A Study on Spreading Direction of Coal-fire Based with TIR Remote Sensing in Wuda Coalfield from 2000 to 2006, Northern China

H. -Y HUO, X.-G JIANG, X. -F SONG, Z. -Y NI, C. –X GAO, Y.-Z ZHANG L. Liu

1 Graduate Univ. of Chinese Academy of Sciences, Beijing 100049, China;
2 School of Geography, Beijing Normal Univ., Beijing, 100875, China
3 Academy of Opto-Electronics, Chinese Academy of Sciences, Beijing, 100094, China

Email: xgjiang@aoe.ac.cn

Abstract. Coal fires are a common and serious problem in most coal producing countries. Coal fires could not only lead to a huge loss of non-renewable energy resources, but it also can cause many environmental problems such as GHG emission, land subsidence and increment of surface temperature. So it is very important to monitor the dynamic changes of coal fires. As far as large scale coal field, remote sensing provided researchers with a new and useful technique for coal fire detection. This paper developed a research over coal fire spreading direction using a multi-temporal TIR remote sensing approach. The results successfully showed that the direction of coal fire spreading and predicted the coal fire direction of development on a regional scale or on a whole coal field scale, and a quantitative analysis of coal fires was made in the research. The results showed that the coal fires had an average annual increase of 0.5 million square meters from 1999 to 2006, and the TIR remote sensing proved to be an available tool for coal fire mapping and prediction of coal fire development.

1. Introduction
Coal fires are a common problem in most coal producing countries like the United States, India, South Africa, Australia, Indonesia, Canada and China [1], which can be divided into surface fire and subsurface fire [2]. Surface fire can be defined as a coal fire which burns in direct contact with the atmosphere [3]. Subsurface fire can be defined as coal combustion that occurs when oxygen reach coal-bed through fractures of abandoned mine tunnels or subsided land surface, and then the coal combustion may begin [2].

China has the largest coal resources in the world, and correspondingly, the coal fire problem is very serious [4]. In northern China, the coal fires occur within a wide region stretching 5000 km east-west and 750 km north-south [5]. Due to the vast dimensions of some burning coal fields (more than 20 million tons

1 X.-G JIANG, corresponding email address: xgjiang@aoe.ac.cn
p.a.), 3 to 5 times of this amount is heavily affected by the fires and is therefore of no economic use [6]. Coal fires could not only lead to a huge loss of nonrenewable energy sources, but also cause many environmental problems such as land surface subsidence and collapse, GHG (Green House Gas) and other toxic gases (e.g., SO2, NO, CO, CH4) emissions along fissures and cracks, and the increment of surface temperature [7, 8].

After the first use of remote sensing as a tool to identify coal fires in 1960s [9], with the time, the efficiency of remote sensing to identify and monitor coal fires has been well established by many researchers [5, 10, 11]. This paper makes an attempt to identify temperature anomalies of the Wuda coalfield to locate the spatial distribution and spreading direction of coal fires. In the research, the satellite images presented in this study are a serial of multi-temporal Landsat TM images. ETM+/TM 6 band image is very useful in distinguishing gross thermal anomalies from the background of solar warming and it can be used for mapping subsurface coal fires [11], with a serial of multi-temperta ETM+/TM 6 images, we predicted the spreading direction of the underground coal fires. Then, we used the Official Coal Fire Map (made by the Local Mineral Bureau) to validate the Results, the spreading direction of coal fires developing we predicted was very identical with the results depicted by the local official bureau.

2. Study area
Wuda coalfield area is located in Wuhai City (See figure 1-b), Inner Mongolia Autonomous Region in North China (See figure 1-a). Its geographic location is extending latitudinally from 39°25′26″ N to 39°34′40″ and longitudinally from 106°32′30″ to 106°45′50″. Physically the study area is bounded by the Yellow River in the east, Gobi desert in the north and west, and Helan Mountain in the south, with a total area of somewhere 35 km² (See figure 1). Wuda coalfield includes three coal mining zones namely, Wuhushan, Suhaitu and Huangbaici by the mining authority (See figure 1-c).

3. Data processing and methods

3.1. Data
The data set includes all 2000 to 2006 cloud-free summer-time multi-temporal Landsat-5 TM band 6 TIR images over the study area, with the spatial resolution 120m, and also the Coal Seam Fire Map made by BRSC (Beijing Remote Sensing Corporation, Beijing, China) and corresponding detailed investigation report of Wuda coalfield, which were used to validate the results retrieval from the satellite images.

### 3.2. Methods

Figure 2 is a flow chart of the data pre-processing and analysis followed in this study and the summer or autumn time cloud free images are listed in table 1 and they were imported and converted to WGS84 (Geodetic Reference System of 1984) with UTM (Universal Transverse Mercator) and zone48 for the base projection.

#### 3.2.1 LST retrieval from ETM+/TM band 6 TIR data

The first step was to, according to the following equation, converted the raw digital numbers (DN) to spectral radiance, $L_{\lambda}$ [12],

$$L_{\lambda} = L_{\min(\lambda)} + \frac{L_{\max(\lambda)} - L_{\min(\lambda)}}{Q_{\text{cal max}}} Q_{\text{cal}}$$  \hspace{1cm} (1)

where $L_{\lambda}$ is the spectral radiance, $L_{\min(\lambda)}$ = Minimum detected spectral radiance for the scene, $L_{\max(\lambda)}$ = Maximum detected spectral radiance for the scene, $Q_{\text{cal}}$ = The grey level for analyzed pixel and $Q_{\text{cal max}}$ = The maximum grey level.

The second step was to establish the relationship between the spectral radiance and the radiant temperature for the pixel. The relationship can be described using the following equation,

$$T_R = \frac{K_1}{\ln\left(\frac{K_2}{Q_{\text{cal}} + 1}\right)}$$  \hspace{1cm} (2)

where $K_1$ and $K_2$ are two calibration constants, $T_R$ = Radiant temperature (K).

In the final step, we converted the radiant temperature, $T_R$, to the surface kinetic temperature, $T_K$ using the following equation,

$$T_R = \varepsilon_{\lambda}^{1/4} T_K$$  \hspace{1cm} (3)

where the $\varepsilon_{\lambda}$ is the spectral emissivity, in this paper, the emissivity is estimated at the value 0.95 [13, 14].

#### 3.2.2 Threshold for coal fire delineation

| Table 1. Data set used in this research. |
|------------------------------------------|
| **Data Type**    | **Scene** | **Acquisition Time** |
|------------------|-----------|-----------------------|
| Landsat ETM+     | 129/33    | 12 Aug. 1999          |
| Landsat ETM+     | 129/33    | 30 Aug. 2000          |
| Landsat ETM+     | 129/33    | 29 May 2001           |
| Landsat ETM+     | 129/33    | 20 Aug. 2002          |
| Landsat TM       | 129/33    | 17 Aug. 2004          |
| Landsat TM       | 129/33    | 07 Aug. 2006          |
| Coal Fire Map of BRSC | Scale: 1:5000 |
Regarding to the different time, climate conditions, different types of surface, and different degree and depth of coal fire, it made some difference of temperatures retrieved from multi-temporal thermal images. So a fix threshold is not suitable for coal fire delineation, then, a dynamic threshold is available for this study. A good review on common dynamic thresholding techniques is presented by Raju et al [11]. In this study, we used the dynamic threshold calculated through the mean temperature plus two times standard deviation for detecting the thermal anomaly pixels.

4. Results

4.1 Analysis of coal fire spreading direction from 1999 to 2000
In figure 3, it is obvious that the fire zones 3-1, 3-2 and 3-3 are in the red circle region A, most of the coal fires in the region are spreading into north or northeast direction, while in the most north part of the study area of Wuda Coalfield, the coal fires are inclined to spreading into southwest. In the most south part of the study area of Wuda coalfield (the yellow circle region), the coal fires spreading direction is almost the same as the most north part, except few coal fires are inclined to southeast direction.

4.2 Analysis of coal fire spreading direction from 2001 to 2002
In figure 4, as the same situation with above, we used a red circle B to describe the middle region of Wuda coal field. In the region B, we can found that the coal fire zone 4-1 and 4-3 are spreading into northeast, while in the most north part of the study area, the fire is spreading into south direction. In the most south part of study area, the coal fires are also spreading into south direction, except small part of coal fires are spreading into middle direction from two directions, e.g. coal fire zone 4-6.

4.3 Analysis of coal fire spreading direction from 2004 to 2006
In figure 5, the coal fire zones 5-2, 5-3 and 5-5 bounded by the red circle C are approximately spreading into northeast. In the most north part of study area, coal fire zone 5-1, the fire is spreading into south or southwest and the most south coal field, coal fire zone 5-4, the fire is spreading into southeast.

Generally, coal fires in the middle part of this study area in Wuda coal field were spreading into north or northeast direction on the whole, and coal fires lied in the most north part and the most south part of this study area were spreading into south direction regardless of southeast or southwest.

4.4 Quantitative analysis of coal fire
From the table 2, we can see that the thresholds are different as the different climate conditions, surface types and the degree difference of combustion and other conditions. From the table 2, we can also conclude that the coal fire area increased by almost 2.5 million square meters from the 1999 to 2006 with average annual increase of 0.5 million square meters. With a comparative analysis combining the results retrieved from the TIR imageries with the coal fire map obtained through field investigation of BRSC (See Figure 6.), the precision of coal fire retrieved from satellite images is 91%.

| Data Type | Scene | Acquisition Time | Threshold | Coal fire | Area of Coal Fire |
|-----------|-------|-----------------|-----------|-----------|------------------|
| Landsat ETM+ | 129/33 | 12 Aug. 1999  | 43.05     | 104 pixels | 374,400 m²       |
| Landsat ETM+ | 129/33 | 30 Aug. 2000  | 26.25     | 216 pixels | 777,600 m²       |
| Landsat ETM+ | 129/33 | 29 May 2001   | 43.85     | 348 pixels | 1,252,800 m²     |
| Landsat ETM+ | 129/33 | 20 Aug. 2002  | 34.80     | 517 pixels | 1,861,200 m²     |
| Landsat TM  | 129/33 | 17 Aug. 2004  | 34.95     | 537 pixels | 1,935,000 m²     |
| Landsat TM  | 129/33 | 07 Aug. 2006  | 36.85     | 786 pixels | 2,829,600 m²     |

5. Conclusion
The coal fire spreading direction study based on TIR remote sensing approach attached much importance as an attempt because there are no people who made any research over coal fire spreading direction by the whole coal field scale. The results were also validated by the later work and research [15] in the Sino-Germany co-project. Other important conclusions of the study are:

- The TIR remote sensing is an available technique to coal fire detection and mapping and its spreading direction especially in the unexplored areas.
The threshold method is useful and adequate for the coal fire quantitative analysis. And as far as the coal fire spreading direction is concerned, the geological map and coal outcrop distribution map are very important.

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