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The Science and Application of Satellite Based Fire Radiative Energy

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1. Introduction

Biomass burning has been a topic of research interest for many years due to the implications for climatic change as a result of landscape alteration and atmospheric loading of aerosols and trace gases from pyrogenic emissions (Crutzen & Andreae, 1990). Crutzen et al. (1979) first highlighted the variety of trace gas emissions from tropical forest fires and the potential these constituents could have in altering atmospheric chemistry and biogeochemical cycles. Subsequent research has demonstrated additional impacts on the biosphere, atmosphere, and directly upon humans. For example, ozone (O_3) is produced photochemically in the troposphere from hydrocarbon and nitrogen oxides released during vegetation burning and results in regional health hazards such as damage to human respiratory systems (Andreae, 2004; Levine, 2003). Cicerone (1994) emphasized that some byproducts of biomass burning, such as methyl chloride (CH_3Cl) and methyl bromide ($MeBr$), can escape to the stratosphere where they are responsible for ozone destruction; resulting in health risks at a much larger scale.

Fire is an integral part of many ecosystems (Kuhry, 1994; Cary and Banks, 2000), but the nature of this relationship may change according to some climate models which show fire frequency and intensity increasing with global warming trends (Intergovernmental Panel on Climate Change [IPCC], 2007). For example, boreal forests, one of Earth's larger biomes, are a key component in global carbon cycling. In particular, peatland in boreal and sub-arctic regions of Earth are estimated to contain 455Gt of carbon, translating to roughly a third of the world's soil carbon pool (Brady & Weil, 1999; Gorham, 1991; Moore, 2002; Pastor et al., 2003), and act as a sink for atmospheric carbon; accounting for an uptake of roughly 12% of the global anthropogenic emissions (Moore, 2002). Carbon sequestered through the process of photosynthesis by living vegetation does not exit the boreal system at the same rate since respiration via decomposition is retarded. However combustion of organic matter contributes to atmospheric loading of "greenhouse" gases (Kaufman et al., 1990; Page et al., 2002) and can affect carbon sequestration regimes (Kasischke et al., 1995). In addition, the influence of anthropogenic ignited fires, which accounts for 90% of all biomass burning (Levine, 2000), may increase with population growth and the added pressure for land and resources. A result of these driving forces will be greater biomass burning emissions, decreased sequestration of carbon, and the potential creation of feedback loops (Kasischke et al., 1995a; Chapman and Thurlow, 1998; Moore, 2002).

In order to understand the spatial and temporal global distribution of biomass burning, and ultimately the potential impacts to the biosphere and atmosphere, regular, broad scale monitoring is necessary. Satellite sensors provide daily, synoptic observations to detect and analyze fires (Justice et al., 2002) and therefore a great deal of research to characterize fires from remote sensing systems has been performed over the past several decades (e.g. Dozier, 1981; Kaufman et al., 1998; Giglio et al., 2003; Wooster et al., 2005; Ichoku & Kaufman, 2005).

2. Remote sensing of fire

Information derived from satellites has many advantages to traditional in situ data collection. A global perspective can be achieved to observe various Earth system processes allowing monitoring of spatially distinct, inaccessible, or remote locations. Regular monitoring is possible from polar orbiting satellite platforms such as National Aeronautics and Space Administration's (NASA) Aqua and Terra satellites and National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR). In the case of the former, the combination of Aqua and Terra provide nominally 4 daily "looks" of most locations on Earth. In addition, geostationary satellites such as NOAA's Geostationary Operational Environmental Satellites (GOES) and the European Organization for the Exploitation of Meteorological Satellites' (EUMETSAT) Meteosat provide high temporal resolution (15-30 minute), continental wide observations.

Many of the channels available from a particular satellite sensor are useful for fire monitoring, for example aerosols can be monitored using the visible and near-infrared bands or burn scars can be monitored with the visible, near, and middle infrared bands. Burned area mapping, a commonly used metric, is important for estimating total biomass consumed and thus emission estimates. Advanced new algorithms for accurate estimation of burned area now address the effect of bi-directional reflectance (Roy et al., 2005); an effect which is a function of the sun-target-view geometry influencing the directional dependence in reflectance and a potential source of error when using time-series data.

The retrieval of fire hot-spots provides additional monitoring and measurement capabilities. The foundation for fire detection is the enhanced middle infrared radiance emitted during flaming or smoldering combustion as described by the Planck function. In the case of an observed fire, radiance values generally peak around 3.7 – 4.0 μm , whereas the peak for background terrestrial surface temperatures is near 10.0 – 11.0 μm ; thus temperature anomalies can be flagged as potential fire "hot-spots". As a result of this rather simple relationship, remotely sensed data has had a significant contribution in fire science and monitoring. Heritage systems such as AVHRR and GOES, though not necessarily intended to include fire detection or monitoring missions, have proven valuable for this task nonetheless (Boles & Verbyla, 2000). Fire characterization from satellites, such as subpixel temperatures and flaming area, was obtained from a method developed by Dozier (1981), who introduced a theoretical procedure that exploits the different responses of two channels (3 and 4) aboard AVHRR (3.75 μm and 10.8 μm , respectively) for sub-pixel hot spot detection; an approach that set the framework for future sensor fire detection and characteristic methodologies (Giglio & Kendall, 2001; Justice et al., 2002; Giglio et al., 2003; Wooster et al., 2003, 2005).

The application of hot-spot detections has been employed in numerous studies and for a variety of uses. Legg & Laumonier (1999) demonstrated the effectiveness of hot spot detections using AVHRR and ATSR (Along Track Scanning Radiometer), as well as burned

area estimates using SPOT (Satellite Pour Observation de la Terra) imagery, during the 1997 Indonesian fire season. Legg & Laumonier (1999) also employed the United States Defense Meteorological Satellite Program (US DMSP) to help eliminate spurious daytime hotspots by detecting highly reflective pixels at night, presumably from fire, while excluding known human related bright spots. Kaufman et al. (1990) used AVHRR fire counts to assess trace gas and aerosol emissions in the tropics. Although some of the assumptions about burned area and fire detections would later be shown to be erroneous, their research set in motion the development of new approaches for using remotely sensed fire information for emission estimates (Kaufman, 1998). Aragão et al. (2007) examined drought and fire spatial distribution in Amazonia using NOAA-12's AVHRR and MODIS hot spot detections and later Aragão et al. (2008) examined specific interactions between precipitation, deforestation, and fires related to the 2005 Brazilian Amazon drought. More recently, Aragão & Shimabukuro (2010), again using MODIS and NOAA-12 hot spots, showed the co-varying nature of deforestation and fire activity trends over the past several years in the Brazilian Amazon. Their research has implications for fire and emission policies such as the United Nation's REDD+ (Reducing Emissions from Deforestation and Degradation). Giglio et al. (2010) used active fire detections to expand their burned area product to pre-MODIS data using the ATSR and Visible and Infrared Scanner (VIRS) aboard the Tropical Rainfall Measuring Mission (TRMM). The active fire burned area was developed using relationships based on regression between MODIS-Terra 500 meter burned area reference maps and Terra active fire counts. Morton et al. (2008) showed a clear correlation between fire hot spot frequency and land use patterns in Amazonia. Their research concluded that trends in land use intensity and fire frequency were linked. Such work offers promise for developing monitoring schemes to characterize land use transitions to inform policy makers.

In addition to the above research, a variety near-real time applications of active fire detections exist. The U.S. Forest Service Active Fire Mapping Program (<http://activefiremaps.fs.fed.us/>) is an operational system providing invaluable, near-real time information about location and timing of fire activity in the United States and Canada allowing fire managers to efficiently monitor fires and allocate resources. The Fire Information for Resource Management System (FIRMS, <http://maps.geog.umd.edu/firms/>) delivers timely fire detections, made by MODIS and processed through the Rapid Response System (<http://rapidfire.sci.gsfc.nasa.gov/>), to fire managers around the world.

Development of "new tools" such as fire radiative energy (FRE) can aid in estimating the biomass combusted and rates of atmospheric loading trace gases and aerosols. Calculated by determining the amount of energy emitted during fire, FRE may offer an accurate measurement of the fire intensity and vegetation consumed per unit time, as will be discussed in more detail below.

3. Combustion, fire energy, and emissions

3.1 Burned area

In theory, remotely sensed data should offer the capability to directly quantify atmospheric emissions from fire events, but in practice this requires determining the source of emissions which involves complex, computationally demanding inversion and geochemical transport modeling. Therefore most current approaches, referred to as the "bottom up" method in this paper, involve multiplying the fuel consumed by an emission factor for the atmospheric

species of interest. Emission estimates for natural and anthropogenic ignited vegetation fires are generally calculated using spatially explicit measures of pre-fire fuel loads, fuel consumption, and the areal extent of fire impact. The model presented by Seiler & Crutzen (1980) has been used extensively to quantify the mass of fuel consumed:

$$M = A \cdot B \cdot \beta \quad (1)$$

M is the total dry biomass consumed (kg); A is the burned area (km²); B is the biomass or fuel load (kg km⁻²); and β is combustion efficiency (fraction of available fuel burned). Adapting this algorithm to calculate the emission of a particular species requires *a priori* information about the emission factor for a given species for the type of vegetation being burned, expressed as grams of species x per kilogram of dry fuel burned (Andreae & Merlet, 2001). The equation to estimate emission is then rather straightforward given the fuel consumed, as calculated in equation (1):

$$E_x = EF_x \cdot M \quad (2)$$

E_x is the emission load of species x (g); EF_x is the emission factor for species x for the specific vegetation type or biome (g kg⁻¹); and M is the biomass burned in equation [1].

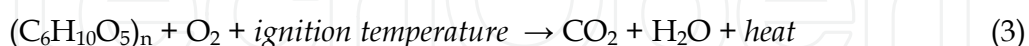
Traditionally, estimates have been made using statistical information such as FAO data on population and land use practices (Robinson, 1989; Seiler & Crutzen, 1980). Statistical information reported at national scales often requires extrapolation due to incomplete information, sporadic reporting, and highly variable estimates, especially within developing countries undergoing rapid land use change (Andreae, 1991). Advances in satellite technology offer the opportunity to make relatively accurate estimates for several of the parameters in equation [2] at synoptic scales (Justice et al., 2002). For example, Michalek et al. (2000) effectively combined Landsat TM data and field measurements to estimate carbon release from Alaskan spruce forest fires because of the high spatial resolution (<30m) and spectral ability to separate between pre-burn biomass and burn severity of Landsat. Page et al. (2002) estimated 0.19-0.23 Gt of carbon were released to the atmosphere from peat combustion during 1997 Indonesian fires. Their estimates were based on peat thickness, pre-fire land cover, and burnt area data collected from ground measurements and Landsat TM/ETM imagery. Satellite imagery proved useful for classifying land cover and determining burn scars, but Page et al. (2000) discovered that due to residual haze after fires and frequent cloud cover, the use of synthetic aperture radar (SAR) was necessary to determine the extent of burnt areas.

Limitations to the “bottom up” approach include fuel loads and burning efficiency, which cannot be directly estimated from satellite observations. In addition, there is a lack of agreement on the proper algorithm to characterize burned area from satellite data (Roy et al., 2005). Korontzi et al. (2004) showed that significant differences between burned area algorithm estimates can lead to differences as large as a factor of two in estimates of biomass consumed. Differences in spatial and temporal estimates of burned area products was demonstrated by Boschetti et al. (2004) who showed that the GLOBSCAR product had a burned area nearly twice as large as the GBA2000. They concluded that such discrepancies have serious implications for accurately quantifying emissions from fires (Boschetti et al., 2004). The difficulty in accurately measuring these variables leads to an uncertainty in emission estimates of at least 50%, and possibly much greater (Robinson, 1989; Andreae and

Merlet, 2001; van der Werf et al., 2003; French et al., 2004; Korontzi et al., 2004). Although datasets used for this application are always improving (Roy et al., 2005; van der Werf et al., 2006), due to the uncertainty in current estimates it is worthwhile to explore other approaches.

3.2 FRP

Vegetation fires can be thought of as the obverse of photosynthesis in which energy stored in biomass is released as heat (equation 3).



The cascade of chain of reactions starts with the pre-heating of fuels ahead of the fire front and partial pyrolytic decomposition. Ignition signifies the transfer from pre-heating to combustion in which exothermic reactions start and the next phase, encompassing a combination of flaming and smoldering combustion, begins. Flaming combustion occurs when flammable hydrocarbon gases released during pyrolysis are ignited with wildfire flaming combustion temperatures in the range of 800 – 1400 K (Lobert & Warnatz, 1993). Pyrolytic action involves the thermal decomposition of fuel resulting in the release of water, CO₂, and other combustible gases (e.g. CH₄) and particulate matter. The heat produced, often measured as heat yield (MJ/kg), is thermal energy transferred via conduction, convection, vaporization, and radiation and provides a metric of the total potential energy released if complete combustion of the fuel occurs. Although other factors, including slope, fuel arrangement, and wind speed influence the actual heat yield in a fire event, the theoretical value varies very little between fuel types (Stott, 2000; Whelan, 1995). As described by Stefan-Boltzmann's Law, the radiant component is emitted as electromagnetic waves traveling at the speed of light in all directions and is proportional to the absolute temperature of the fire (assumed to be a black body) raised to the fourth power. The relationship between fire temperature and spectral radiance was shown to closely match the Stefan-Boltzmann law (Radiance = σT^4) and thus a simple equation incorporating the sample size, emissivity of the fire (with some assumptions needed), and Stefan's constant could provide the rate of fire radiative energy, or fire radiative power (FRP), emitted as shown in equation (4).

$$FRP = A_{\text{sample}} \epsilon \sigma \sum A_n T_n^4 \quad (4)$$

where A_{sample} is the total area of the satellite pixel (m²), ϵ is the fire emissivity, σ is the Stefan Boltzmann constant ($5.67 \times 10^{-8} \text{ J}^{-1} \text{ m}^{-2} \text{ K}^{-4}$), A_n is the fractional area of the i^{th} thermal component, and T_n^4 is the temperature of the i^{th} thermal component (K).

The foundation for using measurements of FRP is based on the fact that the rate of biomass consumed is proportional to the rate of FRE. Kaufman et al. (1996, 1998) suggested that estimates of fuel load combustion and emission rates could be made from satellite observations of the radiative energy liberated during fire events. The hypothesis is that the rate of emitted energy (i.e. FRP), and rate of fuel combustion are proportional to the fire size and fuel load (A and B , respectively) from equation [1]. It follows then that the rate of energy released is directly related to the rate of particulate matter and trace gas emissions. Integrating FRP over the lifespan of the fire event provides the total fire radiative energy (FRE) released, which in turn is directly proportional to the total fire emissions. It is the radiative component that is estimated from Earth observing satellite sensors, offering an

alternative method to quantify the biomass consumed, and assuming an emission factor is known, it also offers the atmospheric emission load.

Unfortunately, sensors are unable to separate the spatially distinct components of the fire, potentially as small as millimeters, and the equation cannot distinguish between fractional areas of the entire fire which often are much smaller than the pixel itself. Thus, different methods have been tested and employed to overcome these limitations. The bi-spectral method, using two distinct channels (usually 4 and 11 μm), can provide details about the fractional size and temperature of sub-pixel fire components (Dozier, 1981; Giglio & Kendall, 2001, Wooster et al., 2005), but is plagued by potential errors associated with channel misregistration and point spread function (PSF) differences between channels (Giglio & Kendall, 2001). Wooster et al. (2005) suggested that the bi-spectral method is effective, but primarily for high resolution sensors (<1km). The current method used aboard MODIS employs a single channel approach with fire and background components retrieved solely from the mid-infrared (4 μm) channel (Justice et al, 2002). Kaufman et al. (1996, 1998) tested this single channel approach using the MODIS Airborne Simulator (MAS), model simulations of fire mixed-temperature pixels (to realistically mimic the non-homogeneous behavior of biomass burning temperatures), and *in situ* measurements. Based on the simulated fires, Kaufman et al. (1998) revealed that an empirical relationship exists between instantaneous FRE (i.e. FRP) and pixel brightness temperature measured in the Moderate Resolution Imaging Spectroradiometer (MODIS) middle infrared channel (4 μm). The result was a semi-empirical relationship which forms the basis for the current FRP algorithm (equation 5) used aboard MODIS. The authors also demonstrated the correlation between rates of smoke emission and the observed rate of energy released from airborne observations with the MAS (Kaufman et al., 1996, 1998).

$$\text{FRP [MW km}^{-2}] = 4.34 \times 10^{-19} (T_{\text{MIR}}^8 - T_{\text{bg, MIR}}^8) \quad (5)$$

where FRP is the rate of radiative energy emitted per pixel (the MODIS 4 μm channel has IFOV of 1km), 4.34×10^{-19} [MW km⁻² Kelvin⁻⁸] is the constant derived from the Kaufman et al. (1998) simulations, T_{MIR} [Kelvin] is the radiative brightness temperature of the fire component, $T_{\text{bg, MIR}}$ [Kelvin] is the neighboring nonfire background component, and MIR refers to middle infrared wavelength, typically 4 μm .

Wooster et al. (2003) showed that FRP could also be derived using satellite-based middle infrared radiances and a simple power law to approximate Planck's law. The 'MIR radiance' method is applicable for temperatures covering the range of typical vegetation fires (600 – 1500 K). As with the 'MODIS' method, the MIR method relies on the difference between the fire pixel and background, but uses spectral radiance differences rather than brightness temperature. According to Wooster et al. (2005) the radiance methods allows perturbations, such as atmospheric effects and pixel area variation across the scan angles, to be accounted for after FRP has been derived.

4. The application of FRE

Kaufman et al. (1996, 1998) first showed the potential application of FRP and FRE for estimating fuel combustion rates and aerosol loading while examining prescribed fires during the Smoke, Clouds, and Radiation (SCAR) experiments. Wooster (2002) investigated the relationship between FRP/FRE and fuel consumption using small-scale experimental fires in which spectroradiometers recorded the radiative emission for the entire burning

process at 5 to 10 second intervals. Wooster et al. (2003, 2005) expanded on their previous work, providing additional evidence of the effectiveness of using instantaneous and total FRE measurements to estimate biomass consumed from fire. Wooster & Zhang (2004) demonstrated the application of MODIS FRP observations by verifying the often proposed hypothesis that North American boreal fires are generally more intense than Russian boreal fires, while Ichoku & Kaufman (2005) used the MODIS FRP and aerosol products to derive near real time rates of aerosol emissions at regional scales. Research by Roberts et al. (2005) has shown the effectiveness of using geostationary satellite estimates of FRP from The Spinning Enhanced Visible and Infrared Imager (SEVIRI) to quantify rates of fuel consumption and characterize the fire intensity daily cycle. A laboratory investigation of FRE and biomass fuel consumption by Freeborn et al. (2008) supported the accuracy of Wooster et al.'s (2005) findings and lends credence to the application of satellite based measurements of FRE. Ichoku et al. (2008a), in a coordinated effort with research conducted by Freeborn et al. (2008), used laboratory investigations to examine rates and total fire radiative energy emitted and associated aerosol emissions. In both the case of Freeborn et al. (2008) and Ichoku et al. (2008a), the relationship between energy emitted, fuels consumed, and trace gas and aerosol emission demonstrated the efficacy of using FRE. Ichoku et al. (2008b) offered another example of using FRP, but at continental scales while investigating the global distribution of MODIS-based FRP estimates and revealed the regional distributions of fire intensity. Their research also showed significant differences in diurnal cycles and categorized intensities of FRP between regions which could not be explained by ecosystem type alone, suggesting perhaps that land use is a factor. Roberts & Wooster (2008) built upon their previous research (Roberts et al., 2005), showcasing the application of high temporal satellite based FRP measurements from the SEVIRI geostationary sensor to calculate FRE and estimate biomass combusted. Boschetti & Roy (2009) demonstrated a novel fusion approach to derive FRE based on temporal interpolation of MODIS FRP across independently derived burned area estimates. Their work was limited to Australia and the MODIS sensor, but as the authors suggest, the methodology could be expanded to other sensors and "is a fruitful avenue for future research and validation" (Boschetti & Roy, 2009). Freeborn et al. (2009) used frequency density distributions developed from MODIS and SEVIRI fire radiative power to synthesize the two sensors as a means for cross-calibration of their respective estimates. However, until Ellicott et al. (2009) and Vermote et al. (2009) no study had derived FRE at a global scale, in part due to limitations in temporal or spatial resolution of satellite sensors.

A current limitation of fire energy retrieval from satellites is that observations are of instantaneous energy (power) over some discrete length of time and space. To address this Ellicott et al. (2009) developed a unique approach to parameterize the temporal trajectory of FRP and calculate the integral (i.e. FRE) using MODIS. The parameterization was based on the long term ratio between Terra and Aqua MODIS FRP and diurnal measurements of FRP and fire detections made by satellites with greater temporal resolution. This included the geostationary sensor SEVIRI and the VIRS aboard TRMM. VIRS's low-inclination orbit (35°) provides observation times which precesses through 24 hours of local time every 23-46 days, depending on latitude, thus capturing the general diurnal trend of fire activity. In addition, high latitude (and thus high overpass frequency) daily observations by MODIS were included. The result was a global FRE product from MODIS at 0.5° spatial and monthly temporal resolution which currently spans from 2001 - 2010 (Figure 1).

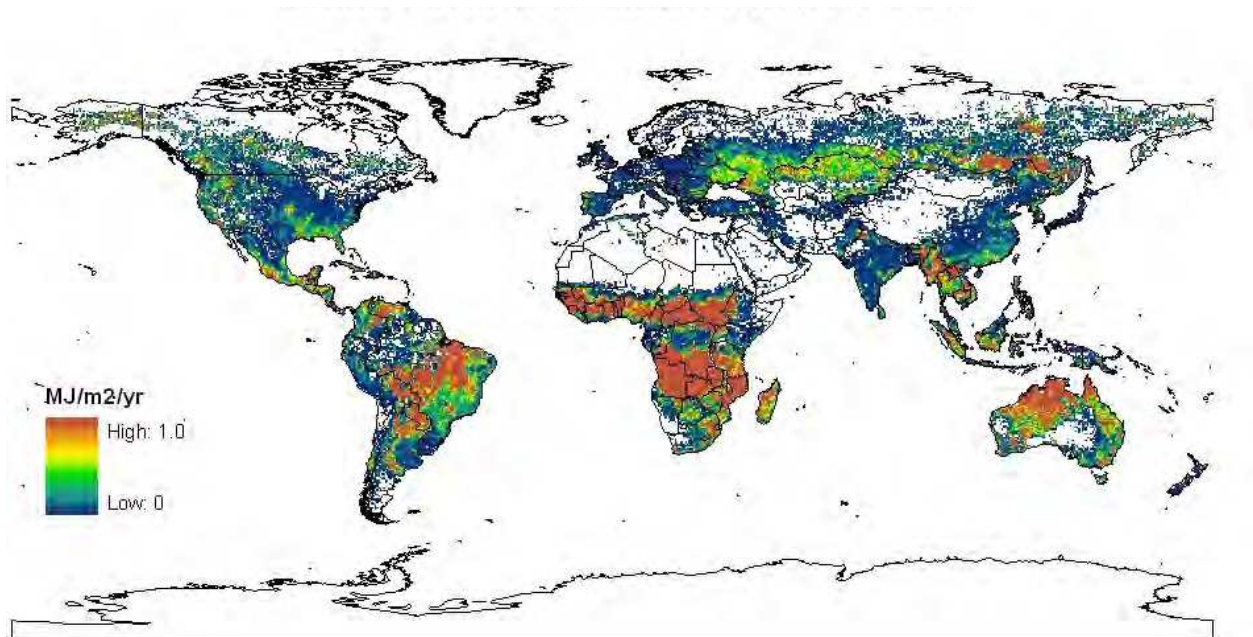


Fig. 1. Estimated annual mean FRE (MJ/m^2) from Aqua (2003-2010) and Terra (2001-2002) MODIS. Integrated energy was calculated from FRP (MW) values derived from a Gaussian function using modeled parameters.

Based on their FRE estimates, Ellicott et al. (2009) estimated biomass consumption totals for Africa using FRE-based combustion factors derived by Wooster et al. (2005). Since Wooster et al.'s combustion factor is based on fuels typical for Africa, the estimates were limited to this continent. The results were compared with Roberts & Wooster (2008) who derived estimates of fuels consumed from the SEVIRI sensor. The results showed good agreement for a 12 month comparison of FRE-based estimates of dry matter consumed from SEVIRI (858 Tg DM) and MODIS (700 Tg DM). The GFEDv2 (van der Werf et al., 2006) though, showed nearly a factor of 3 greater fuel consumption for the same time period and area, suggesting that more work needs to be done to characterize the sources and magnitude of errors in these estimates.

Vermote et al. (2009) applied the FRE-approach described above to estimate organic and black carbon (OCBC) aerosols emitted from biomass burning in 2003. The relationship between the estimated FRE and a new MODIS-derived inversion product of daily integrated, biomass burning aerosol emissions was the foundation of their research. The inversion product (Dubovik et al., 2008) was generated from the MODIS fine mode aerosol optical thickness and inverse modeling transport processes adopted from the Goddard Chemistry Aerosol Radiation and Transport (GOCART) model. The process generated fine mode aerosol sources (locations and intensities) resulting from biomass burning which were then used to derive OCBC estimates. The relationship between FRE and OCBC was analyzed globally within 3 distinct vegetation zones (Figure 2).

The estimated FRE-based OCBC emission in 2003 was 20 Tg and the spatial pattern clearly shows areas of high fire activity and thus OCBC loading (Figure 3). Though lower than the 29.6 Tg and 26.1 Tg estimates made by Generoso (2007) and van der Werf et al. (2006), respectively, the estimate is still within the error bars of both datasets. Nevertheless, the underestimation raises questions about the sources of uncertainty and error in the components used to derive OCBC quantities.

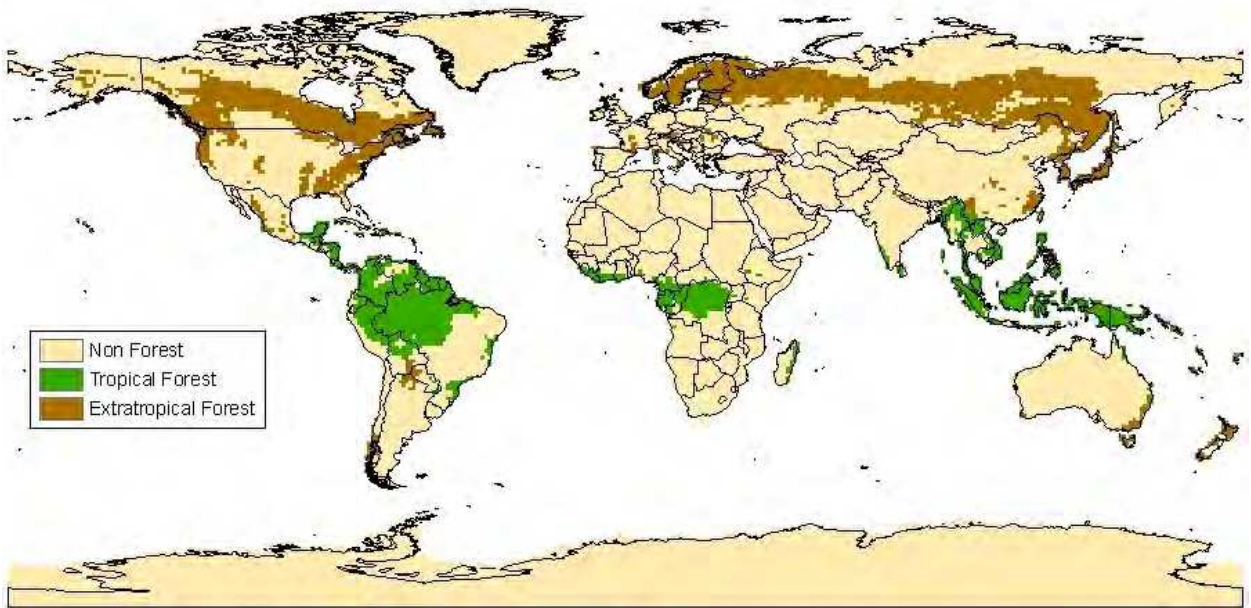


Fig. 2. Biome regions adopted from the Global Fire Emissions Database (GFED, van der Werf et al., 2006) used for analyzing the relationship between FRE and OCBC aerosol emissions (Vermote et al., 2009).

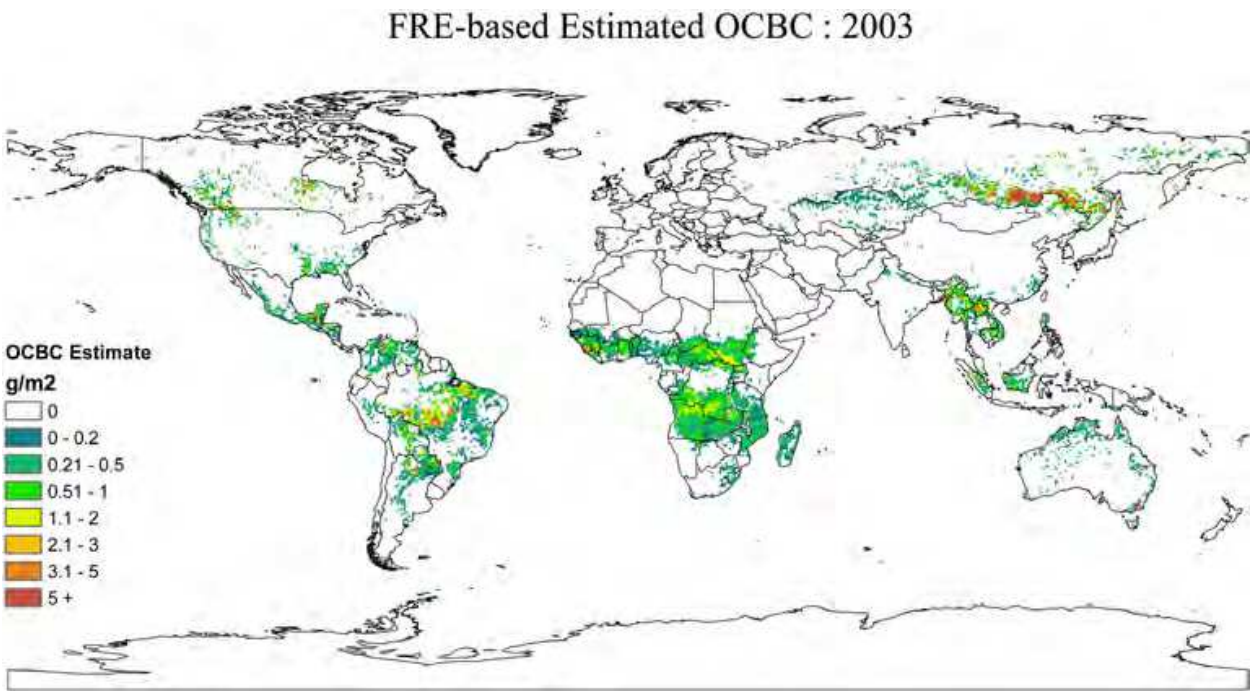


Fig. 3. Total OCBC (g/m^2) emissions estimated from biomass burning for 2003. High source regions include east-central Brazil, central and southern Africa, Southeast Asia, Central America, and southeast Russia.

5. Uncertainty

Remote sensing science involves the inference of *in situ* physical characteristics based on electromagnetic energy received at the sensors. The sensor and inferences made have a degree of error, which propagates through processing and into any results produced.

Giglio & Kendall (2001) explained that while sensors such as AVHRR have effectively generated baseline fire products for fire distribution and basic qualitative information for parameterization of biomass burning, there are fundamental limitations that need to be addressed and could not be improved upon until recently. A limitation prior to sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) and Spinning Enhanced Visible and Infrared Imager (SEVIRI) was that satellite sensors did not have dedicated fire channels or did not possess optimal sensor characteristics for fire detection (Kaufman et al., 1998). AVHRR's mid-infrared channel, for example, is subject to greater atmospheric perturbation and, due to sensor capabilities, increased frequency of saturation. Advancements of new generations of sensors for fire detection and monitoring have included refinements to specific wavelength selection in order to optimize spectral characterization (Giglio & Justice, 2003). Giglio & Kendall (2001) state that in order to reliably determine instantaneous fire temperature and area over a wide range of active fire sizes using Dozier's method, sensors with higher spatial resolution (~100m) and very high (~1000K) middle infrared band saturation would be necessary. However, replacement of the mid-IR channel aboard AVHRR (3.7 μ m) with a wavelength less sensitive to solar radiation (i.e. 3.9 μ m) would reduce the pixel saturation by half (Giglio & Justice, 2003; Kaufman et al., 1998). Defining higher pixel saturation temperatures and including wavelengths that can be used for false alarm detection on MODIS were improvements based on experiences with older systems (Justice et al., 2002).

Earlier work by Schroeder et al. (2008) showed that cloud obscuration in the Brazilian Amazon could lead to fire detection omission errors of roughly 11%. However, commission errors may occur as result of cloud shadows and semi-transparent clouds influencing surface thermal characteristics. Another source of commission errors may also result from the very efforts to correct for cloud obscuration by leading to an overestimate in the number of (assumed) detections. Schroeder et al. (2010) recently provided a thorough analysis of FRP, temperature estimates, and fire area estimates from moderate resolution sensors. Their results showed that location of fires within a pixel can be biased because of the sensor's point spread function leading to as much as a 75% underestimation in FRP. On the other hand, improper characterization of the ambient background surrounding fire pixel(s) can result in an overestimation of FRP up to 80%. This particular situation is mostly prevalent in areas of tropical deforestation.

The accuracy of the empirical formula for computing FRP was taken from the evaluation performed by Kaufman et al. (1998), who showed a potential error of 16% using 150 simulated mixed-energy fire pixels. Wooster et al. (2003) found a theoretical accuracy (RMSD) of 65×10^6 J over a range of 0 to 2000×10^6 J (or 6.5% for the average) using their MIR FRE approach.

MODIS omission rates of small active fires were also observed by Hawbaker et al. (2008). In their study, 73% of Aqua and 66% of Terra active fire detections were missed, primarily because of fast moving fire fronts, cloud cover, or spatial resolution. Hawbaker et al. (2008) was clear though that these small fires likely may have little impact in terms of total emissions as had been stated previously by Kaufman et al. (1998).

Freeborn et al. (2011) highlighted an issue with the MODIS Collection 5 FRP product. In the C5 FRP the calculation of the instantaneous energy (MW) derived from the brightness temperature includes a multiplication by the pixel area. Although this is fundamentally correct, since energy is measured per unit time and space, the adjustment leads to an overestimate with increasing scan angle because the pixel area grows as the scan moves off nadir. Interestingly, the opposite effect occurs when examining fire pixel counts (i.e. greater number of detections near nadir and decreasing detections with scan angle).

With regards to the application of FRE-based biomass consumption estimates published by Ellicott et al. (2009) and Roberts & Wooster (2008), there is some degree of uncertainty. Although the assumption that a single combustion factor is applicable for all fuel types and conditions (i.e. moisture content) will incur some bias, in general, heat yield does not vary much between fuels (Stott, 2000) and therefore until more research demonstrates otherwise, the two cited FRE-based combustion factors (Freeborn et al., 2008; Wooster, 2005) seem realistic.

Atmospheric attenuation is another component generally unaccounted for. In simulations conducted by Ellicott (unpublished), the MODIS FRP may be underestimated by as much as 20% (Figure 4). Similarly, Roberts & Wooster (2008) applied a constant correction factor (0.89) to SEVIRI FRP to account for atmospheric transmission loss.

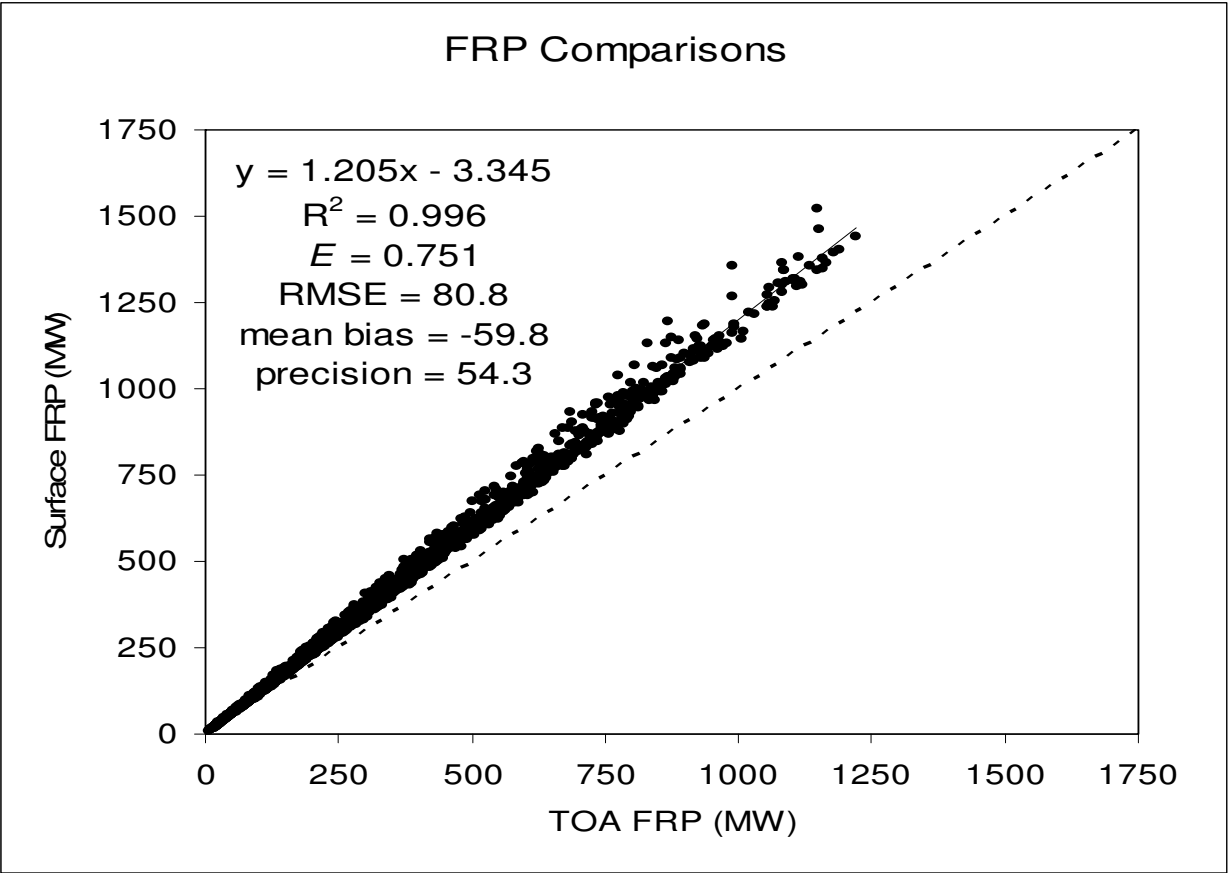


Fig. 4. Comparison of simulated surface and TOA FRP. Radiances were simulated from randomly generated fire pixel temperature and fractional area components (fire, smoldering, and background). MODIS Aqua profiles were used to provide realistic atmospheric parameters used in the radiative transfer modeling. The 1:1 (dashed) line is plotted for reference.

Finally, an error budget provided by Vermote et al. (2009) suggested that the FRE-parameterization approach developed by Ellicott et al. (2009) approaches 20% based on comparisons with the SEVIRI sensor.

6. Discussion

The atmosphere plays a fundamental role in regulating life on Earth. Changes in atmospheric composition can and do affect surface temperatures, hydrology, radiation budgets, weather, and even climate. Therefore, understanding the complex exchanges occurring between the atmosphere and surface requires accurate measurements of the variables characterizing both; for example atmospheric constituents, surface temperatures, and albedo. Quantifying these variables provides the necessary inputs for modeling the dynamic interactions and potential outcomes that result from changes in the relative proportions of atmospheric constituents. In light of the growing evidence for anthropogenic induced climate change, accurate characterization of the impact humans are having, both directly and indirectly, on altering Earth's systems is critical to guiding mitigation policy.

To that end, fire radiative energy may provide a efficient and accurate tool to monitor and measure biomass consumed and emissions from fire events. In order to be truly effective some of the idiosyncratic issues that plague sensors and algorithms need to be addressed, but perhaps most importantly, at least a global scale, is dealing with missed fire detections. For this, more comprehensive and distributed validation must occur.

In order to truly validate FRE estimates, greater spatial and temporal resolution data are needed. The evaluation of the FRE estimates with SEVIRI data offered a comparison with FRP retrievals made at higher temporal resolution, but incurred the downside of coarser spatial resolution. Future endeavors would include a scaling approach to test the temporal trajectory of instantaneous fire energy and total fire radiative energy released from a fire event. This would include the use of *in situ* observations, perhaps with a combination of field and laboratory experiments to reconcile differences between these two approaches. The next tier of retrievals would be from airborne observations, perhaps including both tower platforms (for small scale fires) and unmanned aircraft. The Ikhana unmanned airborne vehicle (UAV) used by the fire research at NASA AMES offers some opportunities in this regard. Recent field work demonstrated that while monitoring FRP from a helicopter seems ideal, many factors can limit the success of this tactic and that greater flexibility in choice of fires to observe and timing allowed for observation is needed. Moderate to high spatial resolution satellite observations would be employed in the next scaling layer and allow for greater spatial coverage while being constrained by higher spatial and temporal observations. To that end, geostationary satellite observations would cap the scaling approach, providing high temporal (15 – 30 minute) retrievals to aid in characterizing the diurnal cycle of fire radiative power as has been shown in this research. Incorporating sensors such as the Geostationary Operational Environmental Satellites (GOES) would offer greater spatial coverage beyond the SEVIRI sensor. Careful consideration of the limitations of comparison between sensors at multiple scales would obviously be needed (Schroeder et al., 2005).

Other considerations worth pursuing to improve FRP retrievals from the MODIS sensor include parameterization of the sub-surface organic layer burning. According to French et al. (2004) surface organic layer burning is largest source of uncertainty in boreal biomass

burning emission estimates. Page et al. (2002) estimated 0.19-0.23 Gt of carbon released to the atmosphere from peat combustion during 1997 Indonesian fires. Their estimates were based on peat thickness, pre-fire land cover, and burnt area data collected from ground measurements and Landsat TM/ETM imagery. Cloud cover has already been revealed by Schroeder et al. (2008) to limit fire detection capabilities for Brazilian fires. The spatial resolution of MODIS is another limitation to detecting fires in peatlands (and thus FRP estimation) as shown by Siegert et al. (2004). Developing a connection between field estimates of surface and sub-surface organic burning, burned area, and FRP would allow for parameterization of this component of fire radiative energy.

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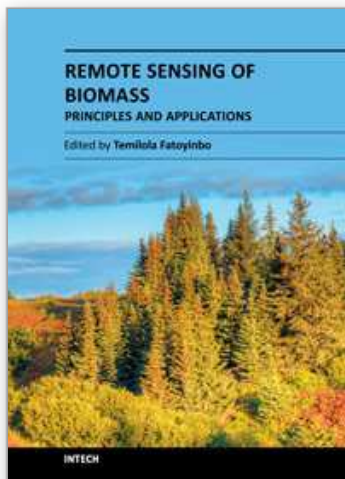
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The accurate measurement of ecosystem biomass is of great importance in scientific, resource management and energy sectors. In particular, biomass is a direct measurement of carbon storage within an ecosystem and of great importance for carbon cycle science and carbon emission mitigation. Remote Sensing is the most accurate tool for global biomass measurements because of the ability to measure large areas. Current biomass estimates are derived primarily from ground-based samples, as compiled and reported in inventories and ecosystem samples. By using remote sensing technologies, we are able to scale up the sample values and supply wall to wall mapping of biomass. Three separate remote sensing technologies are available today to measure ecosystem biomass: passive optical, radar, and lidar. There are many measurement methodologies that range from the application driven to the most technologically cutting-edge. The goal of this book is to address the newest developments in biomass measurements, sensor development, field measurements and modeling. The chapters in this book are separated into five main sections.

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