The Open Oceanography Journal, 2009, *3*, 40-49

Case Studies of SST Variability Derived from AQUA/AMSR-E Satellite Data Near the Sumatra Region Frequently Affected by Under-Sea Earthquakes

S.C. Chakravarty*

Indian Space Research Organisation (ISRO) Headquarters, Antariksh Bhavan, New BEL Road, Bangalore, India-560094

Abstract: A real-time computer model has been developed to monitor Sea Surface Temperature (SST) focussing on specific latitude-longitude grids of interest. The model uses the daily binary file data from AQUA/AMSRE satellite sensors made available through website. The main purpose of the case studies is to explore and demonstrate possibility of any SST anomalies before, during and after the two great earthquakes of 26 December 2004 and 28 March 2005 that occurred near the western coast of Sumatra. The code is used to analyse and plot SST contour maps and time sequence of average SST deviations from the long-term means pertaining to grid sizes of 2° x 2° and 6° x 6° sea surface areas around the epicentres of these two earthquakes. The results indicate a small but significant warming of 0.2-0.3 ℃ in the 2° x 2° grid area starting a week earlier to a week later for the event date of 26 December 2004. Similarly the 28 March 2005 earthquake shows temporal changes in the mean SST anomalies but with reduced clarity due to limitation of data. Wavelet analysis brings out more details of the time sequence of the inherent power spectra. Such computer aided analysis and approach may be useful in other fields like El Nino induced monsoon rainfall, patterns of climate change, distribution of atmospheric pollutants and aerosols over oceans

Key Words: Sumatra-Andaman Earthquake, Asian Tsunami, Sea Surface Temperature, SST Anomalies, Great Earthquakes, MATLAB Programme.

1. INTRODUCTION

The Sea Surface Temperature (SST) is an important global environmental parameter. The study of its morphology provides important clues to understanding many geophysical phenomena such as the state of earth's climate, monsoons, El-Nino and Southern Oscillation (ENSO), genesis of cyclones, hurricanes etc. Most of these processes have global implications in terms of their origin, development, sphere of influence and teleconnections. With considerable progress made in satellite remote sensing technology, SST has become one of the most widely measured oceanic parameters. Accurate data on SST also forms the surface boundary layer parameter in many climate and weather models.

With the availability of near realtime SST and other related data in public domain, it is possible to study synoptic processes and their links to global/regional events. Aspects regarding continuous coverage with attendant accuracies both in temporal and spatial domains are fairly well characterised and scientists take care of this appropriately in their investigations. While the synoptic data is suitable to study large scale processes of the type mentioned above, it would be interesting to check any SST anomalies within relatively smaller dimensions of the sea surface. One of the possible applications would be to explore any correlation between such SST variations around/along the under-sea lithospheric plate boundaries particularly during periods of seismic activities leading to great earthquakes. However, for carrying out any study with SST, the prerequisite is to develop suitable and generalised computer model(s) to analyse voluminous satellite data sets and visualise global/regional SST dynamics.

The present paper deals with the development and demonstration of a realtime model of SST data derived from AMSR-E sensor of AQUA satellite and available at their website (http://www.remss.com/data/sst/daily/tmi_amsre/). To begin with, the pixellated SST values at 25 km x 25 km (0.25° x 0.25° lat-long) grid resolution are monitored for detecting any anomalies before, during and after the occurrence of the Great Sumatra-Andaman earthquake of 26 December, 2004. The results are compared with a repeat of similar analysis for another Great Sumatra earthquake of 28 March 2005.

The premise of such an enquiry stems from the following possibility. While the average continental heat flow from earth's interior is about 65 mW/m^2, the average oceanic heat flow is 101 mW/ m^2. The map in Fig. (**1**) shows color-coded contours of the global distribution of heat flow at the surface of the Earth's crust [1]. Major plate boundaries and continent outlines are also shown. The yellow-orange-red colors indicate higher than average heat flow, the blues are lower. It is shown that the heat flow is greatest along the system of mid-

*Address correspondence to this author at the Indian Space Research Organisation (ISRO) Headquarters, Antariksh Bhavan, New BEL Road, Bangalore, India-560094; E-mail: chakravarty08@gmail.com

1874-2521/09 2009 Bentham Open

ocean ridges. Further, the location of the high heat-flow regions correlates well with regions of shallow ocean depth and the location of earthquake prone regions. Hence if there is a build up of a major earthquake under the seabed, it would be interesting to study the changes in SST around its epicentre (initially as a post facto analysis and later may be as part of prognosis, by using the results of SST-earthquake correlations). The additional heat fluxes generated near the plate bounderies could result in, some local variation of SST depending upon the depth of ocean around the location and magnitude of the earthquake. The purpose of the case study is to take the example of the great Sumatra-Andaman quake to illustrate the efficacy of the model and find answer to the question whether this great earthquake produced any observable effects around the sea surface epicentre in terms of regional/localised SST anomalies.

One of the major anomalies in SST values in the weatern Pacific region happens on year-to-year basis starting at the same time (end December-beginning January) as that of Sumatra-Andaman earthquake due to the occurrence of El Nino event. It is known that enhanced SST values near the Peruvian coast produces El Nino and Southern Oscillation (ENSO) causing inter-annual weather perturbations on global scale [2,3]**.** During most non-ENSO or normal years, the SST has E-W positive temperature gradient resulting in heavy rainfall over the western Pacific while the eastern Pacific region is relatively dry. ENSO anomalies would need to be considered and separated by taking long-term averages. Monthly averages used in the present analysis to derive the SST anomalies related to the earthquake are not contaminated with such perturbations, as 2002-07 has been a non El-Nino period.

A number of investigations have been made to correlate land and sea surface temperature, cloud cover and water vapour anomalies (over the earthquake region) during and after main undersea earthquakes using the thermal infrared (TIR) and high resolution spectrometric data of remote sensing satellites [4-8]. In summary all these studies report SST, cloud cover and related anomalies around the dates of the undersea earthquakes of magnitudes >5 M. Both positive and negative anomalies of SST have been observed under different epochs of tectonic events. Without going into the details of the results obtained by these authors, in the present paper a systematic analysis of long term SST data obtained using microwave sensors under all weather conditions has been carried out for the two great undersea earthquake events near Sumatra coast. As evident from the earlier results the warming or cooling of the sea surface related to under sea earthquakes will be a slowly varying signal spread over a period of 15-20 days or more. Due to the large heat capacity of ocean waters, small fluctuations in SST due to changing cloud cover, wind patterns etc., would appear as small undulations superimposed on any longer period oscillation due to undersea earthquakes in question.

2. SELECTION OF PERIOD AND AREA OF STUDY

In recent times two Great earthquakes occurred over the fault boundary between the Indo-Australian and southeastern Eurasian plates on 26 December 2004 and on 28 March 2005 with seismic moment magnitudes of about 9.3 and 8.6 respectively [9]. The first event also generated strong tsunami waves. The main sea-surface area used for present study covers the region around the epicentre of the main Sumatra-Andaman quake to the west coast of Sumatra island.

Fig. (**2**) shows maps covering 6º x 6º lat-long region around the epicentre (3.316°N, 95.854°E) of the earthquake of 26 Dec 2004. From a comparison of number of earthquakes (M >5.4) indicated by open circles between the two maps it is clear that a large number of earthquakes took place during 2004-2005. The data used in these maps have been extracted from the USGS Data Base available on their website. The maps also show the location of the epicentres of both major earthquakes of 26 December 2004 and 28 March 2005. A large number of earthquakes in the form of aftershocks of these two great earthquakes constitute most of the open circles in these maps. This figure is the starting point of the real-time model described later, and needs an input file with tabulated data on earthquakes with date, lat, long and

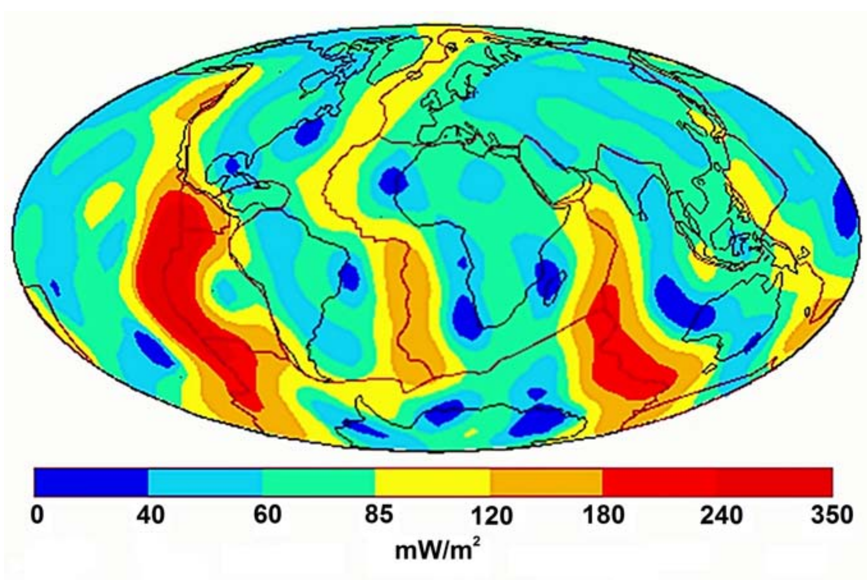


Fig. (1). Variations in the average heat-flow of Earth's interior (after Pollack *et al*. 1993).

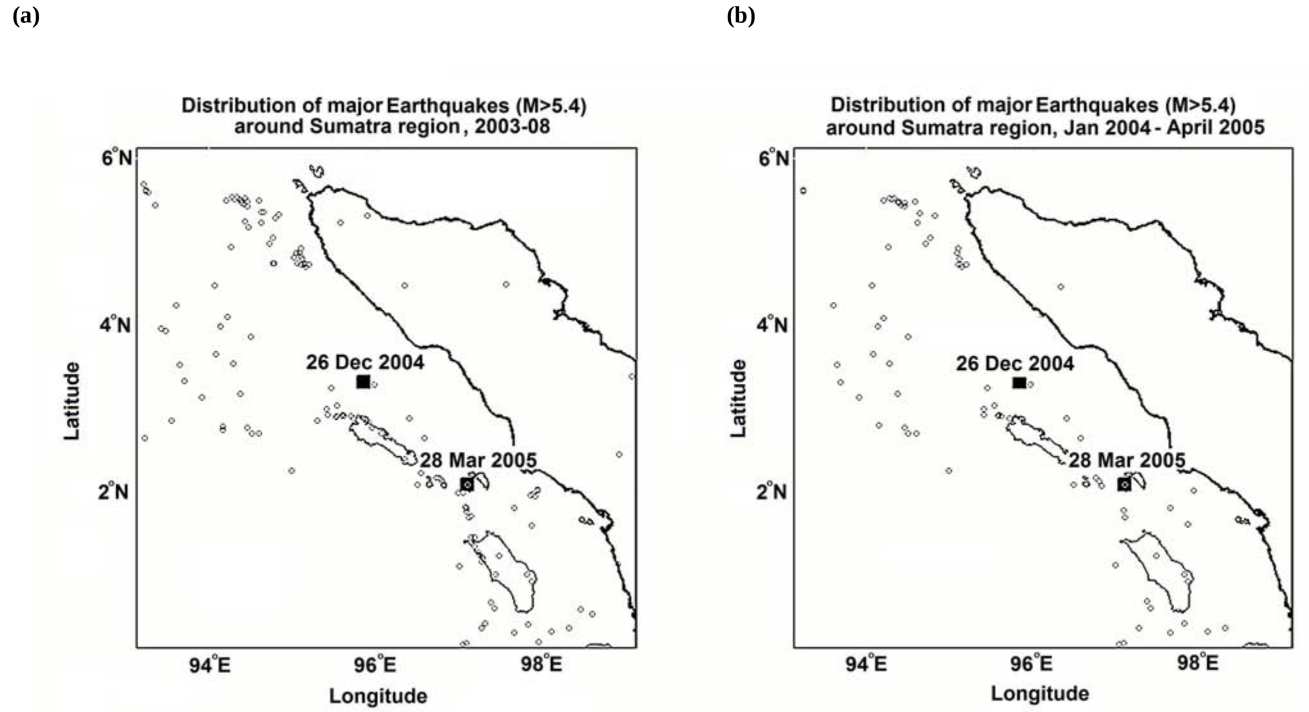


Fig. (2). Distribution of earthquakes (M>5.4) shown with open circles around Sumatra coast (6º x 6º map) for two different periods (**a**) 2003-08 and (**b**) Jan 2004-April 2005. Epicentre locations and dates of the two great earthquakes in 2004 and 2005 are also highlighted.

magnitudes which can be read out and plotted as the distribution shown here in the area of interest.

3. METHOD OF ANALYSIS AND DEVELOPMENT OF SST MODEL USING AQUA/AMSRE DATA

NASA's AQUA satellite launched during 2002 to an orbit of about 700 km has been broadcasting all the data on X-Band. Remote Sensing Systems (RSS), Santa Rosa, California produces Level 3 AMSR-E Ocean Products, *i.e.*, SST, sea surface wind (SSW) speed, atmospheric water vapor, and cloud liquid water. Near real time quick look data is available at the AQUA website. Data is also visualised as daily, 3-day, weekly and monthly aggregates. As against daily maps with gaps in total coverage, the 3-day aggregate data covers the entire globe and represents the values on the present and past two days taken together. The microwave sensors produce all weather data with a high spatial resolution of 25 km. The products are optimally interpolated and corrected for diurnal variations finally providing data normalised to a daily minimum SST, defined to occur approximately 8 AM local time.

The daily data are available as zipped binary files at the REMSES website. The files can be downloaded and unzipped for using in the realtime model. The name of a particular days file is entered as input and SST contour map for designated lat x long cover (in this case 6° x 6°) are plotted both superimposed on actual geographic map as well as a pixellated distribution in the same region. As a sample plot the SST contours for 26 December 2004 are shown in Fig. (**3**). Such maps can be visualised as well as saved as image files for as many days as required to detect any interesting features of changes in SST during the period of study.

While browsing the data as SST maps for different days, a plan for further analysis may be implemented which is possible to carry out with this available realtime SST model providing different options for such analysis.

4. RESULTS OF THE CASE STUDY USING THE REAL-TIME SST MODEL

Some salient results of the SST variations related to the earthquake of 26 Dec 04 are presented here. From a series of maps (not shown here) plotted by the model for different days it is found that short period (within a month) SST variations may take place in relatively smaller area of 100-500 km and hence the analysis for SST changes related to undersea earthquakes could be studied using 6°x 6° grid regions and further focussed to even 2°x 2° grid areas centering the epicentre. For determinig possible SST anomalies, a period of 10 Dec 2004-10 Jan 2005 is selected for the above Sumatra-Andaman quake. For both grid resolutions, namely 6°x 6° and 2°x 2°, the daily SST anomalies from the period (10 Dec 2004-10 Jan 2005) mean are computed first at pixel levels and then for the grid level. The computer programme then produces the plots of time vs. SST deviations from period mean with standard errors (= $\sigma/\sqrt{N}$; where σ is standard deviation and N number of days of data) for both grid sizes. In addition to the figures, the pixel values of daily SST , their deviations, standard errors and the time series are written in the output file selected for the purpose so as to utilise the results for generating additional figures required for further analysis/studies. Fig. (**4**) shows the combined plots of the time series of average daily SST deviations from the period mean values for 6° x 6° and 2° x 2° grids around the epicentre of the 26 December 2004 earthquake. It can be seen that there is a warming of sea surface by ~0.2-0.3 °C between 18

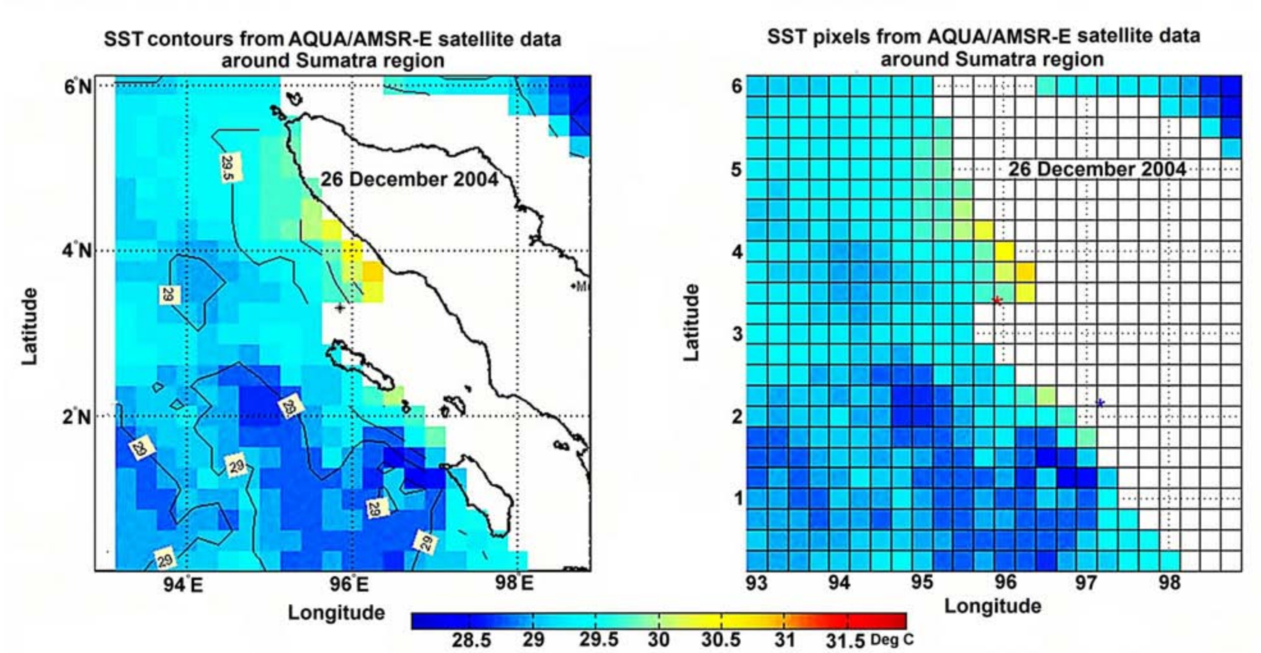


Fig. (3). SST contours for 6°x6° grid area covering oceanic region affected by the 26 December 2004: (**a**) SST contours values west of Sumatra coast showing outlines of the ocean-land boundaries, (**b**) pixellated values of SST showing the gaps in observation as white pixels.

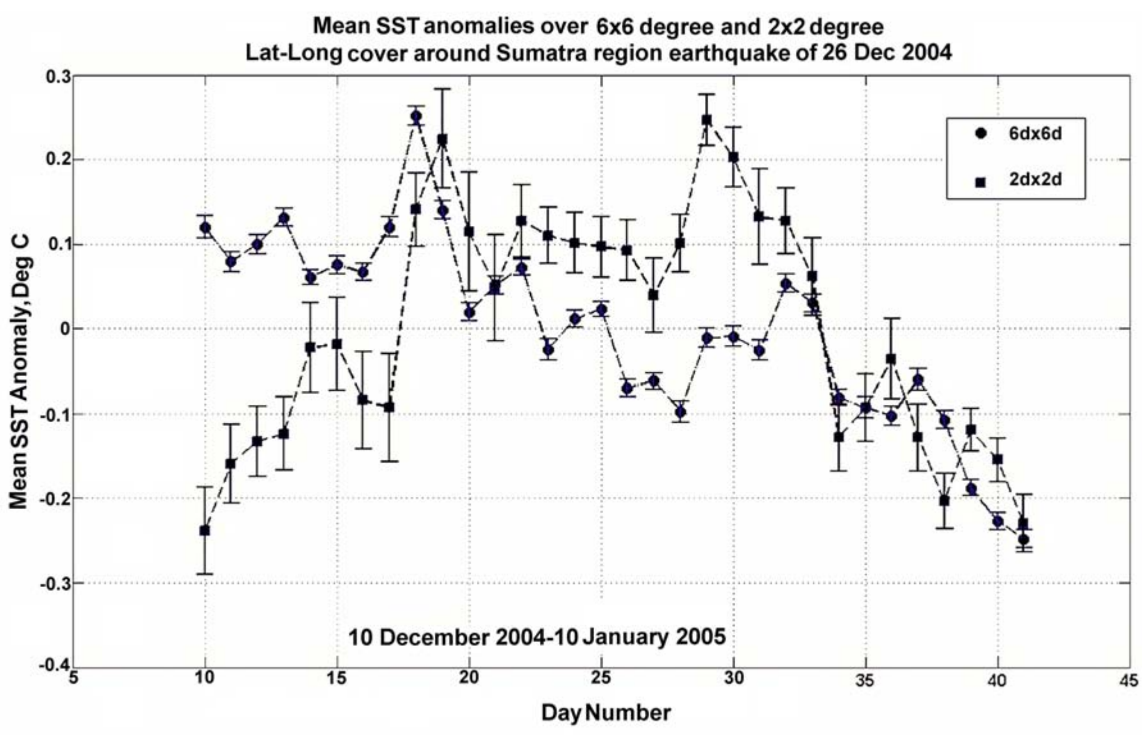


Fig. (4). Time variation of average SST anomalies during 10 Dec 04-10 Jan 05 within 6° × 6° and 2° × 2° grids around the epicentre of the Sumatra_Andaman earthquake of 26 December 2004.

December 2004-2 January 2005. This feature is not seen in the time series SST deviations pertaining to averages taken for 6° x 6° grid size where SST values show a systematic decreasing trend.

As a check to have better confidence in this result, SST data for same days but different years (in the absence of the 2004 quake) can be analysed by the same model. Such analysis has been carried out for Dec 2003-Jan 2004 and Dec

2005-Jan 2006. The results have not shown similar differences in the time series. Fig. (**5**) shows the combined plots for the same period of 2003-04, one year earlier than the earthquake year of 2004. The SST variations within the two grids are similar which is considered to be following normal pattern without the influence of any perturbations due to earthquakes etc., which did not occur during December, 2003. The model efficiently produced such curves for other years (not shown here) but did not find situation similat to that of 2004-05 of the earthquake year. In addition to the above results, the model also provides options for additional analysis. One aspect relates to observing the global picture of SST variation on different days. As a complementary information, a sample global SST contour plot is shown in Fig. (**6**) for the day of Sumatra earthquake. The normal situation of warmer SST values in the western Pacific region can be seen which is representative of a non-El-Nino or normal year. Following the analysis using actual SST values rather than the deviations from a mean value, the model also analyses the histograms showing the distribution of SST values with respect to number of pixels as counts for any defined region i.e., in this case for 6° x 6° or 2° x 2° grids. The number of days can be chosen as required and histograms for each day may be seen as part of multi-plot figure while entering the days and data files. One such multi-plot using 10 days of observations at an interval of 3 days within the period 10 December 2004-10 January 2005 covering the Sumatra earthquake is shown in Fig. (**7**). It can be seen that the individual pixels show heating up which begins by 19 December 2004 and returns to normal condition by about 6 January, 2005. The shift of counts shows larger number of pixels with SST values between 30-31 ºC.

The second large earthquake of 28 March 2005 took place within 150-200 km of the epicentre of the previous one. But this great earthquake was a little smaller in magnitude cmpared to that of of 26 December 2004. The SST model was used to produce a set of results for the period 12 March-12 April, 2005. The combined results similar to the earlier set are shown in Fig. (**8a,b,c**). It may be noted that there are a large number of blank pixels around the epicrntre of this earhquake. The results do indicate some changes in the average values of SST deviations (a cooling followed by heating between 26 March-9 April 2005). The histogram plot is used for the 6º x 6º grid due to presence of very few pixels within 2º x 2º grid sea surface area. The histograms do show concentration of more warmer pixels towards the end of March 2005 continuing upto about the first week of April 2005.

5. CONCLUSION AND DISCUSSION

The author has developed a realtime computer model to utilise AQUA/AMSRE satellite measured daily SST data at 25 km x 25 km spatial resolution made available on the website. The huge resource of this data can be analysed for different studies of SST anomalies at differet time scales by changing user inputs accordingly. One of the new applications considered here is to assess the SST variations at regional or smaller scales like the possible effects before, during and after the occurrence of great earthquakes. Two such recent earthquakes that occurred near Sumatra's western coastal region during 2004-2005 have been taken up as case studies to demonstrate the applicability of the above model. The results show that the model is potentially suited to monitor the SST variations focussing attention to regional anomalies. While SST is used for the purpose of study in this report, the same model could be used for other satellite derived parameters like SSW, Precipitable Water Vapour etc., made available in daily files using similar binary format.

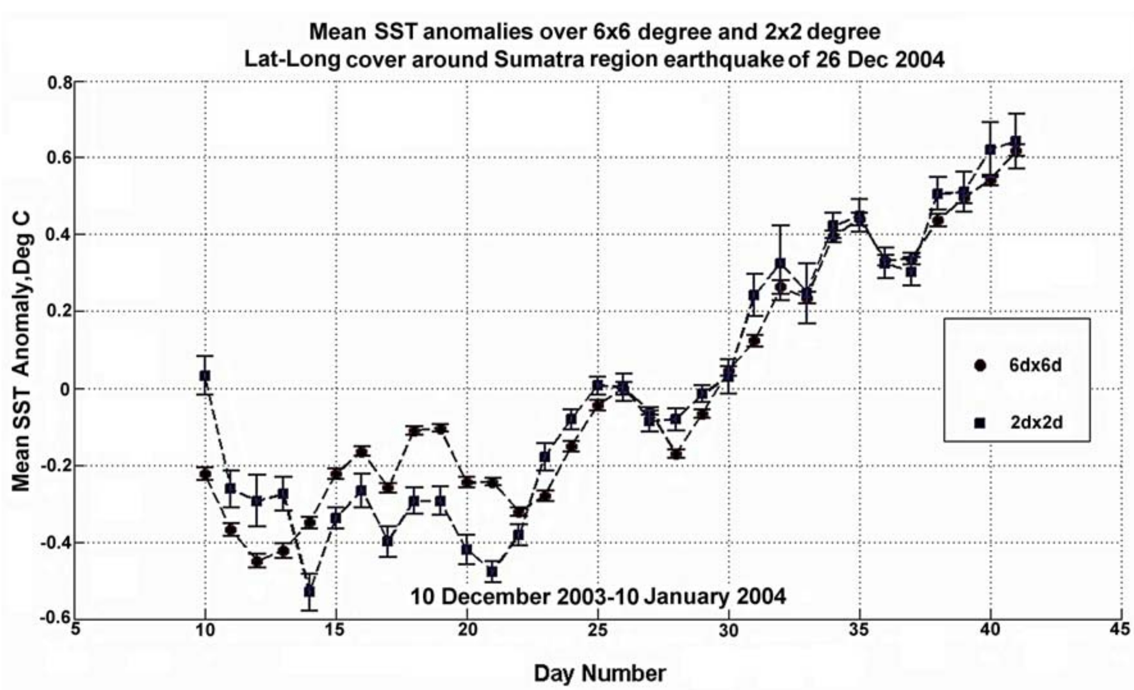


Fig. (5). Time variation of average SST anomalies during 10 Dec 03-10 Jan 04 within 6° × 6° and 2° × 2° grids around the epicentre of the Sumatra_Andaman earthquake of 26 December 2004.

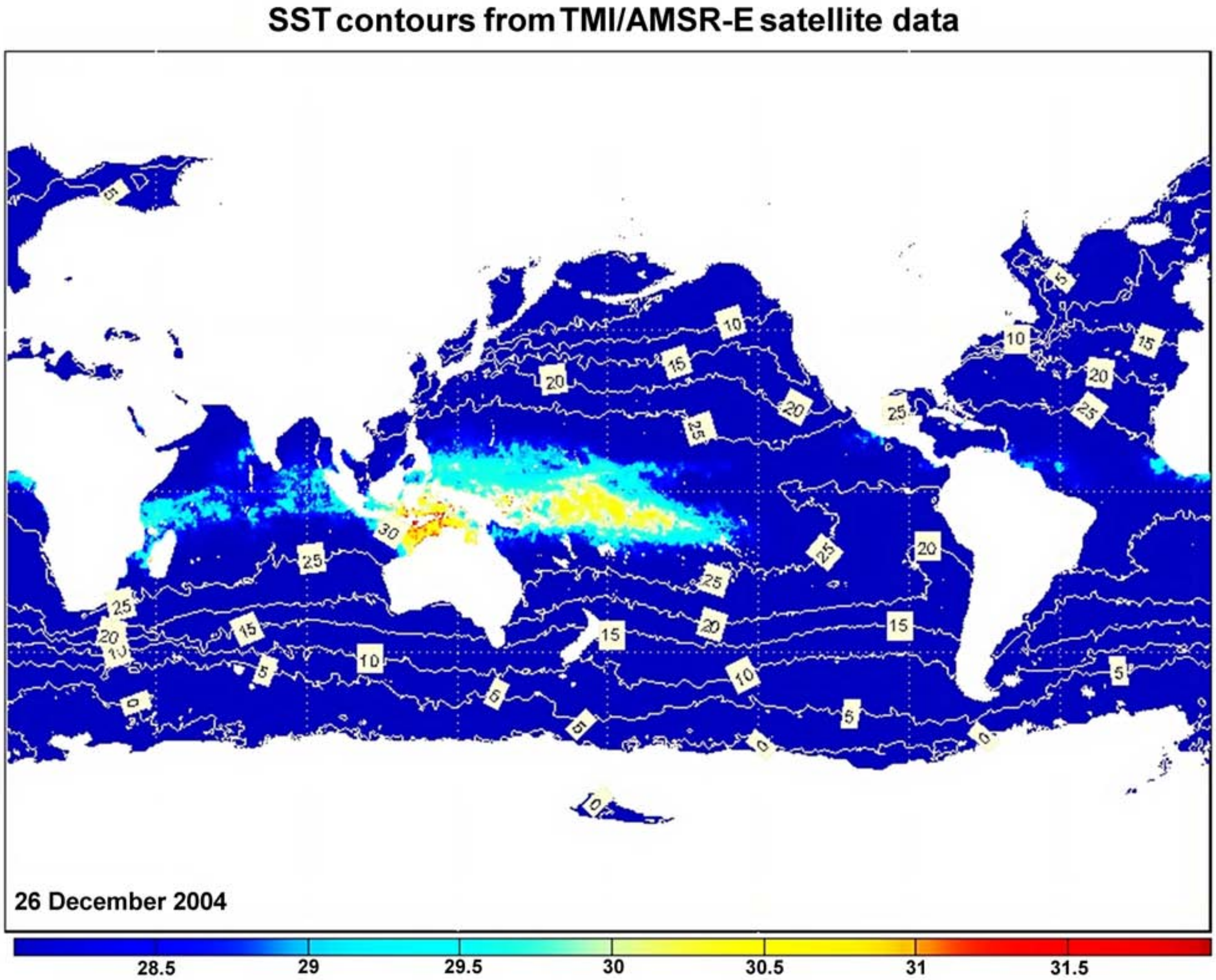


Fig. (6). Global map of SSTcontours for 26 December 2004. The numbers are SST values in Deg C.

The result of the SST anomalies for the Sumatra-Andaman under-sea earthquake shows that due to higher magnitude of the tectonic activity there is a clear indication of warming of 0.2-0.3 ºC at least within 2ºx 2º grid area closer to the epicentre of this earthquake (neglecting any nearby land regions). According to the results presented here, the effect of warming started a week earlier and continued beyond 26 December 2004 by about a week. Similar analysis carried out for other years for the same period did not show such a earthquake related effetcs. As one of the checks and as part of the case studies, a possible sea surface warming episode centering the great earthquake of 28 March 2005 was examined. While there is some evidence of changes in SST anomalies around the period of the earthquake, it is inconclusive due large data gaps within 2ºx 2º grid area around the epicentre making it difficult to realistically evaluate the differential of variations between the two defined grids of 2ºx 2º and 6º x 6º.

To get a better insight into the time evolution and strengths of different power spectral components, the time series of the mean daily SST anomaly data of 2º $\times$ 2º and 6º $\times$ 6º grid regions are subjected to wavelet analysis for both cases of Sumatra earthquakes. The wavelet analysis identifies the time of change of signal spectrum in addition to synthesising power distribution between different scales (frequencies). More power (or higher coefficient values in wavelet spectra) for large scale sizes would represent dominance of relatively smaller frequency or larger periods of oscillation. The results of wavelet analysis of the SST anomalies both within 2º $\times$ 2º and 6º $\times$ 6º-grid regions for both the earthquakes (using db3 wavelet and scales between 1-64) are shown in Fig. (**9**). White arrows in the figure show the event peak dates. It is clear from the 2º $\times$ 2º grid spectra that the change towards larger scales (lower frequency) due to slowly varying temperature anomaly with higher coefficients has occurred for both the earthquakes more or less centred on the respective epochs. While such spectral orientation is not observed for the SST anomaly time series of 6º $\times$ 6º grids for the 26 December event (signifying no dominance of earthquake related slowly varying long period oscillation for the larger grid), in the case of 28 March event the 6º $\times$ 6º grid wavelet parameters still shows the dominance of earthquake related signal with a time shift of about a few days). In summary the existence of earthquake related SST

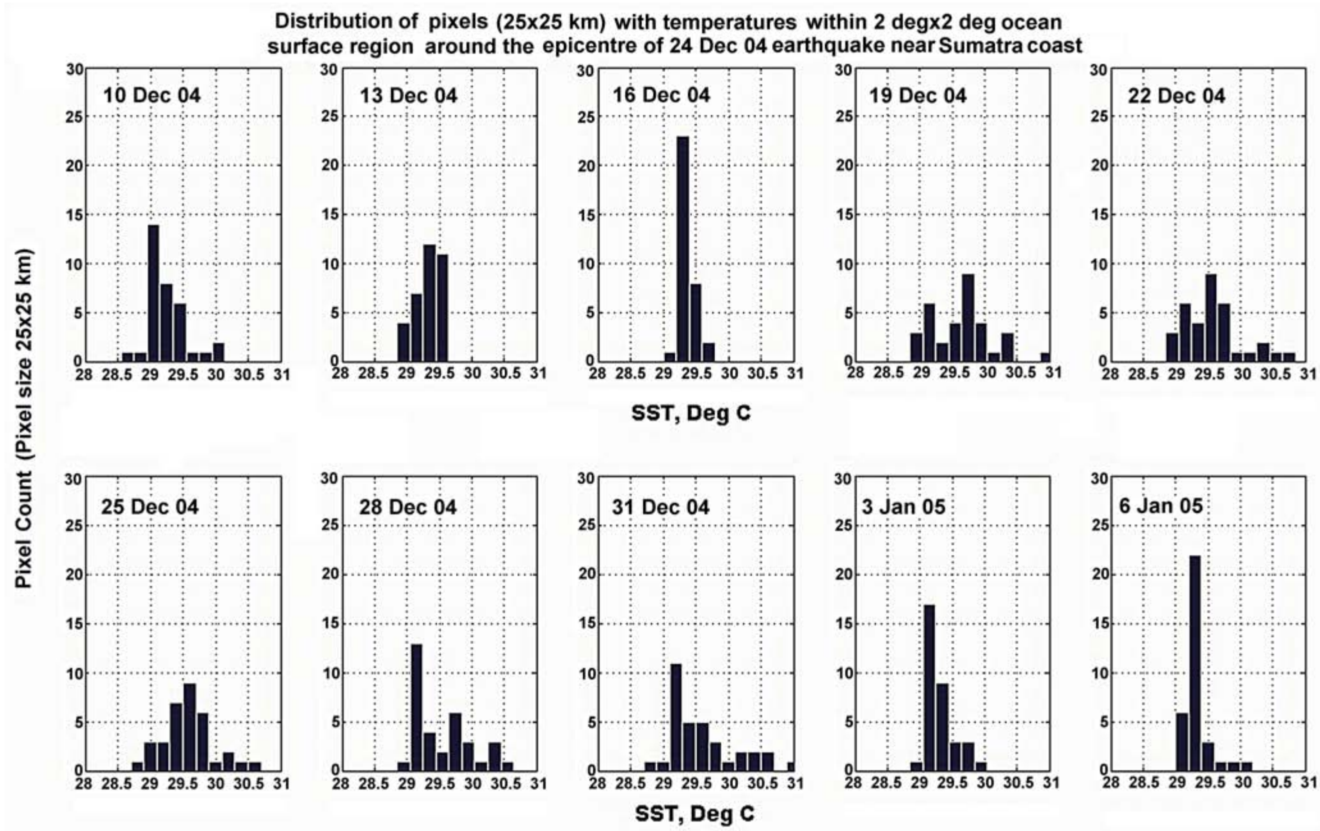
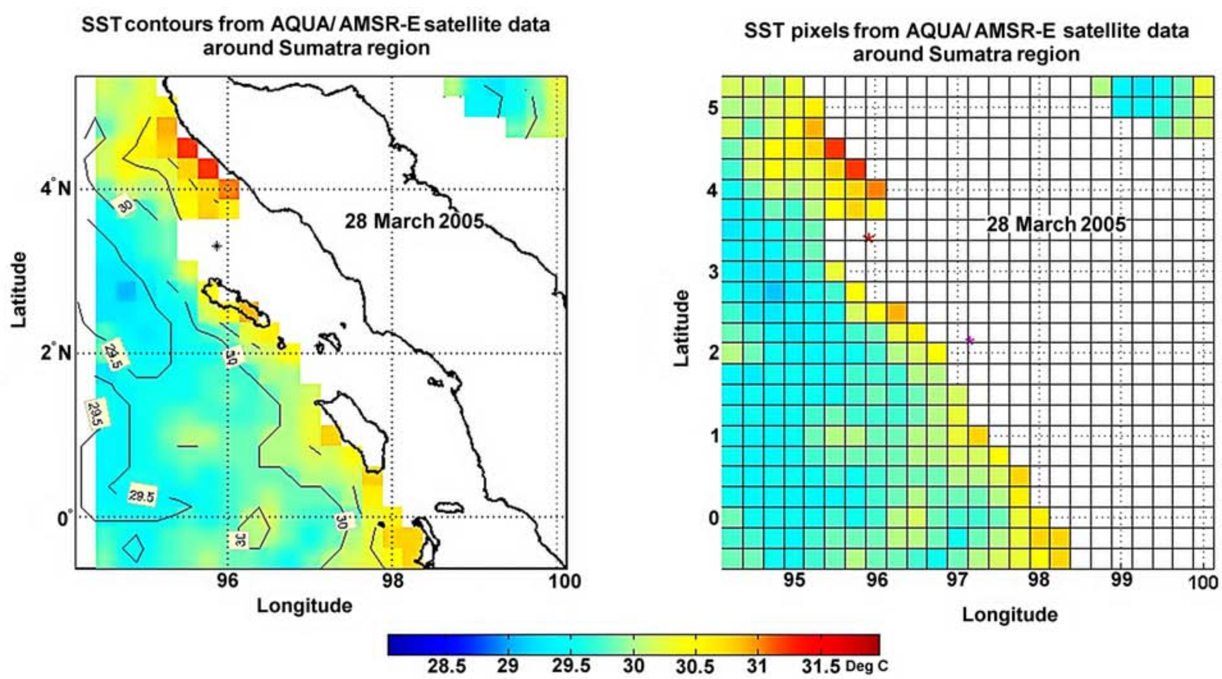


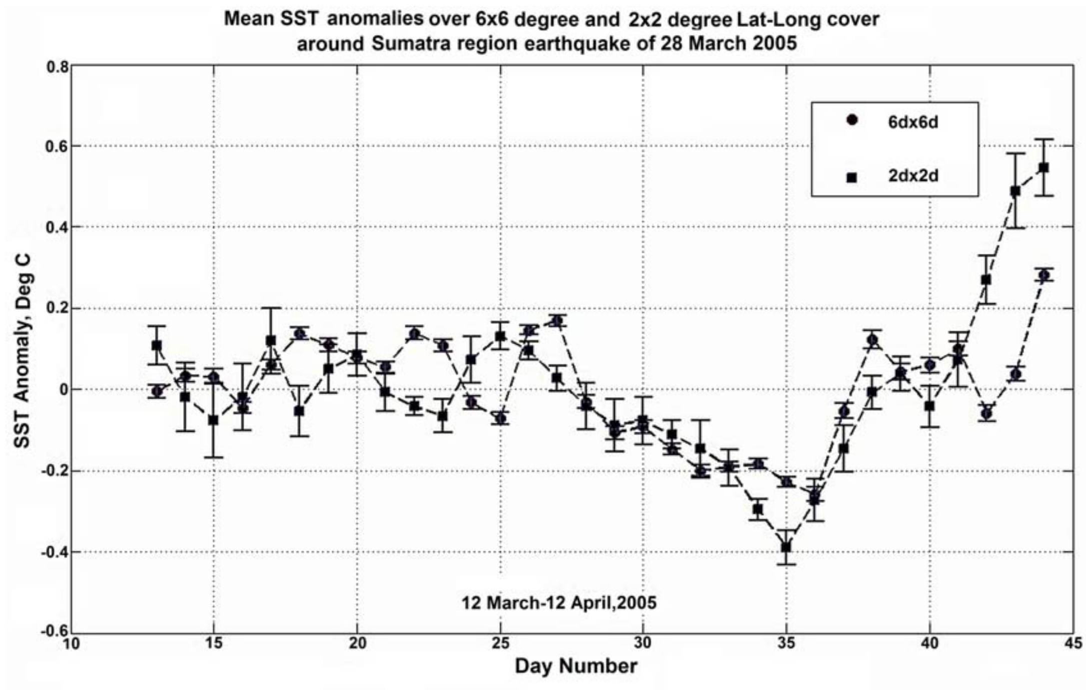
Fig. (7). SST histograms in the 2 x 2 region covering the epicentre of the earthquake of 26 December 2004.

(a)



(Fig. 8) contd….

(b)



(c)

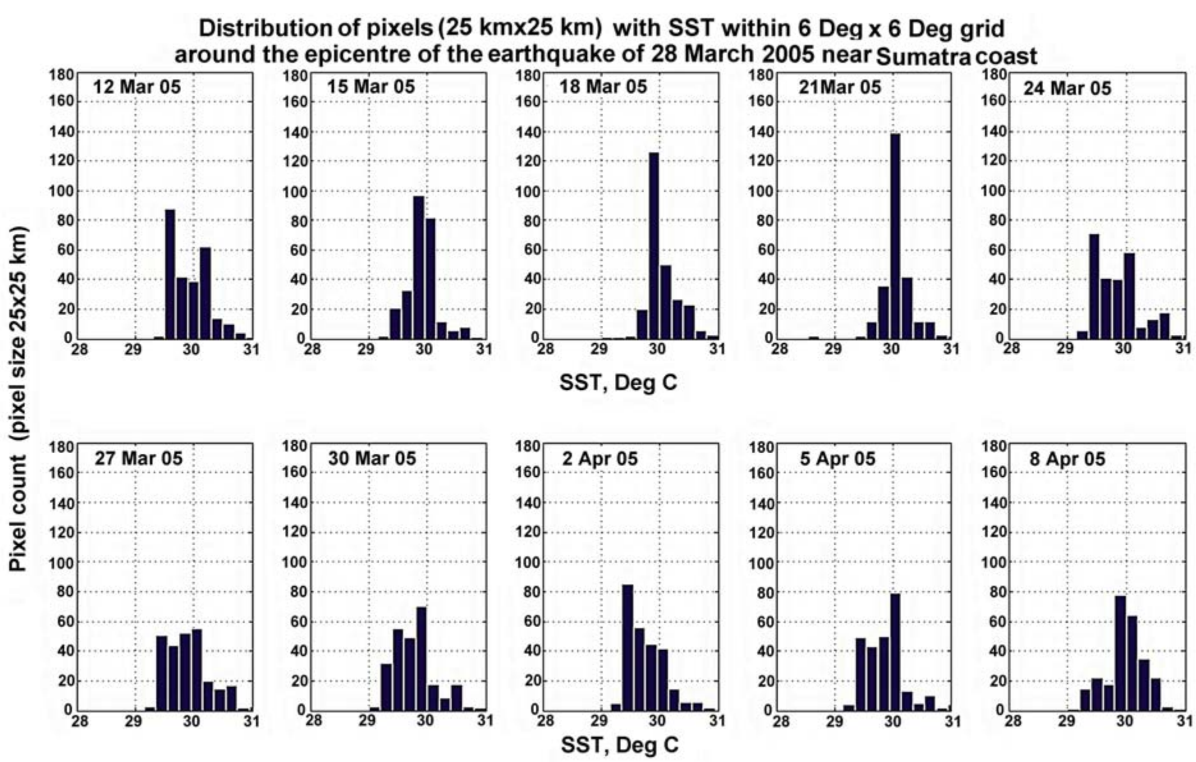


Fig. (8). (**a**) SST contours for 6º × 6º grid, (**b**) SST anomalies for 2º × 2º and 6º × 6º grids, and (**c**) SST histograms for 6º × 6º grid regions around the epicentre of the great earthquake of 28 March 2005.

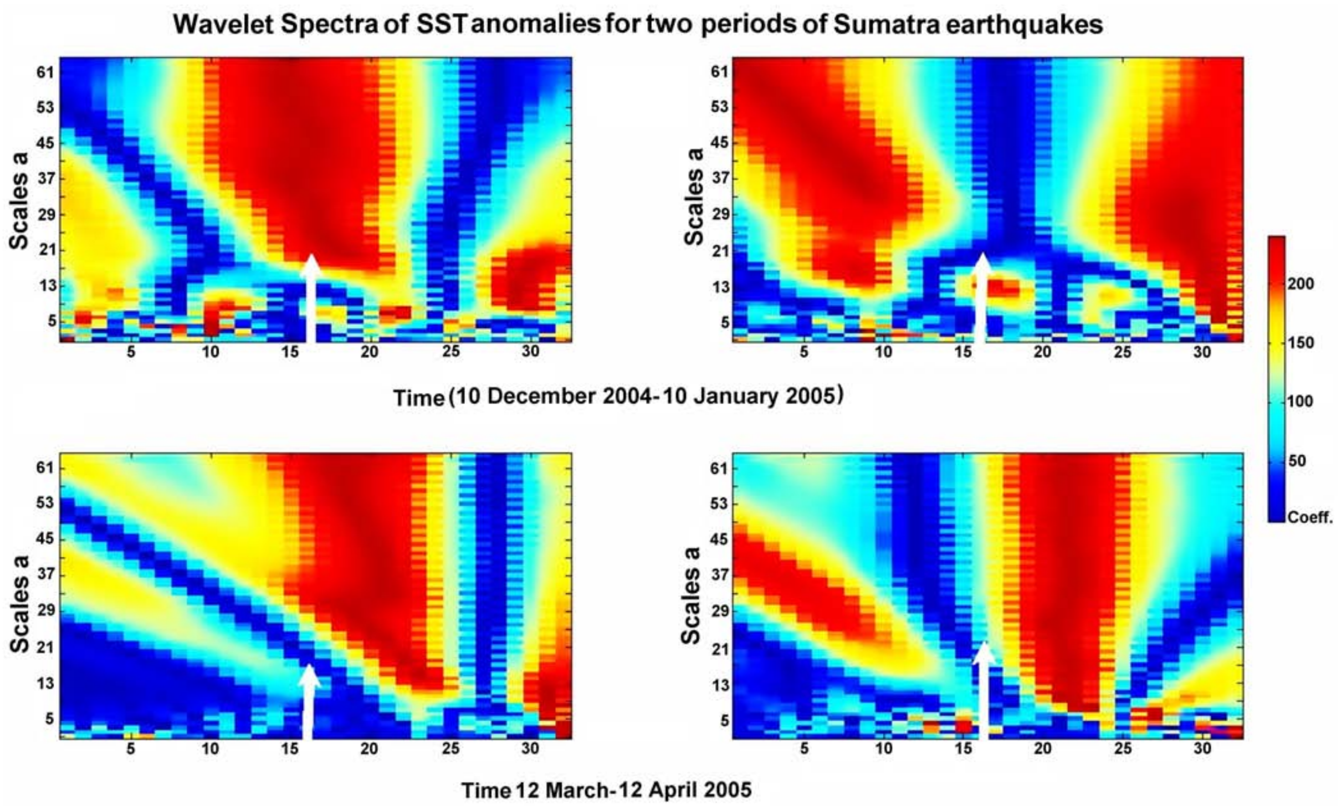


Fig. (9). Wavelet spectra of SST anomalies(for 2° × 2° and 6° × 6° grid regions) during the time period of about a month around the two great earthquakes of 26 December 2004 and 28 March 2005 near Sumatra wesrern coastal region.

anomaly in localised grid (within 200 km x 200 km) closer to the earthquake epicentre is clearly demonstrated for the Sumatra-Andaman quake of 26 December 2004 but similar effect due to the 28 March event though present but cannot be confirmed due to data gaps owing to presence of more coastal area pixel data near its epicentre restricting the availability of full oceanic data as in case of the first event.

The preliminary results of these case studies indicate the need to launch a thorough search for anomalies of sea surface parameters such as SST, Sea Surface Winds (SSW) etc., over the oceanic ridges mentioned earlier during the periods of past and intense tectonic activities. The depth of the ocean bed where the seismic event occurs may be important for better detection of SST anomalies even for weak undersea earthquakes. The Sumatra region ocean bed depth is around 30 km but the magnitude of the undersea earthquakes considered were unusually large and hence such effects studied for other earthquakes under different oceanic regions could provide further interesting results. A conceptual diagram on the possible mechanism of stresses developed at ocean ridges with colliding plate boundaries, venting of additional hot fluid (magma), water vapour and other gases (from asthenosphere/earth's lower mantle), change in the ocean thermal gradients during the life-cycle of enhanced tectonic activity resulting in more heat flow than normal and subsequent warming of ocean surface is shown in Fig. (**10**). However quantitative heat fluxes from such quake affected zones would need to be measured and mathematically modelled for further study and insight.

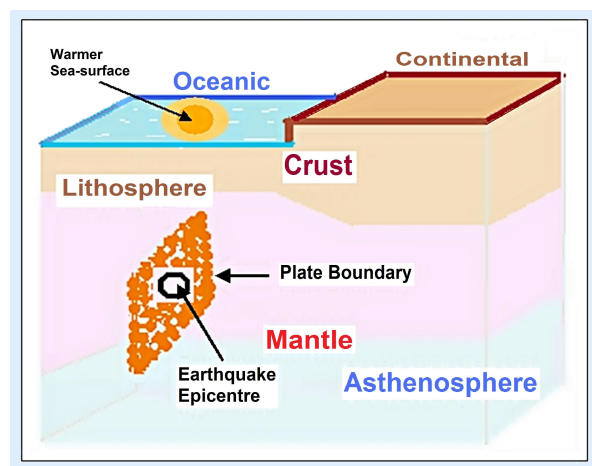


Fig. (10). A conceptual mechanism of linking processes in the earth's interior at plate boundaries with enhanced tectonic activities resulting in possible enhanced heat flow and warmer SSTs near the ocean surface epicentre.

ACKNOWLEDGEMENT

AQUA/AMSR-E data are produced by Remote Sensing Systems and sponsored by the NASA Earth Science REASoN DISCOVER Project and the AMSR-E Science Team. Data are available at http://www.remss.com. Author acknowledges the support and encouragement provided by Chairman, ISRO.

REFERENCES

[1] Pollack HN, Hurter SJ, Johnson JR. Heat loss from the Earth's interior: analysis of the global data set. Rev Geophys 1993; 31: 267-80.

[2] Rassmusson EM, Carpenter TH. Variations in tropical sea surface temperature and surface wind fields associated with the Southern Oscillation/El Nino. Mon Wea Rev 1982; 110: 354-84.

[3] Philander SGH. El Niño, La Niña and the Southern Oscillation. San Diego, CA: Academic Press 1990; pp. 1-289.

[4] Nosov MA. Ocean surface temperature anomalies from underwater earthquakes. Volc Seism 1998; 19: 371-5.

[5] Ouzounov D, Freund F. Mid-infrared emission prior to strong earthquakes analysed by remote sensing data. Adv Space Res 2004; 33: 268-73.

[6] Levin BV, Likhacheva ON, Uraevskii EP. Variability in the thermal structure of ocean waters in periods of strong seismic activity. Atmos Ocean Phys 2006; 42: 653-7.

[7] Agarwal VK, Mathur A, Sharma R, Agarwal N, Parekh, A. A study of air-sea interaction following the tsunami of 26 December 2004 in the eastern Indian Ocean. Int J Remote Sens 2007; 28: 3113-9.

[8] Guo G, Wang B. Cloud anomaly before Iran earthquake. Int J Remote Sens 2008; 29: 1921-8.

[9] Lay T, Kanamori H, Charles JA, *et al*. The great Sumatra-Andaman earthquake of 26 December 2004. Science 2005; 308: 1127-33.

Received: December 30, 2008 Revised: March 18, 2009 Accepted: March 29, 2009