Thermal anomalies in relation to earthquakes in India and its neighbourhood

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Thermal anomalies based on satellite and surface meteorological data in the epicentral region prior to a few earthquakes in India and elsewhere have raised a question whether such inferences can be relied upon keeping in view larger meteorological variability associated with synoptic weather changes. This article examines outgoing longwave radiation (OLR) data by INSAT over Sikkim region to find whether any anomaly developed prior to the earthquake of September 2011 (M_w 6.9). Similar study was made using surface meteorological data (weather observatories or NCAR grid point values) in the meizoseismal areas of Bhadrachalam (1969, m_s 5.7), Kinnaur (1975, m_s 6.9), Bihar–Nepal (1988, m_s 6.9), Uttarkashi (1991, m_s 6.8), Latur (1993, m_s 6.1), Jabalpur (1997, m_s 5.6), Chamoli (1999, m_b 6.5), Bhuj (2001, M_w 7.6) and Muzaffarabad (2005, M_w 7.6) earthquakes. The OLR data from INSAT were also examined during heat-wave conditions prevailing over northern India in summer during non-seismic conditions. It was found that there was no significant thermal anomaly prior to any earthquake in the Indian region. It has been shown that the precursory thermal anomaly reported in earlier studies for Bhuj (2001), Muzaffarabad (2005), Jabalpur (1997) and Latur (1993) earthquakes was misinterpreted since the rise in surface temperature (if any) was found to be well within the meteorological variability caused by synoptic weather conditions. Persistent heat-wave conditions causing very large thermal anomaly for several days in northern India raise false alarms. The synthesis of the results presented in this study should desist geoscientists from considering thermal anomalies as earthquake precursors.

Keywords: Earthquake precursor, meteorological variability, outgoing longwave radiation, thermal anomaly.

OF late, attempts have been made to search for earthquake precursors using thermal anomalies based on surface temperatures near the ground as observed by meteorological observatories or satellites using infrared sensors[1]. While in the case of volcanic eruption, there is direct influx of heat through magma denting the surface of the Earth, its association with earthquakes has raised some fundamental questions, like the mechanism of transfer of heat from the focal region of earthquakes to the surface of the earth to generate thermal anomaly. The earlier studies[1–7] have in general not examined much larger meteorological changes in thermal regime during non-seismic conditions. Sometimes data from a single passage of satellite in a day are used to relate them with impending earthquakes[8]. Blackett *et al.*[9] were perhaps the first to infer that claims of thermal precursors to earthquakes should be treated with caution. Their study, however, did not examine meteorological variability at any Indian station or elsewhere, which could throw more light on the limitation of thermal anomalies as earthquake precursors.

Keeping in view the above, we have examined earthquakes in the Indian region which were of magnitude 6 or more during the period 1968–2011 using outgoing longwave radiation (OLR) anomalies through satellites, temperature as recorded by surface observatories and also from NCAR grid-point values (where no nearest meteorological observatory existed). We have also included Jabalpur (1997, m_s 5.6) and Bhadrachalam (1969, m_s 5.7), earthquake which had magnitude less than 6, in order to study different seismic regimes over peninsular India. Also, the nature of thermal anomalies during heat-wave conditions over northern India has been brought out[10], which could be misinterpreted as an earthquake precursor.

Temperature at and near the surface of the earth

Thermal anomaly is generally measured through infrared sensors in advanced very high resolution radiometers of remote sensing satellites, but surface weather observations are also used to support or validate the inference. The temperatures can be the maximum, minimum, daily mean range of temperature (difference between maximum and minimum temperature) or better daily mean. Thermal anomaly is defined as temperature exceeding a specific threshold for a specific interval of time at a particular place. Sometimes, it is taken as the deviation of the temperature from its 30 years normal for the month.

The main factors controlling the variations of ground and air temperature are the incoming solar and outgoing terrestrial radiations, the nature of the surface and advection of air. Over the Earth, it is the immediate surface

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which absorbs and radiates heat. The radiant energy is emitted during day as well as night, whose peak occurs at 9.7 μm wavelength. The rise in temperature is proportional to the specific heat of rocks, dry or moist soil. The air in contact with the ground surface acquires the temperature of the Earth with some time lag. Therefore, thermal anomalies associated with the surface of the Earth are studied from meteorological instruments kept in Stevenson screen over the surface of Earth. The thermal infrared multispectral scanners in satellites generally record images in six bands ranging from 8.6 to 12.2 μm, from which OLR values (W/m^2) are derived. Different algorithm and calibration methods are used to drive OLR and corresponding temperature values using Planck's law and Stefan–Boltzmann law of black-body radiation. Shah *et al.*[11] compared the maximum and minimum temperature data from MODIS satellite with those from the surface observations reported by the India Meteorological Department (IMD); they found mean absolute error less than ± 2°C and RMSE of about 2.2°C. White–Newsome *et al.*[12] validated satellite-derived land surface temperature with *in situ* stations and found similar results of higher relative temperatures within a city, commonly called micro urban heat islands. Saraf and Chaudhury[13] found less errors, i.e. ± 1°C during Bhuj earthquake 2001. These studies suggest that similar results would be obtained using satellites or surface observations as given by IMD. The thermal data using satellites are also used to differentiate rocks, surface moisture, surface temperature of volcanoes, geothermal areas, forest fires, sea ice, thermal plumes and faults which cause earthquakes. As mentioned earlier, precursory thermal anomalies have been inferred for a few earthquakes in different parts of the world without giving weightage to the meteorological factors which produce similar or larger changes in temperatures at the ground surface. Such large changes in temperatures near the ground occur due to land and sea breeze, orographic ascent or descent, troughs in westerlies or easterlies, western disturbances and/or induced lows, monsoon depressions, axis of monsoon troughs, cyclonic storms or persistence high-pressure areas. Over the oceans, significant changes in sea temperature also occur during the onset of monsoon over the Arabian Sea and Bay of Bengal, El Niño conditions over the eastern Pacific Ocean or with warm ocean currents. The associated meteorological conditions like incursion of warm or cold air, temperature inversions, clouds, spells of rain and snowfall or prolonged dry weather accordingly affect the diurnal or daily variations of temperature giving rise to thermal anomalies. Persistent dry weather for several days during summer gives rise to heat waves when temperatures may rise up to 8°C or even more. The order and range of temperature variations associated with synoptic and dynamic systems vary from case to case and the location of stations, i.e. lesser changes in coastal stations or during the southwest monsoon. An example of such variations due to a dynamic system can be seen from an induced low over Rajasthan due to a western disturbance over Afghanistan and its neighbourhood, which formed on 19 January 1997. Under the influence of these systems, fairly widespread rain occurred in northwest India. Taking representative stations of Jammu, Dharamshala and Delhi, it was noted that the fall in temperature from 19 to 20 September was of the order of 7°C to 8°C at these stations (Figure 1) due to heavy rain. After the passage of these disturbances, the temperatures started increasing by almost the same amount at all the stations during the next 7 days, which could be misinterpreted if an earthquake is associated with the rise in temperature.

The forecast of weather, including temperature is done by synoptic weather charts, radars, satellites and mesoscale (local), regional and global models based on the laws of thermodynamics, equations of motion, equation of continuity, equation of state, radiation physics and ocean dynamics. In addition, many parameters like aerosol loading, cumulus parameterization, air–sea interaction, planetary boundary layer, OLR values, soil moisture and topography are also included. On the other hand, theories propounded about precursory thermal anomalies associated with the earthquakes are not based on any physical basis to explain transfer of heat from the focal zone of earthquakes to the ground surface. The inconsistency in the results with the focal depth, magnitude, area or extent of thermal anomaly further corroborates this view and is discussed later. It may, however, be clarified that the outflow of magma in volcanic regions shows a rise in surface temperature for which thermal anomalies from satellites is widely used, but it is beyond the scope of this article.

NCAR temperature data

National Centre for Atmospheric Research (NCAR), USA, converts surface meteorological observations, satellite and other datasets into grid size of 2.5° × 2.5° and gives temperature values (K) at every 6 h using state-of-the-art analysis and data assimilation. Although the data are valuable to the weather forecasters for numerical

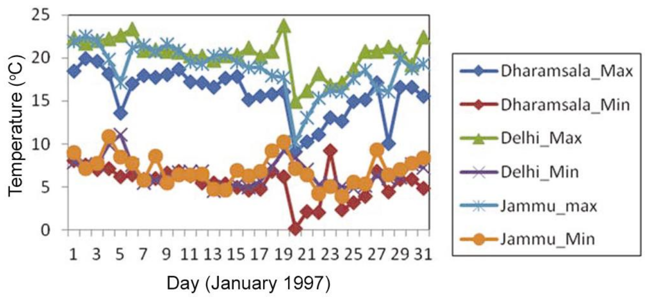

Figure 1. Temperature variations at Jammu, Dharamshala and Delhi associated with induced low over Rajasthan.

weather models, they have been used to study thermal anomalies prior to earthquakes in China[14]. Those data have no problem like cloud cover or extrapolation from satellite OLR observations. In this article, therefore, the grid point nearest to the epicentre has been taken to prepare time series of temperature data keeping in view fault dimension estimated from aftershock area[15]. Also, the NCAR data are converted to daily means and restricted to those earthquakes where no meteorological observatory existed or data were not available.

IMD maintains a network of about 500 surface weather stations throughout India. Besides daily weather observations, monthly, yearly means or long-term normals (1960–1990) of Indian stations are also available at the National Data Centre, Pune, which gives maximum and minimum temperature, mean daily temperature, rain or snowfall or cloud cover, wind speed and direction and atmospheric pressure. Among the above three methods, satellite-based technique though covering a large area fails to detect thermal anomalies in cloudy weather and hence there is limitation to get continuous (daily) time series of temperatures. It may also be mentioned that even thin cloud cover can inhibit the signal strength reflected back to the satellite causing underestimation of ground temperature. In order to reduce diurnal effects, a few workers have used night-time satellite pictures to relate with earthquakes. But minimum temperature rises markedly with influx of moisture, giving inconclusive results. For example, during the first weak of December 2014, Delhi minimum and maximum temperatures were 5°C and 3°C above normal due to anticyclonic conditions over Rajasthan, but without any tremor.

Several satellites have been used to study OLR (thermal) variations in meteorology and also a few earthquakes. Of these, LandSat thermal mapper (LS TM, NASA 2013) was used to study micro urban heat islands in USA. This satellite provides a resolution of 120 m compared with 1000 m for the thermal band of MODIS commonly used by Indian workers for earthquakes[13,16,17]. Advanced space borne thermal emission and reflection radiometer (ASTER) is also used for this purpose. In China, Chinese geostationary meteorological satellite FY-2C/2E has been used. In very few studies, data from microwave remote sensors have also been used as they can penetrate clouds, but their availability is limited to a few areas. In India, the OLR data from Kalpana satellite launched by ISRO are readily available from IMD and are used here. It may, however, be mentioned that temperature observations from surface weather observatories located in the epicentral region provide more reliable data under all weather conditions without any errors arising due to calibration in remote sensing data. Keeping in view the errors reported between OLR-derived observations and surface temperatures, howsoever small (up to + 2°C or so), we prefer to make use of emissivity as measured directly by satellites prior to the 2011 Sikkim earthquake or heat-wave conditions over North India, keeping in view similar approach adopted by many workers[18,19]. Higher values of emissivity are indicative of higher heat or temperature, and vice versa.

Hypocentral data of earthquakes and thermal variation

The hypocentral parameters of earthquakes in India and its neighbourhood, whose thermal anomalies have been discussed in this article, are taken either from the United States Geological Survey (USGS) or IMD (Table 1). Although M_w magnitudes are considered more reliable, they are available from broadband seismographs only recently. Conversion from one magnitude scale to another introduces large errors due to which the magnitudes as reported by USGS have been given in Table 1. The INSAT OLR thermal anomaly during the 2011 Sikkim earthquake is given in Figure 2 *a–c*. The time series of surface temperature data for different earthquakes is shown in Figures 3–10 for the full month during the occurrence of each earthquake. OLR thermal anomaly detected through INSAT during heat-wave conditions over northern India is shown in Figure 11. The thermal anomalies prior to these earthquakes are analysed separately for the Himalayan region and peninsular India due to difference in tectonics.

Himalayan region

The 2011 Sikkim earthquake: The Sikkim earthquake of 18 September 2011 (M_w 6.9), occurred near the eastern Nepal–Sikkim border and took a toll of human lives in Sikkim and adjoining countries of Nepal and Tibet. Its aftershocks reported by IMD were found to be distributed mainly along Tiesta lineament. The mechanism of this earthquake showed strike–slip faulting. Satellite OLR thermal anomaly using INSAT data was examined for this earthquake from 1 to 20 September 2011 (Figure 2 *a–c*). OLR pictures showed almost similar spatial variation of thermal anomaly on all the days preceding the earthquake. It may be noted that the lowest values of the order of 150–200 W/m^2 were found over northeast India, including Sikkim where the earthquake occurred. Although no temperature data from any surface observatory in Sikkim are available from IMD, the lowest values in the region for directly measured emissivity from satellite suggest that for magnitude 6.9 earthquake, there is lowest emissivity or heat emitted and consequently lowest temperature near and around the epicentre contrary to the rise in emissivity or temperature prior to a few other earthquakes reported earlier[13,16–20]. On the other hand, the emissivity or heat emitted increased to about 300 W/m^2 over Pakistan, Arabia and North Africa and as far as near Australia, where no significant earthquake occurred. It

Table 1. List of hypocentral parameters of earthquakes in India and its neighbourhood

Date (DD/MM/YYYY)	Epicentre (°N/°E)	Origin time (HH : MM : SS.S) UTC	Magnitude	Focal depth (km)	Region
18/09/2011	27.73/88.15	12 : 40 : 51.0	6.9 M_w	50	Sikkim
8/10/2005	34.46/73.58	03 : 50 : 39.0	7.6 M_w	19.1	Muzaffarabad
28/03/1999	30.45/79.38	19 : 05 : 11.0	6.5 m_b	21 (IMD)	Chamoli
19/10/1991	30.73/78.78	21 : 23 : 15.0	6.8 m_s	12 (IMD)	Uttarkashi
20/08/1988	26.73/86.59	23 : 09 : 11.0	6.9 m_s	61.9	Nepal–India border
19/01/1975	32.37/78.49	01 : 59 : 00.0	6.9 m_s	Normal (0–30)	Kinnaur
26/01/2001	23.4/70.28	03 : 16 : 41.1	7.6 M_w	16	Bhuj
21/05/1997	23.06/80.08	22 : 51 : 30.0	5.6 m_s	35	Jabalpur
29/09/1993	18.07/76.48	22 : 25 : 51.0	6.1 m_s	6.8	Latur
13/04/1969	17.83/80.68	15 : 24 : 54.0	5.7 m_s	10	Bhadrachalam

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may be of interest to note that such low values of emissivity as observed near Sikkim occur during the onset of monsoon over Kerala and are a diagnostic tool along with other meteorological parameters. The low emissivity values over Sikkim and its neighbourhood in September 2011 are attributed to the monsoon current which had yet to withdraw from the region.

The 2005 Muzaffarabad earthquake: The devastating earthquake of 8 October 2005 (M_w 7.6) occurred in Pakistan and adjoining Kashmir with its epicentre near Muzaffarabad. More than 85,000 people lost their lives, besides extensive loss to property. This earthquake occurred at the western end of the Indian–Eurasian plate interface. Its focal mechanism showed the fault plane oriented NNW dipping towards northeast with thrust-type movement (IMD). Its aftershocks were spread over an area of about 4000 sq. km. The temperature data at the nearest IMD station at Srinagar was utilized to study thermal anomaly for maximum and minimum temperatures during the years 2003, 2004, 2005 and 2006 (Figure 3). Although there was a slight increase in temperature preceding the 2005 earthquake, similar rise in temperature from 1 to 10 October also occurred in 2006 when no earthquake had occurred.

The 1999 Chamoli earthquake: This earthquake occurred on 29 March 1999 (m_b 6.5) in Uttarakhand. Its focal mechanism showed thrust faulting with the fault plane trending WNW–ESE dipping at shallow angle (USGS). The aftershock area was estimated as 510 sq. km (ref. 21). The NCAR data for this earthquake at the nearest grid point of 30°N, 80°E roughly 50–60 km from the epicentre showed a temperature variation of 278–281°K from 1 to 11 March 1999, which fell to 273–275 K on 12 and 13 March 1999. Thereafter, it increased to 284 K only for a day and then started falling till the occurrence of this earthquake and later during the aftershocks up to the end of the month (Figure 4). Saraf *et al.*[20] reported 14°C temperature near Chamoli on 14 March 1999 compared to 11°C from NCAR data. This difference between satellite-derived NOAA-AVHRR and NCAR temperatures is attributed to the difference in the coordinates of Chamoli and grid-point extrapolation. It is interesting to mention that Saraf *et al.*[20] suggested that the thermal line southeast of this earthquake is of different nature and associated with high heat flux and higher tectonic stress near the frontal thrust. They inferred that thermal anomaly near Chamoli could have been shrouded due to the presence of high ruggedness in the terrain, vegetation cover and unsteady meteorological stations.

The 1991 Uttarkashi earthquake: This earthquake of 20 October 1991 (m_s 6.8) caused havoc in Uttarkashi and its neighbourhood in Uttarakhand and took a toll of about 800 lives. Its aftershocks were spread over an area of about 1200 sq. km. Its focal mechanism was of thrust type with the fault plane oriented northwest dipping at a shallow angle towards northeast (IMD). The temperature anomaly was at grid point 30°N, 80°E interpolated from NCAR point data available nearest to the epicentre (Figure 5). It may be noticed that prior to the occurrence of the earthquake, the temperatures were much higher only in the first week and then fell remarkably. It again started fluctuating with rise and fall and again started rising slightly even after the occurrence of the earthquake on 20 October 1991.

The 1988 Nepal–India border earthquake: This earthquake occurred on 20 August 1988 (m_s 6.9) near Nepal–India border with a focal depth of about 62 km. The Geological Survey of India associated this earthquake with Patna fault in conformity to its strike–slip focal mechanism[22]. NCAR (USGS) data during August 1988 at the grid point lat. 27.5°N and long. 87.5° showed a temperature variation of 288–289 K, which decreased by 2 K from 18 October till the earthquake occurred (Figure 6).

The 1975 Kinnaur earthquake: This earthquake (m_s 6.9) occurred on 19 January 1975 near Kinnaur, which caused

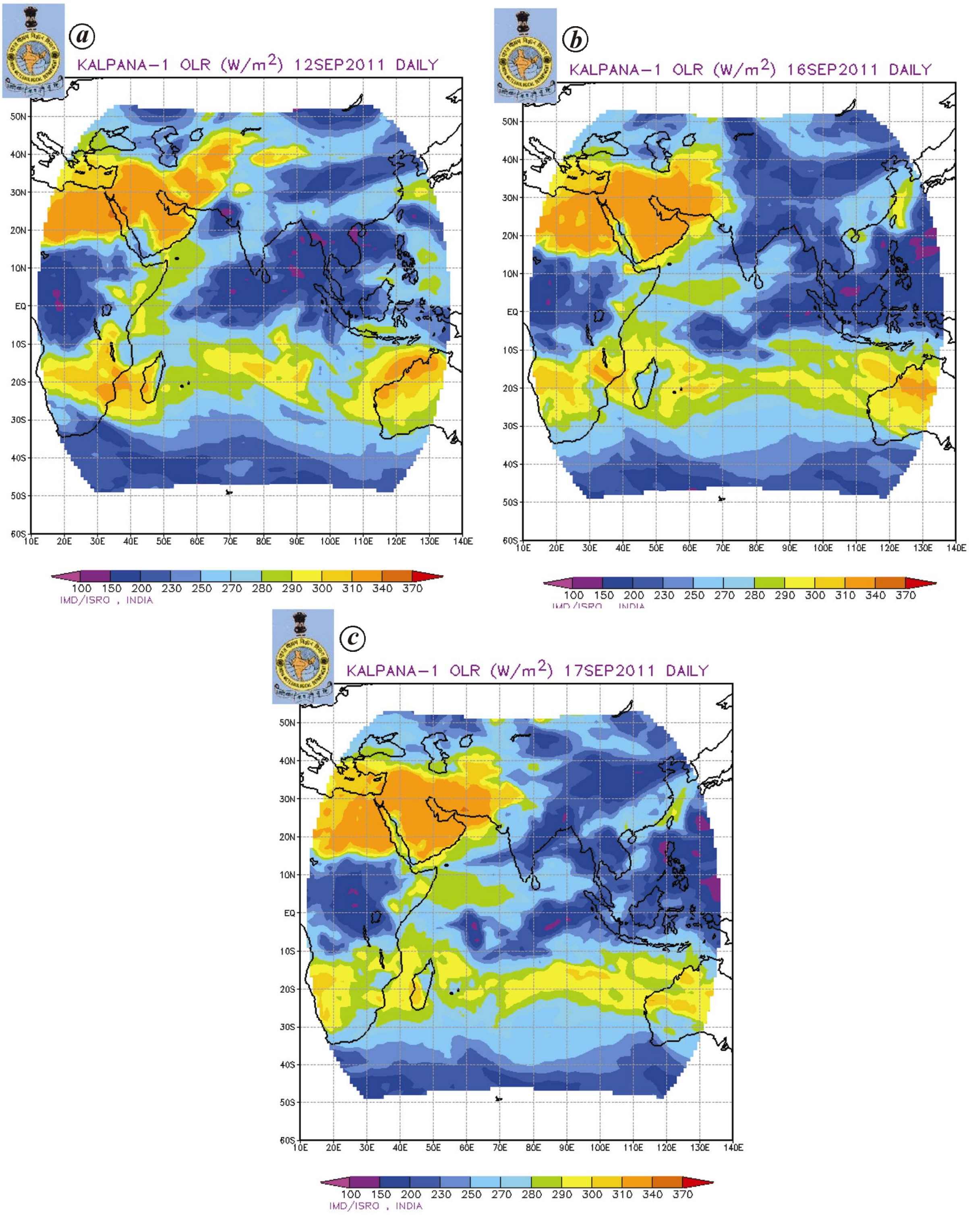

Figure 2. Emissivity (OLR in W/m^2) over India (including Sikkim) and neighbouring countries; ***a***, 12 September; ***b***, 16 September; ***c***, 17 September.

extensive damage and loss of life in Himachal Pradesh. The fault plane solution was normal type with the nodal plane oriented towards NNW dipping towards northeast[23]. The aftershocks were spread over an area of about 2000 sq. km. The NCAR data extracted at grid point lat. 32.5° and long. 77.5°E showed temperatures of 262 to 265 K from 1 to 9 January 1975. This temperature decreased by only 2K on 14 and 15 January. It again rose almost to the same level of 262–263 K and continued till the occurrence of the earthquake (Figure 7).

Peninsular India

The 2001 Bhuj earthquake: The Bhuj earthquake of 26 January 2001 (M_w 7.6) caused death of about 20,000 persons and huge property loss. Major destruction also occurred at about 250 km away at Ahmedabad and further away at Surat particularly in tall buildings. Its focal mechanism showed reverse fault oriented almost east west and south-dipping Kutch mainland fault. The aftershocks were spread over an area of 3100 sq. km (ref. 24). Since this earthquake was earlier reported to have been preceded by satellite thermal anomaly[13], the temperature data for Bhuj observatory (IMD) in the meizoseismal area nearest to its epicentre were re-examined. It was noticed that the order of increase in temperature at Bhuj was within the synoptic variability observed in other years such as 2014 (Table 2). The highest maximum temperature of 44.4°C at Bhuj was reported on 29 April 2014, without being preceded by any earthquake. Similar

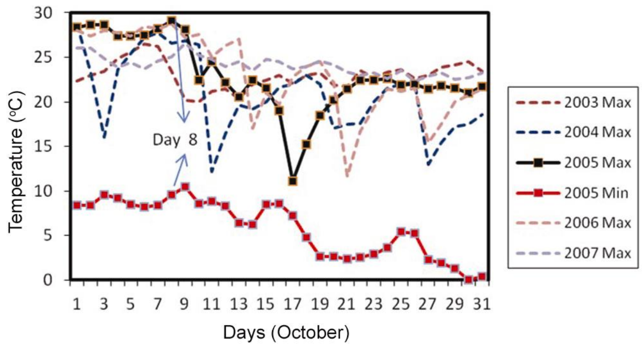

Figure 3. Maximum and minimum temperature variations over Srinagar during 2003–2007.

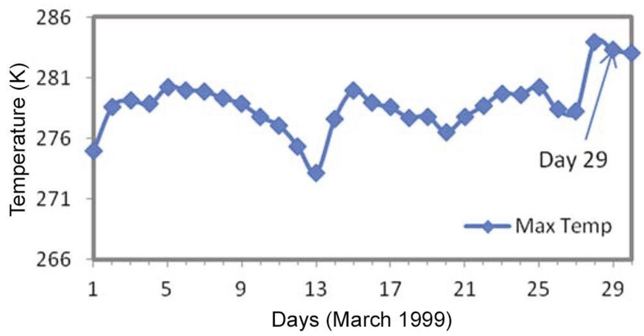

Figure 4. Temperature variation at the nearest grid point to the epicentre of the 1999 Chamoli earthquake.

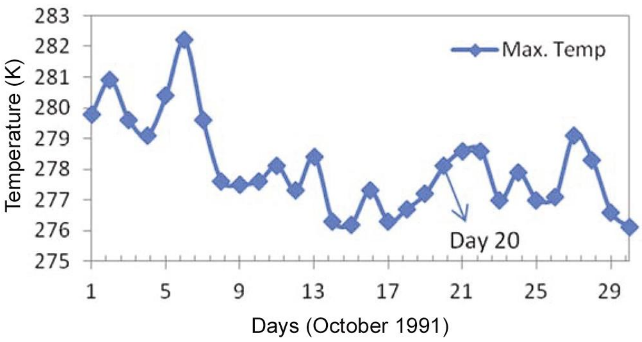

Figure 5. Temperature variation during October 1991 Uttarkashi earthquake at grid point 30°N, 80°E based on NCAR data.

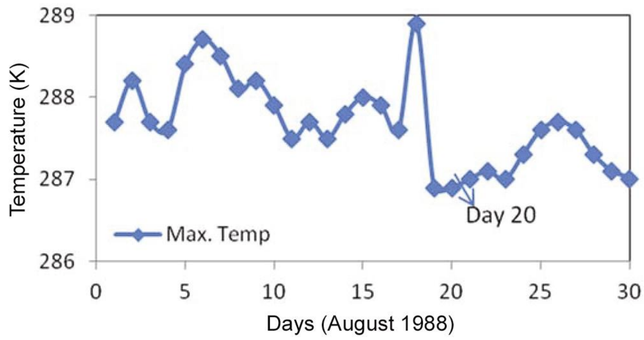

Figure 6. Temperature variation during August 1988 Nepal–India border earthquake at grid point 27.5°N, 87.5°E based on NCAR data.

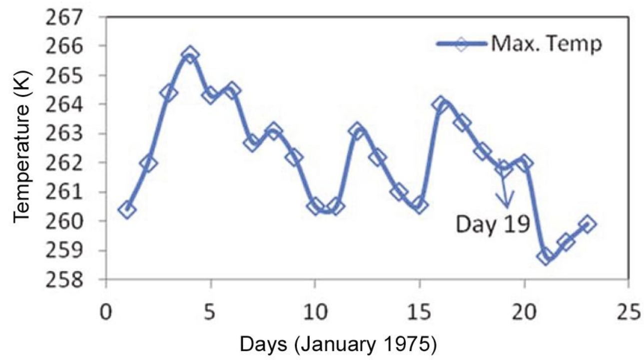

Figure 7. Temperature variation at grid point of 32.5°N, 77.5°E during the January 1975 Kinnaur earthquake (NCAR data).

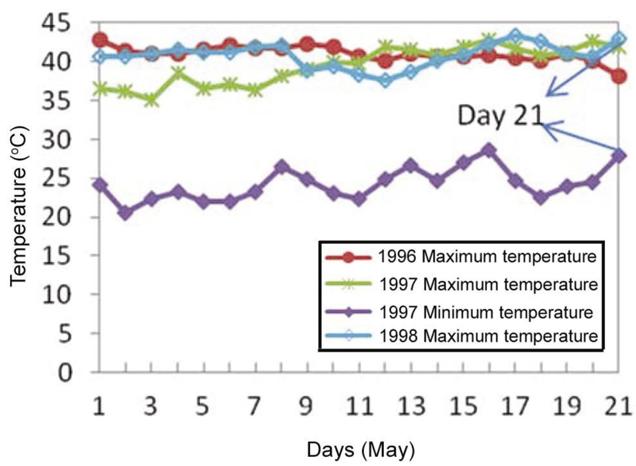

Figure 8. Daily variation of maximum and minimum temperatures during May 1997 at Jabalpur.

was the case in 28 April 1970 (45.4°C), 25 May 1954 (46.7°C) and 2 June 1889 (46.1°C) when the maximum temperatures reached higher values.

The 1997 Jabalpur earthquake: This earthquake struck Jabalpur and adjoining areas in Madhya Pradesh in the early hours of 22 May 1997 (m_s 5.6). The earthquake had deeper focal depth about 35 km and was associated with Son–Narbada fault[25]. Its focal mechanism solution showed a thrust fault with some strike slip component oriented almost vertical, i.e. 80°. The aftershocks were confined to a small area of about 380 sq. km. The data of meteorological station at Jabalpur within the meizoseismal area were used to examine the thermal anomaly prior to the earthquake. Comparison of maximum temperatures during 1996, 1997, 1998 with the mean maximum temperature (1901–2000) of 41.3°C, shows that there was no significant rise above the normal at Jabalpur when the earthquake occurred. The fall in the maximum temperature in the first half of the month in 1997 is attributed to cloudy conditions and short spells of rainfall, which gradually started rising and then fluctuating within a narrow range in 1997 as well as 1998 (Figure 8). Still higher temperatures were recorded on 28 April 1970 (45.4°C), 25 May 1954 (46.6°C) and 2 June 1889 (46.1°C). The minimum temperature in May 1997 shows two maxima with a fall in temperature and then slight increase, displaying ambiguous trend.

The 1993 Latur earthquake: This shallow focus earthquake (m_s 6.1) occurred in the districts of Latur and Osmanabad in Maharashtra (Table 1). It caused extensive damage to rural dwellings and loss of about 7600 lives. Its aftershocks were confined to about 700 sq. km with depth of foci not exceeding about 15 km. The focal mechanism of this earthquake showed thrust faulting. The nodal plane striking about 120° and dipping at about 40° towards south was taken as the fault plane. Thermal anomalies were studied from the meteorological observatory (IMD) located in the meizoseismal area at Osmanabad. No thermal anomaly was found preceding this earthquake at this station (Figure 9). The mean maximum and highest maximum temperatures were lower by 2°C or more in September 1993 compared to 1991 and 1994,

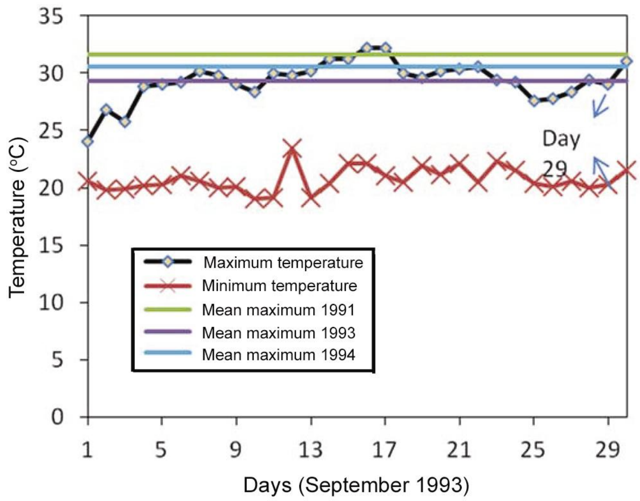

Figure 9. Maximum and minimum temperatures at Osmanabad during September 1993.

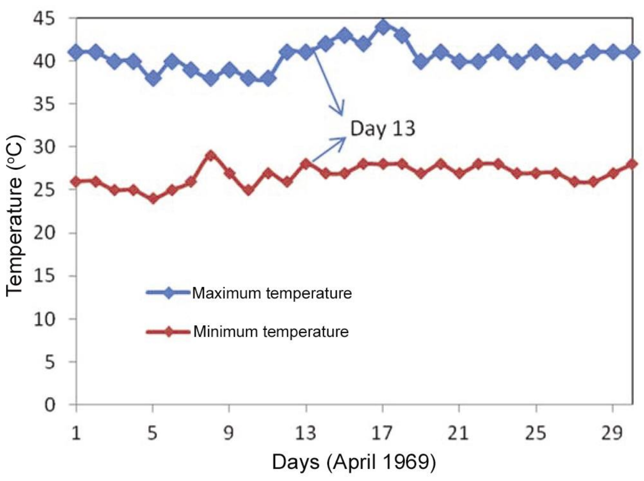

Figure 10. Maximum and minimum temperatures at Khamam during April 1969.

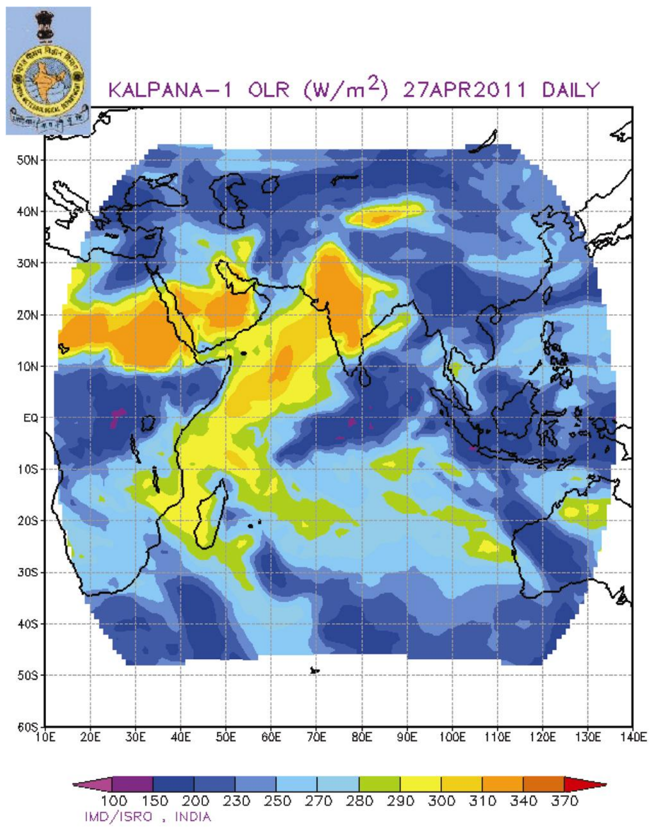

Figure 11. Heat-wave condition in India (27 April 2011; OLR in W/m^2).

Table 2. Maximum and minimum temperatures at Bhuj during January 2001 and 2014

	January 2001		January 2014	
Date	Maximum temperature (°C)	Minimum temperature (°C)	Maximum temperature (°C)	Minimum temperature (°C)
1	26	13	21	7
2	25	12	22	10
3	23	12	26	13
4	24	12	27	10
5	26	11	28	13
6	26	12	26	10
7	28	13	27	11
8	25	11	29	12
9	24	11	24	11
10	23	11	22	10
11	25	12	21	9
12	26	12	24	11
13	27	14	25	9
14	27	13	25	11
15	26	13	25	10
16	26	12	27	10
17	27	12	25	13
18	28	12	28	12
19	29	14	27	11
20	29	15	25	12
21	30	16	26	12
22	27	16	27	12
23	27	13	26	12
24	25	11	27	12
25	26	11	28	11
26	27	12	29	12
27	++	++	30	14
28	++	++	32	13
29	++	++	32	14
30	++	++	31	14
31	++	++	32	15

++Observations after 26 January 2001 were suspended because of damage to the observatory due to the 2001 earthquake.

when earthquake occurred. Also, an increase in temperature by 2°C was observed in 1993 at Osmanabad for 10 days immediately after the earthquake, but not prior to it.

The 1969 Bhadrachalam earthquake: This earthquake occurred near Godavari basin (m_s 5.7). It took place along a fault, striking N63°E, dipping 64° towards north. The motion was left lateral strike slip[26]. The maximum temperature recorded at Khamam observatory in the meizoseismal area showed that the temperature of 40–41°C during 1–3 April 1969 started falling to about 38°C. It rose to 40.6°C on 12 and 13 April 1969 and increased to 43.6°C on 17 April, i.e. four days after the occurrence of earthquake (Figure 10). The minimum temperature also followed the same trend with the highest minimum on the same day (17 April). Similar variations in temperature were also recorded during April 1970 during non-seismic condition. The highest maximum temperatures of 46.4°C, 48.6°C and 46.8°C were recorded at this observatory on 29 April 1973, 9 May 1973 and 7 June 1958 respectively, but no earthquake occurred.

Discussion

The results presented in this study show that OLR thermal anomaly from INSAT was the lowest at or near the epicentre in September 2011 prior to the Sikkim earthquake, which had a magnitude of 6.9 (M_w). It is also interesting to note that during heat-wave conditions caused by prolonged absence of rain in summer in North India, thermal anomalies commonly appear without any seismic activity. Cases of highest maximum temperature were therefore examined to check if any significant earthquake was recorded prior to the heat-wave conditions. As discussed later, no seismic activity was observed prior to the maximum temperatures recorded in different regions in India. Thermal anomalies during heat-wave conditions over India were also examined through OLR data recorded by INSAT (Figure 11). It was noticed that extensive thermal anomalies not only occurred in northwestern India, but also over a small portion of the northern part of the Arabian Sea and over a large part of the African desert on the same days in April.

However, there was no seismic activity near any of these anomalous zones. Thus anticipation of any earthquake under such conditions would be misleading and may raise false alarms.

We now examine four earthquakes, namely Latur (1993), Bhuj (2001), Jabalpur (1997) and Muzaffarabad (2005), which were reported to be preceded by thermal anomalies based on satellite data[4,8,13]. During the Latur earthquake (1993), the temperature started increasing from 24°C to 34°C from 1 September to 17 September 1993. Although the rise in temperature during this period was 10°C, no earthquake occurred. Thereafter, temperature started decreasing to 28°C and then only marginally increased by 2–3°C when this earthquake occurred (Figure 9). The maximum temperature during this month was even lower in 1991 than the mean maximum monthly temperature. Thus a single-day observation from Landsat 5 TM band 6 in thermal band 10.4–12.5 μm of 20 September cannot be considered as precursory, as the temperature on two earlier days, i.e. 17 and 18 September 1993 was higher and it started falling later[27]. In the case of Bhuj earthquake (2001), Saraf and Choudhury[13] reported that on 23 January 2001, the temperature was 5–7°C higher than normal in the epicentral region of this earthquake, with the maximum temperature of about 31°C in the region on the same day. Table 2 gives surface temperatures recorded in the epicentral region at Bhuj during 2001 and 2014. The highest temperature of 30.5°C at Bhuj occurred on 21 January 2001 and not on 23 January as inferred by the authors[13]. It fell markedly to 25–25.6°C on 24 and 25 January 2001 which is 2°C to 3°C below normal (27°C). On the day the earthquake occurred, the temperature rose to normal, i.e. 27°C. The maximum temperature in 2014 remained even higher than that in 2001 (around 30–32°C), consistently for five days from 26 to 31 January. Between 1 and 5 January also, there was a rise in 6°C in the minimum temperature from 7°C to 13°C and a rise of 7°C in the maximum temperature. Yet, no earthquake occurred near Bhuj in 2014. Mean maximum temperature of 28–30°C (higher than the normal maximum temperature) in January also occurred in the years 1965, 1966, 1972, 1981, 1983, 1988, 1990, 1993 and 2000 without any seismic activity. The mean temperatures at Ahmedabad were also examined since this station was included by Saraf and Choudhury[13] to corroborate the spatial extent of the anomalous zone. It was found from the data recorded at IMD that during the years 1909, 1912, 1914, 1939, 1949 and 1990, the maximum temperature in January was about 31°C at Ahmedabad, but no earthquake occurred. These results were corroborated by Blackett *et al.*[9], who did not find convincing evidence of LST precursors to the Bhuj 2001 earthquake. They also cautioned that such claims are due to bias in isolating earthquake thermal anomalies. However, Gunzano *et al.*[28] suggested a technique for monitoring thermal anomaly in seismically active areas by taking the case of the 2001 Bhuj earthquake after considering seasonal variations. But the limitation of the method is obvious from the fact that sudden changes in weather caused by synoptic conditions or dynamic systems cannot be taken into consideration in relation to future earthquake activity. This is also obvious from the fact that a decrease in temperature in Bhuj area was found by their method on 25 January, while the trend in fall of temperature continued from 21 January till the occurrence of the earthquake. Somewhat similar trend in temperature variation was recorded as far as Delhi, where temperatures of 23.2°C and 23.5°C on 21 and 23 January 2001 respectively. It also decreased to 19.4°C and 19.7°C on 24 and 25 January respectively. From 26 January the temperature started increasing from 21.6°C to 27.2°C, i.e. 6°C rise during the next six days, but without any seismic activity near Delhi, if an analogy with Bhuj temperatures is made. The maximum temperature of 43°C at Delhi occurred on 26 May 2001 without any seismic activity. The other major earthquake of 21 July 1956 in Anjar, near Bhuj, occurred when the mean monthly maximum temperature was 30.5°C, while highest maximum of 35°C was recorded on 1 July 1956. Compared to this, higher temperature were recorded in June 1956 (mean maximum 35.9°C and highest on 4 June 1956). In the case of the 1997 Jabalpur earthquake, the interpretational ambiguity[4] is obvious from temperature plot of the Jabalpur observatory located in the epicentral region (Figure 8) for three consecutive years, where the maximum temperatures tend to converge to mean maximum normal temperature of 41.3°C. The fluctuating minimum temperature with two similar maxima also brings out inconsistency to relate it with the earthquake of 1997, rather than atmospheric or synoptic perturbations.

As mentioned earlier, Srinagar being located in the Himalayan valley shows maximum changes due to orographic effect besides western disturbances causing very large variations in temperatures (Figure 3). The temperatures during October 2004 jumped from 16°C to 27–28°C, reaching same maximum value as in 2005 and 2006; yet no earthquake occurred in 2004. Although normal mean maximum temperature during October is 22°C, the maximum ever recorded at Srinagar is 36°C, i.e. 6–7°C higher than in 2004, 2005 and 2006. Thus, the inference[4] that air temperature data of Srinagar support the observations made through MODIS LST data is erroneous. This is further supported by insignificant rise in temperature prior to the 1999 Chamoli earthquake, by this study as that well as by Saraf *et al.*[20] under similar tectonic set-up. Very large variations (rise and fall) in temperature near the ground occur many times in a year at Srinagar or any other station in India (National Data Centre, Pune), but without any seismic activity. Intra-seasonal oscillations of 10–20 days and 30–50 days in meteorological parameters further cause marked changes in thermal anomaly[29].

The earthquake in Bhadrachalam (1969) of magnitude m_s: 5.7 near Godavary rift also did not record notable rise in temperature at Khamam, which is located in the epicentral region. However, Saraf *et al.*[6] reported temperature variations over a very large area in the Himalaya prior to a small magnitude earthquake (5.0) in Yamnotri (22 July 2007), while anomalous areas for Ravar earthquake (2004) though of magnitude 5 only is slightly larger than Dalbandin (Pakistan 2011) earthquake of 7.2 magnitude. The smallest Yamnotri earthquake (*M*5) also showed the largest temperature variation of 5–13°C commonly observed at any hilly station. Closer examination of their data suggests that there is no justification to relate thermal anomaly over the Tibetan plateau as precursory, which is far away from the focal zone. This is also contradictory to their earlier results that the aftershocks were coincident with the anomaly area in spatial position[4]. The elevated Tibetan plateau gets copious heat during summer months which affects monsoon circulation pattern. This gives rise to large thermal anomaly depending upon the atmospheric circulation. Contrary to small area of temperature anomalies reported for a 7.6 magnitude Bhuj earthquake, Wei *et al.*[30] suggested that the thermal anomalies are at least tens of thousands of square kilometres and their size has nothing to do with the magnitudes of earthquakes. Similar inference can also be drawn from the results reported for Yamnotri, Ravar and Dalbandin earthquakes[6].

Well-marked thermal anomalies during heat-wave conditions in North India[10] during summer months and their synoptic variations should desist earth scientists to make false alarms. It may also be interesting to examine data of maximum temperatures with reference to earthquake activity over different parts of India. Maximum temperatures of 46–47.5°C have been recorded at New Delhi (Palam) during April–July with a maximum of 47.5°C on 6 May 1984 and in May 2014; Jabalpur on 25 May 1954 (46.7°C), Bhadrachalam on May 1973 (48.6°C) and at Bhuj on 26 May 1886 (47.8°C) and at several other stations in India, but without any seismic activity. The highest maximum temperature of 41.4°C occurred at Dhubri on 21 April 1939, but the earthquake (*M* 7) at this place occurred many years earlier on 2 July 1930. If we confine our attention to a single station, New Delhi in different months, say 2001, it can be noted that the range of maximum temperature varied from 12.4°C to 27.2°C in January, 21°C to 29.3°C in February, 26.0°C to 34.9°C in March, 29.4°C to 41.0°C in April, 27.9°C to 44.5°C in May, 32.0°C to 39.5°C in June, 30.0°C to 38.0°C in July, 28.2°C to 37.4°C in August, 33.6°C to 38.3°C in September, 32.0°C to 37.0°C in October, 25.0°C to 35.0°C in November, and 16.3°C to 28.0°C in December. The large variations (about 5°C to 16°C) and rise in temperatures in different epochs suggest that many earthquakes occurred near Delhi in a single year if thermal anomalies are presumed to be related to earthquakes. Similar results are also seen at Bhuj and any other station in India and worldwide. Saradjian and Akhoondzadeh[17] reported thermal anomalies 1–20 days before a few earthquakes, but pointed out that the detected thermal anomalies can be related to non-seismic events. Okyay[31] surmised that utilizing LST anomalies based on the 2003 Turkey earthquake observed by MODIS/Terra satellites would not be adequate and feasible since every LST anomaly is not followed by an earthquake. Qu[16] found seasonal appearance of such thermal anomalies over Mongolia when examining two years' NOAA 16 satellite data prior to the earthquake of 24 March 2004 (M_s 5.9). It was concluded that such anomalies are probably caused by atmosphere temperature inversion phenomena instead of earthquakes. All the precursory thermal observations reported prior to earthquakes in Iran[2,13] are also attributed to the passage of western disturbances which originate near the Mediterranean Sea. Zhang *et al.*[32], applying power spectrum technique to the Japan (*M* 9.0) and Myanmar (*M* 7.2) earthquakes in March 2011, found thermal anomalies about six months before the earthquakes. But their results showed that the anomaly disappeared several months prior to both these earthquakes, bringing out limitations of the method. The authors inferred that deep study of non-seismic factors is still lacking. Blackett *et al.*[9] also urged care in the use of approaches at identifying such thermal anomalies. On reviewing most of the cases reported as precursory thermal anomalies worldwide, including those discussed above, the following inferences are drawn:

- Thermal anomaly does not always precede an earthquake, even for a large earthquake like Sikkim 2011. This was corroborated by Okayay[31].
- The size of thermal anomaly does not depend upon the magnitude[6,30] or the focal depth of the earthquake.
- Thermal anomaly need not necessarily be located near the impending epicentre[6].
- The time of occurrence of thermal anomaly may be a few months to a few hours without any relationship with the magnitude of the earthquake.
- Thermal anomaly once shown a few months before the earthquake for a day or so, may disappear and not reappear again, but is taken as a precursor for the earthquake[32].
- Thermal anomaly may show a fluctuating (rise or fall) trend a few times before earthquakes and is transient in nature[19]. Any physical process like heat flux should be sustained continuously till the phenomenon.
- In some cases, thermal anomaly persists after the earthquake while in others it disappears earlier or soon after, although aftershock activity continues for days or months[8,13,33].
- The rise of temperature deduced from OLR data is of the order of 2–13°C or so; maximum rise

being reported for the smallest earthquake in Yamnotri[6].

- Sometimes anomalous zone is taken to coincide with the aftershock area, but mostly not related with its size or magnitude of the earthquake. This is contrary to scale invariant theory that larger the magnitude, larger is the area of aftershocks[15] and the length of faulting[27].
- The size and range of rise of OLR or temperature is not related to local geology, tectonics or mechanism of earthquake[6,18].
- The number of earthquakes occurring worldwide on the same day has been ignored, restricting to a particular earthquake. Also, whether thermal anomaly has been observed in other areas but no earthquake occurred on the same day.
- The number of earthquakes increases according to Gutenberg–Richter magnitude relation, but other earthquakes of similar magnitude have been excluded for the OLR study.
- The heat-wave conditions and dynamic weather systems giving even larger changes in temperatures have not been considered so far, except in the present study cautioning false alarm.
- None of the studies undertaken so far has shown any distinctive parameters like dominant frequency through spectrum analysis or any other method to differentiate the rise in temperature prior to the earthquake from that due to synoptic weather variability.

Ouzounov and Freund[34] compiled many propounded theories to explain thermal anomalies before earthquakes such as: (i) piezoelectric and elastic strain dilatation theory, (ii) rising fluids leading to seepage emitting warm gases, (iii) transient high in thermal conductivity profile of subsurface rocks, (iv) rising water levels, (v) CO_2 spreading laterally causing local greenhouse effect, (vi) seismo-ionospheric coupling, and (vii) p-hole activation. According to Ouzounov *et al.*[18] 'the cause of this phenomenon is not fully understood; one possible explanation is the existence of thermal outgoing radiation as a result of near ground ionization and latent heat change due to change of air humidity and temperature. This phenomenon is hypothesized to be part of a relationship between tectonic stresses, electrochemical and thermodynamic processes in the atmosphere and increasing mid IR flux, all part of a family of electromagnetic (EM) phenomena related to earthquake activity', have also been suggested to cause thermal anomaly. However none of the above explanations has yet been found acceptable[5]. This is because thermal anomaly as earthquake precursor neither obeys scale invariant theory nor the dilatation diffusion model, or any established physical mechanism. The evidence presented in this article suggests to discontinue the search for thermal anomalies prior to earthquakes in non-volcanic areas of the world.

Conclusion

The present study brings out the following conclusions:

1. No significant thermal anomaly was found preceding the earthquakes in 1969, 1988, 1991, 1993, 1997, 1999, 2001, 2005 and 2011 located in the Himalayan region or peninsular India. The OLR thermal anomaly based on INSAT data was not seen prior to the 2011 Sikkim earthquake.
2. The thermal anomalies reported prior to Latur (1993), Jabalpur (1997), Bhuj (2001) and Muzaffarabad (2005) earthquakes as inferred by earlier workers, are not supported by data from meteorological observatories located in the epicentral region. Also, their results cannot be relied upon as they have not considered meteorological variability in different years or the role of dynamic weather systems which cause sudden and very large changes in temperature.
3. Much larger thermal anomaly reported from satellite imagery for a magnitude 5 earthquake in a hilly place like Yamnotri far away from the focal zone brings out inherent weakness in the methodology when compared to much larger earthquakes in Pakistan, Muzaffarabad, 2005 (7.6) and Bhuj, 2001 (7.6), which produced smaller areas of thermal anomaly. Since earthquake occurrence follows scale invariant theory, such discrepancy is attributed to much larger synoptic and dynamic weather causes, rather than tectonic stresses.
4. The persistence of heat waves over northern India and their large synoptic variability should also desist earth scientists from raising false alarms based on satellite thermal anomaly.

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