Research on variation characteristics of fault activity based on satellite thermal infrared remote sensing data taking an example of Songyuan $M_S$5.7 in 2018

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Abstract. In this paper, we use the brightness temperature data of the Chinese stationary meteorological satellite and wavelet transform and power spectrum estimation methods to investigate the thermal infrared anomalies of these three greater than $M_S$4.5 earthquakes in Songyuan area around 2017. The results show that the anomalies gradually expanded along the strike of Yilan-Yitong fault and Mishan-Dunhua fault zone before the $M_S$4.9 earthquake on July 23, 2017 and the $M_S$5.7 earthquake on May 28, 2018. The anomalies existed in the eastern margin of the Songliao Basin, but the epicenter of the earthquake was not in that area. The abnormality was not obvious before the $M_S$5.1 earthquake on May 18, 2019. It is a possibility that greenhouse gases, such as CO$_2$ and CH$_4$, were released in the greatest amount in the basin, before and after the previous two earthquakes.

Keywords: Songyuan earthquake; Thermal infrared brightness temperature; Anomaly of relative power spectrum

1. Preface
In the recent decades, the advances in satellite remote sensing technology have led to the development of global seismic thermal radiation as well as the methods of extraction of abnormal information from the radiation. Such methods include the “RST” method, the method of temperature difference between inside and outside the fault zone, the temperature deviation index method of the same period over the years, and the continuous wavelet transform method and so on. Comparing with the above methods, I adopt the time-frequency relative power spectrum method to remove the influence of non-seismic factors effectively and highlight the seismic abnormal thermal radiation information.
In this paper, we selected three earthquakes as the target objects, namely $M_{S}4.9$ earthquake on July 23, 2017, $M_{S}5.7$ earthquake on May 28, 2018, and $M_{S}5.1$ on May 18, 2019 in Songyuan Jilin. For the three consecutive years, the occurrence of the about 5 magnitude earthquakes in the same area provided necessary conditions for us to study the characteristics of thermal infrared anomalies, before and after the earthquakes in Songyuan area. The Songyuan area belongs to the Songyuan Basin in the Jilin Province of China, which is rich in oil and gas resources. We apply wavelet transform method and power spectrum estimation to study whether the satellite thermal infrared remote sensing data can detect the abnormal thermal radiation differences before the occurrence of these three earthquakes. And we also discuss the connection between fault activity and abnormal features.

2. Thermal infrared brightness temperature data
The satellite thermal infrared remote sensor can directly detect the thermal radiation intensity of ground objects, called the radiance of the corresponding channel (band) post calibration and geometric correction. We calculate the radiation temperature by applying the blackbody (Specific emissivity is 1) radiation formula of Planck's radiation theorem. The true radiation temperature of an object is called the brightness temperature. We used China Geostationary Meteorological Satellite FY-2C/E/G brightness temperature hourly data product (data from the National Satellite Meteorological Center of China Meteorological Administration) for the research. For analyzing the possible thermal anomalies before these earthquakes, brightness temperature data from January 1, 2012 to January 1, 2020 were collected. Solar radiation can cause huge increases of land surface temperature (LST) in daytime, making it difficult to identify minor LST changes, possibly caused by tectonic activities. To avoid the influence of direct solar radiation, we chose five midnight real-time observation data points every day (measurement was taken once an hour), i.e., Beijing time 01:00, 02:00, 03:00, 04:00, 05:00 data points. The observation data points were used to obtain the daily value data through the window-filling method to form the daily brightness temperature data [1].

3. Data processing and results
3.1. Wavelet transform
When Morlet analyzed the seismic wave data in 1984, it was found that the Fourier transform was difficult to solve the unsteady signal, but the wavelet transform could overcome this problem. The biggest features of wavelet transform technology were the adaptability and mathematical microscopy. As an effective tool for current signal time-frequency analysis, it could be reconstructed with almost no loss of the original signal, and could focus on any detail of the signal.

The wavelet transform formula of finite time series is as follows:

$$W_{\varphi} f(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t) \varphi\left(\frac{t-b}{a}\right) dt \quad (1)$$

$f(t)$ is the original signal; $W_{\varphi} f(a,b)$ is each frequency band component after wavelet transform; $a$ is the wavelet scale factor, which controls the expansion and contraction of the
wavelet function, corresponding to the frequency of the variable; b is the time shift factor, which controls the shift of the wavelet function; \( \frac{1}{\sqrt{a}}\psi(t-b) \) is wavelet generating function.

This paper used the db8 wavelet basis function in the Daubecheies (dbN) wavelet system to process the original brightness temperature data by wavelet transform [2].

### 3.2. Power spectrum estimation and relative processing

Common random signals cannot be expressed clearly with common mathematical relations, and their Fourier transform does not exist. However, the power spectrum density of a stationary random signal can be estimated with N samples via the power spectrum estimation method.

Power spectrum estimation is divided into classical spectrum estimation and modern spectrum estimation. The classical spectrum estimation mainly has two methods: periodogram and autocorrelation, and the Welch algorithm is improved based on the periodogram method. In this article, the power spectrum estimation refers to the Welch algorithm. First, the N-length data is divided into L segments, each segment with M points, and then each data segment is windowed to obtain the Fourier transform, and finally we calculate the average value of each segment of the power spectrum. The calculation formula is as follows:

\[
P_i(w) = \frac{1}{L} \sum_{l=1}^{L} \frac{1}{M} \sum_{n=0}^{M-1} x(n) w(n) e^{-j2\pi in/M}, \quad i = 1, \ldots, L \tag{2}
\]

\[U = \frac{1}{M} \sum_{n=0}^{M-1} w^2(n)\]

is the normalization factor, \( w(n) \) is the window function, \( P_i(w) \) is the final calculation result.

The power spectrum was calculated using the satellite brightness temperature data and then transformed by wavelet transform. Taking \( n = 64 \) days as the window length and \( m = 1 \) day as the sliding window length for Fourier transform, the latest time of the data in the window was considered, and a set of power spectra were obtained by sliding the time history data of each pixel once. Relative amplitude was used to compare the similarities and differences of the power spectra, before and after the earthquake. The result was the relative power spectrum value of each pixel (0.05° × 0.05° range). For the calculation and relative processing of the power spectrum, please refer to the article by Guo Xiao et al [2].

### 4. Results and analysis

#### 4.1. Thermal infrared temporal and spatial changes of Songyuan M\(_4\).9 earthquake

The M\(_4\).9 earthquake occurred in Songyuan on July 23, 2017, with the focal depth of 12 km and an epicenter located in 45.3°N, 124.81°E. The relative power spectrum of the 5-band wavelet (Fig.1) was found to gradually increase for the analysis of daily data before the earthquake since June 1, 2017, and the high-value areas expanded on June 20. The amplitude and area reached the maximum on July 5, and then gradually attenuated. The earthquake occurred on July 23 until the high value disappeared on July 27, and the abnormality lasted
for over a month. Analyzing the temporal and spatial evolution of the thermal infrared anomaly, before and after the earthquake, it was found that the relative power spectrum of the thermal infrared brightness temperature data was significantly abnormal, and the abnormal change lasted for a long time. The thermal infrared anomaly before the earthquake was relatively large and the shape was more prominent. The whole anomalous evolution followed a process of 1) anomaly appearance, 2) enhancement, 3) reaching the maximum value, 4) attenuation, 5) earthquake, 6) disappearance of the anomalies, similar to what was observed in the rock experiment results [3]. In other words, the infrared radiation presents little change in the initial stage, slow increase in the elastic stage, and the plastic anomaly gradually returning to the normal background value from the maximum value. The Songyuan M4.9 earthquake occurred at the edge of the abnormal area on the 18th day after the peak that was on July 23.

From the perspective of tectonic space, the anomaly appeared at the intersection of Yilan-Yitong fault and Mishan-Dunhua fault firstly, the strike of the zones gradually expanded on June 20, and the overall trend also showed an increasing trend, which was consistent with the distribution of the northern section of the Tanlu fault zone, mainly distributed on the eastern edge of the Songliao Basin. The anomaly was accompanied by shrinkage of the area after July 15. After the earthquake occurred on July 23, the area of the anomaly was still in a shrinking trend, and the anomalies disappeared after July 27. The spatial evolution of the thermal radiation anomaly, before and after the earthquake experienced a process of extending from the junction of the Yilan-Yitong fault and the Mishan-Dunhua fault to the Songliao Basin, and finally contracted at the intersection of the

Figure 1. Time-space evolution of the 5 band RWPS anomalies before Songyuan M4.9 earthquake on July 23, 2017
faults. The evolution of the anomaly may be related to the accumulation and change in stress. The continuous change in stress has led to an increase in outgassing of regions rich in geothermal resources [4], which may be the reason for the above similarity.

4.2. Thermal infrared temporal and spatial changes in Songyuan M$s_{S}$5.7 earthquake

The $M_{S}$5.7 earthquake occurred in Songyuan on May 28, 2018, with a focal depth of 10 km and the epicenter was located in 45.27°N, 124.71°E. Scanning and analysis of daily data before the earthquake (Fig.2), it was observed that the relative power spectrum of the 5-band wavelet has gradually increased since May 25, 2018. The high-value area expanded on May 27, and the amplitude and abnormal area reached the maximum on June 12, then gradually attenuated, and basically disappeared on June 17. Analyzing the temporal and spatial evolution of the thermal infrared anomaly, before and after the earthquake, the relative power spectrum of the thermal infrared brightness temperature data experienced an abnormal change lasting only 3 days before the earthquake occurred. The largest area of the thermal infrared anomaly was the 12th day after the earthquake. The abnormal process manifested as the process of abnormal appearance-enhancement-earthquake-reaching the maximum value-attenuation-disappearance of the abnormality. Based on the RWPS spatial-time evolution images, the anomaly appeared at the intersection of the Yilan-Yitong fault and the second Songhuajiang fault first. The trend of the second Songhuajiang fault gradually expanded on May 27, and the overall anomaly also increased gradually. It was consistent with the distribution of the northern section of the Tanlu fault zone and mainly distributed on the southeastern edge of the Songliao Basin.

![Figure 2. Time-space evolution of the 5 band RWPS anomalies before Songyuan $M_{S}$5.7 earthquake on May 28, 2018](image-url)

The image shows the time-space evolution of the 5-band RWPS anomalies before the Songyuan $M_{S}$5.7 earthquake on May 28, 2018, with a focus on the southeastern edge of the Songliao Basin.
4.3. **The time series curve characteristics of the average spectral value of the seismic thermal infrared brightness temperature**

The time series curve of the average spectral value of the thermal infrared anomaly area can reflect the duration and relative change rate of the anomaly. The mean value of the relative power spectrum was calculated for more than 8 years from 2012 to 2020.

The abnormal significant area with the two earthquakes overlapping 0.5° × 0.5° (Fig.3) showed: 1) Before the MS4.9 earthquake on July 23, 2017, the pre-earthquake characteristic power spectrum amplitude was greater than 4, the starting time was June 19, and after 32 days, the amplitude decreased to 1.62 on July 21, and the earthquake occurred on July 23. At the same time, the amplitude on the day of the occurrence was 0.63, and it returned to the background level after the earthquake; 2) The starting time for the characteristic power spectrum amplitude was greater than 4 on May 10 before the Ms5.7 earthquake on May 28, 2018 and after 38 days, the amplitude decreased to 3.25 on June 17, and the amplitude on the day of the earthquake was 5.43 on May 28.

According to the time series curve of the average spectral value of the abnormal area, it was observed that the Ms4.9 earthquake occurred when the abnormal peak fell to the normal range on July 23, 2017. However, the Ms5.7 earthquake occurred before the abnormal peak on May 28, 2018. Based on the results of previous earthquake examples and relevant judgment experience, the occurrence of two earthquakes at different stages of amplitude could be related to the rate of stress accumulation in the epicenter area.

![Figure 3](image_url)  
**Figure 3.** Time series curve of RWPS average value in a small range of abnormal area (44.0°–44.5°N, 128°–128.5°E)

5. **Discussion on basin effect**

5.1. **Geological profile of Songyuan area**

Songyuan area is located in the northwest of Jilin Province and belongs to the plain landform. Its geological structure belongs to the northern section of the Tanlu fault zone and the central
depression zone of the Songliao Basin. The Tanlu fault zone is a deep and large fault, stretching for about 2,400 km, that has been active for a long time since the Mesozoic and Cenozoic in the eastern China. Its northern section (Zhaoxing–Changtu section) passes through the east of Songyuan area and starts in Zhaoxing County on the Heilongjiang side in the north with the south end to Changtu County, Liaoning. It strikes NE 40°~45° and extends about 800 km, where it is divided into two main faults, Yilan-Yitong and Mishan-Dunhua. In Songyuan area, the main faults are Fuyu–Zhaodong fault, the north of Fuyu fault, Songhuajiang second fault, Gudian fault, and Chahuagan–Daozijing fault. Songyuan is located in the hinterland of the Songnen Plain. The surface is mainly composed of loose Quaternary sediments with a thickness of 80–100 m [5-6]. The earthquake has led to the liquefaction of surface sediments in the Songyuan area [7], and there are even signs of sand volcanic eruption in the weak stress zone.

5.2. The relationship between the basin and its surrounding seismic heat radiation
Thermal infrared anomalies are obvious at the western edge of the Tarim Basin before the Jiashi–Bachu Ms6.8 earthquake in 2003 as studied by Guo Weiying et al [8]. The distribution of thermal anomalies before the Jiuzhaigou Ms7.0 earthquake in 2017 is similar to the Wenchuan earthquake, and it spreads along the edge of the Sichuan Basin studied by Zhang Lifeng et al [9]. These studies have shown that the satellite thermal radiation anomalies are related to a rich basin in geothermal resources before the earthquake. It is also an active answer for the formation mechanism of seismic thermal infrared, and the proposed seismic basin effect clearly supported the earth deflation theory. It is rich in oil and gas resources in the northern Songliao Basin [10-11]. A large amount of natural gas underground the petroliferous basin is more sensitive to change in stress before earthquakes. When the earthquake stress has accumulated to a certain extent, the active structural belts and some micro-fractures are filled with natural gases in the upwelling channel around the basin, such as methane, carbon dioxide, and other greenhouse gases, overflowing the surface and significantly increasing the temperature. The abnormal radiation temperature in a large area of the basin may be related to the leakage of natural gas before the earthquake. It can be seen from Fig.4 the range of thermal infrared temperature anomalies is also in the Songliao Basin with an altitude greater than 400 m of the edge position before the Jilin Songyuan Ms5.7 earthquake on May 28, 2018 and the Jilin Songyuan Ms4.9 earthquake on July 23, 2017.

6. Discussion and conclusion
In this paper, we use the Chinese geostationary satellite data as the data source, applying the wavelet transform and power spectrum estimation method to analyze the Ms4.9 earthquake on July 23, 2017, the Ms5.7 earthquake on May 28, 2018, and the Ms5.1 earthquake on May 18, 2019 in Songyuan area. The results of the radiation anomaly study are as follows: Obvious thermal radiation anomalies were observed for the Ms4.9 earthquake on July 23, 2017 and the Ms5.7 earthquake on May 28, 2018. The spatial distribution was consistent with the strike of the northern section of the Tanlu fault, and was mainly distributed in the Songliao Basin, rich in oil and gas resources. On the eastern edge, the largest area of thermal radiation anomaly between the two earthquakes was about $1.9 \times 10^6$ km². Moreover, both the earthquakes occurred on the western edge of the warming area. The thermal radiation anomaly before the two earthquakes started expanding from the eastern edge of the basin. The reason could be
that the eastern edge of the basin has higher oil and gas and more developed faults, which is beneficial to greenhouse gases release through developed rock mass cracks. The heat radiation intensity was at a normal level, before and after the M5.1 earthquake. Greenhouse gases, such as carbon dioxide and methane in the basin were possibly released in the greatest amounts, before and after the previous two earthquakes. The temporal evolution characteristics of earthquakes show that the relative power spectrum anomaly amplitude exceeded twice the average value of the M5.9 earthquake and the M6 5.7 earthquake. The relative power spectrum amplitude and the abnormal duration lasted 32 days for the M5.9 earthquake, and the earthquake occurred when the amplitude decreased. The relative power spectrum of the anomaly and the duration of the anomaly lasted 38 d and the Ms4.9 earthquake occurred in the process of increasing amplitude.

According to the temperature anomaly in Songyuan area similar to previous domestic earthquake examples: (1) The anomaly is distributed on the edge of the basin; (2) The epicenter of the earthquake is not in the abnormal area; (3) Earthquakes may occur in the process of increasing or decreasing radiation.

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