Carbon Emissions from Biomass Burning

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Science and Application targets

Natural and anthropogenic fires emit a significant amount of carbon from the biosphere into the atmosphere. It is estimated that global carbon emissions from fires are between 2-4 Gt per year (Seiler and Crutzen 1980, van der Werf et al. 2010. These emissions are a complex mixture of gases, but carbon dioxide (CO_2) is the most abundant, along with carbon monoxide (CO) and methane (CH_4). Aerosols in the form of organic carbon and black carbon particles may also present in abundance. Several authors have demonstrated that the frequency, extent and severity of fires maybe changing in many regions, partly as a result of changes in climate (Pausas 2004, Flannigan 2009), and that deforestation activities hamper the post-fire carbon uptake by vegetation recovery (Davidson et al. 2012). Currently forest and peatland degradation in the tropics are believed to be responsible for between ~ 12 to 20% of the global atmospheric CO_2 growth rate. Even individual fire events can impact the atmosphere at a global scale, with the 1997-98 fires in Indonesia resulting in an amount of carbon release between 13 and 40% of the mean annual global carbon emissions from fossil fuels at that time (Page et al., 2002), which contributed to the single largest annual atmospheric CO_2 increase yet seen (Jones and Cox, 2005)

If fire frequency, severity and extent increase under climate and environmental changes, then carbon emissions will increase accordingly during this fire regime shift (Intergovernmental Panel on Climate Change, 2007). Accurate carbon emission estimates from wildfires are therefore of paramount importance to quantify the transfer from biomass carbon stocks to trace gases in the atmosphere.

Carbon emission estimates from biomass burning are significant compared to the carbon emission from fossil fuels. Estimates of carbon emissions from fires range between 20 to 40 percent of the carbon emissions from fossil fuels (Intergovernmental Panel on Climate Change 2007, van der Werf et al. 2010), with significant interannual variability. However, these estimates have a large uncertainty and differ according to the specific methodologies used (Ellicott et al. 2009, van der Werf et al. 2010, French et al. 2011).

Currently, two approaches are widely used to estimate carbon emission from fires. The first (more traditional) approach utilizes four parameters in a bottom-up approach to estimate carbon emission. These parameters are burned area (BA), fuel load (FL), combustion completeness (CC) and the fraction of carbon in the biomass (FC). Uncertainties in emission estimates propagate as a function of uncertainties in each of the parameters (French et al. 2003, van der Werf et al. 2010). Particularly problematic is the determination of the CC (and to some extent FL), which varies between and across a burned regions and which for the former have sensitivities to short term meteorological influence that cause the moisture of the fuel to vary. The most established methodology to infer the intensity of burning or fire severity for a given area is a bi-temporally differenced spectral index called the differenced Normalized Burn Ratio (dNBR), calculated from two visible near infrared images. However, this index is scene and biome specific and cannot be used across regions without calibration to local in situ measurements, thereby limiting its usefulness for refining CC values in all fire-prone ecosystems (Lentile et al. 2006, Smith et al. 2007, Kasischke et al. 2011).

More recently a second, more top-down approach, has been developed to retrieve carbon emissions estimates from biomass burning - based on the observation that the Fire Radiative Power (FRP) retrieved from the mid infrared (MIR) signal emitted by actively burning fires is linearly related to the amount of biomass combusted (Wooster et al., 2005). Therefore, since almost all vegetation and organic soil is 50±5% carbon, this allows the estimation of carbon emissions - or emissions of other species such as CO_2, CO, CH4 and aerosols - direct from FRP observations (e.g. Wooster et al. 2005, Freeborn et al., 2008; Ellicott et al. 2009, Vermote et al. 2009). The great advantage of the FRP approach is that it does not need any additional information on FL or CC (Wooster et al., 2005). However, frequent measurements of the FRP during burning are needed to accurately retrieve the total fire emissions, rather than simply instantaneous "snapshots" (Ellicott et al. 2009; Freeborn et al., 2011). Such high temporal resolution FRP data are typically acquired from geosynchronous satellite measurements which, while providing frequent coverage, have a much lower spatial resolution and larger pixel areas. This results in an underestimation of carbon emissions because smaller fires, such as agricultural burns, cannot be easily detected using such data with such large pixels. While "smaller fires" each contribute less carbon to the atmosphere because of their size, they are very numerous in certain parts of the world and must therefore be included in order to obtain accurate carbon emission estimates. Randerson et al. (2012) also showed that a similar issue of small fire bias affects bottom up carbon emissions estimates derived from burned area measures.

The uncertainties inherent in current methods of fire carbon emissions estimation is demonstrated by the fact that differences in model assumptions and parameter definitions can change total carbon emission estimates from biomass burning by a factor of 2 when using the bottom-up approach (French et al. 2011). Similarly, Ellicott et al. (2009) showed that carbon emissions from biomass burning using the FRP approach can be 3.5 times lower than those obtained with the bottom-up approach. These two studies highlight the need for an in-depth comparison of the different approaches and assessment of the associated uncertainties. Any Carbon Management System (CMS) must include carbon emissions from biomass burning due to its clear significance, and it is essential that a comparison of the two different methods for calculating carbon emissions from biomass burning is undertaken to understand and reconcile the discrepancies between the two approaches. A CMS-like capability is an essential part of NRC Theme III - "Marine and Terrestrial Ecosystems and Natural Resource Management" and Theme IV – "Climate Variability and Change: Season to Centennial".

Utility of Geophysical Variables

Two approaches are widely used to estimate emissions from fires known as the traditional or bottom-up approach and the more recent top-down or Fire Radiative Power (FRP) approach. Both approaches have their strengths, weaknesses, and associated uncertainties. From a remote sensing perspective, the bottom-up approach generally requires a pre-fire and post-fire image to calculate the carbon emissions from the difference in burned area seen between the two images. However, retrieving the required fuel load (FL) and combustion completeness (CC) parameters from remotely sensed data is not straightforward and usually relies on a vegetation growth model and perhaps necessitates field work to calibrate the FL and CC inputs. For the Continental United States, the US Forest Service has built the Fuel Characteristic Classification System (FCCS) as part of the Landfire project (Ottmar et al. 2007). This 30m data layer provides information on fuel load, and when combined with fire ecology modeling (e.g. the CONSUME model, Ottmar et al. 2006) this layer can also provide information on CC. The FCCS is calibrated with a significant field work effort (Ottmar et al. 2007). A major drawback with the CC used in the current approach is its lack of inclusion of the heterogeneity or severity of the burn. Recent efforts have focused on developing a remotely sensed method to assess within-burn heterogeneity (fire severity) for inclusion with the CC. The differenced Normalized Burn Ratio (dNBR) is the standard approach to assess fire severity (Key and Benson 2005, French et al. 2008, Veraverbeke et al. 2010). However, dNBR values are not directly related to the mechanistic processes on the ground and dNBR values are not easily used to refine CC. Spectral unmixing provides an alternative to the dNBR and allows the output the fraction of burning or vegetation mortality to be included in CC parameter (Lentile et al. 2006, Smith et al. 2007, Kasischke et al. 2011), but this still does not easily convert into an estimate of the fraction of the available fuel that is actually burned (i.e. the CC parameter).

In contrast, the FRP approach has the advantage that it does not need any information on fuel load or CC. However, to retrieve consistent total carbon emission estimates, multiple acquisitions per day are required. For the moment, this type of data is only available from relatively coarse spatial resolution sensors (e.g. MODIS) or geosynchronous sensors (e.g. GOES) which either miss or underestimate the emissions from small fires which, while small, are sufficiently ubiquitous to contribute a significant portion of carbon emissions.

The difficulties in calculating carbon emissions using both approaches can result in significant discrepancies (Ellicott et al. 2009, French et al. 2011), highlighting the need for further efforts to reconcile both approaches. High spatial resolution remotely sensed data are particularly useful for this purpose since they allow direct comparison with ground measurements.

Two types of products are currently generated from low to moderate resolution polar-orbiting and geostationary sensors. These are: 1) burned area products that provide the extent of burn scars based on fire-induced changes in surface reflectance (Roy et al. 2005, Giglio et al. 2009, Zhang et al. 2014); and 2) active fire products which locate and measure intensity of fires based fire-induced changes in brightness temperature (Giglio et al. 2003). Global moderate resolution (500 m) satellite-derived burned area products are currently embedded in bottom-up approaches to quantify fire emissions (van der Werf et al. 2010, French et al. 2011, Giglio et al. 2013). An alternative is to use retrievals of fire radiative power (FRP) made from thermal observations, and integrate this into an estimate of fire radiative energy (FRE) (Wooster et al. 2005). The rationale behind this approach is that the total fire emissions are directly related to the total radiative energy released by the fire's combustion process (Wooster et al. 2005). Burned area products give reliable estimates in areas where fire activity is dominated by large wildfires, however, these products miss many smaller sub-pixel fires that are related to human activity (Randerson et al. 2013). Active fire products are better suited to assess the importance of small fires since fires covering 0.1% of the pixel area generally permits reliable fire detection (Giglio et al. 2003). Randerson et al. (2013) used the enhanced sensitivity of 1 km spatial resolution active fire data from MODIS to quantify the emission of fires that remained undetected by the MODIS 500 m spatial resolution burned area product. They found that the importance of small fires varied significantly across regions, and that the global estimates of burned area and emissions increased by 35% when accounting for these small fires. The small fire fraction was especially important in Equatorial Asia, Central America, Southeast Asia and

Southeastern USA (Figure 1). Small fires in these regions are mostly agricultural or land management fires and generally occur in fragmented landscapes (Eva and Lambin 1998, McCarty et al. 2009).To observe these geophysical variables, a radiometer operating in the mid wave infrared (MWIR) and long-wave infrared (LWIR) is needed.

Measurement and Observation Requirements

Numerous spaceborne systems can provide the high to moderate resolution visible near infrared measurements needed for the bottom-up or traditional approach such as the NASA/USGS Landsat series or Sentinel 2 Multi Spectral Instrument, however, high spatial resolution mid-infrared measurements needed for the FRP approach to include small fires are currently very limited or non-existent.

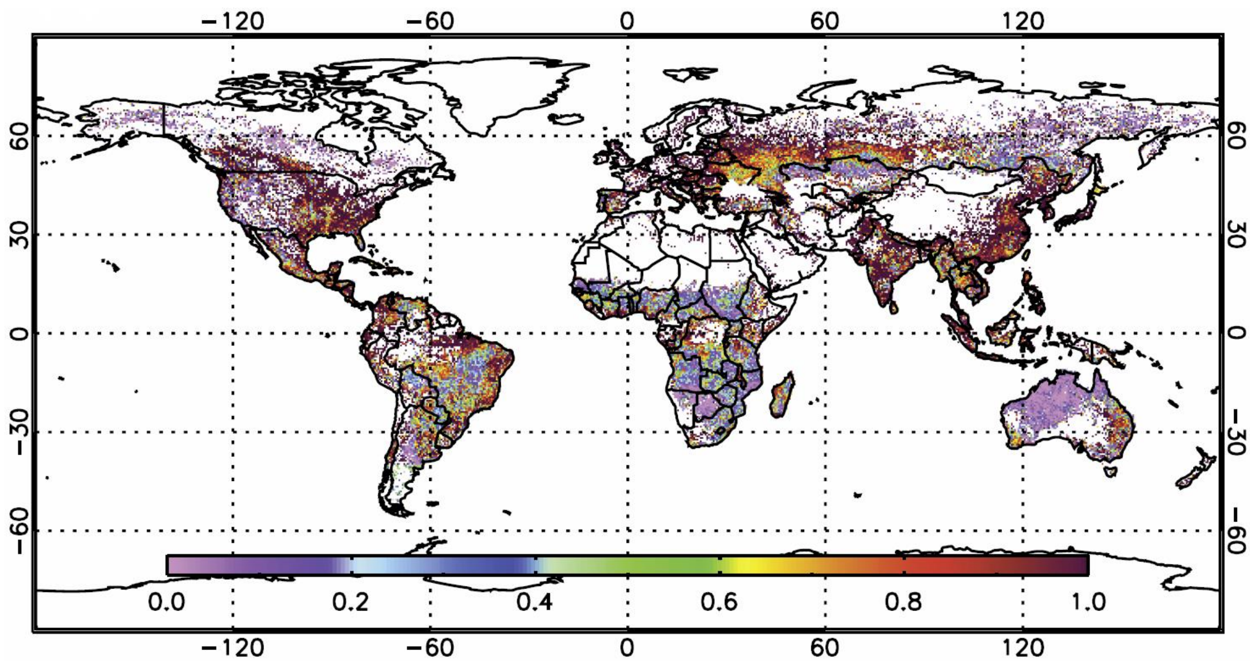

Figure 1 Small fire fraction of total burned area (Randerson et al. 2013). Red and yellows highlight areas where many smaller fires were detected.

The work of Randerson et al. (2013) demonstrated that small fires are widespread in several regions on earth and that these fires must be included in current wildfire emission models in order to accurately represent the role of fire in the global carbon cycle. However, the recent work of Randerson et al. (2013) indicates current estimates were in error by at least 35% utilizing 1 km spatial resolution data which, according to the spectral sensitivity tests of Giglio et al. (2003), are only sensitive to fires between 100 and 10000 m^2 depending on fire temperature. Fires that are smaller than this threshold remain undetected by 1 km data, which has a minimum FRP detection limit of around 8 MW. The majority of fires burning worldwide at any particular time may have an FRP lower than this threshold - but currently this is unknown. Furthermore, even fires where the total FRP is larger than this can be made up of areas which are undetected by MODIS due to its relatively coarse pixel size. Figure 2 illustrates how the MODIS active fire algorithm is unable to detect several pixels in which an active fire is clearly visible based on higher resolution imagery acquired at the same time. Further work is required with higher spatial resolution sensors to determine the reliable detection thresholds for smaller fires when only part of the pixel contains fire for a variety of fire regimes.

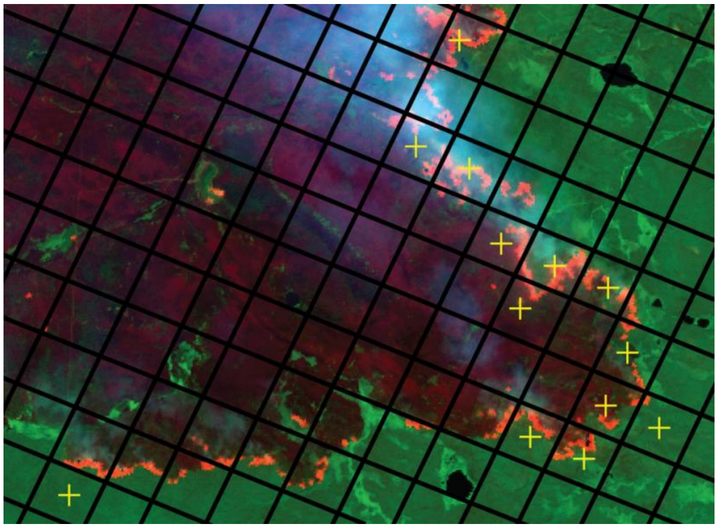

Figure 2. Simultaneous higher resolution 90-m ASTER image with black boxes overlaid corresponding to 1-km MODIS imagery. Yellow crosses represent MODIS pixels where fires were detected. Notice that many pixels where fire is clearly visible in the ASTER image remain undetected in the MODIS image.

An instrument with a spatial resolution of 100 m would make it possible to detect a fire covering an area as small as 10 m^2, and could provide data available at the appropriate time of day (i.e. early afternoon) when the number and distribution of active fires and their associated emissions peak (Giglio, 2007). Such an instrument could therefore resolve total fire emissions at the daily peak of the fire cycle. In order to capture smaller fires an afternoon orbit is required since many man-made fires are lit in the mid-morning and burn out by the late afternoon. An instrument would be required that had two mid infrared bands (low and high saturation temperatures) with ideally three thermal infrared bands for retrieving surface temperature and one band around 1.6 um for cloud detection. Multiple daily revisits would be ideal but a 2-3 day revisit would allow characterization of fire regimes and, for example the derivation of emissions information on monthly timescales. Instruments on 3 or more satellites with a wide swath width would allow multiple daily revisits and global coverage.

MTIR Measurement Characteristics

For fire detections and land surface temperature sustained Mid and TIR radiometric retrievals from a high to moderate resolution instrument with an NEdT of 0.2K and ≥6 bands, with at least 3 bands in the thermal infrared between 8 and 12 µm with saturation temperatures of 450K and two bands in the mid infrared between 3 and 5 µm, one with a 450K saturation temperature and the other with a 1200K saturation temperature and a single band at 1.6 µm for cloud detection. A spatial resolution of better than 100 m will allow mapping of small fires as well as detailed mapping of the fire front. However, a coarser spatial resolution of 300 m may be sufficient, Further work is required with higher spatial resolution sensors to determine the reliable detection thresholds for smaller fires when only part of the pixel contains fire for a variety of fire regimes. A width swath instrument 1500-2000 km would allow global mapping every 2 days and multiple instruments would allow at-least daily sampling.

Feasibility and Affordability

NASA engineering studies have demonstrated the feasibility of a 3-year, Class C mission with a TIR radiometer at <100 m pixel resolution, 1200K saturation in the mid wave infrared, and 2-day temporal repeat at the equator. This radiometer would fit with a Size, Weight and

Power (SWaP) compatible with a Pegasus class launch (Figure 3). Many of the key technologies enabling the mission build on the legacy, in particular ECOSTRESSS including the focal plane, cryocoolers and scan mirror assembly (Figure 4). The mission has an orbital average data volume consistent with readily available onboard solid state recorded (SSR).

An instrument as described above could be built for 30 M$ and accommodated on multiple free flying spacecraft using a Class D approach.

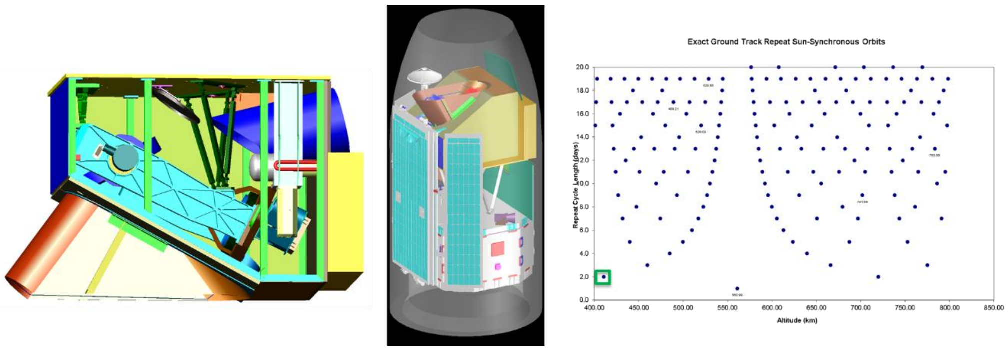

Figure 3. (left) Opto-mechanical configuration for a wide swath, high resolution TIR imaging radiometer system providing 73-degree swath and <100 m sampling. TIR Imaging radiometer with spacecraft (265 kg, 187 W) configured for launch in a Pegasus shroud for an orbit of 410 km altitude, 97.07 inclination to provide 2-day revisit for three years. (right) Orbital altitude and repeat options. An altitude of 410 km with a fueled spacecraft supports the three-year mission with the affordable Pegasus launch. Higher orbits require a larger launch vehicle.

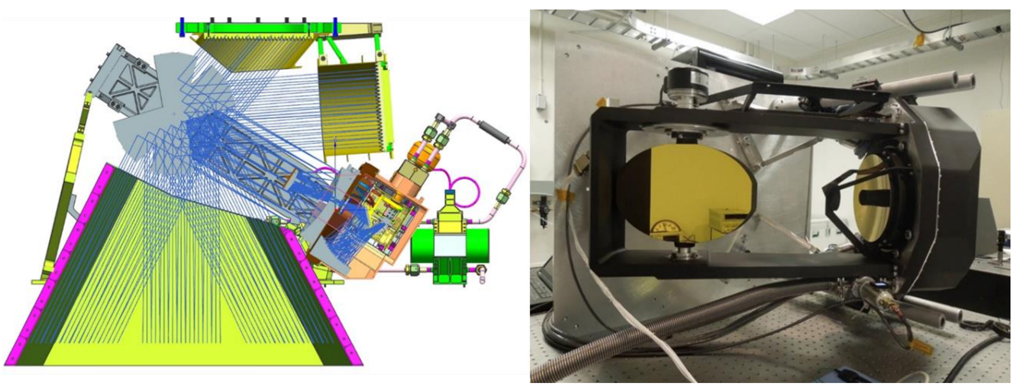

Figure 4. (left) Design of ECOSTRESS TIR Push-whisk scanning system covering a wide field of view with an 8 band SWIR to TIR sensor. (right) Developed, aligned and qualified PHyTIR push-whisk system with TIR full range multi-band detector array.

Synergistic Measurements

It is assumed that moderate spatial resolution mid and thermal infrared measurements will continue to be available from instruments like MODIS, Sentinel-3 SLSTR, and VIIRS and high to moderate spatial resolution measurements will be available from Landsat, Sentinel-2, MSI , MODIS and VIIRS. Geostationary data will provide very high temporal resolution resolving of the fire diurnal cycle, albeit with the small fires missing from the dataset. These synergistic measurements enable the continued assessment of carbon emissions from large fires using either the bottom-up or top-down approaches. However In order to advance fire information products, and in particular FRP, along with carbon emissions estimates, new global measures with increased saturation temperature and which provide near daily data with ≤100m pixel resolution are required.

Acronyms

MODIS – Moderate Resolution Imaging Spectroradiometer
SLSTR - Sea and Land Surface Temperature Radiometer)
SWaP – Size, Weight and Power
VIIRS – Visible Infrared Imaging Suite

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