Remote Sensing of Environment 113 (2009) 2511–2526

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

A MODIS direct broadcast algorithm for mapping wildfire burned area in the western United States

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ARTICLE INFO

Article history:
Received 4 May 2009
Received in revised form 15 July 2009
Accepted 18 July 2009

Keywords:
Fire
Burned area
Fire detection
MODIS

ABSTRACT

Improved wildland fire emission inventory methods are needed to support air quality forecasting and guide the development of air shed management strategies. Air quality forecasting requires dynamic fire emission estimates that are generated in a timely manner to support real-time operations. In the regulatory and planning realm, emission inventories are essential for quantitatively assessing the contribution of wildfire to air pollution. The development of wildland fire emission inventories depends on burned area as a critical input. This study presents a Moderate Resolution Imaging Spectroradiometer (MODIS) – direct broadcast (DB) burned area mapping algorithm designed to support air quality forecasting and emission inventory development. The algorithm combines active fire locations and single satellite scene burn scar detections to provide a rapid yet robust mapping of burned area. Using the U.S. Forest Service Fire Sciences Laboratory (FiSL) MODIS-DB receiving station in Missoula, Montana, the algorithm provided daily measurements of burned area for wildfire events in the western U.S. in 2006 and 2007. We evaluated the algorithm's fire detection rate and burned area mapping using fire perimeter data and burn scar information derived from high resolution satellite imagery. The FiSL MODIS-DB system detected 87% of all reference fires >4 km^2, and 93% of all reference fires >10 km^2. The burned area was highly correlated ($R^2=0.93$) with a high resolution imagery reference burn scar dataset, but exhibited a large over estimation of burned area (56%). The reference burn scar dataset was used to calibrate the algorithm response and quantify the uncertainty in the burned area measurement at the fire incident level. An objective, empirical error based approach was employed to quantify the uncertainty of our burned area measurement and provide a metric that is meaningful in context of remotely sensed burned area and emission inventories. The algorithm uncertainty is ±36% for fires 50 km^2 in size, improving to ±31% at a fire size of 100 km^2. Fires in this size range account for a substantial portion of burned area in the western U.S. (77% of burned area is due to fires >50 km^2, and 66% results from fires >100 km^2). The dominance of these large wildfires in burned area, duration, and emissions makes these events a significant concern of air quality forecasters and regulators. With daily coverage at 1-km^2 spatial resolution, and a quantified measurement uncertainty, the burned area mapping algorithm presented in this paper is well suited for the development of wildfire emission inventories. Furthermore, the algorithm's DB implementation enables time sensitive burned area mapping to support operational air quality forecasting.

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1. Introduction

Biomass fires emit large amounts of trace gases and particles (Ito & Penner, 2004; Michel et al., 2005; van der Werf et al., 2006; Wiedinmyer et al., 2006) and these emissions significantly influence the chemical composition of the atmosphere and the earth's climate system (Langmann et al., 2009; Lapina et al., 2006; Simpson et al., 2006). The pollutants released by biomass burning include greenhouse gases, photochemically reactive compounds, and fine and coarse particulate matter (PM). Biomass fire emissions comprise a substantial component of the total global source of carbon monoxide (40%), carbonaceous particulate matter (35%), and nitrogen oxides (20%) (Langmann et al., 2009). Fires influence climate both directly, by emitting greenhouse gases and aerosols, and indirectly, through secondary effects on atmospheric chemistry (e.g., ozone (O_3) formation) and aerosol and cloud microphysical properties and processes (Lohmann & Feichter, 2005; Naik et al., 2007). Biomass fire emissions contribute to air pollution by increasing the atmospheric levels of pollutants that are detrimental to human health and ecosystems, and degrade visibility. The air quality impacts occur through the emission of primary pollutants (e.g., PM) and the production of secondary pollutants (e.g., O_3,

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0034-4257/$ – see front matter. Published by Elsevier Inc.
doi:10.1016/j.rse.2009.07.007

secondary organic aerosol) when organic compounds and nitrogen oxides released by fires undergo photochemical processing. Air quality can be degraded by transport and transformation of fire emissions on local (Muhle et al., 2007; Phuleria et al., 2005), regional (DeBell et al., 2004; Sapkota et al., 2005; Spracklen et al., 2007), and continental (Morris et al., 2006) scales.

In the United States, heightened concern over the detrimental health impacts of PM and O_3 have brought increased attention to fire emissions. Recently revised National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ and O_3, the Regional Haze Rule (URL: http://www.epa.gov/visibility/program.html), and proposed rulemaking to regulate greenhouse gases have intensified the pressure on both air regulatory and land management agencies to address the air quality impact from biomass burning. Improved estimates of wildfire emissions are needed to support the forecasting and short-term management of regional air quality and to guide the development of land and air shed management policy. Both needs require accurate emission estimates with high temporal (hour to daily) and spatial resolution (sub-grid scale with respect to air quality models which have a minimum grid of about 4 km). Air quality forecasting and mitigation management have the additional requirement that emission estimates be generated in a timely manner to support real-time operations. In the regulatory and planning realm, wildfire emission inventories are needed to quantitatively assess the contribution of wildfire to air pollution. Reliable wildfire emission inventories are also needed for the development of strategies to improve or maintain air quality and to guide land management strategies (e.g. the use of prescribed fire to reduce the occurrence of catastrophic fire events).

The emission of a compound X from biomass burning during a given time period depends on burned area, vegetation loading and condition, fire behavior, and specific emission factors for X (Seiler and Crutzen, 1980). Burned area is one of the key uncertainties in estimating biomass burning emissions. Remote sensing from space-borne platforms is a valuable method for fire detection and the measurement of burned area. High spatial resolution (30 m) Landsat TM and ETM+ imagery has been used to successfully measure burned areas and assess fire effects on vegetation and soil (Cocke et al., 2005; Epting et al., 2005; Key and Benson, 2006; Miller & Yool, 2002; van Wagtendonk et al., 2004). The high spatial and spectral resolution data provided by Landsat is well suited for mapping fire burned area and fire severity. However, with an observation interval of 16 days (Global Land Cover Facility, 2004 ; URL: http://glcf.umiacs.umd.edu/data/landsat/) the data lack the temporal resolution needed for air quality forecasting activities and the development of emission inventories.

Data from satellite sensors that provide higher temporal resolution with moderate to low spatial resolution (500 m to 4 km) such as the MODerate Resolution Imaging Spectroradiometer (MODIS), SPOT-VEGETATION, the Advanced Very High Resolution Radiometer (AVHRR), and the Geostationary Operational Environmental Satellite (GOES) have been widely used to characterize fire activity and estimate burned area (Pu et al., 2007; Simon et al., 2004; Tansey et al., 2004; van der Werf et al., 2006; Wiedinmyer et al., 2006; Zhang & Kondragunta, 2008). Daily burned area estimates covering the Contiguous United States (CONUS) have recently been developed using the GOES (Zhang & Kondragunta, 2008), MODIS (Wiedinmyer et al., 2006), and AVHRR sensors (Pu et al., 2007). Wiedinmyer et al. and Zhang and Kondragunta used active fire detections to estimate burned area, while Pu et al. developed their burned area product by combining active fire detections with changes in the surface reflectance.

The MODIS sensor on the polar orbiting Terra and Aqua satellites has been widely exploited for fire detection and estimation of burned area. The active fire product (MXD14, which refers to the active fire product derived from the MODIS instrument onboard either Terra or Aqua) is the most commonly used MODIS fire product, the details of which are provided by Giglio et al. (2003). While the MODIS active fire product has a nominal spatial resolution of 1-km, MODIS can detect fires as small as 100 m^2 under favorable conditions (Giglio et al., 2003). The common approach for estimating burned area from MODIS active fire detections assumes that the burned area is proportional to the fire pixel count. In some studies the burned area is assumed to be 1 km^2 per fire pixel count, scaled by fraction of vegetation cover (e.g. Wiedinmyer et al., 2006), while others have employed a proportionality constant that varies with vegetation cover and fire-pixel clustering (Giglio et al., 2006).

While MODIS active fire detections have been successfully aggregated to produce monthly burned area estimates on a coarse scale (1° spatial resolution) (Giglio et al., 2006), reliance on the MXD14 product alone to map daily burned area for air quality modeling and management is problematic. At mid-latitudes (at 45 °N) the timing of the Terra and Aqua MODIS overpasses results in a closely spaced (~90 min) midday pair and a nighttime pair with a six hour separation. This leads to omission errors for small, short-lived fires or fire activity ignited following the last pass of a pair. More importantly, the coarse temporal resolution may cause an underestimate of the burned area for large, rapidly moving fires which may traverse multiple MODIS pixels between overpasses. Recently implemented MODIS burned area products derived from changes in the daily surface reflectance time series address the limitations of the MXD14 product and provides a nominal spatial resolution of 500-m (Roy et al., 2008). Loboda et al. (2007) combined the MXD14 product with a differenced Normalized Burn Ratio (dNBR) time series derived from the MODIS Surface Reflectance 8-day composite (L3 Global 500 m product, Vermote et al., 2002) to map burned area in the western U.S. and Central Siberia.

The Missoula Fire Sciences Laboratory (FiSL) has a MODIS direct broadcast (DB) receiving station in place to demonstrate effective methods for monitoring biomass burning in near-real-time and predicting the impact of fire emissions on air quality. In this study we describe and evaluate a MODIS-DB burned area mapping algorithm designed to provide rapid-response burned area measurements for air quality forecasting and to support the development of emission inventories. The algorithm combines active fire locations (MXD14) and single scene burn scar detections (Li et al., 2004) for measurement of fire burned areas as part of a rapid-response wildland fire emissions system. The MODIS MXD14 algorithm is only capable of detecting fires active during the observation, and very recently burned areas that have retained significant heat. A burn scar algorithm enables the detection of burned area, providing information on fire activity that occurs between MODIS observations. Conceptually, the algorithm used in this study is similar to that developed by Fraser et al. (2000), who combined AVHRR active fire detections and normalized difference vegetation index, as well the method more recently employed by Loboda et al. (2007). As with Loboda et al. (2007), in our algorithm burn scar detection from the MODIS surface reflectance product is combined with the MODIS active fire product to map burned area. However, the algorithms differ substantially in their implementation. Our algorithm applies a series of spectral threshold tests to a single MODIS scene to identify burn scars, while Loboda et al. (2007) apply thresholds to the dNBR calculated from the 8-day composite containing the potential burn scar and the same composite period from one year prior.

The combination of active fire detection and a single scene burn scar detection algorithm is the key to producing a rapid, yet robust burned area measurement. The algorithm presented here was designed to provide daily observations of burned area for large (>4 km^2) wildfires in the western U.S., with a 1-km spatial resolution. This MODIS-DB burned area mapping algorithm was developed to produce emission estimates in support of operational air quality forecasting activities.