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A simple method based on the thermal anomaly index to detect industrial heat sources

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ABSTRACT

Because waste gas from industrial burning has a significant effect on urban environment, it is important to detect industrial heat sources from remote sensing data. Given existing pyrometry, it is difficult to identify small factories with low burning temperatures. In addition, existing fire detection methods (such as the contextual algorithm) are cumbersome, complex, and contain multiple thresholds to be determined. With the purpose of detecting industrial heat sources efficiently and simply, we introduced a simple method based on the thermal anomaly index (TAI) to detect industrial heat sources. This index was constructed based on Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) thermal infrared (TIR) data with a detectable temperature of 400 K, which is lower than that used in most high-temperature detection methods. By confirming with the Visible Infrared Imaging Radiometer Suite (VIIRS) Nightfire product and high-resolution images, the TAI confidently detected almost all hot spots with the VIIRS Nightfire product and detected many hot spots that were undetected by the VIIRS Nightfire product. Based on six images acquired over Tangshan, we determined that 54.52% of hot spots were undetected by the VIIRS Nightfire product, while the TAI method was able to detect these hot spots. With the MODTRAN 5 radiative transfer model, we simulated the high-temperature detection ability of the TAI. Compared with the VIIRS Nightfire product, the TAI is more sensitive when detecting hot spots below 700 K. Thus, this method can potentially detect family workshops engaged in the small-scale combustion of fuel.

1. Introduction

The combustion of oil and gas via fossil fuels in factories (e.g., cement factories, coking plants, and steel plants) produces carbon dioxide and other pollutants (Liu et al., 2018). A large amount of carbon dioxide has the potential to enhance global warming (Cherubini et al., 2011). The detection of industrial heat sources aids environmental monitoring and carbon flux cycle analyses (Oda and Maksyutov, 2011). Since strategies focusing on urban–industrial symbiosis aim for carbon mitigation in China (Ramaswami et al., 2017), detailed industrial locations (i.e., factories with combustion processes) will benefit for government management. Because fieldwork and manual visual interpretation are expensive and time consuming, detecting these industrial heat sources with remote sensing methods is a better choice.

However, studies on the identification and extraction of industrial heat sources via remote sensing data are still rare since most fire detection methods seldom distinguish industrial heat sources from wildfire (Schroeder et al., 2008). Liu pioneered the identification and classification of industrial heat sources via time series from the Visible Infrared Imaging Radiometer Suite (VIIRS) Nightfire product. By combining of spatial and temporal aggregations, Liu distinguished static-and-persistent industrial heat sources from ubiquitous biomass burnings (Liu et al., 2018). The Nightfire products used for object segmentation and classification in Liu's study were obtained from multispectral bands, including the visible, near-infrared (NIR), shortwave infrared (SWIR), and midwave infrared (MWIR) bands. The results of the fire products include estimated temperature, source size, and radiant heat of the subpixel heat sources, which are obtained via a Planck curve fit using the simplex optimization method (Elvidge et al., 2013). Temperatures of the thermal anomalies used for classifying industrial heat sources ranged from 500 K to 2500 K because detected temperatures below 500 K had a lower confidence (Liu et al., 2018). With this Nightfire product, the identification of industrial heat sources might miss some small or cooler factories, and these small factories tend to be

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family workshops, whose operating statuses cannot be traced. Therefore, a high-temperature detection method for lower detectable temperatures is required.

Pyrometry combined with remotely sensed data was proposed early by Dozier (1981) to identify the temperature of a subpixel via two thermal infrared (TIR) bands (3.8-μm thermal channel and 11-μm thermal channel). This method was based on Wien's law and Planck's law, and radiance increased more rapidly in the midwave infrared channel at high temperature. Most of the following methods were also based on these two principles. In addition, there was an assumption that mixed pixels were linearly constructed by a target temperature and background temperature. Based on this assumption and the observed radiance in the two channels, the target temperature can be calculated. This method was used to detect high-temperature sources, such as steel plants, waste gas flares (Matson, 1981) and fires (Matson et al. 1987). However, the saturation temperature (i.e., 320 K in both Advanced Very High-resolution Radiometer (AVHRR) channels) was fixed by a sensor design that limited the estimation of fire sizes (Kaufman et al., 1989), but an increase in the saturation threshold and a stretched dynamic range for the sensor can help avoid this problem (Kennedy, 1992). Moreover, a single threshold (e.g., an empirically defined threshold value for the digital number (DN) or temperature) is inappropriate for universal application (GrÉGoire, 1990); therefore, multiple thresholds were used to distinguish biomass burning from clouds and hot soil (Kaufman et al., 1989). Hence, bispectral infrared detection (Matson, 1981) has developed into multispectral detection (Ricardo et al., 1995) with the purpose of eliminating as many problems as possible related to large surface heterogeneity, confusion and bias, which are produced by clouds, smoke, haze, and background emissivity. This multispectral detection method was later developed into a contextual algorithm (Flasse and Ceccato, 1996), which is self-adaptive and consistent over large areas and seasons. The contextual algorithm consists of two stages: the first is the detection of potential fire pixels, and the second is the confirmation of potential fire pixels (Flasse and Ceccato, 1996). It has been successfully used on remote sensing data, such as Moderate Resolution Imaging Spectroradiometer (MODIS) (Giglio et al., 2006, 2003) and VIIRS (Csiszar et al., 2014; Schroeder et al., 2014) data. This method uses fixed thresholds to identify potential fire pixels, while only large flaming fires can be detected with high probability (Koltunov and Ustin, 2007).

To detect small-scale fires, a nonlinear multitemporal detection method modified based on the dynamic detection model (DDM) was applied. This nonlinear DDM adopted a set of basis images combined in a nonlinear way to predict background pixel intensities, and the pixels whose observed intensities were statistically and significantly different from the predicted intensities were flagged as anomalies (Koltunov and Ustin, 2007). In addition, a multitemporal Kalman filter approach was used to detect actively burning fires and quantify their fire radiative power (FRP) because the nonlinear DDM cannot estimate the fire size (Roberts and Wooster, 2014). Although multitemporal detection inherits the advantages of a contextual algorithm and makes full use of high temporal imaging frequencies, it is still limited by costly computation and requires full-day observations (Roberts and Wooster, 2014).

To figure out the limitation of fix thresholds, dynamic thresholds were used to develop the Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR) pre-launch active fire product (Wooster et al., 2012) and the MODIS collection 6 fire product (Giglio et al., 2016). In addition, the SWIR channel was also applied to the high-temperature detection method to replace the midinfrared channel due to the peak radiant emissions of high temperatures are at substantially shorter wavelengths (Elvidge et al., 2013). This change makes it possible for data without midinfrared channels to detect thermal anomalies and was successfully achieved in Landsat 8 (Schroeder et al., 2016) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (Giglio et al., 2008). These modifications help to enrich the study of pyrometry and make available fire products more reliable.

However, when we aim to detect small-scale industrial heat sources, existing high-temperature detection methods are still limited, because the well behaved method (i.e., the contextual algorithm) is cumbersome and complex (Giglio et al., 2003) and relies closely on midinfrared (Giglio et al., 2016) or short-infrared data (Elvidge et al., 2013). In addition, the most widely used data with midinfrared or short-infrared channels for fire detection have low spatial resolutions (e.g., 375 m (Schroeder et al., 2014), 750 m (Elvidge et al., 2013), 1 km (Giglio et al., 2016), and 3 km (Roberts and Wooster, 2014)). Moreover, high-spatial resolution data, such as Landsat 8, used for the extraction of offshore platforms (Liu et al., 2016) are mostly obtained in the daytime, while small factories in China tend to operate at nighttime due to the supervision of the government. Thus, data with a high spatial resolution acquired at nighttime are ideal. Here, we use ASTER data collected at nighttime to detect hot spots for the following reasons:

(1) ASTER data have a high sensor sensitivity in the TIR region with a spatial resolution of 90 m (Yamaguchi et al., 1998), which means that a higher brightness temperature saturation and has the potential to detect cooler or smaller hot spots;
(2) ASTER data have five TIR channels ranging from 8.125 to 11.65 μm, which make up for the short of midinfrared and SWIR channels (SWIR channels are not always available at nighttime) (Abrams, 2000; Yamaguchi et al., 1998).

With ASTER TIR data, we present a simple thermal anomaly index (TAI) for the rapid extraction of thermal anomaly information according to Wien's law and Planck's law. This index is fast and efficient in detecting hot spots, and can extract several thermal anomalies with low temperatures (i.e., approximately 400 K). Then, industrial heat sources are supposed to be derived from those unclassified hot spots. While industrial heat sources derived from time series data (Casadio et al., 2012; Liu et al., 2018, 2016) require a large number of images, we intend to use the VIIRS Day/Night Band (DNB) Nighttime Lights product to simplify this classification process. The reason is that the Defense Meteorological Satellite Program (DMSP) nighttime lights data have already been used for extracting gas flares (Elvidge et al., 2009, 2007) and acted as reference data to confirm the discrimination of flaring sites (Casadio et al., 2012). Although the image for a single date might miss some factories that were not operating when the image was obtained, we aim to operate this TAI to see whether it works.

2. Study area and data

2.1. Study area

Tangshan is the industrial center of the Beijing, Tianjin and Hebei province; it is located northeast of the North China Plain, with a total area of 13,472 square kilometers. With mountains to the north, and plains to the south, Tangshan has a warm, temperate, semihumid continental monsoon climate. There is an abundance of mineral resources in Tangshan, which makes the heavy industries prosperous and the leading type of industry. According to the Statistical Yearbook in 2016 (Aimin, 2016), the total industrial production generated 273.92 billion yuan, ranking first in Hebei Province. In addition, the proportion of steel, coking, cement and other high-energy-consuming industries accounted for 37% of the total industry. Moreover, the proportion of equipment manufacturing accounted for 20% of the total industry. Because the proportion of heavy industries in the entire industry is large, and the type of industry is complex, Tangshan is the representative area to be studied.

2.2. Data

ASTER contains separate visible and NIR (VNIR), SWIR, and TIR optical subsystems. Moreover, the ASTER TIR subsystem has five bands