THE OPERATIONAL MSG/SEVIRI FIRE RADIATIVE POWER PRODUCT GENERATED AT THE LAND SAF

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Abstract

Biomass burning is globally significant source of trace gases and aerosols and a major mechanism controlling both land-cover change and exchanges of carbon between the land and atmosphere. Quantitative estimates of biomass burning emissions are required for many earth science applications, including for operational forecasting of atmospheric state, where such data are required in close to real-time. This is possible only via a satellite remote sensing approach, ideally utilising the high temporal frequency available from geostationary orbit. This work describes a new European Fire Radiative Power product that has been developed to meet these requirements, and which includes both repetitive detection of actively burning fires at 15 minute intervals (thus allowing analysis of the complete biomass burning diurnal cycle) and quantification of the fires radiative power output (which has been shown to relate closely to the rate of fuel consumption and thus trace gas, carbon and aerosol emission). The FRP product is derived from multi-spectral observations provided by the Meteosat SEVIRI imaging radiometer, including all fire-affected regions of Africa, Europe and part of eastern South America. The product is delivered operationally to users by the Land Surface Analysis Satellite Applications Facility (http://landsaf.meteo.pt/). This product provides valuable input to a variety of earth science applications, including real-time forecast models linking pollutant emissions from fires to models of atmospheric chemistry and transport.

INTRODUCTION

Biomass burning is a key process in the Earth system, and in particular the terrestrial carbon cycle, and a globally significant source of atmospheric trace gases and aerosols which impact air quality, atmospheric chemical composition and the Earths radiation budget. Globally, vegetation fires are believed to generate carbon emissions equivalent to between one third and one half of those from fossil fuel combustion, with those from savanna fires responsible for perhaps 50% of this total (Williams *et al*., 2007). Burning is prevalent on every significantly vegetated continent, and Africa is on average, the single largest biomass burning emissions source at the continental scale, responsible for between 30 and 50% of the total annual fuel consumption (van der Werf *et al*., 2006). Burning is typically characterized by strong interannual, seasonal, and diurnal cycles, and this strong variability means that, wherever possible, measurements of fires and their emissions are required for many science applications and the use of 'climatological means' is insufficient. These measurements generally come from data collected by Earth observation satellites, either responding to the active fire thermal emissions, the release of a particular trace gas species or aerosols, or the change in surface reflectance caused by the passage of fire over the landscape.

It has been demonstrated in small-scale experiments that the amount of radiant energy liberated per unit time during a vegetation fire (the so-called Fire Radiative Power) is related to the rate at which the fuel biomass is being consumed (see Figure 1 after Wooster et al., 2003). This is a direct result of the combustion process, whereby carbon-based fuel is oxidised (burnt) with the release of a certain 'heat yield'. Measuring this FRP and integrating it over the lifetime of the fire therefore provides a measure of the total Fire Radiative Energy (FRE), which should be proportional to the total fuel mass combusted (M).

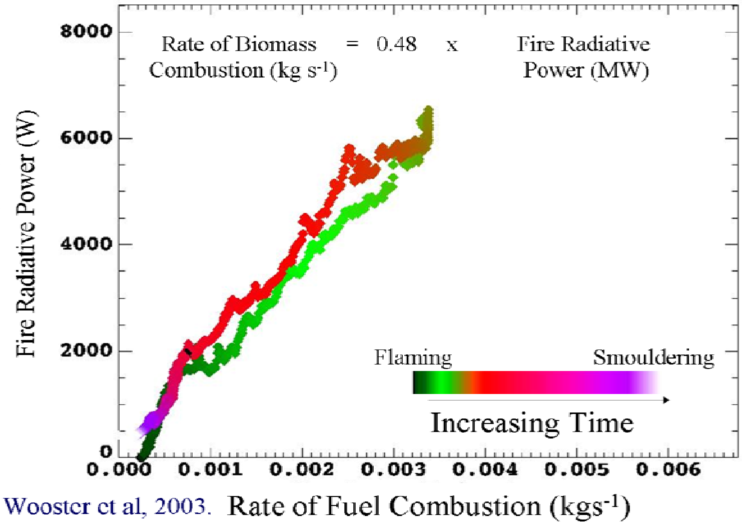

Figure 1: Measured relation between the combustion rate and the FRP (after Wooster el al. 2003).

Current methods to obtain *M* are based largely on burned area mapping approaches, with necessary assumptions on fuel density and combustion completeness (which may vary with land-cover/climate/timing-of-fire). The FRP approach in theory circumvents the requirement to make these assumptions, providing a variable that is more directly related to the amount of combusted biomass. Geostationary observations allow high temporal frequency FRP measurements, and thus the ability to estimate FRE via temporal integration. The main limitation of geostationary observations is likely to be the fact that the larger pixel sizes (compared to polar orbiting systems) will result in a larger fraction of the smaller and/or less intensely burning fires going undetected.

This paper describes the operational FRP product estimated from MSG/SEVIRI observations and its operational generation/dissemination by the Land Surface Analysis Satellite Applications Facility (SAF) ((https://landsaf.meteo.pt/)). An example of application is also provided.

ESTIMATION OF THE RADIAN ENERGY EMITTED BY A FIRE

The MIR radiance method of FRP estimation was first presented in Wooster *et al*. (2003) and is based on simple approximations to the physical laws governing the emission of thermal radiation from fires. The MIR radiance method exhibits two potential advantages over dual-wavelength methods such as those originally presented in Dozier (1981). Firstly it relies only on quantification of the fire pixel in a single spectral channel, removing problems related to inter-channel spatial mis-registration that potentially impact such dual spectral band approaches (Shephard and Kennelly, 2003), and secondly it relies only on quantification of the fire signal in the MIR spectral band only, where spectral radiative emission from wildfires is maximised and thus where the signal increase of the fire pixel over the ambient background window signal is at its greatest. For these reasons, the method used to derive FRP in the official MODIS fire products also uses measurements in the MIR spectral band (Kaufman *et al*., 1998a), though in that case expressed in terms of brightness temperatures rather than radiances. The derivation of the method and associated simplifications can be found in Robert *et al*. (2005). The MIR method relies on the difference between the MIR spectral radiance of the active fire pixel (L_{MIR}) and that of the surrounding non-fire 'background' ($L_{b,MIR}$) calculated as the mean signal of the 'background window pixels, and adjusted for the MIR atmospheric transmission:

$$L_{f,MIR} = p_f \varepsilon_{f,MIR} B(\lambda_{MIR}, T_f) = \frac{1}{\tau_{MIR}}\left(L_{MIR} - L_{b,MIR}\right) \quad (1)$$

The impact of the assumptions made during the derivation and application of the above equation used to estimate $L_{f,MIR}$, the assumptions made during the derivation of Equation 1**Error! Reference source not found.**, will control the theoretical accuracy of the FRP algorithm.

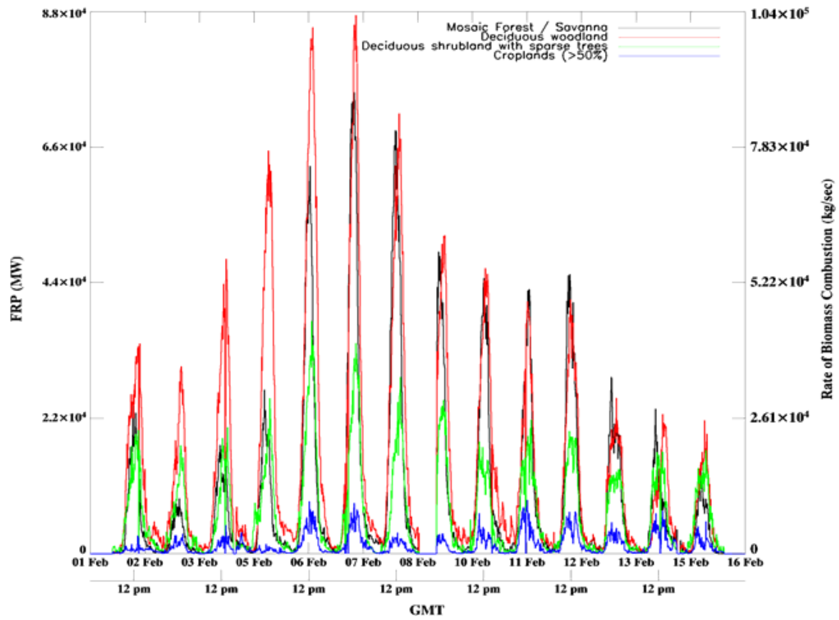

Figure 2: Daily variations of the FRP and the combustion rate averaged over the Sahel region from 1 to 15 February 2004.

DERIVING THE FRP FROM SEVIRI OBSERVATIONS

Since geostationary satellites can provide very high temporal resolution fire detections, they can also be used to calculate the rate of fire radiant energy release repeatedly over a fires lifetime, or over grid cells covering large, continental scale regions. Since Figure 1 shows a strong relationship between the fire radiative power and the rate of fuel consumption, these geostationary-based measures can be integrated over time to produce an estimate of the total fuel mass burned. In particular, active fire data provided by the SEVIRI instrument promised significant advancements in the current state-of-the-art of fire monitoring and emission quantification systems. Since SEVIRI can revisit a same location with a 15 min frequency, it can therefore deliver important information on the temporal behaviour of fire activity which exhibit strong daily variations as can be seen on Figure 2.

Although SEVIRI has been designed for operational weather forecasting and not specifically for fire detection, its MIR channel (thermal band centred at 3.9 µm shown on Figure 3) shows great potential for fire detection and the measurement of FRP using Equation 1. However, several factors limit the optimal use of such type of frequent observations:

- The sub-satellite pixel size is 4.8 x 4.8 km^2 (FWHM), and these 23 km^2 pixels are oversampled by a factor 1.6 in the x and y directions leading to a sub-satellite pixel sampling distance of 3 x 3 km^2. Pixels close to the disk edge reach areas of ~ 90 km^2. The relatively large pixel size limits the detectability of small/low intensity fires having a low FRP, and may lead to a misinterpretation of fire clusters as individual large fire events. The increasing pixel size away from the sub-satellite point is expected to increase the significance of these events relative to smaller fires.
- The MIR channel of the SEVIRI sensor has a saturation level of ~ 335 K, and as a result a certain proportion of the particularly large and/or high intensity fires are expected to cause saturation of the measurements in this spectral band. Whilst this will not impact detection of such fire pixels (indeed their large signal will very likely make them amongst the most detectable such events), it will lead to an impact on the accuracy of the FRP measurements of such fires since their MIR spectral radiance will be underestimated.
- The on-board processing of SEVIRI data and its conversion to the level 1.5 radiance product from which all geophysical datasets including the FRP product are derived (termed here the level 1 to level 1.5 processing) introduces perturbations to the original measurements made in each spectral

band. This will include the introduction of interpolation errors due to the geolocation and projection onto the nominal geostationary projection centered at (0°; 0°).

– The SEVIRI 3.9 µm band is large and encompasses CO_2 absorption, so that the mean transmittance is only about 0.7. Additionally, the radiance exhibits sharp variations in that band which prevent an easy quantitative exploitation of these observations

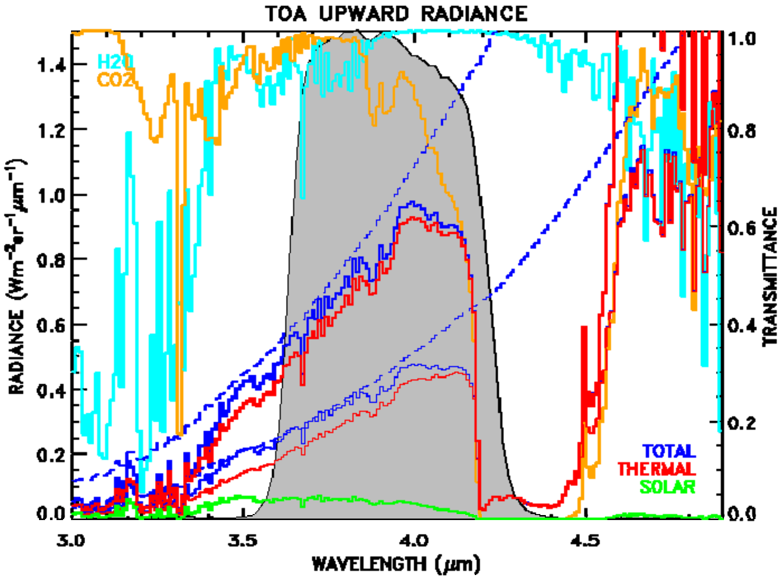

Figure 3: Spectral response of SEVIRI 3.9 µm band (shaded grey) shown for two different pixel temperatures. The dashed line is the total surface radiance, the solid blue line is the total TOA radiance, the solid red line is the thermal TOA radiance, the green line is the solar TOA radiance. The brown (light blue) line is the total CO_2 (H_2O) gaseous transmittance.

The impact of all these limitations has been carefully addressed by Shultz et al. (2008) and have been shown not affect significantly the benefit of the frequent observations delivered by SEVIRI.

THE OPEARTIONAL FRP PRODUCT

The fire detection algorithm implemented for use with SEVIRI is an evolution of that described in Roberts *et al*. (2005), and is based on the principles used to generate active fire detections within the MODIS fire products. The algorithm works mainly on statistics derived from the 3.9 µm and 11.0 µm brightness temperatures, and their differences. On a first pass a series of absolute thresholds are used with these data to detect "potential" fire pixels, which are then further assessed as 'true' or 'false' fire detections base on a series of further "contextual" tests whose thresholds are adjusted based on statistics derived from the immediately neighbouring non-fire "background" pixels. Background pixel statistics are obtained from a window surrounding each potential fire pixel, commencing as a 5 × 5 matrix and being expanded until sufficient window pixels are not themselves classed as potential fire pixels (or clouds). Each potential fire pixel must pass all tests to be confirmed as a "true" fire pixel, and a confidence measure is also assigned to the detection. The second stage of this algorithm is the derivation of FRP at all fire pixels. This is carried out using the MIR radiance method (Equation 1) which assumes FRP is proportional to the difference between the observed fire pixel radiance in the SEVIRI middle infrared (MIR, 3.9 µm) channel and the 'background' radiance that would have been observed at the same location in the absence of fire. This background radiance is at present derived from the set of fire- and cloud- free pixels surrounding each fire pixel. An operational version of this algorithm has been prototyped at EUMETSAT and successfully implemented in the Land SAF (Lattanzio, 2006, Govaerts *et al*., 2008).

The Land SAF system is part of the EUMETSAT ground segment of operational product generation which is taking place in Lisbon at IM. Since June 2008, the FRP product is operationally generated at the Land SAF and disseminated through EUMETCast since September 2008. This product is also available from the Land SAF ftp server. The FRP product is available in KML format of Google Earth for last 24 hours from the Land SAF web page https://landsaf.meteo.pt/.

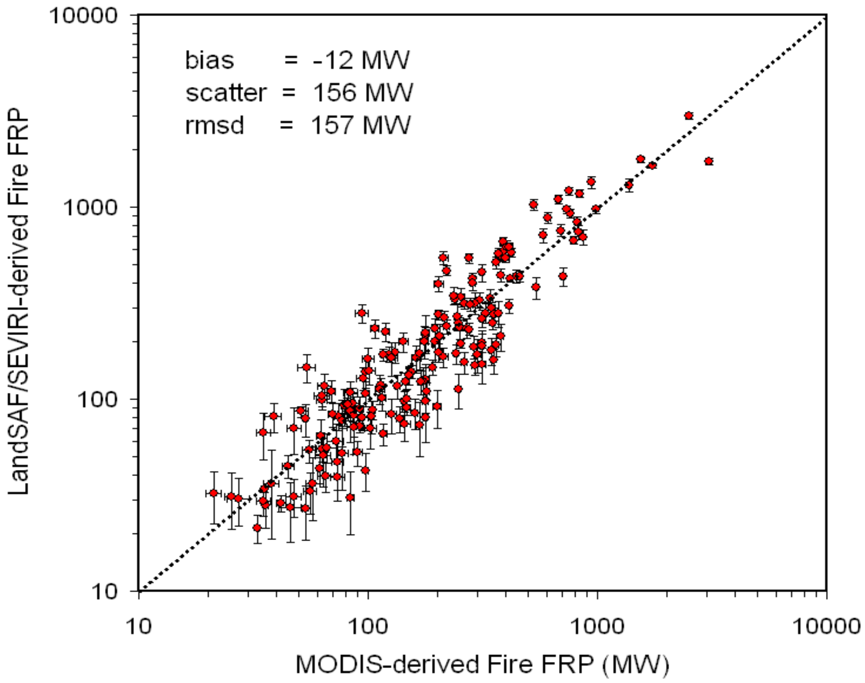

Figure 4: A comparison of per-fire FRP derived from SEVIRI and MODIS observations of 187 fires observed near-simultaneously by each sensor. Fires are designated as contiguous clusters of active fire pixels and SEVIRI FRP measured were taken from the Land SAF FRP per-pixel products of southern Africa collected in August 2007.

VALIDATION

Considering the potential aspects theoretically limiting the accuracy and performace of the SEVIRI FRP algorithm previously outlined in this paper, the strategy adopted to validate the SEVIRI FRP product was to individually assess the following three aspects.

Firstly, the theoretical and actual performance of the SEVIRI fire detection and FRP algorithm have been assessed using model simulations and analysis of the King's College London (KCL) FRP product and matching MODIS-derived FRP data. The theoretical and radiative transfer modelling analysis of the algorithm performance has shown that the MIR radiance method algorithm used within the SEVIRI FRP products has an underlying accuracy of ±12% over the temperature range expected for active fires, and that the assumptions made when implementing this algorithm on data of highly-sub pixel sized fires in theory introduce negligible other errors. In this case, if the fire pixels that comprise an individual fire can be reliably detected, show a sufficiently large MIR radiance increase above the background, and if the MIR atmospheric transmission is reliably known then the FRP can be quantified to this level of uncertainty. Differences between the original KCL algorithm and the Land SAF implementation are negligible in this respect.

Secondly, the accuracy and performance limitations introduced due to the SEVIRI instrument characteristics and data pre-processing procedures have been assessed using model simulations and analysis of matching SEVIRI level 1.0 and 1.5 data and data from SEVIRI 'special' mode operations. In practical terms, the most limiting factor for product accuracy appears to be the current coarse pixel size, of area ~ 23 km² at the sub-satellite point, increasing to ~ 90 km² near the disk edge (assuming full width at half maximum sensitivity values). Numerous fire pixels with FRP values less than 40 MW escape detection by SEVIRI, and the detection and quantification of slightly larger fires (40-100 MW) will be less reliable, because the enhancement of the MIR brightness temperature due to the fire with respect to the (somewhat variable) background temperature of surrounding pixels is rather small. To some extent the impacts of the coarse spatial resolution are balanced by the extremely high temporal resolution of the geostationary observations. As was shown for fires in the Central African Republic, over the course of a day SEVIRI will capture a signal from most fire events that the much higher spatial resolution MODIS instruments on EOS Aqua and Terra can detect during their four-times per day overpasses. We assume that this is related to the ability of SEVIRI to observe the complete fire life cycle and thus capture fires when they reach their peak intensity. However, for any particular SEVIRI observation, the cumulative FRP measured at the regional (e.g. grid cell or country-scale) is likely to be an underestimate of what would have been measured by MODIS had it observed the whole area at the same moment, by on average around 50%. Since the MIR channel on SEVIRI was not designed for fire detection but rather for land surface monitoring, it saturates around 335 K, a temperature that is easily exceeded by larger fire events. The effect of this saturation is an underestimation of FRP for large fires, which can in fact contribute significantly to an underestimation of FRP in a given region. Limited experiments have indicated an FRP underestimation of ~ 10% by day due to pixel saturation and up to 40% at night, though at night there are many fewer fires and much lower regional FRP totals, so saturation of a few nighttime pixels can induce large percentage errors. The spatial filtering and geometric interpolation performed on-board MSG as part of the level 1 to level 1.5 processing induces some additional noise in the MIR field, which further reduces the instrument's ability to detect all the fire pixels associated with an individual fire event, and to accurately quantify their FRP. The "blurring" of fire radiances related to this pre-processing can reduce level 1.5 fire pixel MIR temperatures, and as a consequence fewer pixels appear to be saturated in the level 1.5 data than were originally saturated at the instrument (level 1.0) stage. However, it is be shown through theoretical modelling and targeted data analysis that the effects of the level 1 to level 1.5 processing are generally outweighed by the limitations given by the sensor resolution and the pixel saturation effects.

Finally, the performance of the specific algorithm implementation at the Land Surface Analysis Satellite Applications Facility [Land-SAF]; assessed using the LandSAF FRP product and comparisons to the KCL FRP product and to matching MODIS-derived FRP data. Comparisons with MODIS FRP product were made on a per-fire basis, as well as on a regionally gridded basis (Figure 4). When MODIS and SEVIRI detect the same fire, in 76 % of the cases the FRP retrieved by SEVIRI is within 33 % of that reported by MODIS. Errors of omission and commission are estimated to 54% (68% for the one month of data of the Land SAF product) and 8% (2%), respectively, varying with season.

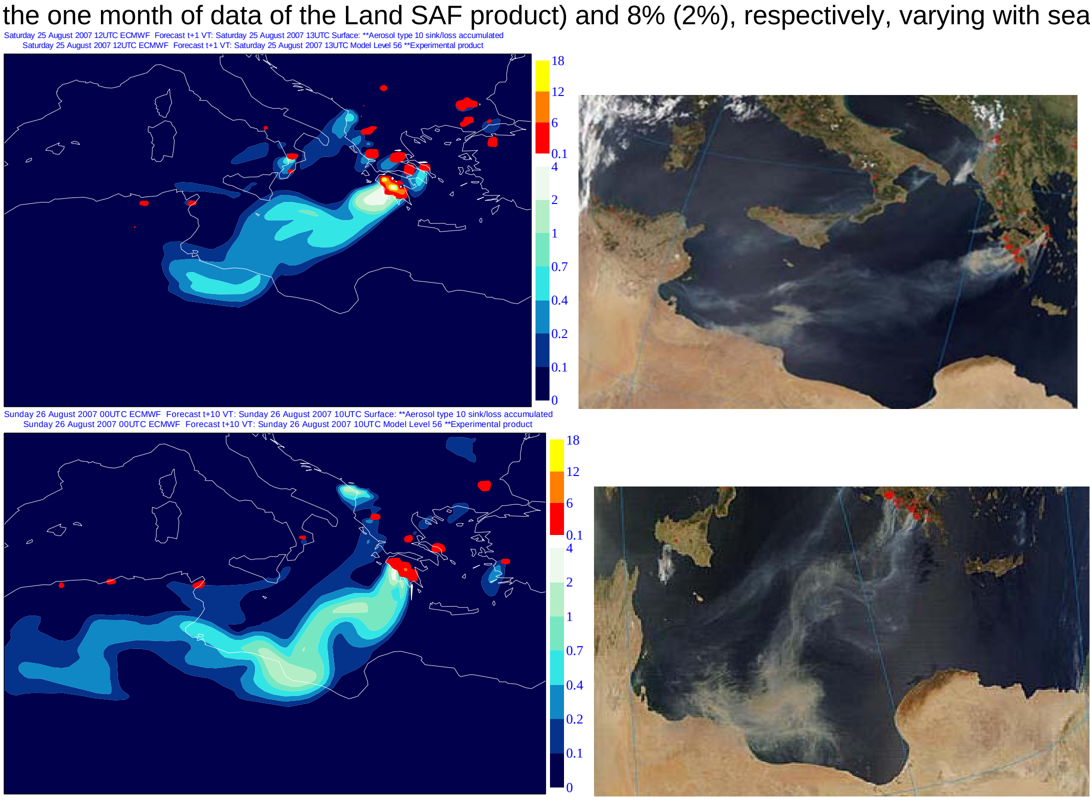

Figure 5: Modelled organic matter plus black carbon AOD [-] (left, blue) and MODIS visual images (right) for an Aqua overpass on 25 August, 1205UTC, (top) and a Terra overpass on 26

August, 0935UTC (bottom). Overlayed with SEVIRI FRP [W/m2] interpolated to model resolution (left, orange) and MODIS hot spots in (right, red) (Courtesy J. Kaiser, ECMWF).

EXAMPLE OF APPLICATION

This section shows the results of a case study initiated in the FREEVAl project (Schultz et al. 2008) on modelling the smoke plumes from fires occurring in the Mediterranean region in August 2007 using SEVIRI FRP derived fire aerosol emission estimates. It allows for some independent validation of the SEVIRI product and also served to identify the necessary technical processing steps and required product characteristics of the pixel and gridded SEVIRI FRP products. Two snapshots of simulated optical depth of organic matter and black carbon aerosols, which dominate the smoke optical depth from fire plumes and have comparably smaller other emission sources, are plotted and compared to concurrent MODIS visual images in Figure 5. The plots also show the fire activity observed by SEVIRI and MODIS. The simulations qualitatively reproduce the key features of the observations, in particular the fact that the smoke plumes are separated into series of individual ”puffs“, which originate from the high fire activity during daytime and are separated by the low activity at night. The AOD comparison of 26 August confirms these findings: The plume shapes are reproduced well, but the plume AOD values are mostly overestimated. Additionally, the background, which originates from different sources, is underestimated. This might be due to cloud cover effects, which are not simulated.

CONCLUSION

The estimation of the FRP from SEVIRI observations has been proven to be feasible and reliable despite the technical limitations of the instrument. The original FRP concept has been developed at KCL in the 2003-2005 time frame in the framework on an MSG RAO project (Wooster et al., 2005) and subsequently prototyped at EUMETSAT in 2006 accounting for the constrains of an operational environment (Govaerts, et al, 2008). This algorithm has been implemented in the Land SAF system in 2007. In May 2008, the FRP product has successfully passed the Operational Readiness Review and declared pre-operational. Since June 2008, it is operationally generated and disseminated (EUMETSAT 2008).

This product is currently routinely used by the GEMS/MACC project at ECMWF for the estimation of aerosol and trace gas emissions from fires. It is expect that this product will benefit other applications related to air quality forecast, carbon cycle modelling or active fire detection.

KCL, EUMETSAT and the Land SAF are currently working on the development of an operational level 3 FRP product. This product will be generated on an hourly basis on a regular 1×1 degree grid. This product will include statistical corrections of the FRP estimation due to the presence of clouds and undetected small fires. This product is expected to become pre-operational in 2009.

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