlled by changes in the surface temperature, which is believed to be a precursory parameter during an earthquake (Tronin 2000). Temperature time series (Fig. 1d) show anomalous rises. The values of the pixel covering the epicenter are below the last-ten-year average during the first half of November and through the whole of January. From one month prior to the main event there is about 1˚C rises in temperature of the coastal water in the epicentral region comparing with the past ten-year average whilst the values are generally less than this average during January. Similar response of SLHF has been found before and during the event. Two big anomalies in SLHF are detected one month before the earthquake followed by other anomalous rises during the main event and in the period of aftershocks until the second half of January when the normal condition returns again (Fig. 1f). The biggest anomalies (180 and 115 W/ $m^2$) in SLHF are observed on November 22 and 25 (about a month before the main event) which are attributed to the high values of SST in this period. However, the other big anomalies (140 and 115 W/ $m^2$) in SLHF may be related to the aftershocks of 28$^{th}$ December 2003, 2$^{nd}$ and 6$^{th}$ January 2004 with magnitudes of 3.8-4.2 (USGS).

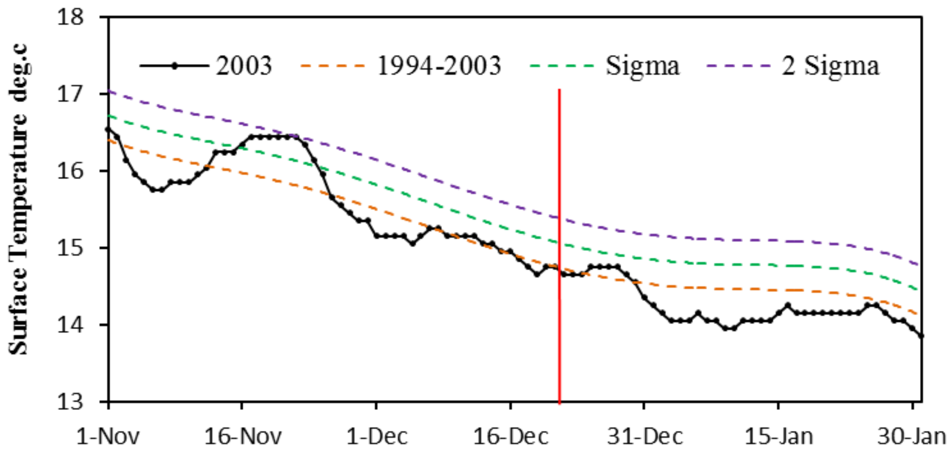



Figure 1d– The SST time series of the epicentral oceanic water of the earthquake of December 22, 2003 generally higher before the earthquake. The effect of aftershocks during the second half of December is also shown.

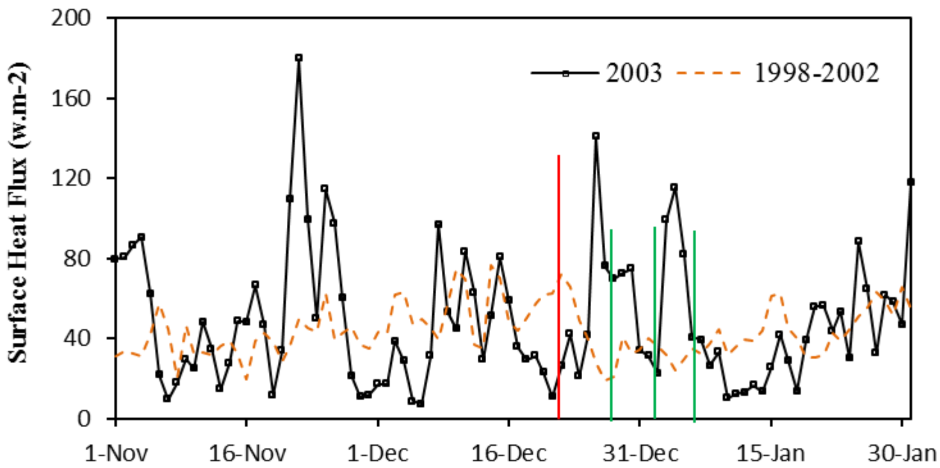



Figure 1f– the anomalous SLHF values before and during the main earthquake of December 2003 and aftershock period is observed; dashed line is the 5-year average of SLHF. Red and green bars indicate days of the main event and aftershocks respectively.

Similar response of Chl-a concentration has been found for the earthquake of September 28th, 2004 occurred in the central California, where The Chl-a maps show general higher concentration (more than 3 $mg/m^3$ ) in the coastal and oceanic water on some occasions during August and from the September 1st, the Chl-a concentration is building up, reaching its utmost (about 10 $mg/m^3$) during 14-23 September, two weeks before the main quake, exactly when the upwelling is showing anomalous rises which confirms the bring-up of nutrient rich water to the sea surface (figures are not shown here).

General raise in temperature form about one month before the main event and the steady decrease during the month afterwards is clear in the surface temperature time series of the epicenter (Fig. 2a) which may be related to the preparation and energy release stages of the earthquake. Temperature reaches the maximum (5° C more than the average) on two occasions; August 11 and September 6-8, 2004. However the temperature regime of the land wasn't changing considerably due to this energy release comparing with that of sea surface.

At the same time of upwelling events the SLHF show a build-up, reaching its highest values between 13 and 20 September (Fig. 2b). SLHF values of the epicentral area can represent the earthquake preparatory activities with three successive sharp rises, each one bigger than the last, from one month before the earthquake event. Like upwelling index, the last meaningful increase in SLHF is seen about 15 days after the earthquake. Sudden rises in SLHF during the second half of the October are observed at the time the temperature and upwelling index are at their lowest state. So these anomalies are not considered as earthquake signs.

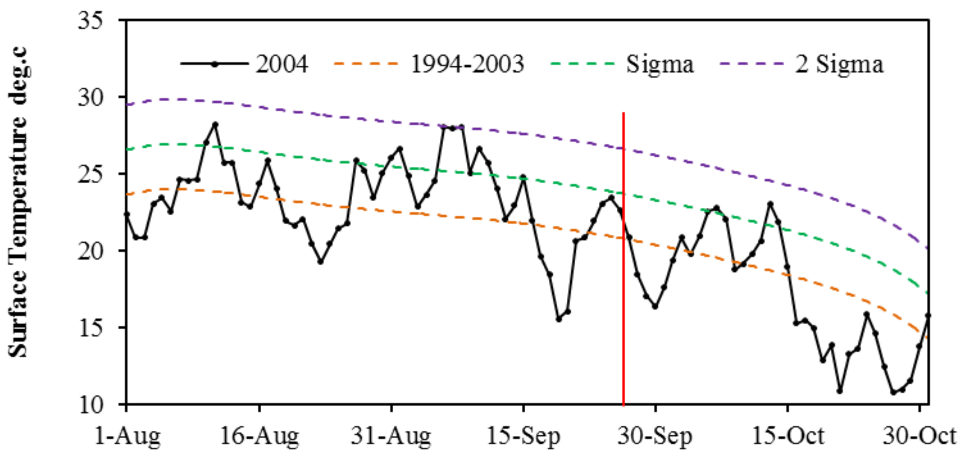



Figure 2a– Time series of surface temperature for the Central California earthquake of September 2004; shows several anomalies during the preparation stage and sudden fall after the main event.

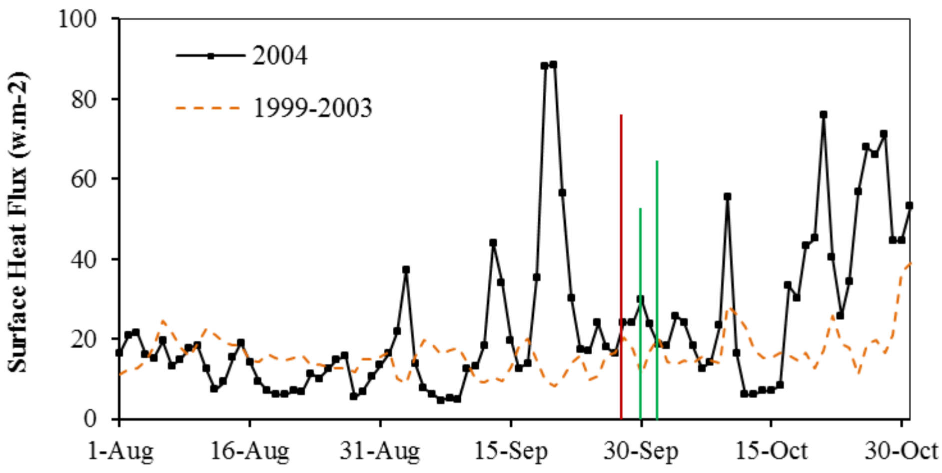



Figure 2b– The anomalous SLHF values before and during the earthquake of September 28, 2004; Red bar indicates the day of the main event and green bars are the aftershocks (>4).

## 4. CONCLUSION

The coastal earthquakes cause significant changes in surface temperature, SLHF and Chl-a concentration in the coastal area and even the offshore water. Increases in SLHF were detected from one month to few days prior to the main quakes in the epicentral area. Remote sensing techniques allow monitoring the SLHF and surface temperature anomalies over large areas to detect tectonic activity and understand the mechanism of earthquake preparation processes to provide possibilities of a reliable prediction of these potential precursors in different parts of the world. the surface temperature anomalies in case of the September 28th, 2004 which occurred about 100 km from the Pacific Ocean are more than 5˚C which is a noticeable increase comparing with that of sea surface. This is certainly a stronger indication of an impending earthquake. Normal SLHF and temperature patterns are observed after both main events unless when the occurrences of aftershocks prevent the re-establishment of normal conditions after the effect of the main events are over.

During the non-productive months spatially-limited changes in Chl-a are detected in coastal earthquake of December 2003. However the earthquake of September 2004 with similar magnitude and focal depth only enhances the coastal Chl-a concentration during the productive season (August-September). Most signifant and earlier changes in all these indicators in case of Dec 22, 2003 earthquake is because shallow coastal water in the immediate neighborhood of the epicenter of this earthquake could be very sensitive to the energy exchanges during an earthquake event. A rapid fall in SLHF and SST together with significant downwelling right after the main events was also detected. The increased Chl-a concentration, SHLF and SST observed some days after the earthquakes may signify the occurance of aftershocks.

## ACKNOWLEDGEMENTS

The SLHF data has been downloaded from NCEP site. MDOIS Chl-a and AVHRR's SST data were also used. AMSR-E data is provided by the National Space Development Agency of Japan (NASDA). Upwelling indices for the Pacific Ocean have been downloaded from Pacific Fisheries Environmental Laboratory (PFEL). Reanalysis data are downloaded from the IRI/LDEO Climate Data Library. Here we greatly appreciate their help. .

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## CONTACTS

Habibeh Valizadeh Alvan
University Putra Malaysia
43400
Serdang
Malaysia
Tel. +60 17 2190 169
Email: habibeh.valizadeh@mutiara.upm.edu.my

Shattri Mansor
University Putra Malaysia
43400
Serdang
Malaysia
Tel. +60 19 2244 333
Email: shattri@eng.upm.edu.my

Husaini Omar
University Putra Malaysia
43400
Serdang
Malaysia
Tel. +60 19 2377 359
Email: husaini@eng.upm.edu.my

Farid Haydari Azad
Zamin Wesal Iranian Consulting Engineers ltd
Tehran
Iran
Tel. +98 912 3359 335
Email: farid@zwiran.com