Satellite Characterization of Biomass Burning and Smoke Emissions in Africa

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Abstract:
Measurement of fire radiative energy (FRE) release rates or power (FRP) from space offers tremendous opportunities for characterization of biomass burning and emissions in a quantitative manner. In essence, it has enabled the rating of fires by five levels of strength, as well as estimation of regional FRP fluxes, which reflect the relative concentrations of biomass-burning activities. Furthermore, it facilitates the estimation of burned biomass and smoke particulate emissions by mass. It has been shown that sub-Saharan African regions are subjected to significant biomass burning, compared to other regions of the world; with potential for a variety of adverse impacts. Fortunately, Africa is favorably situated for fire remote sensing; with the potential for adequate spatial and temporal coverage through the synergy of MODIS and SEVIRI measurements.

Introduction

Biomass-burning is widespread in sub-Saharan Africa; affecting a significant proportion of the forest, grass, and agricultural lands annually. Fires release heat energy, which is propagated by conduction, convection, and radiation. Fire radiative energy (FRE), like other types of electromagnetic radiant energy, propagates in space and facilitates fire detection by remote sensing. Recent advancements in satellite remote sensing technology have enabled actual measurement of FRE from space, principally by the Moderate-resolution Imaging Spectro-radiometer (MODIS) sensors onboard the NASA Terra and Aqua satellites (e.g. Kaufman et al., 1998), and the Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the Meteosat-8 (formerly Meteosat Second Generation) geostationary satellite (e.g. Roberts et al., 2005). However, since every observation by these sensors lasts only an instant, what they actually measure is the rate of release of FRE per unit time (R_{fre}) or Fire Radiative Power (FRP) in MW (*Kaufman et al*., 1998; *Giglio et al*., 2003; *Wooster et al*., 2003). Recent studies have shown that the FRE released by a fire is directly proportional to the biomass consumed as well as the smoke emitted. Tremendous amounts of smoke are emitted annually, and comprise aerosol particulate matter (PM) and trace gases, which constitute air pollutants and contribute to the perturbation of the global radiative balance through the scattering and absorption of solar radiation.

Figure 1 shows a large number of fires burning across West and Central Africa on the afternoon of 17 January 2007 as observed by Aqua-MODIS. Although each of the fires appears to be represented by a dot or a cluster of them, in reality, the fires occur in a variety of sizes and intensities. These two fire attributes together constitute the fire strength, which is expressed quantitatively in the FRP measure retrieved from satellite observations.

The objective of this study is to demonstrate the utilization of satellite measurements of FRE release rates (or FRP) to quantitatively characterize the spatio-temporal distribution of biomass burning and to derive smoke particulate emissions in different regions of Africa. The result holds great potential for application in monitoring the impacts of fire on land-use changes and air-quality in Africa, and can be used as a knowledge base for developing strategies to regulate biomass burning in order to enhance sustainable development.

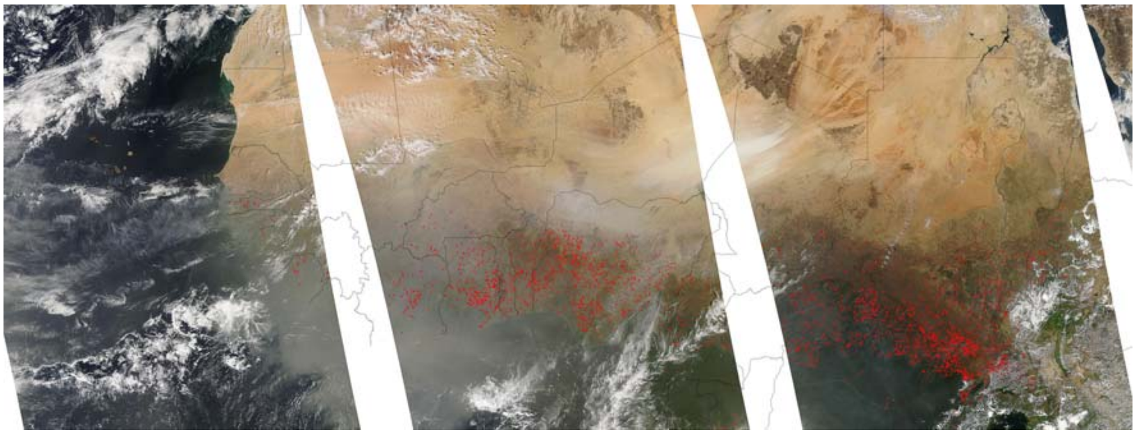

Figure 1: Mosaic of MODIS images of West and Central Africa observed from the Aqua satellite on 17 January 2007, showing numerous fires (red spots) due to seasonal agricultural burning, with the associated smoke (grayish haze), as well as dust emanating from the Bodele depression in Tchad. The near-vertical gaps are the areas missed between consecutive satellite overpasses, which are widest around the equator but continuously diminish toward both poles until the swaths begin to overlap. (Image courtesy of: NASA EarthObservatory: http://earthobservatory.nasa.gov/).

Satellite Fire Characterization

MODIS observes fires and measures their FRP with a 1x1-km footprint at the subsatellite point (SSP) from both Terra and Aqua polar orbiting satellites; Terra crossing the equator at approximately 10:30 AM and 10:30 PM local times, and Aqua at approximately 1:30 AM and 1:30 PM local times. As such, each MODIS sensor observes almost the whole earth once per day and once per night every 24 hours. Therefore, most fires detectable at a 1-km spatial resolution are measured four times a day, except when covered by thick clouds. The SEVIRI sensor, which flies onboard a geostationary satellite, is able to measure FRP every 15 min although at a lower resolution of 3x3 km at the SSP.

Because of the global coverage and relatively good resolution (1 km) offered by MODIS, its measurements of FRP have been used to develop a fire rating scheme, which is globally applicable (*Ichoku et al.*, 2008). FRP values measured in each resolution cell (or pixel) of a MODIS imagery can be classified into one of 5 categories (1 to 5). Figure 2 shows the relative frequency distribution of FRP in seven sub-Saharan African regions, with vertical lines designating the thresholds recommended for fire classification. Using this scheme, it would be easier to condense the values of FRP, which can range from <1 MW to >1800 MW, thereby allowing the fire strengths to be rated in a manner similar to those of other natural disasters such as hurricanes and earthquakes.

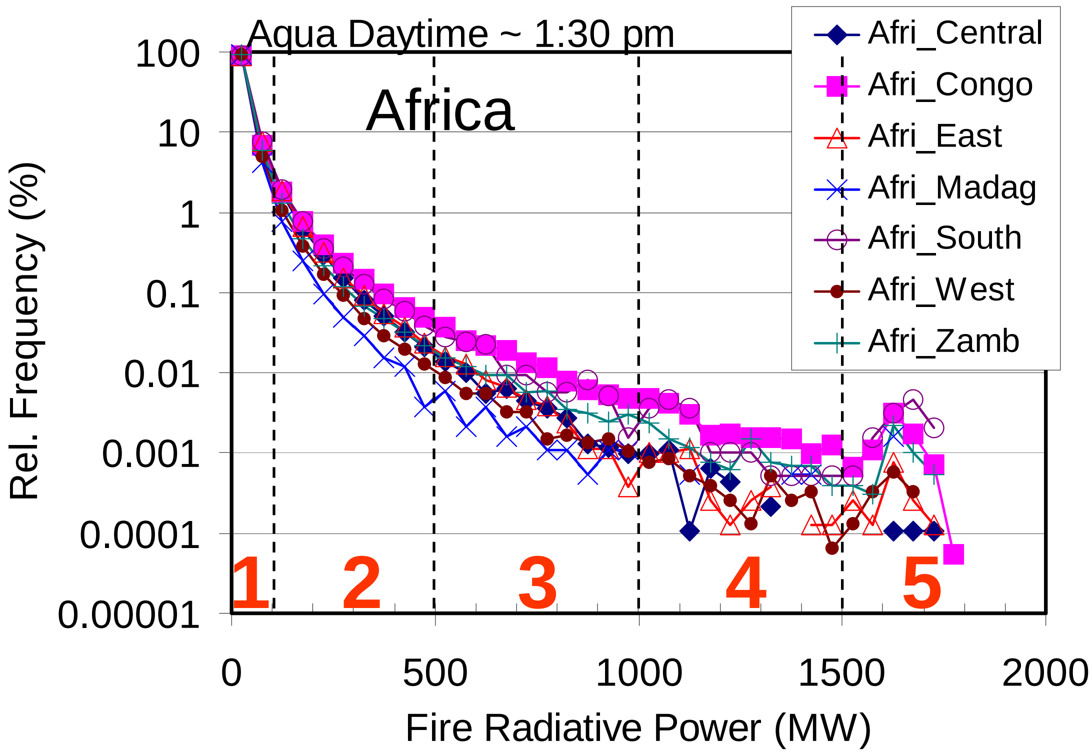

Figure 2: Relative frequencies of occurrence of different FRP ranges in the different regions of sub-Saharan Africa based on the binning of all MODIS fire observations at Aqua daytime overpasses from July 2002 to December 2006. Fires can be classified by strength into 5 categories (bold red numbers) based on the FRP ranges (see *Ichoku et al.*, 2008).

FRP can also be used to assess the degree of biomass burning in various regions. This was done by delimiting the areas of such regions, summing up the FRP values at each MODIS overpass time within that region and dividing it by the area of dry land in km^2 (which does not include any water bodies such as lakes). The result, which is in units of MW/km^2 (or more conventionally, W/m^2) is the FRP flux for each region, and corresponds to the rate of release of fire radiative energy per unit area of land in the region. Like other agents of climate change such as carbon dioxide and aerosols, FRP flux can be a relative measure of the direct regional impact of heat from the fires on weather and climate. In addition, since FRP is directly proportional to the rate of biomass consumption and smoke emission, these fluxes represent the relative measures of ecosystem disturbances and emissions from biomass burning.

Figure 3 shows a stacked column chart of the monthly mean FRP fluxes derived from Aqua-MODIS afternoon overpass data for the seven African regions considered in this study. It reflects the relative concentration of biomass burning in these regions from month to month for the period of July 2002 to December 2006. Aqua-MODIS afternoon overpass (~1:30 PM local time) data were used because it is the time of day with the most intense biomass-burning activity, among the four MODIS overpasses. There are significant differences in intensity and seasonality between the regions. For instance, peak biomass burning occurs in November-January in regions located north of the equator (West, Central, and East Africa), but in June to October in the southern regions.

It is remarkable that for all regions biomass burning is very low in March, but minimal to non-existent in April.

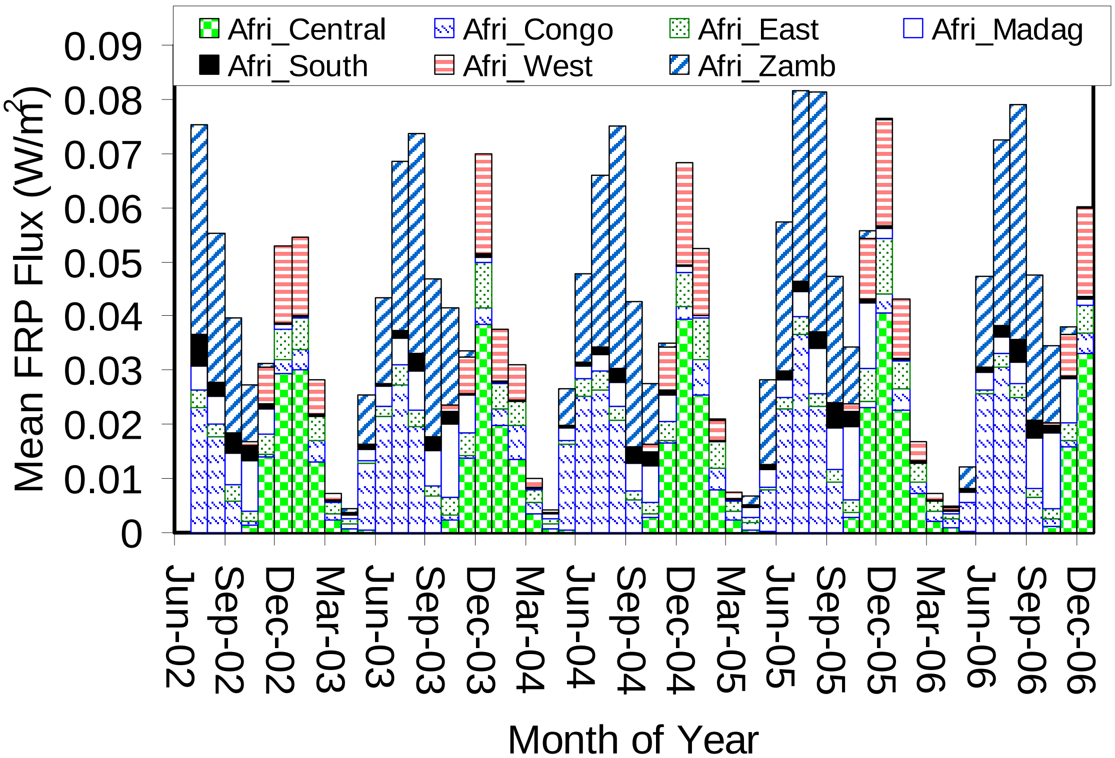

Figure 3: Monthly mean distribution of FRP flux (W/m^2) from Aqua-MODIS afternoon (~1:30 PM) overpass for different regions of sub-Saharan Africa.

Satellite Smoke Emissions Estimation

Prior to the advent of satellite remote sensing, traditional estimation of biomass burning emissions was based on the relationship (e.g. *Andreae and Merlet*, 2001):

$$M_x = EF_x \times M_{biomass} \qquad (1)$$

where M_x is the mass of emitted gaseous or particulate species *x*, EF_x is the emission factor for the emitted species *x*, while $M_{biomass}$ is the mass of the dry biomass burned, which was determined from the relationship (*Seiler and Crutzen*, 1980):

$$M_{biomass} = A \times B \times \alpha \times \beta \qquad (2)$$

where A is the burned area, B is the biomass density, α is the fraction of aboveground biomass, and β is the burn efficiency. Although equation (1) seems very simple, the main complication is that for real fires, it is extremely difficult to determine $M_{biomass}$ to an acceptable accuracy because of the gross uncertainties associated with the determination of its constituent factors on the right had side of equation (2).

A number of improvements are being made to emissions estimations within the last decade because of the continuing advancement in satellite remote sensing. One group of studies attempts to alleviate the uncertainties associated with equation (2) by estimating some of its constituent factors, such as burned area A (e.g. *Roy et al*., 2002; *Li et al*., 2004, *Simon et al*., 2004; *Tansey et al*., 2004; *Giglio et al*., 2006) or burn efficiency β (e.g. *Chuvieco, et al*., 2004) from satellite measurements. Another group of studies conducted experimental studies with small fires to determine the empirical relationships between *FRE* and $M_{biomass}$ (*Wooster*, 2002; *Wooster et al*., 2003, 2005), whereupon such a relationship was applied to FRE (based on time-integration of SEVIRI measurements of FRP) to calculate $M_{biomass}$ directly (*Roberts, et al*., 2005); by-passing all the intricacies involved in determining its constituent factors as expressed in Equation (2), and allowing emissions estimation directly from equation (1).

A new satellite approach develops an alternative way of quantifying emission rates and total emissions from measurements of FRP, without estimating $M_{biomass}$ first. One of the main advantages of such an approach is that, unlike $M_{biomass}$ which can only be evaluated after a fire is over, FRP can be used as soon as it is measured while the fire is still going on to estimate the mass rate of emission of a given species *x* using the following simple relationship (*Ichoku and Kaufman*, 2005):

$$R_{Mx} = C_e^x \times R_{fre} \tag{3}$$

where, in this case R_{Mx} is the mass rate of emission of species x (expressed in Kg/s), R_{fre} is FRP (expressed in MW or MJ/s), and C_e^x is the emission coefficient of species *x* (expressed in kg/MJ). However, if a time-integrated total FRE (in MJ) is used instead of R_{fre}, then R_{Mx} would become M_x, which is the emitted total mass expressed in Kg. *Ichoku and Kaufman* (2005) developed a methodology for calculating the smoke PM emission coefficients (C_e^{PM}) for various biomass-burning regions of the globe. Figure 4 uses the West African case to illustrate the methodology employed. MODIS measurements of FRP were collocated with corresponding measurements of aerosol optical thickness (AOT), which represents the relative amount of aerosol over the fires. By performing spatial analysis between the AOT values over the fires and those around it, and applying the wind dynamics model from assimilated meteorological data sets, it was possible to estimate the rate of smoke PM emission rates (R_{PM}). Scatterplots of R_{PM} against R_{fre} retrieved over any given region for a certain period of time, such as a year, allowed the fitting of zero-intercept linear regression, whose slope represents C_e^{PM}, which can be used in equation (3) to estimate emission rates directly (*Ichoku and Kaufman*, 2005).

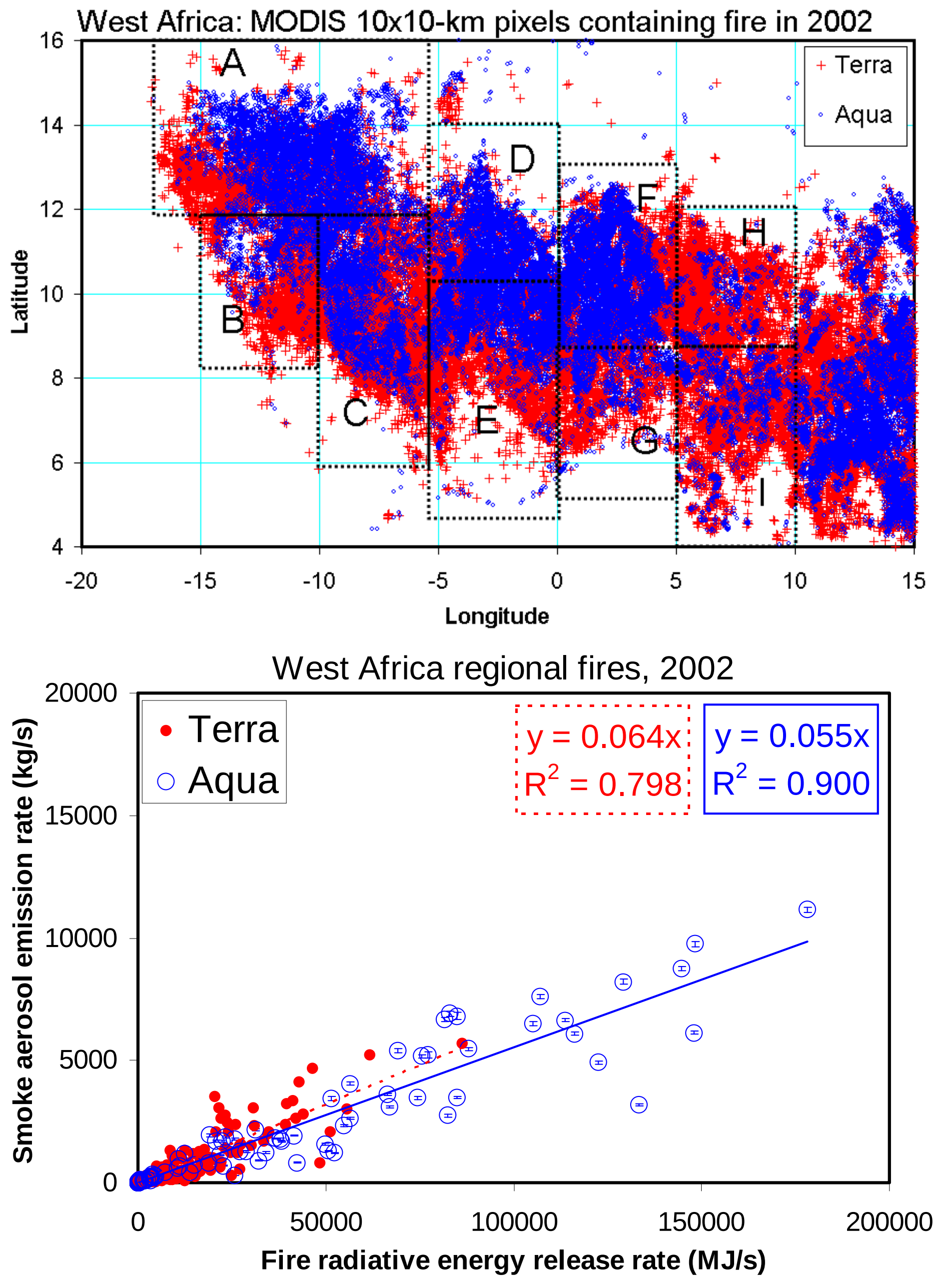

Figure 4: (Top) Accumulated fire occurrence in West Africa during 2002, as retrieved from MODIS on Terra and Aqua. (Bottom) Scatter plot of smoke aerosol emission rate derived from MODIS AOT measures against FRE release rate (or FRP). Linear least squares fits gave good correlations. The slopes correspond to the FRE-based smoke-aerosol emission coefficient, which when multiplied by FRP from satellite gives the rate of smoke aerosol emission (see *Ichoku and Kaufman*, 2005).

Discussion and Conclusion

Advancements in satellite remote sensing during the last couple of decades have, not only enabled fire detection from space, but have facilitated significant improvement in fire monitoring and characterization as well as burned biomass and emissions estimation. The ability to measure fire radiative power (FRP or R_{fre}) from space has helped to widen the horizon in this domain of research and applications. It is now possible to rate individual fires by strength using a simple scheme based on FRP ranges, which will facilitate active fire evaluation and information communication between fire fighters and managers, the Press, and the general public; in a manner similar to the strengths of other natural disasters such as hurricanes and earthquakes, which are expressed in terms of simple dimensionless numerical indices, such as “hurricane category” or “earthquake magnitude”. Also, regional fire activity can be easily evaluated individually or comparatively using FRP fluxes. In addition, it is now possible to quantify burned biomass and emitted smoke based mainly on satellite FRP measurements; a near impossible undertaking before the advent of satellite remote sensing.

Africa is in a relatively advantageous position to enjoy the benefits of such advancements in fire remote sensing. This is because the only two operational satellite systems currently capable of measuring FRP (MODIS and SEVIRI) cover Africa adequately. MODIS offers the advantage of good spatial resolution and global coverage, while SEVIRI, which covers mainly Africa and Europe, offers the advantage of high temporal resolution. A constructive synergistic integration of the products of these two unique sensors will enable Africa to implement a much wider diversity of applications relating to biomass burning monitoring than most other regions of the world.

Indeed, Africa needs to take advantage of these unprecedented satellite resources to begin to monitor and control biomass-burning in the continent. This is because, based on the analysis of monthly mean FRP fluxes from MODIS data for different regions of the world, it was found that sub-Saharan African regions burn more biomass per unit area of their land annually than most other regions of the world. This intense biomass burning activity is apt to exert adverse impacts both directly (heat release) and indirectly (particulate and gaseous smoke emissions) on a variety of phenomena affecting the society, including (but not limited to): air quality, water quality, disease outbreaks, invasive species, agricultural productivity, drought, and climate.

References

Chuvieco, E., Cocero, D., Aguado, I., Palacios, A., & Prado, E. (2004) Improving burning efficiency estimates through satellite assessment of fuel moisture content, *J. Geophys. Res.*, 109(D14S07), doi:10.1029/2003JD003467.

Giglio, L., Descloitres, J., Justice, C. O., & Kaufman, Y. J. (2003). An enhanced contextual fire detection algorithm for MODIS. *Remote Sens. Environ.*, 87, 273–282.

Giglio, L., van der Werf, G. R., Randerson, J. T., Collatz, G. J., & Kasibhatla, P. S. (2006). Global Estimation of Burned Area using MODIS Active Fire Observations. *Atmospheric Chemistry and Physics*, 6, 957-974. SRef-ID: 1680-7324/acp/2006-6-957.

Ichoku, C., Giglio, L., Wooster, M. J., and Remer, L. A., (2008) Global characterization of biomass-burning patterns using satellite measurements of Fire Radiative Energy. *Remote Sens. Environ.*, (In Press).

Ichoku, C., & Kaufman, Y. J. (2005). A method to derive smoke emission rates from MODIS fire radiative energy measurements. *IEEE Trans. on Geosc. & Rem. Sens*., 43 (11), 2636-2649.

Kaufman, Y. J., Justice, C. O., Flynn, L. P., Kendall, J. D., Prins, E. M., Giglio, L.,Ward, D. E., Menzel,W. P., & Setzer, A.W. (1998). Potential global fire monitoring from EOS-MODIS. *J. Geophys. Res*., 103, 32215– 32238.

Li, R.-R., Kaufman, Y. J., Hao, W. M., Salmon, J. M., & Gao, B.-C. (2004) A technique for detecting burn scars using MODIS data, *IEEE Trans. Geosci. Remote Sensing*, 42(6), 1300 – 1308.

Roberts, G., Wooster, M. J., Perry, G. L. W., Drake, N., Rebelo, L.-M., & Dipotso, F. (2005). Retrieval of biomass combustion rates and totals from fire radiative power observations: Application to southern Africa using geostationary SEVIRI imagery. *J. Geophys. Res*., 110, D21111, doi:10.1029/2005JD006018.

Roy, D.P., P.E. Lewis, and C.O. Justice, (2002) Burned area mapping using multi-temporal moderate spatial resolution data—a bi-directional reflectance model-based expectation, *Remote Sens. Environ.*, 83**,** 263–286.

Seiler, W. & Crutzen, P. J. (1980), Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning, *Climate Change*, 2, 207–247.

Simon, M., Plummer, S., Fierens, F., Hoelzemann, J. J., & Arino, O. (2004) Burnt area detection at global scale using ATSR-2: The GLOBSCAR products and their qualification, *J. Geophys. Res*., 109, D14S02, doi:10.1029/2003JD003622.

Tansey, K., Grégoire, J.-M., Stroppiana, D., Sousa, A., Silva, J., Pereira, J. M. C., Boschetti, L., Maggi, M., Brivio, P. A., Fraser R., Flasse, S., Ershov, D., Binaghi, E., Graetz, D. & Peduzzi, P. (2004). Vegetation burning in the year 2000: Global burned area estimates from SPOT VEGETATION data. *J. Geophys. Res*., 109, D14S03, doi:10.1029/2003JD003598.

Wooster, M. J. (2002). Small-scale experimental testing of fire radiative energy for quantifying mass combusted in natural vegetation fires. *Geophys. Res. Lett*., 29(21), 2027, doi: 10.1029/2002GL015487.

Wooster, M. J., Roberts, G., Perry, G. L. W., & Kaufman, Y. J. (2005). Retrieval of biomass combustion rates and totals from fire radiative power observations: FRP derivation and calibration relationships between biomass consumption and fire radiative energy release. *J. Geophys. Res*., 110, D24311, doi:10.1029/2005JD006318.

Wooster, M. J. & Zhang, Y. H. (2004). Boreal forest fires burn less intensely in Russia than in North America. *Geophys. Res. Lett*., vol. 31, L20505, doi:10.1029/2004GL020805.