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Thermal Remote Sensing Technique in the Study of Pre-Earthquake Thermal Anomalies

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ABSTRACT
Pressure built-up due to tectonic activities and also associated subsurface degassing might create changes in thermal regime prior to an earthquake event and if by any technique this change is detected, it can provide very important clues about future earthquake activities. Thermal satellite remote sensing which can sense the earth's surface emissivity at regular interval introduces a new way of analyzing this phenomenon. Using NOAA-AVHRR thermal datasets, few major past earthquakes (Bhuj (India), Boumerdes (Algeria), Bam (Iran) etc.) were analyzed for studying the thermal changes before and after the earthquakes. The study was successful in detecting pre-earthquake thermal anomalies prior to all these earthquakes. Significant thermal anomalies with a rise in temperature of about 5-10°C in the vicinity of the epicenters have been observed. The anomalies disappeared along with the earthquake events. Further, using passive microwave SSM/I sensor datasets from DMSP satellites the occurrence of the phenomenon of pre-earthquake thermal anomalies for few more earthquakes around the world were observed.

INTRODUCTION

Remote Sensing technology has been an unbiased monitor of the earth's surface. The use of thermal remote sensing has brought out new trends in earthquake research. Land surface temperature (LST) can be calculated with the aid of thermal sensors like Advanced Very High Resolution Radiometer (AVHRR) on board National Oceanic and Atmospheric Administration (NOAA), Multi-spectral Visible and Infrared Scan Radiometer (MVISR) on the Feng Yun (FY) Chinese series of satellites, Moderate Resolution Imaging Spectroradiometer (MODIS) on board satellites Terra and Aqua, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) on board the satellite Terra, and other thermal Infrared sensors. The passive microwave radiometer, Special Sensor Microwave Imager (SSM/I) on board the Defense Meteorological Satellite Program (DMSP) has the advantage of being more transparent to clouds and has an all weather advantage to sense the thermal emission of the earth's surface.

Three earthquakes were analyzed using NOAA-AVHRR datasets in India, Algeria and Iran. The presence of thermal anomalies in regions around the earthquake epicenter prior to the earthquakes was observed in all these earthquakes. The anomalies disappeared along with the earthquakes [Saraf & Choudhury 2003, 2004 (a), (b) and (c)]. Further, SSM/I datasets were used to analyze a few earthquakes around the world, including the Bhuj Earthquake in India.

BHUJ EARTHQUAKE, GUJARAT, INDIA

The powerful Bhuj Earthquake struck Gujarat on 26 January 2001, at 03:16 (UTC) (local time 08:46 hrs) with a USGS magnitude of 7.9 (M_w). The location of the epicenter was at 23.40°N latitude and 70.31°E longitude, near Bhuj in the state of Gujarat. The earthquake is the result of an east-west thrusting attributed by stresses due to the Indian plate pushing northward into the Eurasian plate. However, no surface rupture was observed after this earthquake.

OBSERVATIONS

Thermal channel 4 of NOAA-AVHRR satellite data was used to calculate the LST of the study area. The LST calculation is based on the method provided in http://perigee.ncdc.noaa.gov/docs/podug/html/c1/sec1-410.htm. Cloud cover was delineated and avoided. The data of days which were cloudy could not be studied for thermal changes as AVHRR cannot penetrate clouds.

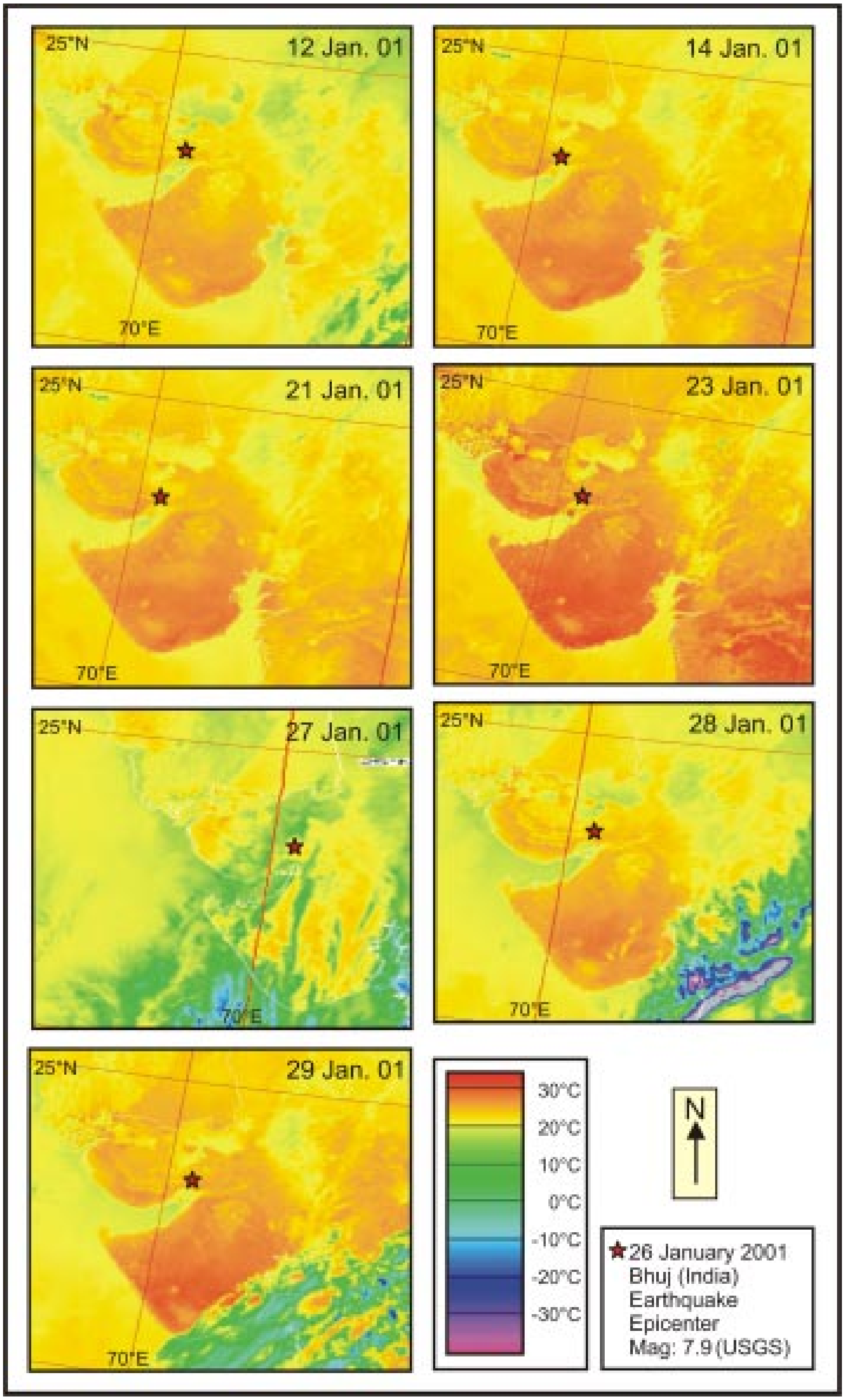

Figure 1 (a). Time series Land Surface Temperature (LST) maps prior to the earthquake of 26 January 2001 in Bhuj, India. Thermal anomaly over the region appeared on 14 January 2001 and was seen to be maximum on 23 January 2001.

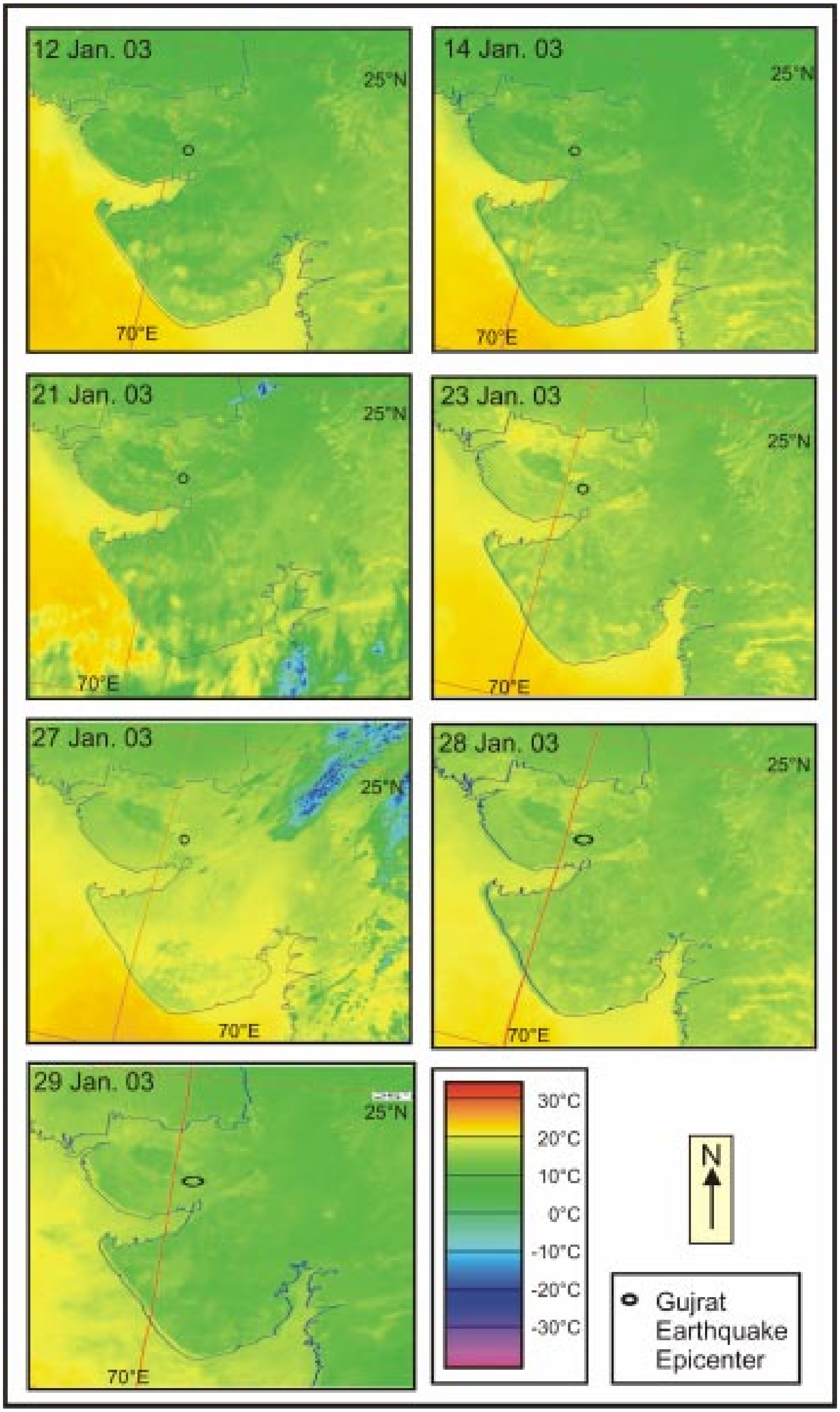

Figure 1 (b). Land Surface Temperature (LST) maps of the year 2003 over Gujarat shows normal thermal scenario.

Pre- and post- LST images revealed a positive thermal buildup on 14 January 2001 in southwest Gujarat with respect to the surrounding. The temperature increased to a maximum on 23 January 2001, just three days before the earthquake hit Gujarat (Fig.1a). On this day the LST was seen to be 28ºC - 31ºC. This rise in temperature was about 5-7ºC higher than the usual temperature of the region. After this boost the temperature started to drop [Saraf & Choudhury 2003 and Saraf & Choudhury 2005]. NOAA-AVHRR data of the year 2003 of the same region and of the same dates were used to study the LST scenario. It was seen that in the year 2003, there was a completely normal thermal scenario in and around the epicenter (Fig. 1b).

To ascertain that this rise was due to the earthquake on 26 January 2001, the trend of the available weekly average temperature data (1951-1980) of a few India Meteorological Department (IMD) stations was analyzed. Using this weekly average temperature data as a base, the average weekly temperature for the period from December 1999 to February 2001 (3 months) of IMD stations around the epicenter was compared. The base period trend shows that in the third week of the year, the temperature for those years from 1951 to 1980 is lowest as compared to second and fourth weeks of those years (Fig. 2a). But in the year 2001 there was a peak of temperature increase in the third week (Fig. 2b) [Saraf & Choudhury 2003 and Saraf & Choudhury 2005]. This is in contrary to the observed trend for the past thirty years. This ground observation is in accord with the observed satellite thermal detection during January 2001.

BOUMERDES EARTHQUAKE, ALGERIA

A powerful shallow focus earthquake of magnitude 6.8 (M_w) hit Algeria on 21 May 2003 at 18:44 (UTC) with its epicenter located at 36.90°N latitude and 3.71°E longitude. This earthquake was accompanied by a series of aftershocks (ranging in magnitude from 5.7 to 2.4 (M_w)) in and around the epicenter in Boumerdes in Algeria, which continued till 28 May 2003. The African plate is moving towards the Eurasian plate along the Mediterranean coastline of Algeria at a rate of about 6 mm per year. This results in a compressional force, which manifests itself as a series of thrust and normal faulting. The movement of the South Atlas Fault (SAF) (which is considered to be responsible for the Boumerdes Earthquake) is a manifestation of such forces [Saraf & Choudhury 2004 (a)].

OBSERVATIONS

LST maps generated using three daily nighttime NOAA-AVHRR datasets obtained from German Aerospace Center (DLR), Koln, Germany were used to study the thermal conditions over Boumerdes before and after the Boumerdes earthquake. The calculation of LST is based on Becker & Li (1990) 'split window' algorithm, using the channels 4 and 5 of the AVHRR datasets. Use of nighttime images avoids solar heating during the day. Nighttime data also deducts the chances of partial sun illumination. Any cloud pixel was excluded from LST calculation.

The LST composite map of the night of 13 May 2003 showed the appearance of a positive thermal anomaly towards an area south of the Boumerdes earthquake epicenter. This anomaly intensified to a maximum buildup of thermal anomaly on the night of 20 May 2003, covering an approximate area of 91,100 km². The temperature rose to around 20-24ºC, about 5-10ºC higher than the surrounding area. After two main shocks occurred, of magnitudes 6.8 and 5.7(M_w), on 21 May 2003, the anomaly weakened. A less intense anomaly on the night of 21 May 2003 was probably a precursor to an earthquake of magnitude of 5.5 (M_w), which occurred on 22 May 2003 at 3:14 (UTC). The anomaly disappeared on the night of 22 May (Fig.3). A weak anomaly again appeared around the same area on the night of 23 May 2003. Clouds, which covered the study area, hampered the study of the development of any anomaly for the 5.8 magnitude earthquake on 27 May. A weak anomaly was again noticed on the night of 28 May (Fig.3). An earthquake of magnitude 4.9 rocked Algeria on 29 May. The location of the thermal anomaly concur with the South Atlas Fault (SAF), which is a thrust running east to west in northern Algeria. The offshore location and shallow depth (10 km) of the epicenter indicates that the focus lies on the thrust plane of the SAF [Saraf & Choudhury 2003 and Saraf & Choudhury 2004 (a)].

BAM EARTHQUAKE, IRAN

The devastating earthquake in Bam, Iran struck on 26 December 2003 at 01:55 (UTC) with a magnitude of 6.6 (M_w). The location of the focus was at a depth of 10 km and the epicenter was located at 29.00º N latitude and 58.33º E longitude near the 2000 years old ancient city of Bam, which was destroyed by the earthquake. The 26 December earthquake is generated by right-lateral strike-slip motion on the North-South trending Bam fault. The Bam fault passes from the vicinity of the city of Bam and between the cities of Bam and Baravat.

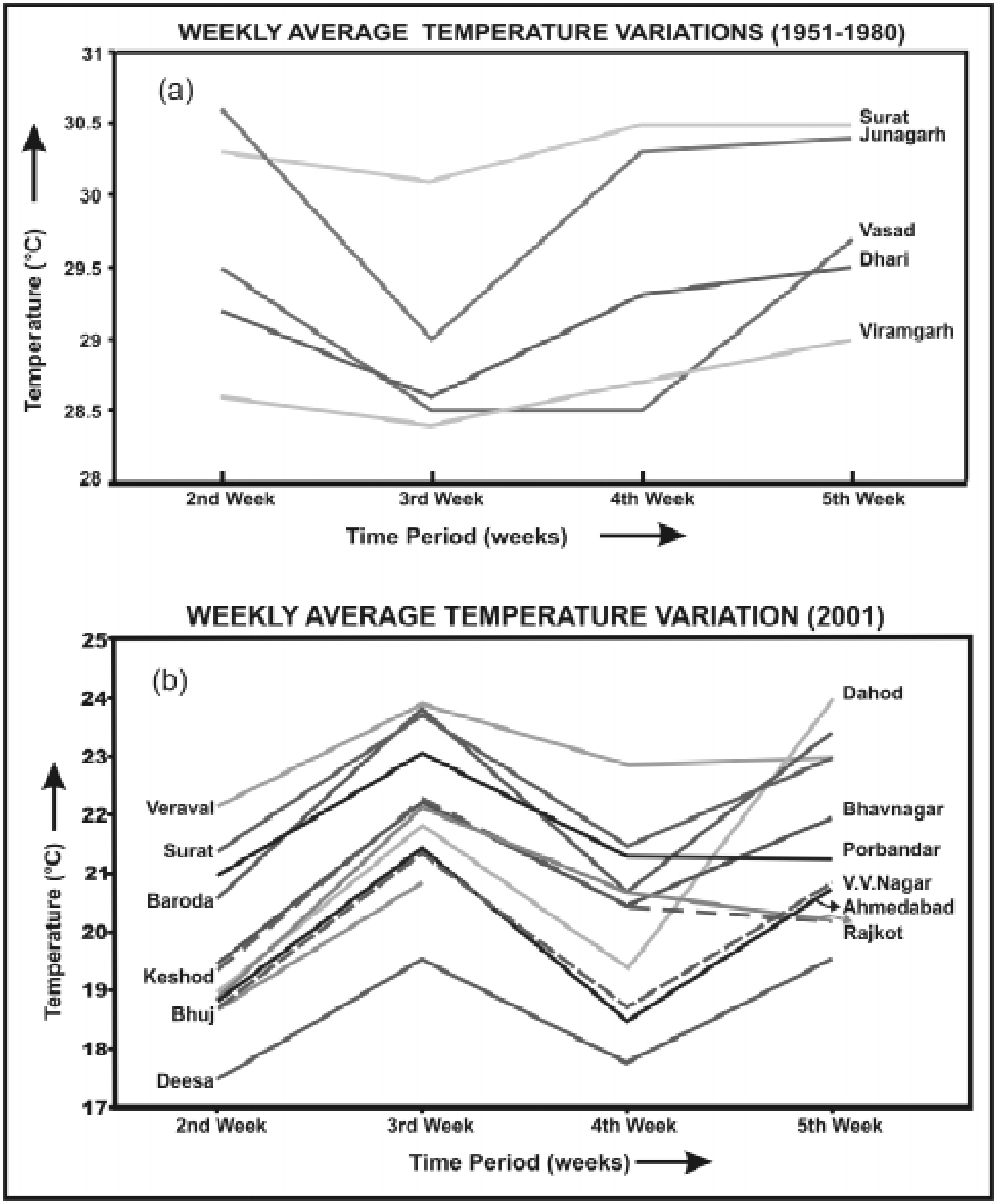

Figure 2. (a) Weekly average meteorological temperature trend in 30 years (1951-1980) shows a usual low in the third week of the year and (b) Weekly average meteorological temperature in the year 2001 shows a high in the third week (when the AVHRR-derived anomaly was observed).

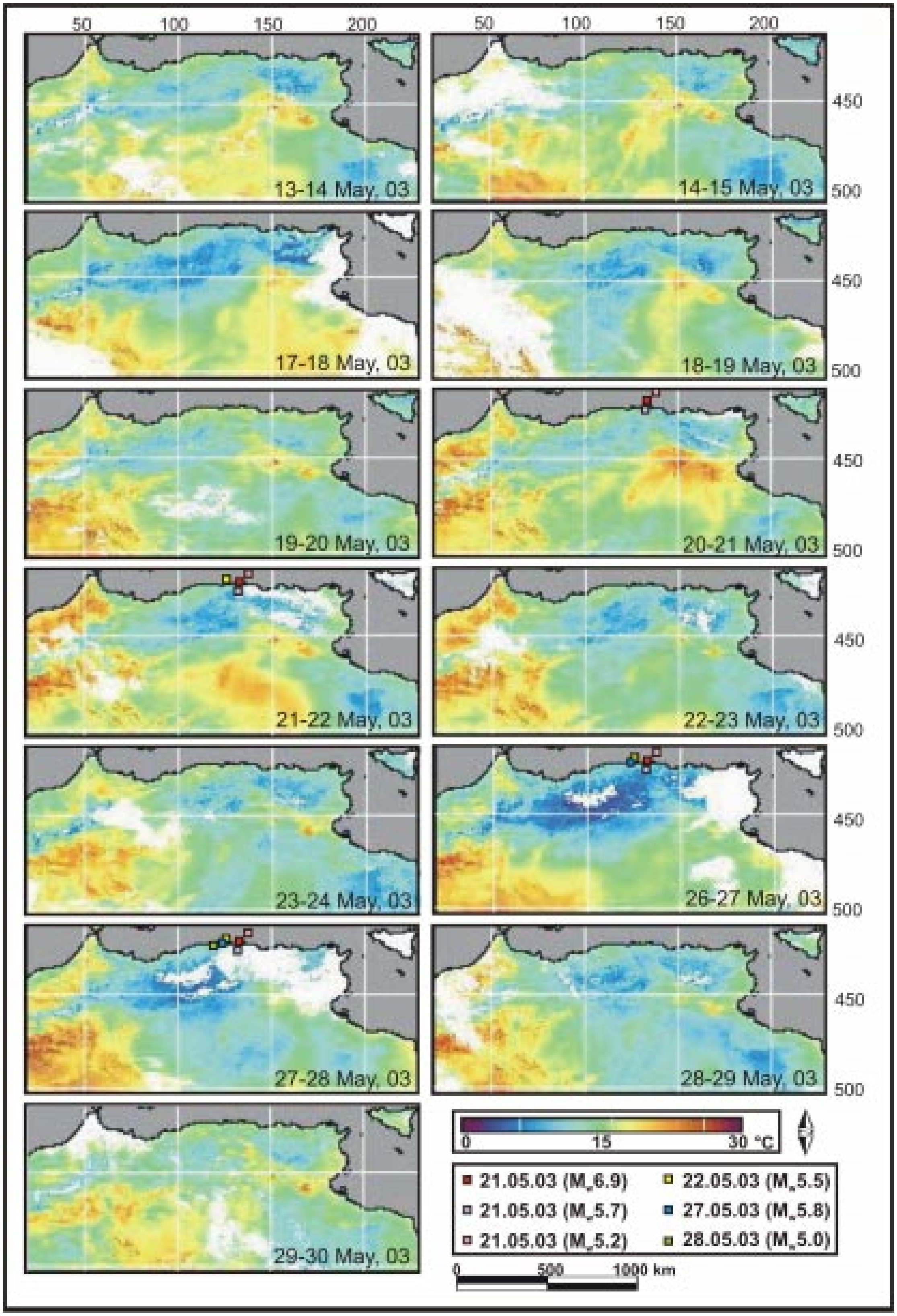

Figure 3. Time series composite maps of Algeria before and after the earthquake. The temperature was seen to be maximum on 20 May 2003.

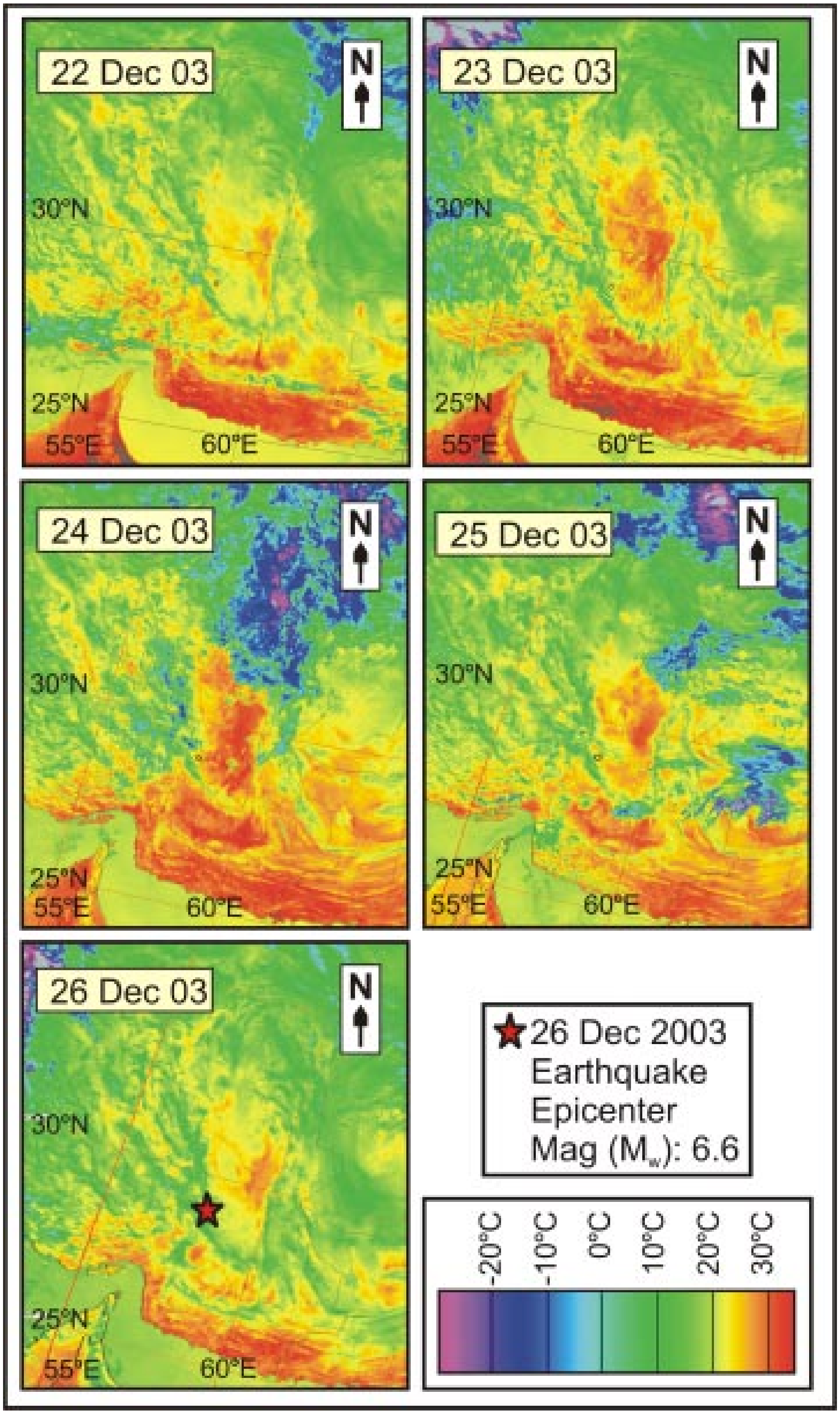

Figure 4. AVHRR-NOAA time series data show thermal anomaly before the 26 December 2003 BamEarthquake in Iran. The maximum anomaly was seen on 24 December 2003, two days before the earthquake.

LST maps for Iran were prepared using the channel 4 of the NOAA-AVHRR datasets using the method mentioned in http://perigee.ncdc.noaa.gov/docs/podug/html/c1/sec1-410.htm. Cloud covered pixels were delineated and masked.

OBSERVATIONS

A thermal anomaly was observed to appear before the devastating earthquake of 26 December 2003. The LST increase was about 5 - 7°C than the usual temperature of the region. At some places, the temperature was about 8 - 10°C higher than normal.

LST time series maps over Iran shows that the rise in temperature started from 22 December 2003 and stayed on till 24 December 2003 (figure 4). On 24 December, just two days prior to the earthquake, the temperature around the entire region and even surrounding the epicenter was around 8°C - 10°C higher than the normal temperature of the region. The rise in temperature dropped on 26 December, the day when the earthquake occurred.

KALAT EARTHQUAKE, PAKISTAN AND HINDUKUSH EARTHQUAKE, AFGHANISTAN

SSM/I on board the DMSP series of satellites is a passive microwave sensor having the advantage to penetrate clouds. The spatial resolution of this sensor is 30 km for all the products. Temperature anomalies derived from SSM/I data are with respect to the mean climatological values between the years from 1988 to 2002. Composite maps of seven days of satellite observation are prepared as a weekly derivative. The weekly anomaly is calculated with reference to 14 years mean temperature data. The temperature scale, therefore, actually represents thermal difference in degree Celsius with respect to the base period of 14 years. A value of +1 on the temperature scale will represent an increase of temperature of 1°C with respect to the base for that particular week on an average, i.e., the region was 1°C warmer than usual for that particular week of the year with respect to all the 14 years [Saraf & Choudhury 2004 (b)].

The Kalat Earthquake in Pakistan on 4 March 1990 (epicenter at 28.92° N and 66.33° E) and the Hindukush Earthquake in Afghanistan on 25 March 2002 (epicenter at 35.97° N and 69.18° E), both with magnitude 6.1 M_w (USGS), have shown interesting observation with SSM/I data. Both these earthquakes were preceded by thermal anomalies. The location of the epicenters of these earthquakes is in similar tectonic region, but these earthquakes have different focal depths. They are both shallow earthquakes, the Kalat Earthquake has a focal depth of 10 km, while the Hindukush has a focal depth of 33 km.

It was seen that the thermal anomaly of the earthquake with the deeper focus, i. e., the Hindukush Earthquake showed an anomaly with a greater spatial extent and the earthquake with the shallower focus, i.e., the Kalat Earthquake showed an anomaly with a lesser spatial extent (Fig.5).

Weekly temperature anomaly maps for the Kalat earthquake in Pakistan showed the development of a thermal anomaly close to the epicentral area two weeks before the earthquake hit the Kalat region in Pakistan. In the next week, the anomaly intensified to a maximum during 19-25 February 1990 with around 2-10°C difference of temperature than base temperature in the region. The anomaly remained for over a week and occupied a small area as a linear arch around the epicenter. This anomalous rise was seen to disappear in the week from 26 February -4 March 1990, i.e., just before the earthquake.

IZMIT EARTHQUAKE (KOCAELI), TURKEY

The active North Anatolian Fault, similar to the San Andreas Fault in California, generates numerous earthquakes in Turkey. SSM/I derived anomaly maps for the devastating 17 August 1999, magnitude 7.6 Izmit earthquake clearly show an increase in temperature of the region before the deadly earthquake. The anomaly, which started building in the week beginning from 6 August, 1999, was centered on the epicenter, but spread over a vast area over Western Turkey (Fig.6). The anomaly maps of this week show a difference in temperature of 2-6°C in the region. The next week probably with active degassing, witnessed a boost of temperature with an increase of 6-10°C with respect to the base period. This anomaly disappeared right after the 19 August 1999 earthquake and since 20 August 1999 showed similar temperature values as normal. The North Anatolian Fault is a strike slip fault, traversing the northern part of Turkey from east to west and forces the bulk of Turkey lying to the south of the fault to drift to the west for about 1200 km.

DISCUSSION AND CONCLUSIONS

The history of the application of thermal remote sensing in natural resources perhaps started in Russia in the nineteen sixties. Thermal data in seismic studies were first used in Russia. Such studies were carried out in Russia, Japan and China. Scientists in China, Russia and Japan observed the occurrence of thermal anomalies (Zu ji, Xiu-Deng & Chang-Gong.

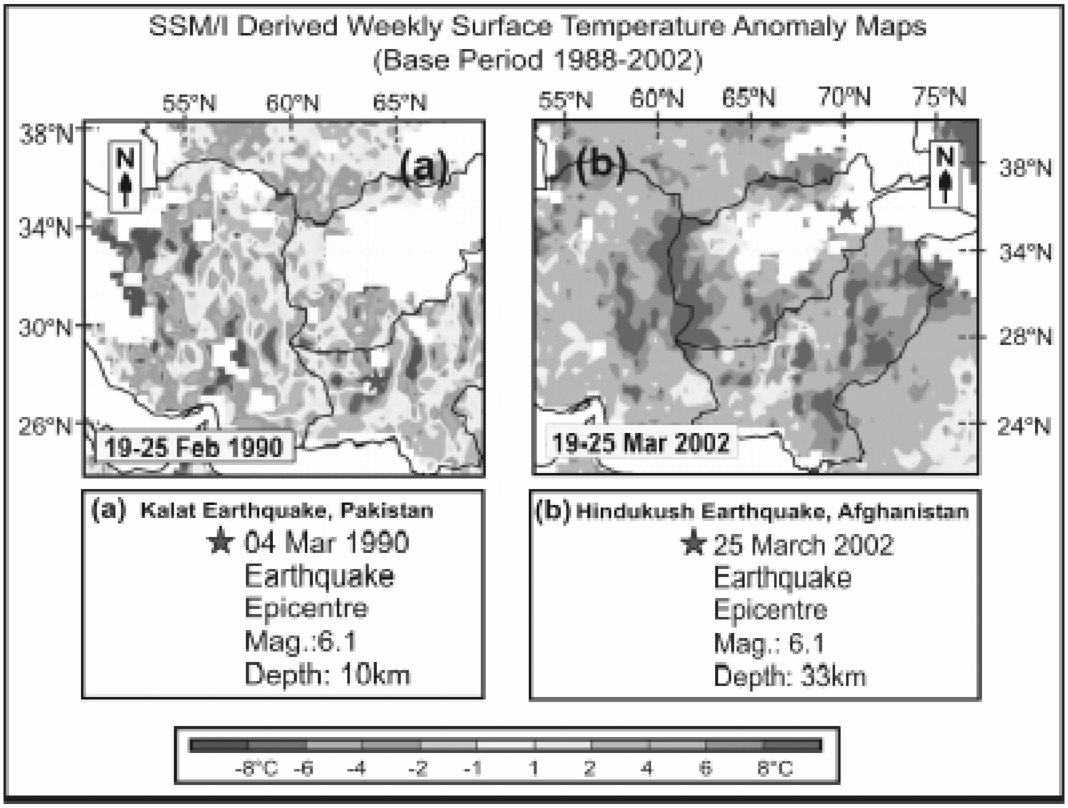

Figure 5. (a) Thermal anomaly prior to the 3 March 2002 earthquake and (b) Thermal anomaly prior to the 25 March 2002 earthquake. Both these earthquakes have the same magnitude, are located in similar tectonic locations but differ in their depth of focus.

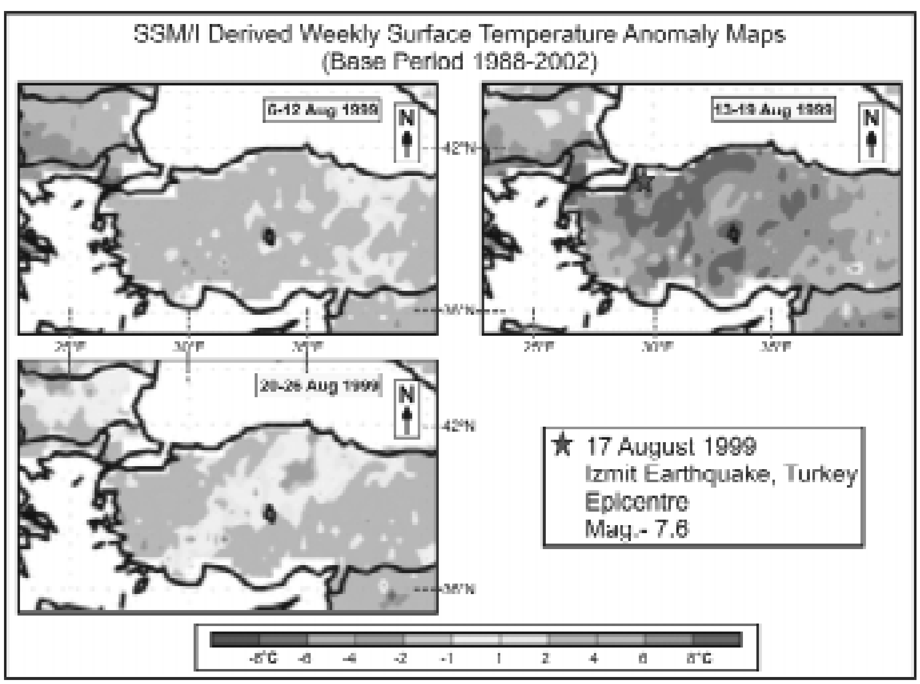

Figure 6. Thermal anomaly prior to the 17 August 1999, Izmit Earthquake in Turkey.

1991, Gorny & Shilin 1992, Tronin 1996, Zu ji et al. 1999, Tronin 2000). Zu ji et al. successfully studied and tried to predict a number of earthquakes based on thermal anomalies. Zu Ji, Xiu-Deng & Chang-Gong (1991) also state that rock breaking tests in laboratories have verified the escape of gases due to subsurface deformation. Infrared emission under action of enormous pressure has also been experimented upon and verified by Ouzounov and Freund (Ouzounov and Freund, 2003).

Prior to an earthquake, crustal deformation is due to a stress field. It is a known fact that increases in pressure leads to an increase in temperature. Due to the acting stress field, sub-surface pressure increases with the consequent increase in temperature. Such deviation from normal in the thermal regime can pose to be an interesting observation in earthquake studies. The strengthening of stresses in tectonic regions also results in the production and extension of micro-cracks. The gases trapped in these pores escape and create a localized green house effect and thus create a thermal anomaly near earth's surface. An abnormality in the thermal properties of the near earth's surface, detected by thermal channels like AVHRR, can prove to be a valuable indicator of an impending earthquake. As successfully demonstrated in the present study, the earthquakes in Bhuj (India), Boumerdes (Algeria), Bam (Iran), Izmit (Turkey), Hindukush (Afghanistan) and Kalat (Pakistan) were associated with the presence of pre-earthquake thermal anomalies. The anomalies appeared a few days to a few hours before the earthquakes. The increase in temperature ranges between 4-10°C. These anomalies are seen to disappear after the earthquakes.

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