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Identifying industrial heat sources using time-series of the VIIRS Nightfire product with an object-oriented approach

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ABSTRACT

Carbon-based fuels burned at industrial facilities account for a large proportion of greenhouse gas emissions, and an up-to-date spatiotemporally detailed inventory is essential for a better understanding of global carbon emission patterns. The Visible Infrared Imaging Radiometer Suite (VIIRS) Nightfire product offers a quantitative estimation of the temperatures of sub-pixel heat sources, providing the potential for detecting thermal anomalies from industrial sectors across the globe. However, identifying subcategories of various industrial heat sources is challenging because there are scarcely any stable and typical characteristics for their classification at a single thermal anomaly scale. Specifically, these nighttime thermal anomalies exhibit a strong spatiotemporal heterogeneity (e.g., fluctuations in retrieved temperature, spatial shifts in position, and presence of false positives), even in industrial heat sources that do not vary through time. Here, we demonstrate an object-oriented approach to robustly segment and accurately classify various industrial heat sources from a time-series of the VIIRS Nightfire product. The approach operates from the cluster level of spatially adjacent nighttime thermal anomalies (i.e., nighttime-heat-source objects rather than individual thermal anomalies) to generate fingerprint-like characteristics and to address the challenge of spatiotemporal heterogeneity. Specifically, the spatial-aggregation characteristic of nighttime thermal anomalies from continuously operating industrial heat sources and the temporal-aggregation characteristics of biomass burnings were incorporated to differentiate industrial nighttime-heat-source objects from ubiquitous biomass burnings. Subsequently, the similarity of the thermal signals of nighttime thermal anomalies from identical industrial heat sources was used to generate highly recognizable characteristics for their identification. A spatiotemporally detailed inventory of industrial heat sources across the globe was then established from this object-oriented classification. The inventory included a total of 15,199 industrial heat sources, representing 49.52% of all higher confidence nighttime thermal anomalies in the VIIRS Nightfire product. Validation of the results showed that only 218 objects (1.43%) were biomass burnings or active volcanoes that were misclassified as industrial heat sources. Further validation of sub-categories indicated an overall classification accuracy of ~77%. Our findings suggest that the VIIRS Nightfire product has great potential for monitoring the global distribution and dynamics of industrial heat sources, and combined with the object-oriented approach developed here the methodology is simple, robust, and cost-effective.

1. Introduction

The use of fire was an essential part of the development of human civilization, and the ongoing transition from subsistence to industrial economies is typified by the manner and diversity of fire use (Bowman et al., 2009). The ubiquity of fire/combustion-related activities, such as the burning of tropical rainforest, the flaring of associated petroleum gas in oil fields, and the combustion of fossil fuels in factories (e.g., cement plants, steelworks, etc.), exacerbates the problem of the rising concentration of greenhouse gases (GHGs) in the atmosphere and imperils ecosystems (Abram et al., 2003; Hoegh-Guldberg and Bruno, 2010; Peltier and Tushingham, 1989). Consequently, a spatiotemporally-detailed inventory of varying combustion sources across the globe would serve as a priori knowledge in the carbon flux cycle (Gurney

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et al., 2005; Oda and Maksyutov, 2011), and a source of ground truth data for validating the emerging satellite inversion approaches (Chevallier et al., 2007; Schneising et al., 2008). In addition, since the landmark Paris Climate Change Agreement has implemented a ratchet mechanism, and conducts a global stock-taking every five years (United Nations, 2016), comprehensive and timely knowledge of the amount and distribution of global combustion sources is of crucial importance for measuring, reporting, and verifying whether mitigation actions are effective (Dimitrov, 2016).

In practice, several industrial sectors, including smelting industries, petrochemical industries, and cement industries (which are high-energy consumers, major GHGs emitters, and sometimes heavy polluters) have a close relationship with fire/combustion-related activities. Their GHG emissions are usually difficult to survey/inspect/regulate – partly for reasons of remote distribution and partly because of intentional nighttime discharges. The unusually high temperatures (which are extremely distinct at night) from industrial heat sources can be tracked by satellite remote sensing which collects day-and-night, consistent, and extensive data. Therefore, satellite remote sensing may be the most effective way to monitor the dynamics of these thermal anomalies. The past decade has witnessed a number of fire/combustion-related products generated from thermal-infrared (TIR) sensors. These include the Advanced Very High Resolution Radiometer (AVHRR) (Stroppiana et al., 2000), Along Track Scanning Radiometer (ATSR) and Advanced ASTR (AATSR) (Arino et al., 2012; Casadio et al., 2012), Visible and Infrared Scanner (VIRS) (Giglio et al., 2003), and Moderate Resolution Imaging Spectrometer (MODIS) (Justice et al., 2002) sensors. Their products provide valuable information about heat sources generated by biomass burnings, such as the global spatiotemporal distribution of active fires (Dwyer et al., 2000; Giglio et al., 2006a; Ichoku et al., 2008; Kasischke et al., 2003; Schultz, 2002), burned areas (Giglio et al., 2006b; Roy et al., 2008), volume of fire emissions and the corresponding contribution of different biomass burnings (Giglio et al., 2013; Hoelzemann et al., 2004; Kaiser et al., 2012; Randerson et al., 2012; van der Werf et al., 2010). However, to date, there are only a few products related to industrial heat sources. The MODIS Collection 6 active fire product only provides a coarse classification (i.e., volcanoes, onshore, and offshore flaring) of static and persistent hot spots (Giglio et al., 2016), and finer subcategories are not presented. This may be due, in part, to the fact that the size of industrial heat sources is usually substantially smaller than the spatial resolution of satellite images, and consequently the derived brightness temperature has both background and heat source components, and therefore may not be sufficient to determine the exact subcategory. Similarly, other fire properties (e.g., density, peak month, season length, mean fire radiative power), derived from the traditional "gridded fire count" approach by statistically counting the daily/monthly/annually/multi-year fire product (Giglio et al., 2003), are also inadequate to serve as highly-recognizable and semantically significant characteristics for the reliable identification of various subcategories of industrial heat sources.

The Visible Infrared Imaging Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (S-NPP) satellite provides higher-resolution (~750 m) data than its predecessors. It is equipped with multi-spectral bands for day- and night-time measurements (Csiszar et al., 2014; Schroeder et al., 2014), providing the potential for identifying various kinds of static-and-persistent heat sources from industrial sectors. The Earth Observation Group (EOG) of the National Oceanic and Atmospheric Administration (NOAA) has firstly developed a Nightfire system to detect global nighttime thermal anomalies (Elvidge et al., 2013). The VIIRS Nightfire product offers a quantitative estimation of the area and temperature of heat sources, and has been operationally applied to detect gas flaring, resulting in improved estimation of the volume of global gas flaring (Elvidge et al., 2016). However, generic application of the VIIRS Nightfire product to identify other industrial heat sources remains challenging because of the following limitations: (*i*) *Temperature overlap among heterogeneous heat sources*. For instance, practitioners have found it extremely difficult to separate adequately gas flares from other heat sources based solely on their temperatures, due to the overlap between high-temperature biomass burning and low-temperature gas flaring. (*ii*) *Variation among homogeneous sources*. The inherent variability of nighttime thermal anomalies properties, such as fluctuations in retrieved temperature, spatial shifts in position, and even the presence of false positives, may also result in point-to-point variation of homogeneous heat sources along the temporal dimension. Therefore, it is extremely difficult to classify nighttime thermal anomalies into accurate subcategories based on the unstable and atypical characteristics of a single thermal anomaly. For the same reasons, it is highly desirable to overcome these difficulties to extend the use of the VIIRS Nightfire product in Earth science.

The objective of this study is to test the feasibility of mapping and identifying different subcategories of industrial heat sources from a time-series of the VIIRS Nightfire product. To generate fingerprint-like characteristics, and to address the challenge of spatiotemporal heterogeneity of nighttime thermal anomalies, an object-oriented approach was developed. This approach combines features of nighttime thermal anomalies from the spatial/temporal/thermal dimensions, or from the cluster perspective of spatially adjacent and/or temporally coherent nighttime thermal anomalies, rather than individual thermal anomalies. To our knowledge, this is the first time that the medium-resolution VIIRS Nightfire product has been used to successfully generate a highly-recognizable and semantically significant temperature pattern (to identify various industrial heat source subcategories) and to create a spatiotemporally-detailed inventory of industrial heat sources across the globe.

In the following section, we provide a summary of the VIIRS Nightfire product used for this study, followed by a description of the object-oriented segmentation and classification framework. Next, we describe the characteristics of industrial heat sources calculated from time-series of the VIIIRS Nightfire product and the distribution of global industrial heat sources. Finally, we present an error analysis and intercomparison with known related datasets, and further discuss the significance of integrating the VIIRS Nightfire product and the object-oriented.

2. Datasets

2.1. VIIRS Nightfire product

The daily Nightfire product generated by NOAA EOG (http://www.ngdc.noaa.gov/eog/viirs/) was downloaded and used for mapping the worldwide industrial heat sources. The EOG Nightfire system utilizes S-NPP VIIRS multispectral bands including visible (Day/Night Band, DNB), near infrared (NIR, M7 and M8), short-wave infrared (SWIR, M10), and mid-wave infrared (MWIR, M12 and M13) to detect sub-pixel heat sources and retrieve their estimated temperature, source size, and radiant heat. The M10 band data are used initially to detect a thermal anomaly, and the five spectral bands (DNB, M7, M8, M12, and M13) are used to confirm the initial detection. In the Nightfire product, the M10 detections not confirmed by any other spectral bands are labeled with the value of 999,999 in the BB_Temp field (before 31 March 2014) or Temp_BB field (after 31 March 2014). The M10 detections only confirmed by the DNB band are set to 1810 K (it was switched to 999,999 in the Prerun 2.1 version). For confirmed M10 detections (hereafter referred to as higher confidence nighttime thermal anomalies), a Plank curve fitting using the Simplex Optimization Method is adopted to estimate the temperature of the background and sub-pixel heat sources from an identified thermal anomaly (Elvidge et al., 2013).

The Nightfire product used spans the interval from 1 September 2012 to 30 September 2016 (a total of 1470 days), covering the area between 65°N and 65°S (Fig. 1a). The Nightfire product includes a total of 35,474,293 nighttime thermal anomalies with 23,144,010