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Estimating biomass consumed from fire using MODIS FRE

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[1] Biomass burning is an important global phenomenon impacting atmospheric composition. Application of satellite based measures of fire radiative energy (FRE) has been shown to be effective for estimating biomass consumed, which can then be used to estimate gas and aerosol emissions. However, application of FRE has been limited in both temporal and spatial scale. In this paper we offer a methodology to estimate FRE globally for 2001–2007 at monthly time steps using MODIS. Accuracy assessment shows that our FRE estimates are precise ($R^2 = 0.85$), but may be underestimated. Global estimates of FRE show that Africa and South America dominate biomass burning, accounting for nearly 70% of the annual FRE generated. Applying FRE-based combustion factors to Africa yields an annual average biomass burned of 716–881 Tg of dry matter (DM). Comparison with the GFEDv2 biomass burned estimates shows large annual differences suggesting significant uncertainty remains in emission estimates. **Citation:** Ellicott, E., E. Vermote, L. Giglio, and G. Roberts (2009), Estimating biomass consumed from fire using MODIS FRE, *Geophys. Res. Lett.*, *36*, L13401, doi:10.1029/2009GL038581.

1. Introduction

[2] Wildland fire is a global phenomenon which plays a pivotal role in affecting the dynamics of vegetation, hydrology, and atmospheric composition [*Innes*, 2000]. Recently, *Running* [2008] pointed to the impacts of fire disturbance in altering ecosystem carbon cycles; often shifting large carbon reservoirs to carbon sources. Projected increases in burned area with climate change, such as reported by *Flannigan et al.* [2005], underscore the importance of understanding fire in current and future climate conditions.

[3] Quantifying the biomass consumed by fires is a key component to elucidate these dynamics. The biomass consumed (kg) is typically calculated as the product of burned area (km^2), fuel load ($kg\ km^{-2}$), and combustion completeness (fraction of available fuel burned) [*Seiler and Crutzen*, 1980]. However, accuracy of these components remains an issue that leads to an uncertainty in estimates of biomass consumed and related emissions of at least 50% [*Robinson*, 1989; *Korontzi et al.*, 2004; *van der Werf et al.*, 2006]. Despite improved datasets, uncertainty in current estimates suggests the need to explore alternative and complementary approaches.

[4] The foundation for using measurements of fire radiative energy (FRE) is based on the fact that the rate of biomass consumed is proportional to the rate of FRE. Integrating the rates over time and space yields the total FRE and total biomass consumed. Using simulated fires, *Kaufman et al.* [1998] revealed that an empirical relationship exists between instantaneous FRE (fire radiative power, or FRP) and pixel brightness temperature measured in the middle infrared channel (4 μm). This relationship is the algorithm currently used with the Moderate Resolution Imaging Spectroradiometer (MODIS) to estimate FRP. Field experiments by *Wooster et al.* [2005] demonstrated the use of instantaneous and total FRE measurements to estimate biomass consumed from fire. A recent 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. *Roberts and Wooster* [2008] showcased the application of high temporal satellite based FRP measurements from the SEVIRI geostationary sensor to calculate FRE. However, to date no study has derived FRE at a global scale, in part due to limitations in temporal or spatial resolution of satellite sensors.

[5] This paper presents an approach to estimate MODIS FRP beyond the nominal retrievals. We integrate FRP estimates to calculate FRE and then apply FRE-based biomass consumption coefficients to calculate the total biomass burned from fire in Africa. Finally, we compare our biomass burned estimates with previously published estimates and offer concluding remarks.

2. Materials and Methods

2.1. Data Sets

[6] In this research, fire radiative energy (FRE) was estimated at 0.5° spatial and monthly temporal resolution for 2001–2007 using the MODIS climate modeling grid (CMG) standard product [*Giglio*, 2005]. A full description of the methodology for estimating MODIS FRP is given by *Vermote et al.* [2009].

[7] The MODIS sensors, onboard the sun-synchronous polar-orbiting satellites Terra and Aqua, acquire four observations of nearly the entire Earth daily at 1030 and 2230 (Terra) and 0130 and 1330 (Aqua), equatorial local time. For each satellite the MODIS CMG FRP product is the summation of daily retrievals constituting daytime and nighttime fire detections and is corrected for cloud and overpass effects. We calculated the total FRP for each grid cell and month by multiplying the CMG reported mean FRP by the corrected pixel count.

[8] Estimating the total radiative energy emitted from biomass burning requires characterization of the temporal cycle of FRP. Most fires follow a pattern of increasing hourly fire energy flux from morning into the early afternoon

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followed by a decline through the evening. The pattern was clearly demonstrated by *Giglio* [2007] using the Visible and Infrared Scanner (VIRS) onboard the processing Tropical Rainfall Measuring Mission (TRMM) satellite and by *Roberts and Wooster* [2008] using the Spinning Enhanced Visible and Infrared Imager (SEVIRI) geostationary sensor for Africa.

[9] The SEVIRI geostationary satellite sensor, centered on Europe and Africa, provides 15-minute temporal resolution across 11 spectral channels (0.6 μm–14 μm) which allows for description of the temporal trajectory of FRP [*Roberts and Wooster*, 2008]. We used SEVIRI FRP retrievals from February and July, 2004, as these two months capture periods of intense fire activity in the northern and southern African hemispheres, respectively, and provide a large number of observations ($\sim 1.3 \times 10^6$ and 2.1×10^6, respectively) with which to characterize the diurnal fire cycle.

[10] The Visible and Infrared Scanner (VIRS) aboard the Tropical Rainfall Measuring Mission (TRMM) was launched in late 1997 and though intended to monitor rainfall variability it has proven successful at fire detection and monitoring, owing to channel placements at 3.75μm and 10.8μm [*Giglio*, 2007]. TRMM has an inclined, precessing orbit (35°) so that VIRS observes the Earth between 38°N and 38°S. The precessing orbit also means that local overpass time changes to cover each hour of a day approximately once per month. This drift in overpass time allowed *Giglio* [2007] to characterize the diurnal cycle of fire observations for a "typical" 24 hour period after corrections for overpass and cloud obscuration biases. VIRS data were provided by L. Giglio for several globally distributed regions.

[11] Finally, since neither SEVIRI nor VIRS provide high latitude observations (e.g., boreal fires), we supplemented the temporal trajectory characterization with daily MODIS Level 2 FRP retrievals from Terra and Aqua because their polar orbits provide more frequent retrievals at high latitudes than the 2 nominal overpasses. On average, we found each satellite made 4–6 FRP retrievals per satellite for our boreal regions.

2.2. Method

[12] To characterize regionally representative fire energy temporal trajectories we used a combination of observations from SEVIRI, VIRS, and MODIS. Examination of the temporal trajectories was performed in 15 globally distributed regions. These were chosen to be large enough to be statistically robust, yet small enough to allow for spatial variability between regions (Figure 1). We found that a modified Gaussian function (equation (1)) provided a simple and accurate representation of the observed diurnal cycle:

$$FRP(t) = FRP_{peak}\left(b + e^{-\frac{(t-h)^2}{2\sigma^2}}\right) \qquad (1)$$

where t is time [hour], FRP_{peak} is the peak of the curve, h is the hour corresponding to the peak, and σ is the standard deviation. The function also includes a background FRP, b, which is a constant independent of time. Figures 2a–2c show examples of the diurnal cycle observed by SEVIRI, VIRS, and MODIS and the associated Gaussian function fit to the observations.

[13] The parameters in equation (1), h, σ, and b, were examined as a function of Terra-to-Aqua FRP (T/A) ratios. The T/A ratio is based on monthly CMG FRP values for 2003–2007 ($n = 60$), representing the average ratio between Terra and Aqua FRP retrievals within a given region, offering a long term characterization of the temporal variability between the two satellite observations. As stated above, the CMG FRP for Terra and Aqua is the summation of the nominal overpass values. Figures 2d–2f provide examples of the T/A ratio for 3 spatially distributed regions, each corresponding with the diurnal curves in Figures 2a–2c. We contend that given the simple Gaussian form adopted for the diurnal cycle, the variation in the T/A ratio can serve as a proxy for the fire energy diurnal cycle. Figure 3 highlights the relationship between the T/A ratio and the Gaussian function parameters for the 15 regions used to examine the fire radiative energy temporal cycle.

[14] Using the relationships calculated in Figure 3 we estimated FRE using MODIS CMG FRP and the T/A ratio for 2001–2007. Terra MODIS FRP was used to estimate FRE for 2001 and 2002 as Aqua MODIS was not yet available (only partial availability in 2002). Subsequent years (2003–2007) were estimated with Aqua. Examination of the yearly difference between Terra and Aqua estimated FRE for 2003–2007 (when both sensors were available) revealed only a small underestimation in Terra FRE (4.1%). This bias was applied to Terra MODIS FRE estimates for 2001 and 2002 to adjust for the underestimation.

3. Results and Discussion

3.1. FRE

[15] We first analyzed our MODIS-based FRE estimates with those produced from SEVIRI. Results suggest a good agreement between monthly estimates of FRE ($y = 0.76\times$, $R^2 = 0.85$, $p < 0.01$). The RMSE was 58e + 09 MJ, or approximately 30% of the SEVIRI monthly mean FRE. (Note that the MODIS and SEVIRI estimated-FRE have been adjusted for atmospheric effects using MODTRAN.) The underestimation of FRE may be due to incomplete characterization of the temporal cycle of FRP in our methodology as well as overcorrection in the SEVIRI product, which is intended to account for omission errors [*Roberts and Wooster*, 2008].

[16] Regional distribution of FRE shows that Africa, South America, and Australia dominate in terms of energy liberated from biomass burning. Africa, often referred to as the "fire continent", was responsible for nearly half of the global annual average fire radiative energy. Partitioning global results using the Global Fire Emissions Database region map (see Figure 1) [*van der Werf et al.*, 2006] shows Africa (NHAF and SHAF) generated, on average, 47% of the global FRE. South America (NHSA and SHSA) was responsible for another 20% of the mean annual FRE with SHSA accounting for 18.5% of this. Of particular interest in South America is the "arc of deforestation" which was responsible for 72% of the average FRE in the southern-hemisphere South America (SHSA) region and 13% globally. Other regions of intensive fire activity are Australia (9.25%), boreal

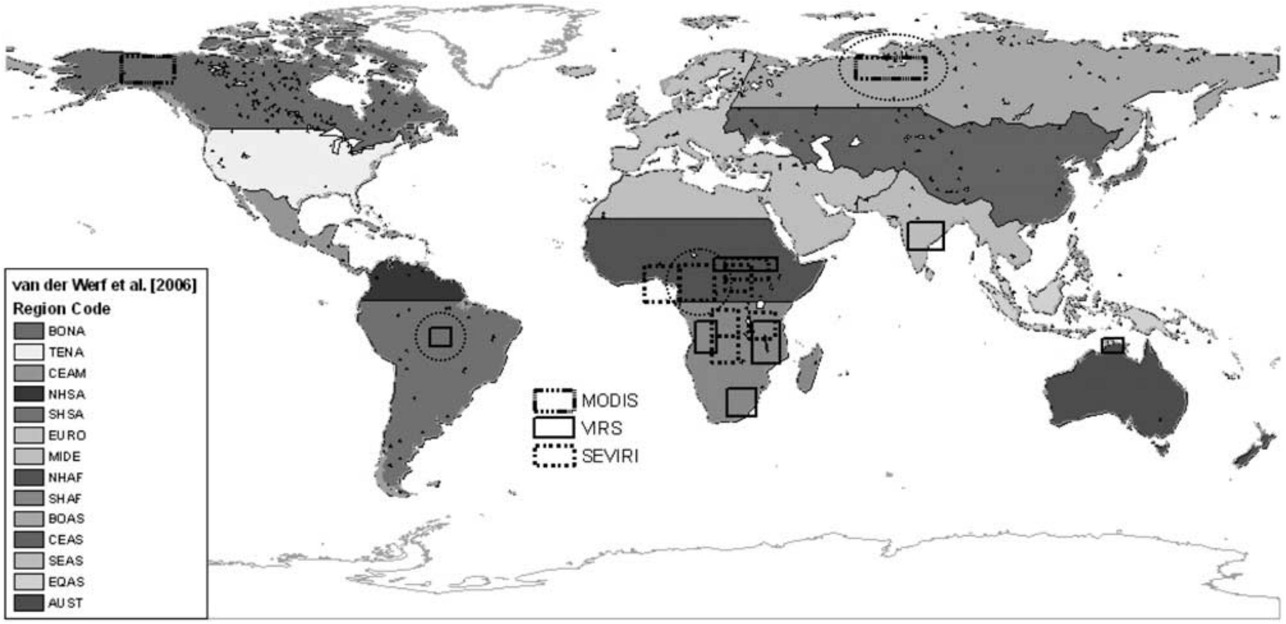

Figure 1. Global extent of regions used to analyze the diurnal cycle from SEVIRI, TRMM, and MODIS observations. The dotted circles highlight regions used as examples in Figure 2. The base map is the regional categorization from the Global Fire Emissions Database (GFEDv2) [*van der Werf et al.*, 2006].

fires (BONA and BOAS) which made up roughly 7.5% and Central and Southeast Asia (CEAS and SEAS) with approximately 5% each. These proportions are consistent with previous estimates of fire detections and emissions [*Bond et al.*, 2004; *Dwyer et al.*, 2000].

3.2. Biomass Consumed

[17] We estimated the dry biomass consumption from fire using an FRE-based combustion factor (0.368 kg/MJ) established by *Wooster et al.* [2005]. The combustion factor was developed from experiments using fuels representative

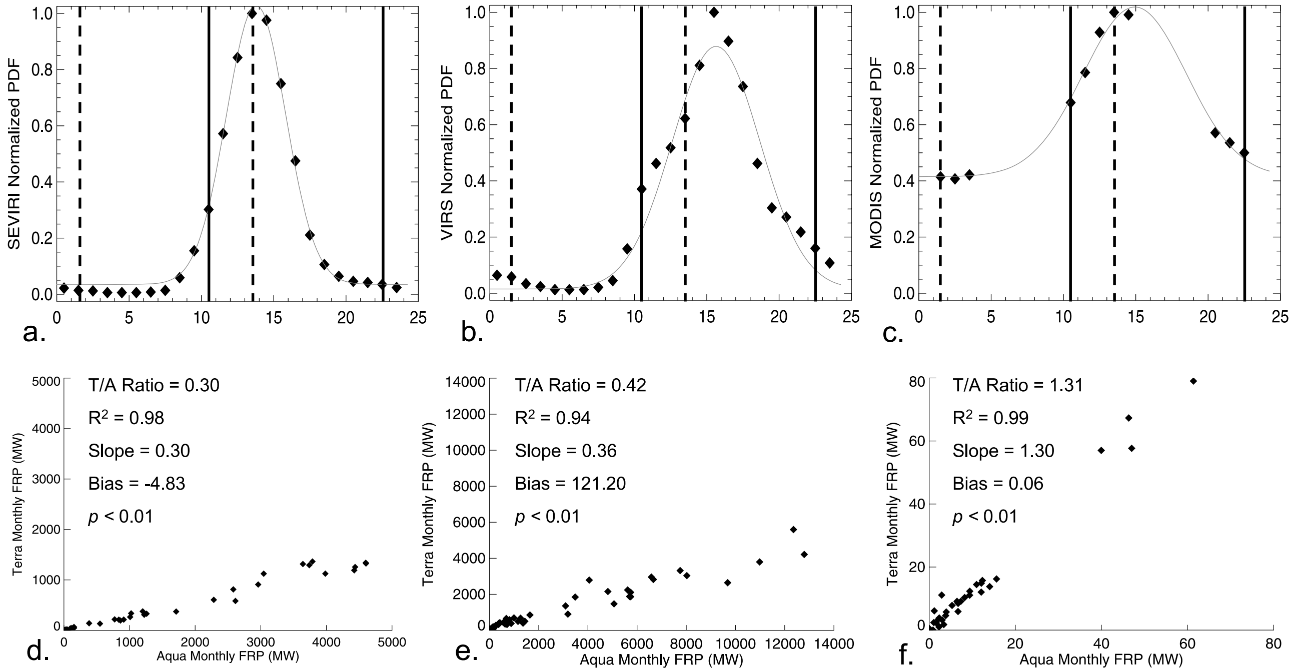

Figure 2. Fire radiative power diurnal cycles: The curve shows the fit of the diurnal cycle using a modified Gaussian function (equation (1)): (a) northern Africa SEVIRI study region; (b) VIRS “Brazil deforestation” region; (c) MODIS boreal region (each site is circled in Figure 1). Shown for reference are MODIS overpass times (solid vertical lines for MODIS-Terra and dashed vertical lines for MODIS-Aqua). Scatter plots show the ratio between monthly Terra and Aqua (T/A) CMG FRP from 2003–2007 ($n = 60$) for study sites (see Figure 1) used to develop relationship with the diurnal curves; (d) central Africa SEVIRI ratio corresponds with Figure 2a; (e) T/A ratio plot for VIRS corresponds with Figure 2b; and (f) corresponds with MODIS boreal region, Figure 2c.

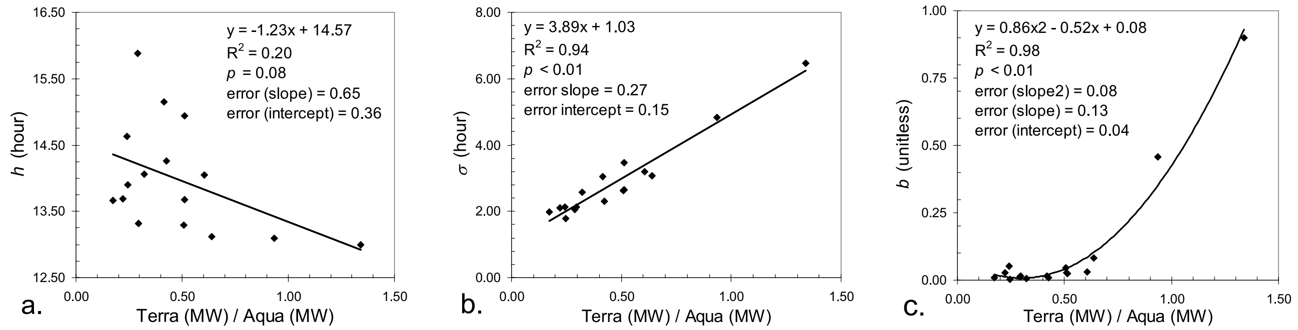

Figure 3. (a) Variation in the peak hour of the diurnal cycle, h, as a function of the Terra/Aqua FRP ratio; (b) σ corresponds with the width of the curve at half-maximum FRP, as a function of the Terra/Aqua FRP ratio and; (c) variation of the background level of the diurnal cycle, b, as a function of the Terra/Aqua FRP ratio.

of dry season savanna vegetation fires. As such, we constrained our comparison of biomass consumed to Africa for which the fire experiments were intended [*Roberts et al.*, 2005; *Roberts and Wooster*, 2008].

[18] A 12 month total biomass consumed comparison using SEVIRI FRE (859 Tg DM) and MODIS FRE (678 Tg DM) reveals agreement in the estimates, but underestimation by MODIS estimates. Although using a static FRE-based combustion factor based on *Miscanthus* fuels may seem to neglect the heterogeneous nature of wildland fires, *Freeborn et al.* [2008] demonstrated that fuel type was relatively insignificant (<12%) in explaining the variability in biomass consumption as a function of FRE. This is supported by previous investigations of fuel heat yield [*Stott*, 2000].

[19] Comparing our biomass consumed estimates for Africa with the GFEDv2 highlights the significant differences in annual estimates. We estimated an average biomass burned of 716 Tg DM for Africa between 2001 and 2007, or roughly 3.5 times less than reported in the GFEDv2 (2586 Tg DM). Alternatively, if we use the recently published combustion factor (0.453 kg/MJ) from *Freeborn et al.* [2008] the margin of difference is reduced (881 Tg DM), but is still nearly a factor of 3. Based on a similar result found by *Roberts and Wooster* [2008] we investigated fuel load (kg/m^2) estimates as the potential source of bias. The FRE-based fuel load was estimated using biomass burned (described above), burned area from *Giglio et al.* [2009], and the annual mean combustion completeness for Africa (0.77) reported in the GFEDv2. Mean fuel load for Africa between 2001 and 2007 were estimated to be 1.58 kg/m^2 in the GFEDv2 while we calculated 0.37 kg/m^2 indicating the discrepancy in biomass consumed may be directly related to this difference. *Reid et al.* [2005] reported a mean grassland/savanna fuel load from a literature review of 0.4 kg/m^2 which corresponds well with fuel load measures for Africa savannas made by *McNaughton et al.* [1998] and *Hély et al.* [2003] (0.35 and 0.38 kg/m^2, respectively). These results suggest that the fuel load estimates used in the GFEDv2 are indeed high. Although these values are for grassland/savanna only, which are generally lower than woody vegetation biomes, their use is appropriate in most cases for Africa since this is the dominant biome in which fire occurs [*Dwyer et al.*, 2000].

[20] Finally, we estimated annual emissions of carbon and CO_2 for Africa. Applying the combustion factor by *Wooster et al.* [2005] and assuming a dry matter carbon content of 45% we calculated a range of 284–391 Tg C yr^{-1} and a CO_2 range of 1040–1434 Tg CO_2 yr^{-1}.

4. Summary and Conclusions

[21] A method to estimate fire radiative energy from discrete MODIS FRP observations is presented. The approach is developed from SEVIRI, VIRS, and MODIS data to characterize the fire diurnal cycle as a modified Gaussian function. The function variables are parameterized based on the relationship with monthly Terra/Aqua (T/A) FRP ratios from 15 globally distributed regions. The FRE calculation described in this paper is a potentially significant contribution to remote sensing science as the calculation of FRE from MODIS FRP has not yet been achieved, and therefore presents a first of its kind. Comparison is limited, but initial evaluation against FRE estimated from the geostationary SEVIRI sensor indicates that our approach produces realistic estimates. The underestimation of MODIS FRE suggests room for improvement in our process as well as potential overcorrection for omission errors in the SEVIRI product [*Roberts and Wooster*, 2008].

[22] Improvements to our FRE estimate may yield greater biomass burned, however this is unlikely to account for the large difference observed in our comparison with the GFEDv2. The gap in biomass burned estimates between the FRE-based approach and the GFEDv2 burned area approach highlights the need for reconciliation to reduce uncertainty. Collaboration between researchers making *in situ* and remotely sensed measures of the variables discussed herein (rate of energy release, emissions, fuels consumed, fuel load, etc.) and the various approaches employed would offer a better understanding of the dynamics of estimating biomass burned and associated emissions.

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