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Integrated active fire retrievals and biomass burning emissions using complementary near-coincident ground, airborne and spaceborne sensor data

Wilfrid Schroeder [a,*], Evan Ellicott [a], Charles Ichoku [b], Luke Ellison [b,h], Matthew B. Dickinson [c], Roger D. Ottmar [d], Craig Clements [e], Dianne Hall [e], Vincent Ambrosia [f], Robert Kremens [g]

[a] Department of Geographical Sciences, University of Maryland, College Park, MD, United States
[b] NASA Goddard Space Flight Center, Greenbelt, MD, United States
[c] USDA Northern Research Station, Delaware, OH, United States
[d] USDA Pacific Northwest Research Station, Seattle, WA, United States
[e] San José State University, San José, CA, United States
[f] California State University, Monterey Bay, CA, United States
[g] Rochester Institute of Technology, Rochester, NY, United States
[h] Science Systems and Applications, Inc., Lanham, MD, United States

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A B S T R A C T

Ground, airborne and spaceborne data were collected for a 450 ha prescribed fire implemented on 18 October 2011 at the Henry W. Coe State Park in California. The integration of various data elements allowed near-coincident active fire retrievals to be estimated. The Autonomous Modular Sensor-Wildfire (AMS) airborne multispectral imaging system was used as a bridge between ground and spaceborne data sets providing high-quality reference information to support satellite fire retrieval error analyses and fire emissions estimates. We found excellent agreement between peak fire radiant heat flux data (<1% error) derived from near-coincident ground radiometers and AMS. Both MODIS and GOES imager active fire products were negatively influenced by the presence of thick smoke, which was misclassified as cloud by their algorithms, leading to the omission of fire pixels beneath the smoke, and resulting in the underestimation of their retrieved fire radiative power (FRP) values for the burn plot, compared to the reference airborne data. Agreement between airborne and spaceborne FRP data improved significantly after correction for omission errors and atmospheric attenuation, resulting in as low as 5% difference between Aqua/MODIS and AMS. Use of in situ fuel and fire energy estimates in combination with a collection of AMS, MODIS, and GOES FRP retrievals provided a fuel consumption factor of 0.261 kg MJ^{-1}, total energy release of 14.5e + 06 MJ, and total fuel consumption of 3.8e + 06 kg. Fire emissions were calculated using two separate techniques, resulting in as low as 15% difference for various species.

1. Introduction

Global biomass burning is a major source of aerosols and trace gases that are known to impact the physics of the atmosphere and therefore to influence the Earth's climate (Crutzen & Andreae, 1990). Climate oscillations and feedbacks can induce large inter-annual variability in regional biomass burning activity creating wildfire-prone areas as a result of dryer and warmer climate conditions (Hoffmann, Schroeder, & Jackson, 2003; Phillips et al., 2009; Westerling, Hidalgo, Cayan, & Swetnam, 2006). Biomass burning is also a key disturbance factor at landscape and regional scales, often associated with rapid deterioration of air quality as well as long-lasting effects on surface properties including land cover change and runoff alteration (DeBell et al., 2004; Jaffe et al., 2004; McKenzie, Gedalof, Peterson, & Mote, 2004; Moody, Martin, Haire, & Kinner, 2007). Accurate characterization of biomass burning is therefore crucial to enable quantification of its impacts on local biomes and on regional and global climate feedbacks, as well as for the development of land management strategies to help prepare for wildland fires and to mitigate their effects.

Wildland fires create unsafe conditions for people, subject ground instrumentation to harsh conditions, and are diverse in their timing, duration, and geographical location and extent. These issues are commonly addressed with the use of airborne or spaceborne remote sensing data that capture the radiative component of the energy released during combustion (Dozier, 1981; Giglio, 2007; Kaufman, Justice, et al., 1998; Prins & Menzel, 1992). Kaufman, Justice, et al. (1998) pioneered the retrieval of satellite-based fire radiative power (FRP) using an empirical approach based on brightness temperature

* Corresponding author at: Department of Geographical Sciences, University of Maryland, 2181 LeFrak Hall, College Park, MD 20742, United States. Tel.: +1 202 341 7763.
E-mail address: wilfrid.schroeder@noaa.gov (W. Schroeder).

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data in the 4 μm region. Wooster, Zhukov, and Oertel (2003) introduced an alternative FRP retrieval using a physical approach based on 4 μm radiance data. Meanwhile, laboratory and small field plot data analyses quantified the relationship between the time-integrated FRP retrievals, or fire radiative energy (FRE), and fuel consumption (Freeborn et al., 2008; Ichoku, Martins, et al., 2008; Kremens, Dickinson, & Bova, 2012; Wooster, Roberts, & Perry, 2005).

The emission of a range of gas species and particulates from fire is traditionally related to fuel consumption through their emission factors (e.g., Andreae & Merlet, 2001). However, emission factors found in the literature vary significantly depending on the experimental conditions, variables and assumptions used to derive them, resulting in a factor of 2–4 uncertainty (e.g., Kaiser et al., 2012). The new satellite fire characterization approach based on FRP has fostered the development of simplified fire emissions calculation methods based on the use of fewer variables and assumptions than the traditional approaches, hence showing great potential to reduce retrieval errors (Ellicott, Vermote, Giglio, & Roberts, 2009; Ichoku, Giglio, Wooster, & Remer, 2008; Ichoku & Kaufman, 2005; Vermote et al., 2009).

The launch of the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Earth Observing System Terra and Aqua satellites in 1999 and 2002, respectively, was a major step in the development of improved quantitative characterization of biomass burning (Justice et al., 2002). The MODIS sensors provided, for the first time, systematic global detection and characterization of active fires using FRP with negligible pixel saturation rates (Giglio, Descloitres, Justice, & Kaufman, 2003; Kaufman, Justice, et al., 1998). Subsequently, fire retrievals similar to the routinely derived MODIS FRP were also developed for the operational Wildfire Automated Biomass Burning Algorithm (WF_ABBA) using coarser spatial resolution Geostationary Operational Environmental Satellite (GOES) imager data. However, a non-negligible pixel saturation rate of up to ~10%, which is dependent on fire and observation conditions, can negatively impact the GOES FRP retrievals (Pereira et al., 2009). Nonetheless, the higher observation frequency provided by geostationary platforms represents a major advantage, which can be exploited using the available saturation-free fire pixels (Xu, Wooster, Roberts, & Freeborn, 2010). Other operational environmental monitoring satellite sensors including the Advanced Very High Resolution Radiometer (AVHRR) onboard the NOAA polar orbiter series may also be used to derive fire characterization data, although high pixel saturation rates undermine their application (Setzer & Verstraete, 1994).

Airborne sensors have also been used extensively in support of fire management in the United States, and to a lesser extent in support of fire science studies in different geographic regions (Kaufman, Kleidman, & King, 1998; King, Platnick, Moeller, Revercomb, & Chu, 2003; Oertel et al., 2003; Riggan et al., 2004). Use of airborne platforms for quantitative fire imaging requires that sensors operating in the middle-infrared (≈4 μm) spectral region have a high dynamic range because it is in this region that fires emit most of their radiation. These sensors must be able to resolve fires at spatial resolutions typically finer than 30 m and accommodate temperature fields ranging from ~300 K background to flaming fronts reaching upwards of 1200 K. Currently, no airborne system fulfills those fire imaging requirements although a few instruments show reasonable configurations (e.g., Ononye, Vodacek, & Saber, 2007; Riggan et al., 2004). NASA's Autonomous Modular Sensor-Wildfire (AMS) has been flown in support of fire science missions aboard both manned and unmanned aircraft (Ambrosia & Hinkley, 2008). The sensor has a multi-spectral channel configuration covering the visible and infrared parts of the spectrum and a nominal saturation temperature of approximately 620 K at its middle-infrared (≈3.75 μm) channel. The application of the AMS sensor over numerous fire imaging missions has successfully demonstrated its potential to both map and quantify biomass burning, generating fire retrievals at much higher spatial resolution compared to the available spaceborne active fire data sets (Peterson, Wung, Ichoku, Hyer, & Ambrosia, 2013). Because of its high radiometric and geometric data quality, AMS can serve as a bridge instrument linking ground and spaceborne fire retrievals. As such, AMS qualifies as a stand-alone fire management data system as well as a science support tool with great potential for use in satellite fire data validation applications.

The objective of this study is to advance the use of complementary ground and airborne fire data sets in support of the development and validation of satellite-based active fire retrieval methods and emissions estimates. We build on a collective effort to map and characterize a prescribed fire near San José, California, during which near-coincident fire retrievals were generated using an array of ground plots, airborne imaging, and spaceborne polar-orbiting and geostationary sensor data. Active fire retrievals were derived first using near-coincident ground and airborne data over small ground control plots to develop robust airborne reference data. Then, FRP was estimated for the entire fire from airborne data, and the results compared with near-coincident spaceborne retrievals. Fire emissions estimates were calculated using two separate methods based on the FRE data derived from the integrated airborne and spaceborne FRP retrievals. We discuss the merits and limitations of the techniques tested and their potential application in support of quantitative biomass burning analyses.

2. Data and methods

The data set analyzed in this study arises from a prescribed fire implemented on 18 October 2011 by the Santa Clara Unit of the California Department of Forestry and Fire Protection (CAL FIRE) and California State Parks at the Henry W. Coe State Park, hereafter abbreviated as HCSP, located approximately 100 km southeast of San Francisco, California. The park is the largest state park in northern California, comprising ~35,000 ha of rugged terrain. The prescribed fire was implemented in a 450 ha plot composed of a mix of grassland, oak woodland, chaparral and ponderosa pine forest (Fig. 1).

Data collected in this study included fuel loading and consumption and ground-, aircraft-, and satellite-based fire radiation measurements. All data acquisition times are reported in Universal Time Coordinated (UTC). The local time at the HCSP site during the sampling period is equivalent to UTC-7 h.

2.1. Ground fuel sampling

Ground-level measurements of fuel loading, fuel consumption, and moisture content were collected from two 100 × 200-m (2 ha) blocks located next to ground fire sampling instruments (Section 2.2). A grass fuel component consisting of a non-native slender oat (*Avena barbata*) and a native blue wild rye (*Elymus glaucus*) was the primary fuel that carried the fire through these blocks. Fifteen pre- and fifteen post-burn clip plots (1-m^2) were established at 10 meter intervals along 3 grid lines spaced 20 m apart within the blocks. Fuel from within each clip plot was collected and separated into a grass or forb fuel types, oven dried, then weighed to determine pre- and post-burn loading. Consumption was calculated by subtracting the average pre-burn loading from average post-burn loading, for each set of plots. Five to ten 6-liter plastic bags of fuel moisture content samples representing the grass and forbs were collected immediately before each burn. The samples were weighed and oven dried at 70 °C for 24 h to determine percent moisture content. Time limited the ability to establish fuel loading and consumption sampling sites in a forested or shrub area within the fire boundary. This would have represented a more complex fuel bed found within the fire perimeter with grass and forbs along with a dead woody and litter fuel component.

2.2. Ground fire measurement

Fire radiative power was estimated using nadir-viewing dual-band radiometers placed at 2.5 m above ground on steel tripods. Calibration and use of dual-band radiometers similar to the ones deployed in this experiment are described in Kremens et al. (2012). The middle infrared