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ORIGINAL ARTICLE

Spatial-temporal variation of the land surface temperature field and present-day tectonic activity

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Earthquake

Abstract This study attempts to acquire information on tectonic activity in western China from land surface temperature (*LST*) field data. On the basis of the established relationship between heat and strain, we analyzed the *LST* distribution in western China using the satellite data product MODIS/Terra. Our results show that: 1. There are departures from annual changes of *LST* in some areas, and that these changes are associated with the activity of some active tectonic zones. 2. When annual-change background values caused by climate factors are removed, the long-period component (LST_{LOW}) of temperature residual (ΔT) of the *LST* is able to serve as an indicator for tectonic activity. We have found that a major earthquake can produce different effects on the *LST* fields of surrounding areas. These effects are characterized by both rises and drops in temperature. For example, there was a noteworthy temperature decline associated with the Sumatran *M*9 earthquake of 2004 in the Bayan Har-Songpan block of central Tibetan Plateau. 3. On the other hand, the *LST* field of a single area may respond differently to major shocks occurring in different areas in the regions surrounding China. For instance, the Kunlun *M* 8.1 event made the *LST* on the Longmen Mountains fault zone increase, whereas the Zaisan Lake *M* 7.9 quake of 2003, and the Sumatran *M* 9 event of 2004, caused decreases in the same area's *LST*. 4. The variations of land surface temperature (*LST*) over time are different in different tectonic areas. These phenomena may provide clues for the study of tectonic deformation processes. On the basis of these phenomena, we use a combination of temperature data obtained at varied depths, regional seismicity and strain results obtained with GPS

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measurements, to test the information related to tectonic activity derived from variations of the *LST* field, and discuss its implications to the creation of models of regional tectonic deformation.

1. Introduction

1.1. Study significance, approach and previous work

The tectonic activities are accompanied with material movements and energy transfer, which must change the state of thermal radiation on the ground. Thus it is possible to infer present-day tectonic activities based on variations of the thermal radiation state on the ground derived from the satellite data. Earthquake preparing is a transient dynamic process. The traditional observations at a point or in a small area cannot see the temporal and spatial process in whole. Thus earthquake monitoring needs urgently new methods that are conducted both at stations and in the field continuously in a real-time manner.

The satellite infrared data shows a great advantage in this issue. Satellite measurements provide researchers with information on both points and fields which cannot be acquired by ground investigations and station observations. Because satellite missions can be quickly repeated, their data can exhibit processes of variation in time which static aerial photographs, by contrast, cannot. The received satellite infrared information is, however, likely influenced by many kinds of factors. Therefore, the first problem needs to be solved is to extract information associated with tectonic activities and eliminate effects of non-tectonic factors.

Since the end of the 1980s, many researchers made effective efforts to study the relationship between thermal infrared information obtained via satellite and earthquakes, as can be seen in the representative work of В.И.Горный и др (1988), the following reports by Qiang et al. (1990), and others (Xu et al., 1991; Cui et al., 1993; Geng et al., 1993; Morzova, 1996; Tronin, 1996; Deng et al., 1997; Morzova, 1997; Wu and Wang, 1998; Liu et al., 1999; Tronin, 1999; Morzova, 2000; Freund, 2002; Ouzounov and Freund, 2004).

Previous studies on this problem took precursors of major earthquakes as their goals. It is, however, very difficult to test and compare various interpretations of this data. It is generally accepted that earthquakes are generated by fast motions along faults. We have shifted our attention toward a more comprehensive approach, which is to explore the relationship between thermal information from satellite data and tectonic activity, and then provide verification by using further lines of evidence obtained from other types of observations (Ma and Shan, 2000; Ma et al., 2006b). Therefore the shift of research focus from seeking seismic precursors to monitoring processes of active faults will provide more chance to utilize infrared information and more definite physical evidence for the efforts of earthquake prediction.

Our methods are as follows: firstly, we analyze the compositions of thermal infrared information obtained via satellite, remove data unrelated to tectonic activity, determine which data are correlated with tectonic processes, and accentuate this data using several methods (Liu et al., 2004b; Chen et al., 2006). Secondly, we study the relationship between strain and heat through laboratory experiments and theoretical analysis (Liu et al., 2004a, 2007; Ma et al., 2007, 2008; Chen et al .,2009a). Thirdly, we analyze data on ground temperature at varied depths collected by meteorological bureaus and conduct real-time temperature measurements in the shallow subsurface in a presumably meaningful area (Liu et al., 2006; Liu et al., 2009). Finally, we compare the surface data and satellite information, and establish the possible relationship between these two kinds of observations.

1.2. Data processing

Due to many influential factors, the land surface temperature (*LST*) derived from satellite observations can be divided into several components. Among them, the stable component (T_0) and annual changing component (T_a) compose the normal annual variation field, with changing amplitudes of several tens of degrees. These components are associated with solar activity and the subsequent responses of objects on the ground, and do not contain information on tectonic deformation (Chen et al., 2004, 2009b). Besides, there is a strong negative correlation between elevation and T_0, and the influence of relief on T_0 is relatively small in winter and large in summer (Guo et al., 2004).

The temperature variation related with tectonic activity is probably contained in the temperature residual (ΔT) after the normal annual variation field is subtracted from the total field (Eq. (1)). As a randomly varying component, ΔT is influenced by many factors, such as sunspots, atmosphere, monsoons, vegetation, human activity, and the Earth's internal activity. Short-term variations in ΔT are usually produced by climate changes, while long-term variations may contain thermal information associated with tectonic activity and can thus serve as indicators for the tectonic research. We perform wavelet analysis to data of ΔT and separate it into changes of *LST* on varied frequency bands (Eq. (2)) (Chen et al., 2006):

$$T_{LST} = T_0 + T_a + \Delta T \quad (1)$$

$$\Delta T = T_{HIGH} + T_{MID} + T_{LOW} \quad (2)$$

where T_{HIGH}, T_{MID} and T_{LOW} are components of high, medium, and low frequencies reflecting periods of 0−0.36, 0.36−1.4, and 1.4−4 years, respectively. Comparison of ground measurements *in situ* and measurements derived from satellite observations show that the temperatures at night from both sources accord well with one another, and that the long-term component of satellite information better corresponds with ground measurements. Thus we firstly use the long-period component of the *LST* field for this study, which is obtained by removing the normal annual variation field from the total field. To distinguish it from the long-period component of the surface bright temperature T_{LOW}, which was derived from the synthetic infrared data of NOAA/AVHRR in previous work, the long-period component extracted from the *LST* product of MODIS/Terra (with a spatial resolution of 0.05° and a temporal resolution 8 days) is hereafter called LST_{LOW}.

1.3. Experimental and observed validation of relationship between strain and heat

In order to interpret the tectonic stress field by using observed temperature variation, we firstly elucidate its physical implication.

Previous experiments have proved that the heat field is closely related with the stress or strain field. Analysis of variations of the heat field for different stages of deformation suggests that there are two temperature elevating mechanisms, one caused by deformation, and the other by friction. The former is associated with volume change at the elastic deformation stage, and exhibits as a temperature rise with contraction and a temperature decline with dilation. The latter mechanism is related with fault motion (Liu et al., 2004a, 2007; Ma et al., 2007, 2008). In a case without fault slip, the change of the heat field is primarily related with volume variation. As soon as an unstable slip starts, temperature increase depends upon friction on the fault. Moreover, it is found that there is a linear relationship between volume strain change ($\Delta\theta$) and temperature variation (ΔT) in a case of elastic deformation, which is written as $\Delta T = aT\Delta\theta$, where a is the constant and T is the initial temperature. In other words, the change of thermal infrared radiation is proportional to the variation of volume strain, which is in agreement with existing thermodynamic theory (Xie, 1980). Biaxial compressive and extensional experiments have been conducted on steel blocks and rock specimens. The results indicate that in the state of elastic deformation, temperature variation is only related with volume strain change, which exhibits temperature rising by compression and temperature declining by extension; no temperature change caused by pure shear is detected. With monotonic increasing or decreasing load, temperature measured at the rock specimen's surface also rises or declines monotonically. The above findings illustrate a direct manifestation of the relationship between strain and heat (Chen et al., 2009a).

In a previous study, we made a comparative analysis of borehole strain data from Xinjiang and thermal infrared radiation data for the same region, with both data sets spanning more than decade (Chen et al., 2008). We noted that thermal infrared radiation changes in accord with variations in strain, and that a large-amplitude of strain change can produce large variations in thermal infrared radiation. As strain can be separated into both volume change and shape variation, the relationship between thermal infrared radiation and strain has different expressions in these two cases. The field measured data suggest that when volume strain is dominant, the variations of strain and thermal radiation have a consistent tendency in two directions. However, in the case of dominant shape change (shear), the variation tendencies of strain and thermal radiation are same in one direction and opposite in other direction. This observation is supported by laboratory experiment.

Still, there are some difficulties applying this method: 1. Laboratory experiments and field measurement suggest that temperature variation is closely related to volume strain in the elastic deformation state. It is commonly accepted that early preparation period of earthquakes are associated with elastic deformation. 2. There are some obstacles using surface temperature data to study fault activity due to that land surface temperature variation is sensitive to volume strain but not to shear strain, and that volume strain is not directly connected with fault activity or earthquakes. 3. Moreover, although laboratory experiments show a clear relationship between temperature variation and volume strain, whether this relationship can be found in the field is a question to be tackled in further research, because inferences stemming from laboratory experiments were arrived at in an environment with a stable temperature and the absence of influence from various other factors.

2. Some results on the relationship between the LST field and tectonic activity

In this section, we use the *LST* data MODIS/Terra to search for information associated with tectonic activity. Our analysis focuses on areas in the western Chinese mainland.

2.1. Regional distortion from the annual variation LST field

Analysis of the *LST* product (V4) of MODIS/Terra shows that deviations from the annually-varying *LST* values on the Xianshui River fault occurred in 2005 (red curve in Fig. 1a), while there was no such phenomenon in other areas in western China (Tarim, Erdos and Qilian Mountains). In the second half of 2007, the *LST* annual variation in the Longmen Mountains zone also underwent such a deviation (Fig. 1b). It seems that deviation in annual variations is not ubiquitous, and instead only occurs in certain areas, and therefore probably contains information related to tectonic activity.

In earthquake prediction research, deviation from annual variation in *LST* (or distortion of annual variation) is usually used as evidence for an anomaly at a seismic station or in an area. It is reported that the Sumatran *M* 9 earthquake produced co-seismic changes of surface deformation and groundwater levels in many regions of China (Zhang et al., 2005a; Zhang et al., 2005b). Because of the short time span of ground temperature measurements, it is difficult to prove whether or not the deviation from annual variation of the *LST* field on the Xianshui River fault, as mentioned in the last section, was caused by subsurface factors. The records at the Mianyang meteorological station, which located at the N-S seismic zone

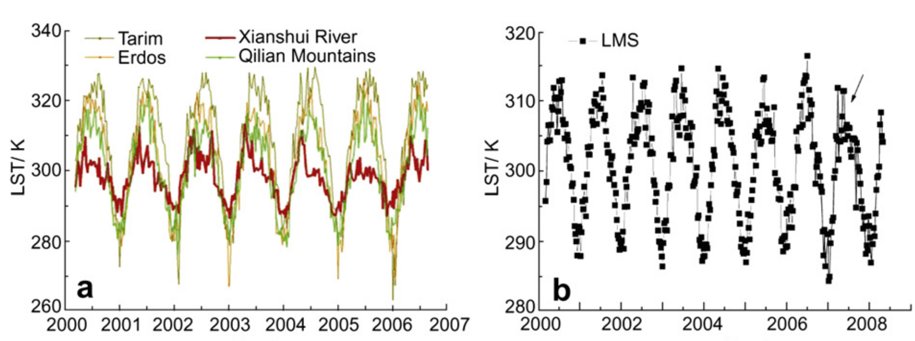

Figure 1 Annual variations of land surface temperatures at Xianshui River fault (a) and Longmen Mountains fault (b) derived from LST data of MODIS/Terra satellite observational data. List the LST curves of Tarim, Erdos and Qilian Mountains in (a) for comparison with Xianshui River. LST data (V4) are provided by MODIS/Terra Land Surface Temperature Group from the Institute for Computational Earth System Science (ICESS), University of California, Santa Barbara.

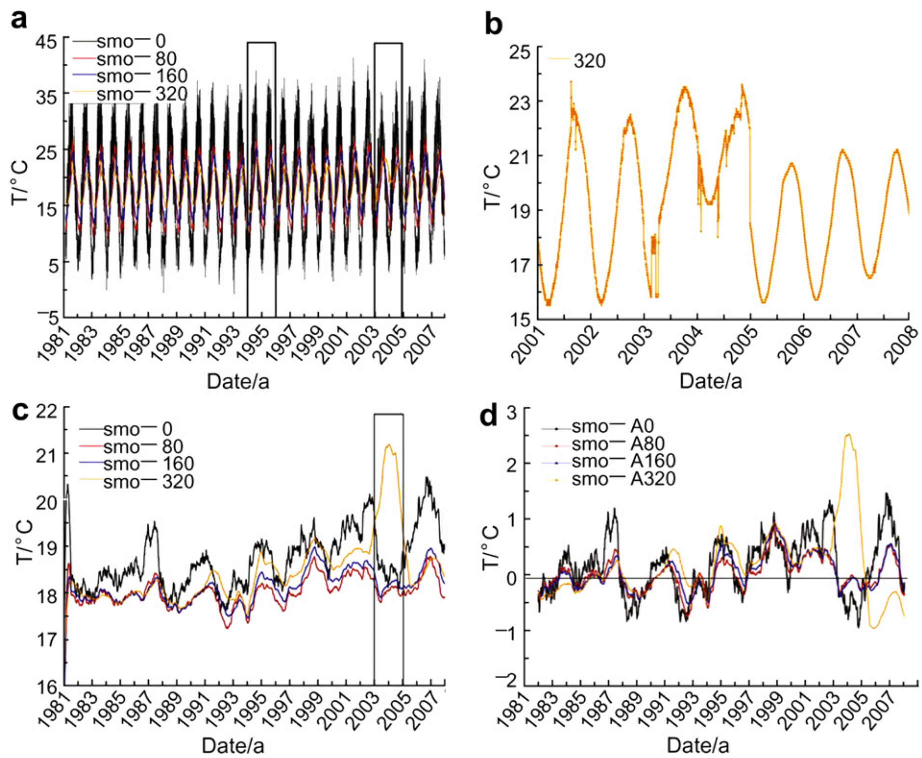

Figure 2 Data of ground temperature in different depths at the Mianyang observatory. (a) Temperature values at 4 depths; (b) Enlarged picture for temperature at depth 320 cm since 2001; (c) Temperature variations at varied depths after removing annual change; (d) Abnormal values (difference from average value) of temperature at varied depths after filtering.

and near the epicenter of the Wenchuan earthquake, reveal fairly stable annual variations of ground temperatures at four depths for many years (Fig. 2). But the annual variation of ground temperature at the depth of 320 cm at this station showed remarkable changes (curve parts marked by black frames in Fig. 2a) during 1994−1995 and 2003−2005, comparing with other depths. Its enlarged diagram (Fig. 2b) shows that the temperature at depth 320 cm indeed experienced abnormal deviations from the regular annual variation during 2003−2005, amongst which the sudden downward drop at the end of 2004, is presumably a co-seismic response of the Sumatran event. To make this change more prominent, filtering is performed to the temperature data at varied depths at the Mianyang station to remove annual variations (Fig. 2c). The resultant anomalous value represents differences between the ground temperature at a depth on a certain day and the average value. Considering that sunspot activity occurs in 11 year periods, the anomalous value (difference from average value) refers to the difference between the temperature at a depth on a certain day and the average value of the same day over the past 11 years. The filtering (with a window of 365 days) result is shown in Fig. 2d. From Fig. 2c and d, we can note that the temperatures at depths of 80 cm and 160 cm do not show an evident change, while that at a depth of 320 cm exhibits considerable abnormal change since 2001, particularly during 2003−2005. This observation suggests that the subsurface temperature below the Mianyang station experienced abnormal changes before and after the Sumatran earthquake in December, 2004.

2.2. Varied effects of the same earthquake on different tectonic regions

The above section deals with information on tectonic activity derived from the annual variation of *LST* at a single location or in a small area. Next we will analyze this issue in a large-scale space. We choose the post-earthquake variation of *LST* to study the relationship between the *LST* field and tectonic activity. The reasons are as follows: 1. A wealth of observations indicates that the deformation after a great earthquake can be larger than that before the event by one order of magnitude (Ma et al., 1982). 2. It is easier to understand the variation of *LST* following an earthquake in terms of known seismic parameters and deformation trends. 3. Furthermore, research on post-earthquake adjustment of the stress field is of importance to the analysis of the seismic situation after a major or great shock. Here we employ the relevant data related to the Sumatran great event on 26 December, 2004, which was the largest quake in the world in recent years and not far from Chinese mainland.

Using the method presented in section 1.2, we derived the increment field of average LST_{LOW} for different tectonic regions after the 2004 Sumatran event from the MODIS/Terra *LST* product. This variable likely contains tectonic information and secondary information stemming from the change in tectonic stress, as well as weakened information on non-tectonic factors. In the case that there is no better alternative method to reveal spatial-temporal change of the stress field, we suggest that the processed field of *LST* can be used as an indirect indicator of the stress field.

To study the influence of the Sumatran quake on the Chinese mainland, we divided the mainland into tectonic regions as follows: 35 regions in western China and 18 regions in eastern China, including northeast China, North China and South China. These regions are named by faults, basins, or other tectonic blocks (Fig. 3).

Taking the time of occurrence of the Sumatran earthquake in 2004 as the starting point, we separately calculated the increments in average LST_{LOW} over time for the regions above. It was found that in comparison with the values at the starting point, the values of LST_{LOW}

increased in some regions and decreased in others. Fig. 3 displays the increments of LST_{LOW} in tectonic regions of Chinese mainland half a month after the 2004 Sumatran earthquake. The most remarkable variation is in the form of a large-amplitude temperature decline that occurred in and to the west of the Bayan Har-Songpan block. Conversely, along the entire N-S seismic zone, especially its southern section, there is no evident variation in LST_{LOW}.

The data analysis above suggests that the Sumatran *M*9 earthquake indeed caused variations in temperature, which is different in varied tectonic regions. This phenomenon implied that a great shock can influence the large-scale temperature field surrounding the epicenter, and that these changes in the temperature field contain tectonic information.

2.3. Distinct effects caused by earthquakes in varied areas on the temperature field of same region

Since the launch of the satellite Modis/Terra, two *M* 8 events (Kunlun *M* 8.1 in 2001 and Wenchuan *M* 8.0 in 2008) and several $M > 7$ shocks occurred in mainland China and surrounding countries, such as the Zaisan Lake earthquakes (*M* 7.9, *M* 7.5 and *M* 7.3, named Chuya M_s 7.5 event in foreign reports (Zhao et al., 2005; Lunina et al., 2008)) in September 2003, the Sumatran *M* 9 earthquake in December 2004, and the Pakistan *M* 7.6 in October 2005 (their locations are shown in Fig. 8b). Here, we study the effects of the Kunlun, Wenchuan, Sumatran, and Zaisan Lake events mentioned above on the temperature field.

Each image From the Modis data has a spatial resolution of 5 km and represents the *LST* field over a period of 8 days. The increment field of LST_{LOW} at every pixel point can be calculated by subtracting the values of LST_{LOW} when the earthquakes occurred from that of the image two weeks after the event. Fig. 4 displays the increment fields of LST_{LOW} two weeks after the four shocks in order of occurrence.

As shown in Fig. 4, the increments of LST_{LOW} in western China caused by the four great earthquakes are all within ± 1 °C of varied amplitudes. The variations of LST_{LOW} caused by the 2001 Kunlun and 2008 Wenchuan events are less than ± 0.5 °C; the rise generated by the 2003 Zaisan Lake event was up to 1 °C; and the change caused by the 2004 Sumatran event was relatively large in terms of both the rise and decline of LST_{LOW}, with a variation of up to 1 °C.

These four great quakes produced different patterns of LST_{LOW} variations. Two weeks after the Kunlun *M* 8.1 on 14 November, 2001, small variations occurred mostly in western China (Fig. 4a), except for a relatively appreciable increase, though of small amplitude, near the Longmen Mountains area, which will be discussed later. There are also decreases around southwest of Tarim, Karakorum, and Pakistan. The Zaisan Lake event of 2003 caused LST_{LOW} increase over a large area two weeks after its occurrence,

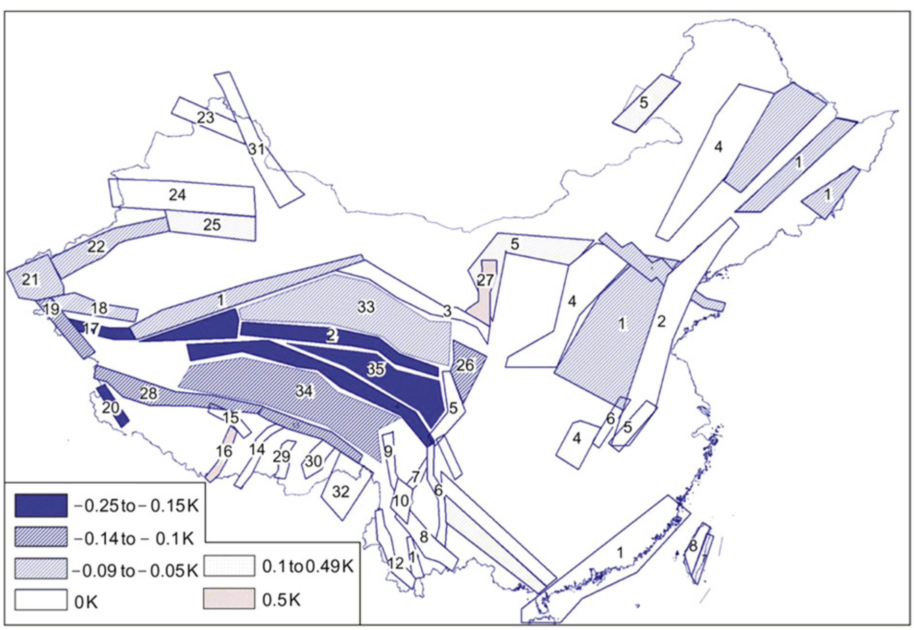

Figure 3 Regional increment fields of land surface temperature LST_{LOW} in mainland China half month after the Sumatran *M* 9 earthquake of 2004 (calculated using satellite data of MODIS/Terra 5 km-*LST*-V4-day). Blue lines and red dots denote temperature decrease and temperature increase, respectively. The amplitude of temperature changes is represented by color shade and line density. Tectonic regions in western China: 1. Altyn Tagh fault; 2. East Kunlun (or Kuma) fault; 3. Qilian Mountains fault; 4. Yushu-Xianshui River fault; 5. Ming Mountains-Longmen Mountains fault; 6. Anning River-Xiaojiang fault; 7. Lijiang-Xiaojin River fault; 8. Red River fault; 9. Jinshajiang fault; 10. Lijiang region; 11. Pu'er-Simao fault; 12. Lancang-Gengma fault; 13. Jiali fault; 14. Dangxiong graben; 15. Shenzha fault; 16. Dingri basin; 17. Kangxiwa fault; 18. West Kunlun range-front fault; 19. Karakorum fault; 20. Shiquanhe fault; 21. Wuqia region; 22. Southwest Tianshan Mountains region; 23. Ertix fault; 24. North Tianshan Mountains region; 25. South Tianshan Mountains region; 26. Tianshui River-Wudu region; 27. Helan Mountains-Xiangshan Mountains region; 28. Bangong Co fault; 29. Sangri-Cuona graben; 30. Medog-Mainling fault; 31. Keketuohai-Ertai fault; 32. Zayü region; 33. Qaidam block; 34. Qiangtang block; 35. Bayan Har-Songpan block. Tectonic regions in northeast China: 1. Wangqing deep focal-depth region; 2. Yilan-Yitong fault; 3. South Songliao plain; 4. North Xiao Hinggan Ling; 5. Da Hinggan Ling; 6. Hulun Nur fault. Tectonic regions in South China: 1. Southeast coastal tectonic zone; 2. Bama-Bobai fault; 3. Baise-Hepu fault; 4. Jianghan-Dongtinghu lake area; 5. southern section of Tancheng-Lujiang fault; 6. Macheng fault; 7. Plate margin on East Taiwan; 8. Central Range and West Taiwan area. Tectonic regions in North China: 1. Zhangjiakou-Bohai fault; 2. Tancheng-Lujiang fault; 3. North China plain; 4. Fenwei graben; 5. Yinchuan-Hetao graben.

within which area decreases are seen north and south of the Longmen Mountains of eastern Bayan Har block (Fig. 4b). Most of western China exhibited increases in LST_{LOW}, especially along faults, two weeks after the Wenchuan event of 2008 (Fig. 4d). Note that boundary lines of varied colors in southern Tibet are traces produced by the assemblage of satellite pictures.

Fig. 4c shows the influence of the 2004 Sumatran great quake on the temperature field of western China. It refers to the pixel increment calculated using the night time LST_{LOW} data from MODIS/Terra V5, for the same time span as that of Fig. 3, which is the regional average of daytime LST_{LOW} data of MODIS/Terra V4. Comparison of Figs. 3 and 4c indicates that both are largely consistent. In Fig. 4c, one increase of LST_{LOW} occurs in the Sichuan-Yunnan diamond-shaped block, and another appears to the north of the Qilian Mountains. This area is not directly calculated for in Fig. 3, but the nearby region 27 in the east and Qilian Mountains itself (region 3) show LST_{LOW} increase (Fig. 3). Most conspicuous of all in Fig. 4c is a broad area of LST_{LOW} decrease to the south of the East Kunlun fault presumably caused by Sumatran event, which corresponds to the delineated area in the Bayan Har-Songpan block and its west in Fig. 3. It is noted that all strong earthquakes occurred on the boundary of the Bayan Har-Songpan block, such as the Pakistan *M* 7.5 event in February, 2005, the Wenchuan *M* 8.0 quake and the Gerze, Tibet and Yutian, Xinjiang events in early 2008. We can infer that the decline of LST_{LOW} around Bayan Har-Songpan block in western China caused by the Sumatran great earthquake in 2004 may contain some information on tectonic activity in this region.

In sum, great earthquakes in a variety of regions can produce different patterns of LST_{LOW} variations in western China. The Kunlun event, which is of sinistral strike-slip faulting, did not generate temperature changes in a vast area, but merely a temperature increase in the eastern Bayan Har-Songpan block and a temperature decrease in the western Karakorum. The 2004 Sumatran quake made the temperature of the Bayan Har-Songpan block decline. The temperature of the south-central section of the N-S seismic zone decreased due to the Zaisan Lake quake of 2003, whereas the 2008 Wenchuan earthquake made many faults experience temperature increases. The tectonic implications of such patterns of LST_{LOW} variations will be elucidated in the discussion section of this paper.

2.4. Different temporal processes of temperature variations in varied regions

For comparison, we have calculated values of the LST_{LOW} for different tectonic regions using night time data from the MODIS/Terra V5 product. In particular we analyze the change of the maximum LST_{LOW} values over time on the Longmen Mountains zone in 2000−2009, and their correlation with the earthquakes of

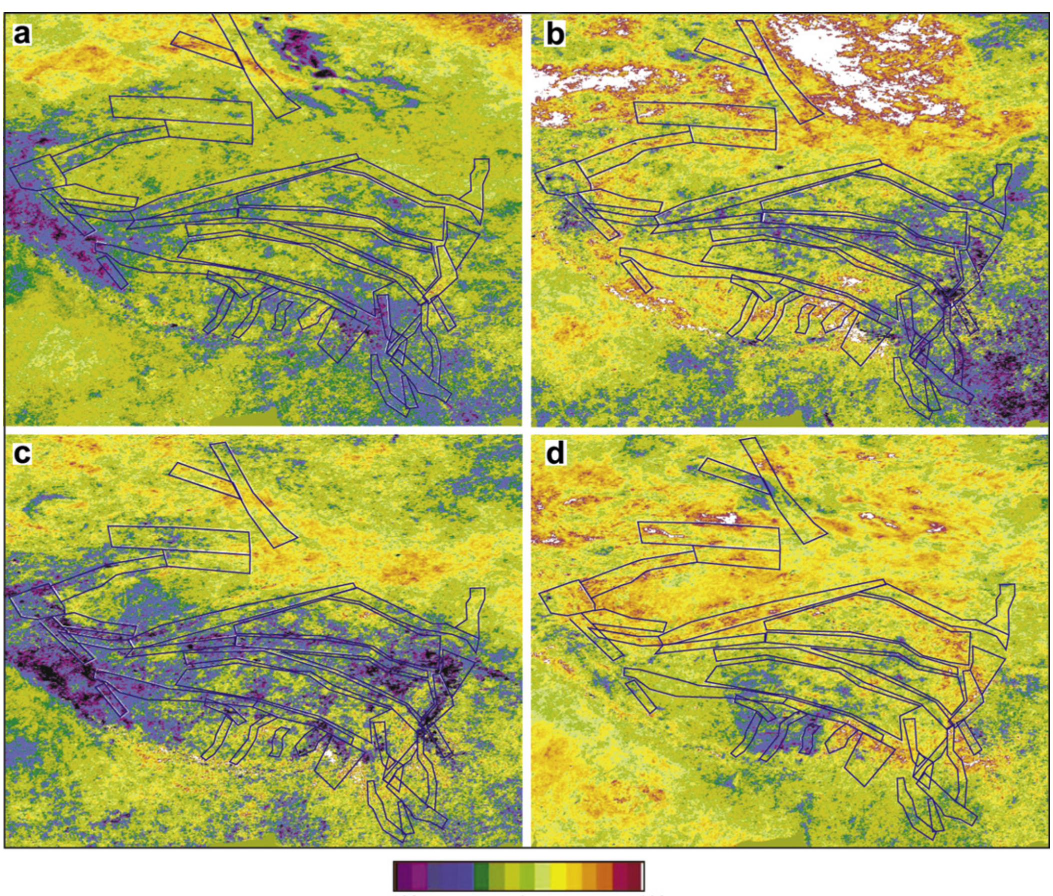

Figure 4 Increment field of land surface temperature LST_{LOW} in western China two weeks after four strong earthquakes (calculated by data of Terra 5 km *LST*-V5-night). (a) Kunlun quake, (b) Zaisan Lake quake, (c) Sumatran quake, (d) Wenchuan quake. A unified color table is used, so temperature variations in all scenes can be compared. The 33 tectonic regions in western China are delineated by black thin frames (numbered the same as in Fig. 3).

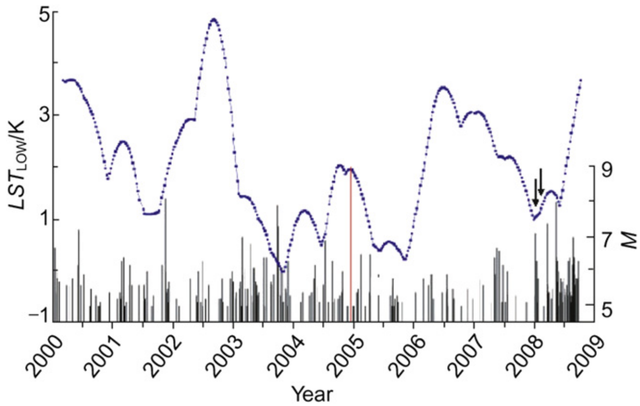

Figure 5 Variations of LST_{LOW} values with time in the Longmen Mountains area (blue curve) and *M-t* chart of China and adjacent regions. Red line in *M-t* chart denotes the Sumatran *M* 9 earthquake of 26 December, 2004.

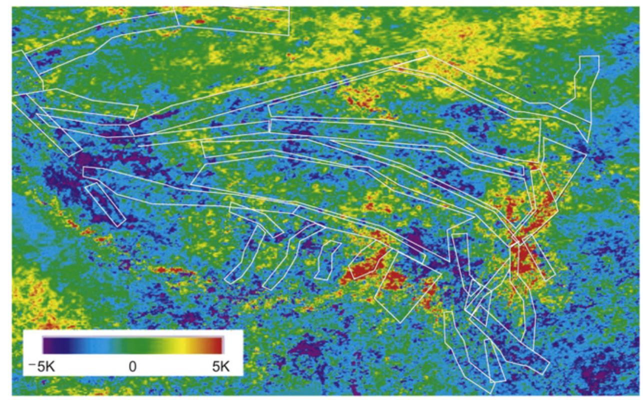

Figure 7 Thermal image of LST_{LOW} from data MODIS/Terra *LST* (V5) in night of early June, 2002. Note relatively high values on Longmen Mountains and Xiaojiang fault.

this period in China and adjacent regions (Fig. 5). Since 2000, the LST_{LOW} on the Longmen Mountains experienced two periods of increase: one was after the 2001 Kunlun *M* 8.1, and the other was in 2006. The temperature in this zone was relatively low in 2003−2005. It declined drastically in the second half of 2007 and then rose in early 2008, this rise coinciding with the Gerze (Tibet) quake in January and the Yutian (Xinjiang) event in March of that year. The Wenchuan *M* 8 quake occurred when the temperature of the Longmen Mountains turned again towards decline. Although these changes are of small amplitudes, they exhibit prominent turns, implying rapid variations of the temperature field.

As the Wenchuan earthquake is associated with the N-S seismic zone and the Bayan Har-Songpan block, we calculated the values of the LST_{LOW} over time for all units in these two regions. Then these values were normalized with respect to their minimum value and transformed into temperature values which are still denoted by LST_{LOW}, so that relative variations are accentuated (Fig. 6). In the following section we compare the resultant values of the Longmen Mountains with that of other related tectonic regions, localities and numbers for which are shown in Fig. 3.

The variations of the Pu'er-Simao region (No. 11) and Longling-Lancang region (No. 12), which lie in the southernmost part of the N-S seismic zone, have very small amplitudes that are not comparable with the Longmen Mountains zone (Fig. 6a).

The Tianshui-Wudu region (No. 26) and Helan Mountains-Xiangshan Mountains region (No. 27) in the northern part of N-S seismic zone have similar change processes of LST_{LOW} when compared with the Longmen Mountains (Fig. 6b). But, the temperature rise of 2002 in the Longmen Mountains shows much larger amplitude, and the rise of 2006 began earliest and displayed largest amplitude.

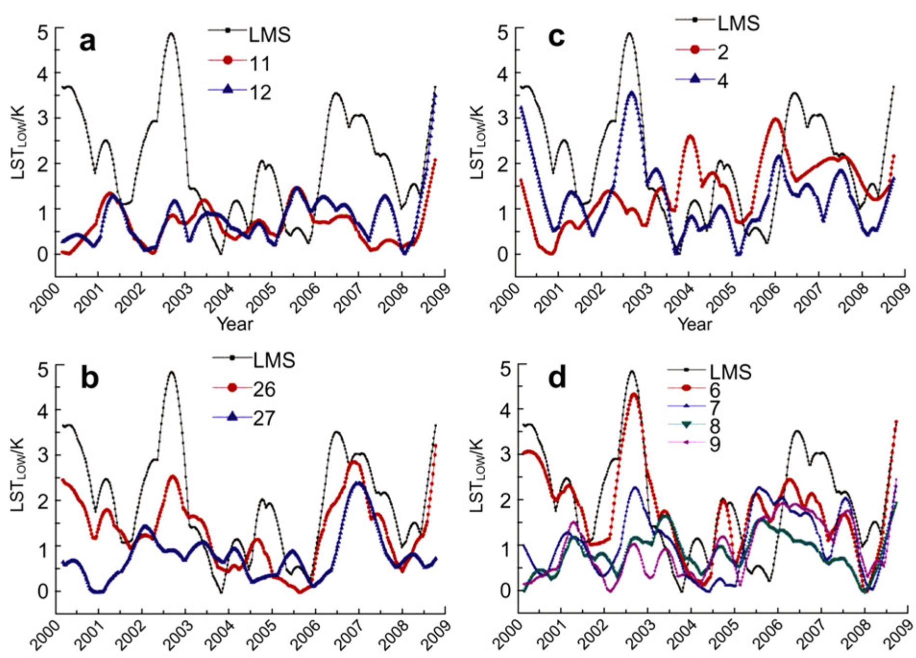

Figure 6 Comparison of the variations with time of LST_{LOW} values between the Longmen Mountains area and its surrounding areas. (a) Contrast with southernmost N-S seismic zone; (b) Contrast with northern section of N-S seismic zone; (c) Contrast with East Kunlun and Yushu-Xianshui River faults; (d) Contrast with Sichuan-Yunnan block. Numbers of curves represent the tectonic regions in Fig. 3.

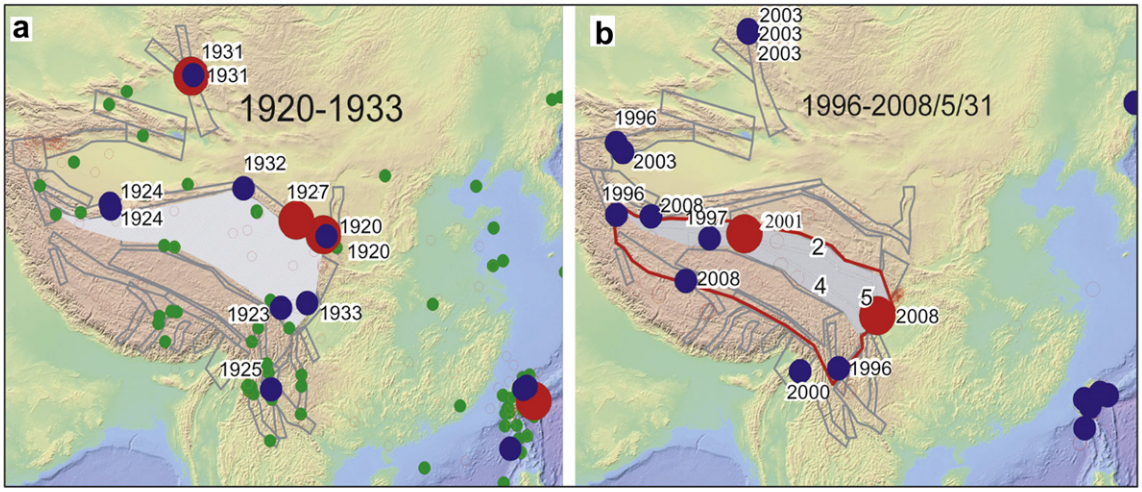

Figure 8 Clustering large earthquakes in China during time periods 1920−1933(a) and 1996−2008 (b) In (a) grey area denotes combined Bayan Har-Songpan and Qaidam block; (b) grey area is Bayan Har-Songpan block and the area with red frame denotes combined Bayan Har-Songpan and Qiangtang block.

As boundaries of Bayan Har-Songpan block, the East Kunlun fault (No. 2), Yushu-Xianshui River fault (No. 4), and Ming Mountains-Longmen Mountains (No. 5) sometimes have consistent variations of LST_{LOW}, sometimes don't (Fig. 6c). For instance, the East Kunlun fault had a considerable temperature rise in the second half of 2003, while there was no large change in the other two regions. In early 2002, the Longmen Mountains (No. 5) and Yushu-Xianshui River (No. 4) all experienced temperature increase and decrease, both of large-amplitude, as well as temperature decline in early 2003, but the amplitude of change of the Yushu-Xianshui River was smaller than that of the Longmen Mountains. In 2005, these three regions underwent successive temperature rises. Temperature in the East Kunlun fault was the first to rise, and in the Longmen Mountains was the last, but with the largest amplitude.

Comparison of the variations with time of LST_{LOW} values between the Longmen Mountains area and the Sichuan-Yunnan block, which lies in the southern N-S seismic zone, shows both similarities and differences (Fig. 6d). There are a series of faults surrounding the Sichuan-Yunnan block, such as the Anning River − Xiaojiang fault (No. 6), Lijiang-Xiaojin River fault (No. 7), Red River fault (No. 8), and Jinshajiang fault (No. 9). Most of these faults experienced temperature rises in 2002, amongst which the Anninghe-Xiaojiang fault, like the Longmen Mountains fault, displayed the largest amplitude, as shown in Fig. 4a (also see Fig. 7). Around 2006, the Longmen Mountains zone and these other faults all underwent temperature rises, but such change at the Longmen Mountains occurred latest, with the largest amplitude compared to other areas. After the Longmen Mountains and other areas underwent a fast temperature decrease in second half of 2007, the temperature at the Longmen Mountains rose at the beginning of 2008 as the first one.

The comparisons above indicate that the variation processes in different tectonic regions are different. The Longmen Mountains zone has the following features compared to other areas: the temperature rise of largest amplitude occurred in 2002; the temperature decline of largest amplitude occurred in 2003; the temperature increase of greatest amplitude compared to other areas on the Longmen Mountains in 2005 and 2006, occurred later than temperature increases in the southern part of N-S zone and earlier than increases in the northern part; then it changed into temperature rise as the first and accelerate this trend (denoted by the arrows in Fig. 5) in June−December, 2007 when most of other regions underwent a rapid temperature decline. Although these variations of LST_{LOW} on the Longmen Mountains are of small amplitudes, they are different from the surrounding regions, and are probably associated with the special tectonic stress state of this zone proper.

3. Conclusions

This work demonstrates that some information on aspects of tectonic activity can be derived from LST_{LOW} data related to great earthquakes.

3.1. The influence field of Kunlun M 8.1 event on 14 November 2001

The sinistral-lateral sliding on the East Kunlun fault led to this great earthquake. Tao et al. (2007) have suggested that the motion on its southern wall is greater than that on its northern wall. This fact indicates that the southern wall is more active during this earthquake. In this case then, along the slip direction, a tensile area should appear behind the rear end and a compressive area ahead of the frontal end (involving the Longmen Mountains and Anninghe − Xiaojiang fault) at the southern wall of the fault. These effects on the southern wall are more evident than those on the northern wall, because the motion on the southern wall is greater. The image of LST_{LOW} derived from the Modis satellite's night data from early June, 2002, indicates that the rear and frontal areas on the south side of the fault mentioned above are of relatively low and high temperatures, respectively, whereas little change in temperature was observed in the northern part of the East Kunlun fault (Fig. 7). At the same time, the picture of the increment field (Fig. 4a) shows temperature decline at the rear of the southern wall of the fault and temperature increase at the front. Following facts provide more evidences: it was reported that in 2002, short-baseline measurements at some stations along the

Xianshui River fault, such as Zhuwo, Xuxu and Goupu, as well as geodetic short-leveling at Daofu, revealed transition GPS data suggest that the front area is of areal contraction and the rear area is of areal dilatation of the southern wall of the fault (Jiang, 2005); Also in 2002, many anomalies, such as groundwater and animal behaviors, were observed in the areas of temperature increase. Some earthquake researchers submitted a prediction that a major shock was soon to happen, causing local residents to stay outdoors for safety. Although the expected event never occurred, the observed abnormal variations may constitute corroborative evidence for the enhancement of mean stress in this region. As stated previously, laboratory experiments demonstrate a rock behavioral tendency of exhibiting temperature rise under compression and temperature decline under extension. On the basis of this laboratory evidence, it is inferred that the temperature increase in the Longmen Mountains and the temperature decrease in the Karakorum derived from satellite data analysis are associated with the compression and extension caused by sinistral strike-slip along the East Kunlun fault.

3.2. *Evidence of intensified activity in the Bayan Har-Songpan block influenced by Sumatran event in 2004*

Several kinds of *LST* data suggest that tectonic activity in the Bayan Har block became intensive influenced by the Sumatran earthquake in 2004. For instance, the annual variations of directly measured *LST* along the Xianshui River fault (Fig. 1a), the increment field of the regional average values of LST_{LOW} derived from MODIS/Terra *LST* (V4) daytime data (Fig. 3), and the compilation of the pixel increment field from MODIS/Terra *LST* (V5) night time data (Fig. 4), all display a temperature decline of the Bayan Har block a half month after the Sumatran event. The observations at the Mianyang meteorological station (Fig. 2) show variations of ground temperature in the shallow subsurface during 2003−2005 as well as a temperature decline that occurred simultaneously with the event. All these data involve the Bayan Har-Songpan block and its surrounding regions. GPS measurements (Guo et al., 2009; Liu et al., 2009) provide support to our inference that temperature decrease in the Bayan Har-Songpan block presumably caused by extension of this block. We found that the Bayan Har-Songpan block particularly its western portion, had relatively large principal strain rates in 2001−2007, the tensile values of which exceeded the compressive values. Thus, there is supposed to be a major deformation zone, which located in the central of Tibet plateau, exhibiting prominent increase in the tensile value of the strain rate. This localized deformation from GPS and decrease of the surface temperature field, in conjunction with relevant laboratory experiments, jointly attest to the inference that extensional deformation occurred in the Bayan Har-Songpan block, and that this phenomenon was closely related to the highly active earthquakes from 1996 to 2008 in this region (Fig. 8).

3.3. *Special information on the Longmen Mountains zone from surface temperature data*

The Sumatran *M* 9 event on 26 December, 2004 produced remarkable co-seismic effects as well as largest post-seismic stress adjustment along the N-S Seismic Zone of China. The overall level of earthquake activity in mainland China appeared low in 2005 and 2006. The temperature increase on the Longmen Mountains came later than that on the Sichuan-Yunnan block in south, and earlier than that in the northern part of N-S Seismic Zone. This pattern probably implies that the strain adjustment caused by the 2004 Sumatran quake migrated from south to north. After a long period of quiescence in western China, 6 ($M \geq 6$) shocks occurred successively in Yunnan, Xinjiang, and other areas from May to July of 2007, and an *M* 8.5 quake hit southern Sumatra, Indonesia on 12 September, 2007, which is the third great shock since 2004 within this area. During and after this period, acute declines in surface temperature occurred on most of the N-S seismic zone, while only the Longmen Mountains zone experienced change into rise and accelerating rise in temperature in early 2008 (see the arrow in Fig. 5). Although its amplitude is not large, this rise indicates the specialty of the Longmen Mountains zone. This fact further proves that LST_{LOW} values derived from the Modis data contain information on tectonic stress.

4. Discussion

There seems to be no doubt that the land surface temperature field contains information about tectonic activity, however, how to apply this theory to interpret the deformation still required further studies with a proper model. In the following section, we discuss this issue in conjunction with the major earthquakes in Chinese mainland since 2000.

4.1. *Discussion on dynamic condition for cluster earthquakes surrounding the Bayan Har block*

The historical records show that major earthquakes do not occur in isolation, and instead often occur in clusters. Such clusters of tectonic events tend to happen in a short period time and in places not far apart. The clustering character of quakes in mainland China is associated with its tectonic block pattern (Zhang and Li, 1997; Fan et al., 2001; Ma, 2009). The events of one cluster are probably generated by common conditions.

From 1996 to 2008, two *M* 8 (Kunlun *M* 8.1 and Wenchuan *M* 8.0) and several *M* 7 events took place in western China, their locations mainly surrounding the Bayan Har-Songpan block (Fig. 8a) and forming an appreciable cluster. The *M* 7.9 at Zaisan Lake, China-Mongolia border in 2003 and the *M* 7.6 in Pakistan in 2005 are the major events in the adjacent regions associated with the above seismic clustering.

History has documented other similar earthquake clusters in western China. For example, a cluster of major and great events occurred from 1920 to 1933, including three *M* 8 and six *M* 7 events which were located on the boundaries of the combined Qaidam and Bayan Har-Songpan block (Fig. 8a). During this period, an *M* 8 shock also took place at the Keketuohai-Ertai fault in northern Xinjiang, while there were no quakes equal to or greater than a magnitude of 7 in other regions in West China.

Comparison shows that the earthquake clusters which formed during 1920−1933 and 1996−2008 have some common features. Firstly, these shocks all occurred on the boundaries of tectonic blocks, i.e. the combined Qaidam and Bayan Har-Songpan block (Fig. 8a), and Bayan Har-Songpan block (Fig. 8b), or the combined Bayan Har-Songpan and Qiangtang block, both including the Bayan Har-Songpan block. Secondly, during these two periods great earthquakes took place at the NNW trending Keketuohai-Ertai fault near the China-Mongolia border, namely the Fuyun

(Xinjiang) *M* 8 in 1931 and the Zaisan Lake *M* 7.9 in 2003. These two quakes have nearby epicenters and same faulting manner of dextral-slip with a tensile component, implying a similar dynamic context. This implication is discussed in detail below.

From Baikal to northwestern China, there are two sets of fault systems, one trending nearly east-west and the other striking in a NNW direction. A NNW trending major fault, lying between the EW trending fault in the southern part of Baikal and the EW directed East Kunlun fault, links the two fault systems above to form a reverse "Z" shape. The northern section of this major fault is the 700 km-long Hovda fault zone (Shen et al., 2003). The 1931 Fuyun *M* 8 event occurred at one branch of this fault zone, the Fuyun fault (also called Keketuohai-Ertai fault) (Xinjiang Earthquake Administration, 1985). From topography, it is inferred that this fault probably extends toward the southeast.

In the conjunction area of the EW trending fault of Baikal and the Keketuohai-Ertai fault (No. 31)(Hovda fault), as well as the conjunction area of the East Kunlun fault and the Keketuohai − Ertai fault, forms a series of lakes and depressions. These lakes and depressions imply an extensional area with a tensile axis directed NWW, which accommodates sinistral strike-slip on the EW striking fault and dextral-slip on NNW trending fault. Strain release of these two faults accounts for the 2001 Kunlun *M* 8.1 and 2003 Zaisan Lake *M* 7.9 events, subsequently. The northwestward motion of the block between these two fault systems results in extension of the depression block that may be the cause of surface temperature decline (Fig. 4b). The 2004 Sumatran *M* 9 quake further enhanced this deformation.

5.2. High stress level is not indicator for inevitable occurrence of future great earthquakes

As stated previously, the Longmen Mountains zone has been in relatively high temperature state for twice and in a low temperature state for several times. In 2006, we analyzed the associated fault activity of the N-S seismic zone using 20 years of thermal infrared data (July 1981−September 2001) from the United States Distributed Active Archive Center (DAAC) and NOAA/NASA Pathfinder Program (Ma et al., 2006a). We noted that the Ming Mountains − Longmen Mountains area (tectonic region No. 5 in Fig. 3) experienced relatively high T_{LOW} in 1987, 1990, 1995 and 1998 (see Figs. 1 and 2 in Ma et al. (2006a)), while no major earthquake took place in this region during this period. It was also mentioned earlier that the Longmen Mountains zone and Anninghe-Xiaojiang fault (No. 6) experienced large-amplitude LST_{LOW} rises in 2002, but the expected seismic events did not happen at that time. Laboratory experiments show that an LST_{LOW} rise means a likely increase in tectonic stress, whereas an LST_{LOW} rise may indicate the increased probability of major earthquakes, but not the definite occurring of such events.

Why did the LST_{LOW} rise by several times in the Ming Mountains − Longmen Mountains area during 1981−2008, while the great Wenchuan quake did not occur until 2008? We attempt to explain this issue from the standpoint of tectonic setting. The N-S Seismic Zone is neither a single boundary between blocks, nor a fault belt that developed independently. Rather, it is a combined fault zone within which boundaries of different blocks serve as distinct sections. Because of the relative integrity of blocks, each block has its own tendency of motion. Only a special condition can generate joint motion of N-S fault zone with blocks. The Ming Mountains − Longmen Mountains zone lies in the middle of the N-S Seismic Zone and is also the eastern boundary of the Bayan Har-Songpan block. Because of its particular strike, the Ming Mountains − Longmen Mountains zone is an important portion as a brake of the N-S Seismic Zone, and its activity is associated both with the N-S Seismic Zone as well as the boundary between the Bayan Har-Songpan block and neighboring blocks. The great earthquakes in this area are likely related to the dynamic balance between this zone and the block. A suitable condition must be reached to trigger the occurrence of a great earthquake. We speculate that the several instances of temperature decline in 2003 and 2004, and especially in the second half of 2007, probably reflected change in the relative positions of the combined block, ultimately accommodating the occurrence of a sudden seismic rupture, the Wenchuan earthquake of 2008.

This work merely constitutes preliminary research into some observations and needs further comparative analysis based on more data drawing from multiple disciplines. Nonetheless, it demonstrates that it is possible to extract information on tectonic activity from land surface temperature derived from satellite remote sensing data. The method allows us to transform isolated observations of the surface into a field and a development process as a supplementary means. It is not advisable to deny this method totally; otherwise, it is clearly over-optimistic and impracticable to make earthquake predictions merely using several images or some pieces of information for a period without removing the effects of non-tectonic factors such as solar activity.

Further laboratory experiments and theoretical studies are called for to facilitate the utilization of data on the land surface temperature field in seismotectonic research. In some areas with established models of tectonic deformation, observations using multiple methods and comparisons should be carried out to verify the tectonic implication of the *LST* variation. Additionally, it is necessary to develop new methods of data processing that can accentuate tectonic information derived from *LST* data.

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