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Meteosat SEVIRI Fire Radiative Power (FRP) products from the Land Surface Analysis Satellite Applications Facility (LSA SAF) – Part 1: Algorithms, product contents and analysis

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**LSA SAF SEVIRI FRP
product algorithms,
contents and
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Abstract

Characterising changes in landscape scale fire activity at very high temporal resolution is best achieved using thermal observations of actively burning fires made from geostationary Earth observation (EO) satellites. Over the last decade or more, a series of research and/or operational "active fire" products have been developed from these types of geostationary observations, often with the aim of supporting the generation of data related to biomass burning fuel consumption and trace gas and aerosol emission fields. The Fire Radiative Power (FRP) products generated by the Land Surface Analysis Satellite Applications Facility (LSA SAF) from data collected by the Meteosat Second Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI) are one such set of products, and are freely available in both near real-time and archived form. Every 15 min, the algorithms used to generate these products identify and map the location of new SEVIRI observations containing actively burning fires, and characterise their individual rates of radiative energy release (fire radiative power; FRP) that is believed proportional to rates of biomass consumption and smoke emission. The FRP-PIXEL product contains the highest spatial resolution FRP dataset, delivered for all of Europe, northern and southern Africa, and part of South America at a spatial resolution of 3 km (decreasing away from the west African sub-satellite point) at the full 15 min temporal resolution. The FRP-GRID product is an hourly summary of the FRP-PIXEL data, produced at a 5° grid cell size and including simple bias adjustments for meteorological cloud cover and for the regional underestimation of FRP caused, primarily, by the non-detection of low FRP fire pixels at SEVIRI's relatively coarse pixel size. Here we describe the enhanced geostationary Fire Thermal Anomaly (FTA) algorithm used to detect the SEVIRI active fire pixels, and detail methods used to deliver atmospherically corrected FRP information together with the per-pixel uncertainty metrics. Using scene simulations and analysis of real SEVIRI data, including from a period of Meteosat-8 "special operations", we describe some of the sensor and data pre-processing characteristics influencing fire detection and FRP uncertainty. We show that the FTA al-

gorithm is able to discriminate actively burning fires covering down to 10^{-4} of a pixel, and is more sensitive to fire than algorithms used within many other widely exploited active fire products. We also find that artefacts arising from the digital filtering and geometric resampling strategies used to generate level 1.5 SEVIRI data can significantly increase FRP uncertainties in the SEVIRI active fire products, and recommend that the processing chains used for the forthcoming Meteosat Third Generation attempt to minimise the impact of these types of operations. Finally, we illustrate the information contained within the current Meteosat FRP-PIXEL and FRP-GRID products, providing example analyses for both individual fires and multi-year regional-scale fire activity. A companion paper (Roberts et al., 2015) provides a full product performance evaluation for both products, along with examples of their use for prescribing fire smoke emissions within atmospheric modelling components of the Copernicus Atmosphere Monitoring Service (CAMS).

1 Introduction

1.1 Meteosat Second Generation and biomass burning observations

Smoke emissions from landscape scale fires are strong influencers of atmospheric composition, chemistry and climate (Williams et al., 2010), and the repetitive and timely data provided by Earth Observation (EO) satellites are key to characterising the phenomena. The European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) currently operates the Meteosat Second Generation (MSG) system, Europe's geostationary EO programme for studying weather, climate and the Earth environment. Meteosat carries the Spinning Enhanced Visible and Infrared Imager (SEVIRI), whose multispectral, radiometrically calibrated data can be used to detect actively burning fires and to estimate their Fire Radiative Power (FRP) output, a parameter that has been shown to be proportional to rates of fuel consumption and smoke production (Freeborn et al., 2008; Kremens et al., 2012; Pereira et al., 2011; Wooster

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et al., 2005). Since the first MSG launch in 2002, SEVIRI has observed Europe, Africa, and a part of South America every 15 min at a 3 km spatial resolution at the west African sub-satellite point (SSP). SEVIRI in fact provided the first geostationary EO data to be used to estimate FRP from landscape-scale fires (Roberts et al., 2005; Wooster et al., 2005; Roberts and Wooster, 2008), and the data delivery and processing chains that characterise operational meteorolgocial satellites such as Meteosat enable them to provide unique views of landscape scale fuel combustion even whilst the fires are burning. SEVIRI-derived FRP data are now used to paremeterise high temporal resolution smoke emissions fields for atmospheric modelling (Baldassarre et al., 2015), including in the prototype Copernicus Atmosphere Monitoring Service (CAMS) (Roberts et al., 2015). Here we describe the algorithms and characteristics of the SEVIRI FRP products available operationally from the EUMETSAT Land Surface Analysis Satellite Applications Facility (LSA SAF; landsaf.meteo.pt). These products are available via both near-real time and offline dissemination routes, and have already provided information used in a number of biomass burning emissions inventories (e.g. Turquety et al., 2014), and in instances of the Global Fire Assimilation System (GFAS) that provides fire emissions data to the CAMS (e.g. Hollingsworth et al., 2008; Kaiser et al., 2012; Andela et al., 2015).

1.2 Landscape scale fires and smoke emissions

Determining a sufficiently accurate spatio-temporal description of landscape scale fire emissions is a fundamental pre-requisite for the development of many types of atmospheric "information services", including those aimed at studying the long-range transport of air pollutants (Reid et al., 2009), the near-real time monitoring and forecasting of air quality (e.g. Sofiev et al., 2009; Kaiser et al., 2012) and the determination of atmospheric composition variations (Clerbaux et al., 2009; Ross et al., 2013). Furthermore, carbon accounting parameters derived from EO-derived FRP data are contributing to long-term regional and global biomass burning emissions inventories (e.g. Remy and Kaiser, 2014; Roberts et al., 2011; Vermote et al., 2009; Zhang et al., 2012), which

in turn can be used to gauge compliance with international treaties on GHG and pollutant emission ceilings. In this context, the type of very high temporal resolution active fire information available operationally and in near real-time from SEVIRI (Fig. 1a) are very complementary to the higher spatial resolution, but more temporally limited, views of the same fires available from polar orbiting EO systems (Fig. 1b) (e.g. Giglio et al., 2003; Wooster et al., 2012; Schroeder et al., 2014). The high temporal resolution view is particularly important for fires, because they typically show substantial short term activity variations and radical shifts in behaviour over the daily cycle (Roberts et al., 2009a; Andela et al., 2015). This type of rapidly supplied, remotely sensed active fire information can even provide useful information for the early warning and tracking of new fire activity (e.g. Dlamini, 2007).

Because of their orbiting equatorial position above west Africa, the MSG satellites provide high temporal resolution FRP data relating to fires burning across the African and European continents, and also on the eastern edge of South America (Fig. 2). Africa is considered the most "fire affected" continent, responsible for ∼ 30–50 % of global annually burned area and a consequently very significant proportion of global fire emissions (Andreae, 1991; van der Werf et al., 2003, 2006). Although fires are far less prevalent in Europe than in Africa, wildfires remain relatively common in much of southern Europe, and occasionally extreme wildfire outbreaks can threaten large population centres and/or deliver acute air quality impacts (Liu et al., 2009; Baldassarre et al., 2015; Roberts et al., 2015). The region of South America viewed by SEVIRI is a region of primarily dry and moist forest, cerrado and croplands, where many fires are found. However, due to the large SEVIRI viewing angles the version of the FTA algorithm applied to GOES Imager data provides a better geostationary FRP dataset here (Xu et al., 2010).

1.3   LSA SAF Meteosat SEVIRI FRP products

Two Meteosat SEVIRI FRP products are delivered operationally in near real-time and archived form by the LSA SAF (landsaf.meteo.pt), whose role is to take full advantage

of remotely sensed data to support land, land–atmosphere and biosphere applications, with an emphasis on the development and implementation of algorithms allowing operational use of EUMETSAT satellites (Trigo et al., 2011).

The primary LSA SAF output is the Level 2 FRP-PIXEL product, delivered at the full spatial and temporal resolution of SEVIRI, and a secondary output is a Level 3 spatio-temporal summary of these termed the FRP-GRID product. In the following sections we document the algorithms and information content relevant to both these products, focusing in particular on enhancements made to the prototype geostationary "Fire and Thermal Anomaly" (FTA) active fire detection algorithm first described in Roberts and Wooster (2008) and to the retrievel of FRP and its uncertainty. We illustrate how the SEVIRI pre-processing chain influences product uncertainties, and indicate basic product performance by showing illustrative data on individual fires and larger areas, including demonstration of the type of emerging biomass burning patterns revealed through the increasingly long geostationary record. We include a brief comparison to alternative active fire products (WFABBA) now being generated from the same SEVIRI input data, whist the companion paper (Roberts et al., 2015) provides a much more detailed performance evaluation of both SEVIRI FRP products, and demonstrates their use for high temporal resolution fire emissions characterisation with models used as part of the CAMS. Finally, we use our analyses to provide some recommendations for future strategies related to the pre-processing of Meteosat Third Generation (MTG) data.

2 Overview of the LSA SAF Fire Radiative Power (FRP) product generation

2.1 Active fire data from the Meteosat Second Generation satellites

At the time of writing (December 2014) there are three spin-stabilised MSG satellites currently in orbit, Meteosat-8, 9, and 10 (formerly MSG-1, 2, and 3), launched in 2002, 2005 and 2012 respectively. Each rotates at 100 rpm and provides Earth imagery from the SEVIRI spin scan radiometer (Aminou et al., 1997; Aminou, 2002). Meteosat-10 is

the currently the primary full Earth disk observatory located at 0° longitude; Meteosat-9 provides a Rapid Scanning Service over a reduced fraction of the Earth disk at 9.5° E; and Meteosat-8 acts as an in-orbit spare at 3.5° E. MSG-4, the last in the MSG series, is planned for launch in 2016.

5   SEVIRI operates in 12 spectral channels (Table 1; Aminou et al., 1997), and the mid-wave infrared (MWIR: IR3.9) and longwave infrared (LWIR: IR10.8 and IR12.0) bands (Channels 4, 9 and 10 in Table 1) are differentially sensitive to the thermal radiance emitted by high temperature sources such as landscape fires (Prins et al., 1998; Prins and Menzel, 1994; Roberts et al., 2005). This allows SEVIRI in theory to detect ac-

10   tively burning fires covering as little as 10^{-4} of a SEVIRI pixel (Roberts et al., 2005; Wooster et al., 2013), but the FTA algorithm used for this must take care to prevent sunglint and other potentially confounding features being falsely identified as active fires (Fig. 1c and d), as detailed in Sect. 3. Confirmed active fire pixel detections have their FRP estimated using techniques based on those of Wooster et al. (2003, 2005)

15   and discussed in Sect. 4, with delivery of a full per-pixel uncertainty measures as detailed in Sect. 5.

2.2   SEVIRI data capture and pre-processing

As the satellite spins from east-to-west, SEVIRIs scan mirror is stepped from south-to-north in steps of 125.8 μrads to build up an 11 channel image of the full Earth disk

20   (Aminou, 2002) over a period of ~ 12.5 min. The ground sampling distance between SEVIRI pixel centres at the sub-satellite point (SSP) is 3 km, whereas the instantaneous field of view (IFOV) for each detector is 4.8 km × 4.8 km (full width at half maximum; FWHM), resulting in a final image resolution of around 6 km6km (Just, 2000). Fortunately, actively burning fires covering an area very many orders of magnitude

25   smaller than a SEVIRI pixel can be detected using the FTA algorithm described herein. SEVIRI pixels are diamond shaped and oriented at an angle of 45° with respect to the E/W spin and S/N scan directions (Aminou, 2002; Schmetz et al., 2002; Calle et al., 2009). SEVIRIs IFOV and ground sampling distances increase with view zenith

angle, yielding larger and more widely separated ground footprints further from the SSP (Fig. 2). Data from SEVIRIs 12th channel (1 km broadband visible HRV) is only captured over the part of the Earth disk, and is not used in the FRP product processing chain. A blackbody calibration view and retracing of the scan mirror to the start position

5   gives a final SEVIRI full disk repeat cycle of ∼ 15 min, shorter if only part of the Earth disk is imaged during rapid-scan or "special operations" periods.

Captured SEVIRI data are transmitted from the MSG satellites to the Primary Ground Station (PGS) in Usingen (Germany), and then sent to the Image Processing Facility (IMPF) hosted at EUMETSATs Darmstadt headquarters (Just, 2000; Murphy, 2013).

10 Here they are radiometrically/geometrically corrected and geolocated (Fig. 1c and d), moving them from level 1.0 to level 1.5, and then forwarded to users including the LSA SAF who are headquartered at the Instituto Portugues do Mar e da Atmosfera in Portugal (DaCamara, 2006; Trigo et al., 2011).

2.3   Introduction to the LSA SAF Meteosat SEVIRI FRP product suite

15 At the LSA SAF, the primary Meteosat FRP product is the Level 2 FRP-PIXEL product, and as with all other LSA SAF products (Trigo et al., 2011) it is currently generated separately for the four geographic regions of the Meteosat disk: Europe (Euro), Northern Africa (NAfr), Southern Africa (SAfr), and South America (Same) (Fig. 2). The Level 3 FRP-GRID product summarises the FRP-PIXEL product information at a reduced

20 spatio-temporal resolution and incorporating data across all four LSA SAF geographic regions, making adjustments for cloud cover and for SEVIRI's low spatial resolution FRP bias caused by the inability to detect the lowest FRP fires (Freeborn et al., 2009).

Each FRP-PIXEL product covering a single LSA SAF geographic region actually consists of two separate product files: (i) an "FRP-PIXEL List Product" file that stores

25 variables derived at each detected active fire pixel, and (ii) an "FRP-PIXEL Quality Product" file that contains a 2-D array of flags recording the processing status of each SEVIRI pixel, not just those identified as containing active fires (e.g. it reports whether each pixel was classified by the FTA algorithm as water, cloud contaminated, sun glint-

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affected, cloud-free but with no fires, or was a confirmed active fire pixel etc.). The various codes used within the FRP-PIXEL Quality Product files are shown in Table 2. The eight individual files making up the full FRP-PIXEL product output are expected to be replaced later in 2015 by a simpler two file List and Quality Product structure,
5 each covering the full Earth disk. All FRP product files are stored in HDF5 format, and Sect. 8 provides further details on their content and accessibility.

FRP-PIXEL products are delivered to users within one hour of image acquisition, and are therefore both more frequent and more timely than most other EO active fire products. This can be an important consideration given the high frequency fluc-
10 tuations shown by landscape scale fires, and demands for "rapid response/decision support" products (Frost and Annegarn, 2007). Figure 3 illustrates one example of the spatio-temporal distribution of active fire data extracted from the 96 FRP-PIXEL List Product files collected over the southern African LSA SAF geographic region during a single day. Freeborn et al. (2014a) recently demonstrated that over regions of Cen-
15 tral Africa, the FTA algorithm successfully detects fire pixels having an FRP down to around 10 MW, though below about 40 MW active fire numbers are increasingly underestimated, and hence adjustments are applied in the FRP Grid Product to better estimate landscape-scale regional FRP totals (Sect. 7).

3 Operational implementation of the geostationary Fire Thermal Anomaly
20 (FTA) algorithm

3.1 The FRP-PIXEL product processing chain

The LSA SAF FRP product processing chain ingests level 1.5 SEVIRI data arriving from the IMPF, calibrated into units of $mW\,m^{-2}\,sr^{-1}\,(cm^{-1})^{-1}$ and then into brightness temperature (Kelvin) for the infrared channels, and the subsequent processing flow is
25 illustrated in Fig. 4. The product Algorithm Theoretical Basis Document (Govaerts et al., 2010) provides full detail, and here we review the key features and the operational

enhancements made beyond the Roberts and Wooster (2008) prototype of the FTA algorithm.

3.2 Pre-processing stage: water, cloud and smoke discrimination

Sunglints from water can result in false active fire detections (Fig. 1), so SEVIRI pixels containing major water bodies are first masked using the 1 km Global Land Cover (GLC 2000) map of Mayaux et al. (2004). Clouds can cause similar problems (Zhukov et al., 2006), and both unmasked water bodies and cloud can bias the background window characteristics used in the active fire pixel confirmation stage (Sect. 3.5). Cloud must also be masked out therefore, but the tests used must as far as possible not mask out areas of smoke since active fires usually remain highly detectable through smoke (Libonati et al., 2010). FRP-PIXEL product processing currently uses the Nowcasting and Very Short Range Forecasting SAF (NWC SAF; www.nwcsaf.org) cloud mask (CMa; Derrien and Le Gleau, 2005) to identify cloud-contaminated SEVIRI pixels, but with some modifications to optimise its use in this application. Specifically, CMa pixels are reclassed as non-cloudy if their classification as cloud is based on one of the following conditions, which are fully detailed in Derrien and Le Gleau (2005) and MeteoFrance (2010):

i. The Local Spatial Texture test, applied to a 3×3 pixel window to detect broken clouds and cloud edges by exploiting the higher spatial variation of visible (0.6 μm), NIR (0.8 μm) and/or LWIR channel measures typical around such features. Areas of active fire and smoke often show similar spatial variations.

ii. The Brightness Temperature Difference (BTD; $BT_{3.9} - BT_{10.8}$) test, which detects semi-transparent clouds at night and low-level clouds during the day, exploiting the lower water cloud emissivity in the SEVIRI IR3.9 channel as compared to the IR10.8 channel. Active fires also cause BTD to increase substantially, and indeed this is the basis of most active fire detection algorithms.

iii. The Spatial Smoothing test, which fills in cloud detection "gaps" in areas of semi-transparent cloud. If a CMa pixel detected as cloudy based on the Spatial Smoothing test has at least three surrounding CMa pixels also marked as cloudy based on that test, then the pixel is re-classed as non-cloudy.

CMa cloud mask pixels remaining after the above adjustments are assigned Class 3 ("Cloud") in the FRP-PIXEL Quality Product file (Table 2). Furthermore, to aid cloud masking reliability for the active fire application after these modifications to the CMa mask, a SEVIRI pixel is also assigned to Class 3 if it passes each of the following three tests and is not yet classed as cloudy:

$$BT_{3.9} - BT_{10.8} > 6.0 \, K \tag{1}$$

$$BT_{10.8} - BT_{12.0} > 1.5 \, K \tag{2}$$

$$\frac{L_{3.9}}{L_{0.64}} < 0.7 \tag{3}$$

where $BT_{3.9}$, $BT_{10.8}$, and $BT_{12.0}$ are the pixel brightness temperatures in the SEVIRI IR3.9 (MWIR), IR10.8 μm (LWIR) and IR12.0 μm (LWIR) spectral channels respectively, and $L_{3.9}$ and $L_{0.64}$ are the spectral radiances in the IR3.9 and VIS0.6 μm (visible) channels respectively (Table 1).

An example of the success of the adaptations made to the CMa cloud mask are illustrated in Fig. 5, where use of the original CMa BT difference test ($BT_{3.9} - BT_{10.8}$) causes many active fire pixels to be incorrectly classified as cloud (Fig. 5c). A wider analysis of the southern Africa data of the same day indicates that 22 % of the FRP-PIXEL product active fire pixels would have remained undetected had the above adjustments not been made to the standard CMa cloud mask. However, whilst the adjusted CMa cloud mask is far better suited to cloud screening an active fire product than is the standard CMa mask, Freeborn et al. (2014a) recently demonstrated that it may still be a limiting factor in current FRP-PIXEL performance, simply because its ability to detect cloud far surpasses that of simpler cloud detection routines used, for example, within

the MODIS MOD14/MYD14 Active Fire and Thermal Anomaly products. Whereas the adjusted CMa masks out areas of thinly or partially cloud-covered land, the MODIS products often allow fires to be detected in such areas (Fig. 6). Work is ongoing to consider potential use of less sensitive cloud masks in future LSA SAF product updates, to lessen the issues highlighted by Freeborn et al. (2014a).

Figure 7a shows an example of the final European FRP-PIXEL Quality Product classification scheme, with cloudy and non-cloudy land pixels dominating alongside "not processed" water pixels (which are masked prior to the cloud masking stage). To further minimize numbers of false active fire detections caused by unmasked cloud or water, the FTA algorithm masks certain pixels immediately neighbouring cloudy pixels or which are within two pixels of a "not processed" water body pixel. Such pixels are masked as "Cloud/Water Edge" (Class 8; Table 2) if they fail to show a strong IR3.9 channel ($BT_{3.9}$) signal:

$$BT_{3.9} < 320\,\text{K} \tag{4}$$

Whilst this Cloud/Water edge test helps limits errors of commission, it has the disadvantage of causing true fires burning next to clouds or water to remain undetected. This disadvantage is probably most pertinent to the European (Euro) LSA SAF geographic region, which has a particularly high number of pixels adjacent to a water body (Fig. 7b). Work is ongoing to determine if this impact can be lessened without significantly adding to false alarms.

3.3 Identification of Potential Fire Pixels (PFP's)

This part of the FTA algorithm (boxed in Fig. 4) identifies all SEVIRI level 1.5 pixels potentially containing active fires. First, two spectral thresholding tests related to the IR3.9 ($BT_{3.9}$) and BTD ($BT_{3.9} - BT_{10.8}$) signals must be passed, with thresholds varying

with solar zenith angle (θ_s):

$$BT_{3.9} > C_{11}\theta_s + C_{12} \tag{5}$$
$$BT_{3.9} - BT_{10.8} > C_{21}\theta_s + C_{22} \tag{6}$$

where C_{11} (−0.3 and 0.0), C_{12} (310.5 and 280 K), C_{21} (−0.0049 and 0.0) and C_{22} (1.75 and 1.0 K) are constants applied during the day (first value) and night/twilight (second value; $\theta_s > 60°$). The advantage of using these relatively low BT thresholds to discriminate any pixel conceivably containing an active fire is somewhat counteracted by fact that large areas of homogeneously sun warmed areas can often also exceed them, leading to significant and unwanted computational demands during subsequent processing stages. To avoid this, a series of standard high pass "edge detecting" spatial filters of size 3×3, 5×5 and 7×7 pixels are applied to the BTD ($BT_{3.9} - BT_{10.8}$) image, and each PFP output from Tests (5) and (6) must pass the following two tests to remain as a PFP:

$$P = HP_{filter} \geq DT \times \delta_{filter} \tag{7}$$
$$DT = 2.5 - 0.012 \times \theta_s \tag{8}$$

where HP_{filter} is the output of the spatial filter, and δ_{filter} is a threshold that in the FTA prototype was taken as the standard deviation of the filtered BTD image. However, to further minimise computational demands during real-time processing, in the operational FTA algorithm δ_{filter} was derived once for each filter size for each daily timeslot using four exemplar SEVIRI images, and the minimum δ_{filter} for each timeslot and filter size used in Eq. (7) during operational processing.

3.4 Sunglint detection

A sunglint angle (θ_g) is defined for each SEVIRI pixel according to Prins et al. (1998), and those pixels with $\theta_g < 5°$ are coded as glint-affected "Class 4" in the FRP-PIXEL Quality Product (Table 2) and removed prior to the tests described in Sect. 3.3. Two

further glint tests are applied after PFP identification, to discriminate more ambiguous areas of glint using the ratio of the IR3.9 and VIS0.6 channel spectral radiances:

$$\frac{L_{3.9}}{L_{0.64}} < \frac{0.7}{p} \tag{9}$$

$$(2-p) \cdot \frac{L_{3.9}}{L_{10.8}} < 0.0195 \tag{10}$$

where $L_{3.9}$, $L_{0.64}$ and $L_{10.8}$ are the spectral radiance of the IR3.9, VIS0.6 and IR10.8 channels respectively, and p can take a value of either 1 or 2. We assume that the absence of nearby cloud makes it less likely that a particular PFP is caused by glint, so Tests (9) and (10) work on the 15 × 15 pixel window surrounding each PFP, and if this window contains a cloudy pixel then p is set to 1, otherwise p is set to 2. Pixels satisfying these two tests are coded as "possibly glint affected" (Class 5), whilst all processed pixels not belonging to the potential fire pixel (PFP) set and which have not yet received an alternative classification are coded as Class 0 ("not a potential fire pixel").

3.5 Contextual active fire detection

During this Stage, an expanding "background window" surrounding each PFP is used to calculate a set of metrics against which the PFP signal is compared, to confirm whether or not it is a true fire pixel. The window starts at 5 × 5 pixels in size, and continues expanding until sufficient numbers of its pixels meet the validity criteria outlined in Roberts and Wooster (2008); namely being cloud free, not a PFP, and passing the tests below which relate, respectively, to not showing the types of spectral signature associated with a possible fire pixel (Tests 11 and 12), not being affected by remaining sunglint (Test 12), and having spectral signatures less like a fire than that of the PFP

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under test (Tests 14 and 15).

$$\frac{L_{3.9}}{L_{10.8}} < 0.0195 \tag{11}$$

$$BT_{3.9} - BT_{10.8} < 10\,K \tag{12}$$

$$\theta_g > 2° \tag{13}$$

$$BT_{3.9} - BT_{10.8} < (BT_{3.9} - BT_{10.8})_{PFP} \tag{14}$$

$$BT_{3.9} < BT_{PFP_{3.9}} \tag{15}$$

Where the terms retain their already identified meanings, and BTD_{PFP} and $BT_{PFP_{3.9}}$ are, respectively, the BT difference of the potential fire pixel calculated using the IR3.9 and IR10.8 SEVIRI channels, and the PFPs IR3.9 channel BT.

When defining the details of the operational FTA algorithm, we first investigated the detailed characteristics of the aforementioned background window, aiming to elucidate the cause and consequences of certain SEVIRI imaging artefacts that impact the required statistics (e.g. the lowered IR3.9 brightness temperatures seen surrounding active fire pixels in Fig. 9b).

To deliver the anti-aliased properties specified for SEVIRI level 1.5 imagery (Just, 2000; Deneke and Roebeling, 2010), a Finite Impulse Response (FIR) digital filter is applied to each line of SEVIRI data, the filter consisting of a symmetric Sinc function having 17 coefficients (including some negative coefficients), multiplied by a modified Kaiser window function (Fig. 9a). Such filtering can have particularly significant consequencies in areas of high image contrast, and to investigate this we convolved the FIR filter with the SEVIRI point spread function (PSF) (Fig. 8b) and applied the result to simulated active fire thermal imagery derived at a spatial resolution 10× higher than that of the native SEVIRI pixels. The convolution of the negative coefficients of the FIR filter and the strong IR3.9 channel active fires signals led to substantial decreases in the output IR3.9 channel brightness temperatures, both up- and down-scan of the fire pixel itself (Fig. 8a), an effect mirroring that seen in real level 1.5 SEVIRI data (Fig. 8b).

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Further simulations, including of larger fires (e.g. Fig. 8c and d), indicated that the orientation of the fire along or perpendicular to the SEVIRI scan line, and even the fires sub-pixel location, affects the details of the final output imagery. Freeborn et al. (2014b) recently demonstrated how the sub-pixel fire location affects the MODIS-measured FRP, an effect previously identified with the BIRD HotSpot Recognition Sensor (Zhukov et al., 2006). Calle et al. (2009) also reported related phenomena using SEVIRI. Our simulations led us to conclude that FIR-filter "smearing" of the fire emitted spectral radiance into neighbouring pixels, and the depression of the IR3.9 channel BT of neighbouring pixels, can have significant consequences for active fire observations, particularly so if pixels now containing some of the fire emitted signal are not themselves strongly radiating enough to be detected as active fires and/or if the background window statistics are unduly contaminated by lowered IR3.9 BTs.

Based on our simulations, we requested a period of "special operations" where near-simultaneous data from two MSG satellites could be compared with and without the standard FIR filter applied. These data are fully described in Sect. 6.2, and they fully confirm that the effect of decreased IR3.9 channel BTs neighbouring strongly radiating active fire pixels is absent from SEVIRI Level 1.5 imagery pre-processed without the FIR filter (Fig. 10). Further analysis confirmed that excluding the eight pixels immediately neighbouring the potential fire pixel (PFP) from the background window improved the ambient background representation, since it is these pixels that are most affected by the FIR filtering (Fig. 10). This exclusion is implemented in the operational FTA algorithm, as well as the requirement that during the day ($\theta_s > 70°$) any further retained background window pixel must satisfy $BT_{3.9} > 270 \, K$.

The expanding background window starts at size 5×5 pixels, and expands by two in each direction until 65 % of its pixels are considered valid according to the aforementioned criteria (excluding the central 3×3 pixels). For more than 95 % of PFPs a 5×5 window is already sufficient to meet this criteria, but the window expands up to a maximum of 15×15 as necessary. In the very rare cases where this is still not sufficient, the PFP is coded as having "insufficient background pixels" for confirmation as an active

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fire ("Class 6") in the FRP-PIXEL Quality Product (Table 2). In all other cases, a series of statistical metrics derived from the correctly sized background window are used in a series of "spatial contextual" tests to confirm whether the PFP can be confirmed as a true fire pixel. These confirmatory tests are fully described in Roberts and Wooster

5 (2008), and remain unaltered in the operational FTA implementation and so are not detailed here. The tests rely on the assumption that the statistical average of the valid background window pixel signals is representative of the signal the central "PFP" would have had if it has not contained a fire, and we examined the appropriateness of this assumption by selecting random non-fire pixels from SEVIRI level 1.5 scenes, and re-

10 classifying them as PFPs such that their signals could be compared to those of their background windows (Fig. 11). Apart from pixels classed as "swamp" in the GLC2000 map, for 80 % of the cases examined the mean background window IR3.9 channel BT was within 1 K of the central "PFP" pixel $BT_{3.9}$, and was always within 2 K. For "swamp" pixels, which form a very small fraction of the SEVIRI disk, differences increased to

15 a maximum of 6 K, presumably due spatially varying percentage covers of water and land. Furthermore, the standard deviation of the background window IR3.9 channel spectral radiance was always larger than the actual difference between the central pixel and the window mean. Since the former provides a measure of the background window characterisation random error for use in the per-pixel FRP uncertainty speci-

20 fication (Sect. 6.1), this indicates the conservative nature of the resulting uncertainty estimate.

Based on the results of the background window spatial contextual tests, a PFP confirmed as a true fire pixel is coded as Class 1 in the Quality Product (Table 2), and has its FRP derived (Sect. 5). For confirmed fire pixels with a saturated IR3.9 channel

25 signal ($BT_{3.9} \geq 335$ K), FRP is still estimated but with adjustments for channel saturation (Sect. 6.2.1) and with the pixel is coded as Class 2 "FRP from saturated pixel". PFPs failing the spatial contextual tests altogether are coded as Class 7 "PFP but not confirmed as a fire pixel".

After this each confirmed fire pixel is given a detection confidence measure (0 to 1), based on the approach of Giglio et al. (2003) as described in Roberts and Wooster (2008).

4 FRP Derivation

4.1 Derivation of per-pixel FRP values

All confirmed active fires (Classes 1 and 2 in the FRP-PIXEL Quality Product) have their FRP estimated using the MWIR radiance method of Wooster et al. (2003, 2005). This requires quantification of the fires' contribution to the active fire pixels elevated IR3.9 channel signal, and bases this on the difference between the fire pixels' IR3.9 channel spectral radiance (L_f) and the mean spectral radiance (L_b) of the surrounding background window:

$$\text{FRP} = \frac{\pi \sigma A_n}{\tau_{\text{MWIR}} C_a \cos(\theta_v)} (L_f - L_b) \tag{16}$$

where L_f and L_b are expressed in $\text{mW m}^{-2}\,\text{sr}^{-1}\,(\text{cm}^{-1})^{-1}$, τ_{MWIR} is the atmospheric transmittance calculated for the SEVIRI IR3.9 channel, C_a ($\text{mW m}^{-2}\,\text{sr}^{-}\,(\text{cm}^{-1})^{-1}\,\text{K}^{-4}$) is a constant determined according to Wooster et al. (2003, 2005), θ_v is the view zenith angle (°), σ is the Stefan-Boltzmann constant ($\text{J m}^{-2}\,\text{sr}^{-1}\,\text{K}^{-4}$) and A_n is the SEVIRI ground pixel area at the sub-satellite point (km^2).

4.2 Method for FRP atmospheric correction

From first principles, Wooster et al. (2005) demonstrate that the primary atmospheric effect with regard to FRP derivation is the non-unitary MWIR atmospheric transmission (τ_{MWIR}), and that upwelling atmospheric path radiance and reflected downwelling atmo-

spheric radiance are neglectable due to their similarity at the fire pixel and surrounding background pixels, whose MWIR radiances are differenced in Eq. (16).

The appropriate value of τ_{MWIR} to use in Eq. (16) is complicated by the fact that the transmittance and fire-emitted spectral radiance signals are far from uniform across the SEVIRI's IR3.9 spectral bandpass. Figure 12 shows on the lhs y axis the SEVIRI IR3.9 band (Channel 4) relative spectral response function, along with the transmittance of a standard atmosphere across the same wavelength range. The impact of the strong CO_2 absorption band on overall atmospheric transmission upwards of $\sim 4.0\,\mu m$ can be clearly seen. Also apparent are the many other atmospheric absorption features present across the IR3.9 band, many of which depend on the atmospheric total column water vapour (TCWV) content. Figure 12 indicates that SEVIRIs IR3.9 band remains sensitive to MWIR radiation at wavelengths longer than 4.2 µm, though in fact no surface-emitted radiance reaches the sensor directly at these wavelengths due to CO_2 absorption (whose atmospheric concentration maybe further elevated close to fires). Also included in Fig. 12, plotted on the rhs y axis, is the bottom of atmosphere (BOA) spectral radiance emitted by a 310 K blackbody, along with the equivalent top of atmosphere (TOA) measure calculated after applying the estimated standard atmosphere transmittance estimated using MODTRAN 5 (Berk et al., 2005).

When selecting the appropriate atmospheric transmittance to derive a band-integrated TOA radiance signal from a BOA measure, it is quite common to use a band-averaged τ_{MWIR} (e.g. Qin and Karnieli, 1999). However, as can be seen in Fig. 12, this not fully appropriate with regard to SEVIRI's IR3.9 spectral band, across which the atmospheric transmittance and ground (and fire) emitted spectral radiance vary significantly. Specifically, across SEVIRI's IR3.9 band, atmospheric transmittance generally decreases with increasing wavelength, whereas upwelling spectral radiance generally increases. Converting the band-integrated TOA spectral radiance to a BOA measure simply using the mean τ_{MWIR} calculated across the IR3.9 spectral bandpass would therefore increase the contribution of the shorter wavelength TOA signal to the band-integrated BOA spectral radiance too much, and the longer wavelength signal too little.

This effect is more significant here than for narrowband channels such as the MODIS 3.95 µm Band 21, because SEVIRIs IR3.9 band has significant sensitivity in the CO_2 absorption region where MWIR atmospheric transmittance is at its lowest but the surface emitted signal is at its highest. Using a band-averaged τ_{MWIR} to convert the TOA radiance simulated in Fig. 12 to a BOA signal results in a latter estimate almost 10 % too low, even when the band-averaged transmittance includes consideration of the spectral response function weighting.

In simulations such as those shown in Fig. 12, the spectral shape of the surface emitted signal and the atmospheric transmittance spectrum are known, and this can be use to apply the correct transmittance at each observation wavelength. However, true SEVIRI IR3.9 observations do not actually resolve the spectral behaviour of the incoming signal, so this is not an option for real measurements. Therefore, the τ_{MWIR} to include in Eq. (16) is best calculated as an effective (or "pseudo") atmospheric transmittance, determined from pre-computed radiative transfer simulations of top-of-atmosphere (TOA) and bottom-of-atmosphere (BOA) fire pixel and background pixel spectral radiance difference signals:

$$\tau_{MWIR} = \frac{\left[\int_3^5 \widetilde{B(T_f)}^{TOA} - \int_3^5 \widetilde{B(T_b)}^{TOA} \right]}{\left[\int_3^5 \widetilde{B(T_f)}^{BOA} - \int_3^5 \widetilde{B(T_b)}^{BOA} \right]} \tag{17}$$

Where $\int_3^5 \widetilde{B(T)}$ indicates the spectral radiance calculated using the Planck function at brightness temperature T (Kelvin), convolved with the spectral bandpass of the SEVIRI IR3.9 band and integrated over the 3–5 µm spectral range, the subscripts f and b correspond to the fire pixel and the background pixel respectively, and the superscripts BOA and TOA indicate bottom- and top-of-atmosphere measures respectively.

For the operational LSA SAF processing chain generating the FRP-PIXEL products, Eq. (17) was used to generate a look-up-table (LUT) of τ_{MWIR} using the MODTRAN5 and RTMOM atmospheric radiative transfer models (Berk et al., 2005; Govaerts, 2006). Pre-computed values of τ_{MWIR} were derived, based on varying total column atmo-

spheric water vapour (TCWV) content (U_{H_2O}; varying between 0.5 and 60 kg m^{-2}), view zenith angle (θ_v), a range of standard atmospheres (tropical, mid-latitude summer, etc.), fire pixel (T_f) and background pixel (T_b) pixel integrated brightness temperatures (300–330 K and 290–320 K respectively), aerosol optical thicknesses, and atmospheric CO$_2$ and ozone column amounts. At the latitude/longitude location and view zenith angle (θ_v) of each confirmed active fire pixel identified by the FRP-PIXEL processing chain, τ_{MWIR} is retrieved from this LUT based on the TCWV content taken from ECMWF short-term forecasts available at 0.5° spatial resolution every 3 h. As an example, at the sub-satellite point ($\theta_v = 0$) for a typical U_{H_2O} of 20 kg m^{-2} and a mid-latitude summer atmosphere, Eq. (17) indicates τ_{MWIR} as 0.69 for use in Eq. (16), compared to 0.74 for the IR3.9 band-averaged value. During this process, the uncertainty in the effective τ_{MWIR} (σ_τ) is also specified for use in the uncertainly calculations described in Sect. 6, based on uncertainties in the ECMWF forecast of U_{H_2O}, other atmospheric parameter uncertainties (e.g. CO$_2$ mixing ratios), and the resulting variation in τ_{MWIR} coming from the radiative transfer calculations.

5 FRP uncertainty calculations and the MSG "special operations mode" obsevervation period

5.1 FRP uncertainty formulation

A full per-pixel FRP uncertainty (σ_{FRP}, MW) is specified at each detected active fire pixel in the FRP-PIXEL product, derived by combining the absolute uncertainties (σ_k) of the four terms (C_a, τ_{MWIR}, L_f and L_b) of Eq. (16):

$$\sigma_{FRP} = FRP\sqrt{\sum_{k=1}^{4} \sigma_k^2 \left(\frac{\partial FRP}{\partial k}\right)^2} \tag{18}$$

Where k represents the terms of Eq. (16) (C_a, τ_{MWIR}, L_f and L_b respectively) and where the absolute uncertainties (σ_k) in these are assumed uncorrelated. Solving for the partial derivatives in Eq. (18) gives:

$$\sigma_{\text{FRP}} = \text{FRP} \left[\left(\frac{\sigma_{C_a}}{C_a} \right)^2 + \left(\frac{\sigma_{\tau_{\text{MWIR}}}}{\tau_{\text{MWIR}}} \right)^2 + \left(\frac{\sigma_{L_b}}{L_f - L_b} \right)^2 + \left(\frac{\sigma_{L_f}}{L_f - L_b} \right)^2 \right]^{1/2} \quad (19)$$

where each term takes the following values:

σ_{C_a} is the variability in the C_a "FRP coefficient" ($\text{mW m}^{-2}\,\text{sr}^-\,(\text{cm}^{-1})^{-1}\,\text{K}^{-4}$) used in Eq. (16), which across the specified active fire temperature range of 650–1350 K equates to a (σ_{C_a}/C_a) value of $\sim 10\,\%$ (Wooster et al., 2005).

$\sigma_{\tau_{\text{MWIR}}}$ is the variability in calculated atmospheric transmissivity, specified in Sect. 5.2 and resulting from uncertainties in the TCWV and in other atmospheric parameters used in the radiative transfer modelling.

σ_{L_b} is the standard deviation of the background window pixels spectral radiance ($\text{mW m}^{-2}\,\text{sr}^{-1}\,(\text{cm}^{-1})^{-1}$), calculated as discussed in Sect. 3.5 and adjusted for the atmospheric pseudo transmittance (τ_{MWIR}).

σ_{L_f} is the uncertainty in the measured fire pixel spectral radiance ($\text{mW m}^{-2}\,\text{sr}^{-1}\,(\text{cm}^{-1})^{-1}$) resulting from a combination of (i) the SEVIRI sensors radiometric noise (σ_L), (ii) instances of IR3.9 band sensor saturation (σ_S), and (iii) influences from the pre-processing steps used to generate the SEVIRI level 1.5 data from the raw observations (termed here ε_p), for example the application of the FIR filter detailed in Sect. 3.5. These three contributions are represented by the three fractional terms of Eq. (20), where L_f remains as the measured radiance of the active fire pixel ($\text{mW m}^{-2}\,\text{sr}^{-1}\,(\text{cm}^{-1})^{-1}$) and S is its estimated adjusted radiance in the case of IR3.9 channel saturation:

$$\sigma_{L_f} = L_f \sqrt{\left[\left(\frac{\sigma_L}{L_f} \right)^2 + \left(\frac{\sigma_S}{S} \right)^2 + \varepsilon_p^2 \right]} \quad (20)$$

The "end of life" radiometric noise prediction of the SEVIRI IR3.9 channel is 0.17 K (Schmetz et al., 2002; Hewison and Muller, 2013), translating to $\sigma_L = 0.038\,\mathrm{mW\,m^{-2}\,sr^{-1}\,(cm^{-1})^{-1}}$ $(0.025\,\mathrm{W\,m^{-2}\,sr^{-1}\,\mu m^{-1}})$. To specify the remaining terms, a series of unique Meteosat-8 SEVIRI observations were made during the southern
5 African fire season, as discussed in the following section.

5.2 Meteosat-8 special operations mode: data collection and analysis

Between 3–7 September 2007, Meteosat-8 was operated in "rapid scan" mode, imaging every four minutes between 3° N and 33° S, with a cycle of additional adjustments:

 i. Operation of the IR3.9 channel in "low gain" mode, allowing non-saturated mea-
10 surements up to 375 K.

 ii. Alteration of the Meteosat Main Detection Unit (MDU) standard SEVIRI Finite Impulse Response (FIR) digital filter coefficients seen in Fig. 9 from a Sinc function to a 1 pixel wide rectangular "top-hat" function, allowing the original "unfiltered" observations to be transmitted to the Primary Ground Station for use in generating
15 a "special" SEVIRI level 1.5 dataset.

Table 3 provides the full details of how Meteosat-8 was configured during this "Special Operations" period. This aimed at both assessing both the individual uncertainty terms in Eq. (20), and their aggregate effect. Near-simultaneous observations from the normally operating Meteosat-9 were aquired for comparison.

20 ### 5.2.1 Effect of IR3.9 band saturation

SEVIRI is a 10-bit sensor saturating at DN 1023. When in standard operating mode, this equates to an IR3.9 channel brightness temperature ($BT_{3.9}$) of just over 335 K ($\sim 3.6\,\mathrm{mW\,m^{-2}\,sr^{-1}\,(cm^{-1})^{-1}}$). Roberts and Wooster (2008) reported that IR3.9 saturation normally occurs in no more than a few percent of the level 1.5 active fire pixels,

coded as Class 2 in the FRP-PIXEL Quality Product (Table 2). Although such pixels share the same $BT_{3.9}$, application of Eq. (16) would not necessarily give them the same FRP, since their FRP depends also on the background window spectral radiance, the pixel area (and thus view zenith angle; θ_v) and atmospheric pseudo transmittance.

5 Around the SSP, IR3.9 saturation occasionally occurs at FRPs as low as 45 MW, if the fire is burning upon a particularly warm daytime background (≥ 330 K), but more typically at ~ 250 MW. At locations further from the SSP, FRPs more than double this can be measured without saturation. Our primary aim with this part of the study was to determine which FRP (S) to record at saturated IR3.9 pixels, and to specify their un-

10 certainty (σ_s) for use in Eq. (20). Recently Barnie et al. (2015) tackled a similar problem with respect to volcanic thermal features using SEVIRI.

We first explored the impact of the level 1.0 to level 1.5 conversion procedures conducted at the IMPF. Here, SEVIRI data are normally geometrically resampled using a function that includes some interpolation of pixel values (e.g. bi-cubic splines, as shown

15 in Fig. 1c and d). Our comparisons of SEVIRI level 1.0 and 1.5 imagery (e.g. Fig. 13), indicated that IR3.9 saturation is actually more prevalent prior to this resampling, which has the effect of smearing fire pixel signals in a similar manner to that shown previously in Fig. 8. To quantify this effect, we use the Meteosat-8 "special operations" data that included a low-gain IR3.9 operation (Table 3). When the IMPF used a nearest neighbour

20 geometric resampling scheme on the level 1.0 data, rather than the standard resampling scheme, the resulting level 1.5 data showed not a single saturation event, with the highest IR3.9 signal being $6.7 \, \mathrm{mW\,m^{-2}\,sr^{-1}\,(cm^{-1})^{-1}}$ (373 K) and an FRP of 1989 MW (Eq. 16 at a θ_v of 14°). Figure 14 shows the frequency distribution of per-pixel FRP recorded at the active fire pixels detected in the level 1.5 data, which would have been

25 saturated under standard SEVIRI operation. Artificially capping the IR3.9 brightness temperatures of these pixels at the standard 335 K saturation temperature and recalculating their FRP using Eq. (16) allowed for a FRP comparison of these "simulated saturated" data to the actual unsaturated (low-gain) observations. Not unexpectedly, the greatest impact of IR3.9 band saturation occurs near the peak of the typical fire

diurnal cycle seen in Fig. 3, when around 5 % of the level 1.5 pixels would have been saturated under "standard" operations and where total southern African FRP would consequently be underestimated by around 13 %. At night these values alter to a maximum of 4 and 5 % respectively, and since regional FRP at night is typically very low (Fig. 3) the absolute amount of FRP underestimation at night appears rather negligible.

We use the statistical distribution of FRP shown in Fig. 14, and the equivalent distribution derived from our "simulated saturated" data, to provide a statistical adjustment to the FRP values of pixels coded as Class 2 in the FRP-PIXEL Quality Product ("FRP estimated but from a saturated IR3.9 measurement"; Table 2). The appropriate values for the adjusted FRP was determined by identifying a new IR3.9 band spectral radiance value for use at saturated pixels (specified as S and the associated uncertainty σ_S in Eq. 20) and also used to replace the value of L_f in Eq. (16). Due to the non-normal nature of the distribution shown in Fig. 14, S and σ_S were based on the median ($4.08\,\mathrm{mW\,m^{-2}\,sr^{-1}\,(cm^{-1})^{-1}}$) and median absolute deviation from the median ($0.49\,\mathrm{mW\,m^{-2}\,sr^{-1}\,(cm^{-1})^{-1}}$) of the IR3.9 spectral radiance, rather than the mean and standard deviation. Figure 15 shows the median recorded FRP of the pixels from Fig. 14, stratified by θ_v (intervals 25 to 30 and 30 to 35° contain the vast bulk (79 %) of the data). Since pixel area and atmospheric transmittance increase with θ_v, the FRP of pixels that would saturate under standard operating conditions generally increases with view zenith angle (θ_v). For each of these active fire pixels, which would have saturated under standard SEVIRI operations, replacing their spectral radiance with S and specifying the uncertainty σ_S gives a "predicted" median FRP for each θ_v interval that is a reasonable fit to the actually observed distribution calculated using the unsaturated IR3.9 observations.

5.2.2 Impact of SEVIRI level 1.0 to 1.5 conversion

Raw SEVIRI data undergoes pre-processing prior to its conversion to level 1.5 (Fig. 1c and d and Sect. 2.2). To assess further the impacts of this pre-processing

we again used the "Special Operations" Meteosat-8 data, specifically that when the onboard and on-ground processing chain of SEVIRI was altered to replace the Sinc function FIR filter (Fig. 9a) with a simple top-hat rectangular filter of single pixel width, and where the level 1.5 data were delivered using both the interpolated and nearest neighbour geometric resampling schemes. Meteosat-8 and -9 SEVIRI level 1.5 "Standard Mode" data full disk data intercomparisons were undertaken first to elucidate initial differences between the two sensors. Using simultaneous observations of over 35 000 active fire pixels, Meteosat-8 was found to measure IR3.9 spectral radiances on average 1.0 ± 7.7 % (mean $\pm$ SD) lower than Meteosat-9 (Fig. 16), with the small bias mostly likely resulting from the fact that Meteosat-9 was at the time positioned 3.4° further West than Meteosat-8, changing the view zenith angle and ground pixel area. The variability most likely stems from the different sub-pixel positions of the fires within the two sets of imagery, as illustrated recently by Freeborn et al. (2014c) for MODIS. The degree of difference between the Meteosat-8 and -9 observations altered as the rapid-scan and "special operations mode" Meteosat-8 data were substituted, with the observations now being made approximately 1 min apart due to the different scanning schemes used on the two satellites (Fig. 16). From these comparisons, we estimated the separate uncertainty contribution from the measurement time-differences and the differing data processing chains, and determined the uncertainty impact of the level 1.0 to level 1.5 processing chains (ε_p) as 0.084 (8.4 %) for use in Eq. (20).

For illustration of the impact that different SEVIRI pre-processing operations can have on the active fire data, Fig. 17 includes comparisons of Meteosat-8 data processed using the standard FIR (Sinc) and top-hat filters, and nearest neighbour and interpolation (bi-cubic) geometric resampling schemes. The top hat filter allows lower FRP active fire pixels to be detected, giving a lower minimum total scene FRP than is obtained when applying the standard FIR-filter (which "smears" out fire pixel radiances as detailed in Sect. 3.5). The geometric resampling scheme used also impacts total scene FRP to a greater extent when the FIR filter is applied, with larger impacts for scenes containing only a relatively few active fire pixels having lower FRP (upon

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whose detectability the filter selection will impact most strongly). Further investigation shows that the radiometric uncertainty of the active fire pixel radiance is the largest contributor to the overall FRP uncertainty defined by Eq. (19), and that consideration should be given to optimising SEVIRI level 1.0 to level 1.5 pre-processing operations with respect to active fire data in order to minimise uncertainty.

6 LSA SAF SEVIRI FRP-GRID product

Just as with any active fire detection algorithm, the ultimate performance of the FTA algorithm is limited by the characteristics of the SEVIRI level 1.5 data (Wooster et al., 2013). Whilst the analysis of Sect. 5 shows that some optimisation of the IMPF level 1.5 data pre-processing chain could still be made for the active fire application, when viewing the same ground area at the same time, MODIS (with a higher spatial resolution and higher MWIR band saturation limit) will generally always offer a better opportunity to detect the true regional-scale FRP of landscape-scale fires than will SEVIRI. However, apart from at high latitudes, MODIS only views a particular ground region a few times per day, whereas SEVIRI provides 96 observations a day to fully sample the fire diurnal cycle (e.g. Roberts et al., 2009a). Nevertheless, a comparison of the frequency-magnitude distribution of concurrent and collocated SEVIRI and MODIS FRP observations indicates the notable biases of SEVIRI (Fig. 18). SEVIRI's statistical distribution of measured per-pixel FRP ($\mathcal{H}$) is right skewed, and can be divided into three broad regimes. Between $\mathcal{H}_L$ and $\mathcal{H}_U$, the distribution follows a power-law, with SEVIRI detecting fewer active fire pixels with increasing FRP owing to the true rarity of extreme (high FRP) fire behaviour on the landscape. In the lower regime (below $\sim 40\,\mathrm{MW}$), $\mathcal{H}$ deviates from this power-law as the performance of the FTA algorithm applied to SEVIRI data is increasingly limited by the thermal signal emitted by the subpixel combustion components becoming so diluted that it can no longer be statistically distinguished from that of the ambient background and many lower FRP active fire pixels remain undetected. Roberts et al. (2015) provide a full assessment of this

effect using scene-to-scene comparisons between SEVIRI FRP-PIXEL products and MODIS active fire data. Finally, above $\mathcal{H}_U$ the statistical distribution of SEVIRI's per-pixel FRP distribution suffers from right hand truncation due to IR3.9 band saturation, though in the final FRP-PIXEL product this is adjusted for using the methods detailed in Sect. 6.2.1.

The above issues lead to a general underestimation of regional-scale FRP totals measured by SEVIRI when compared to those simultaneously measured by MODIS, as demonstrated for example by Roberts and Wooster (2008) and Roberts et al. (2015). To provide adjustments for this underestimation, and for varying cloud cover, whilst maintaining a temporal resolution still significantly higher than that offered by polar orbiting systems, is the role of the SEVIRI Level 3 FRP-GRID product. The product combines information contained within all FRP-PIXEL product files collected each hour, and delivers a cloud-cover and bias-adjusted, spatio-temporal full-disk summary product at a 5°, 1 h^{-1} resolution (Fig. 19).

Freeborn et al. (2009) indicated that, in general, when viewing African areas simultaneously, MODIS measures on average around twice the FRP measured by SEVIRI. However, large regional and temporal variations exist, and Freeborn et al. (2014a) recently demonstrated that over smaller 1° areas within a single country (in this case the Central African Republic, one of the most fire-affected African countries) SEVIRI's active fire error of omission with respect to MODIS varies between 25 and 74 % (depending on the locations fire regime), causing a similar variation in the degree of FRP underestimation. It is clear from such analysis that the bias-adjustment factors used in the FRP-GRID product are required to vary spatially, and the necessary factors were derived using a set of coincident SEVIRI and MODIS active fire observations collected between May 2008 and May 2009, with the MODIS FRP measures atmospherically corrected using the same scheme as developed for SEVIRI (Sect. 5.2). SEVIRI active fire pixels were accumulated over one hour to match the temporal resolution of the FRP-GRID product, and to achieve a sufficient active fire pixel sample size over this duration the matching MODIS and SEVIRI active fire detections were accumulated

within 5° grid cells, whilst to minimize MODIS edge-of-scan effects (Freeborn et al., 2009, 2011, 2014b) only MODIS data within the centre two thirds of the swath were used. Half the resulting data were used as the training dataset, and half for the subsequent product performance evaluation reported in Roberts et al. (2015). Figure 20 illustrates the methodology, with the summed atmospherically corrected FRP measured by MODIS within each 5° grid cell ($\sum FRP_G$) related to that measured by SEVIRI using:

$$\sum FRP_G = \alpha_{ROI} \left(\frac{1}{n} \sum_{t=1}^{n} \sum FRP_{SEVIRI,t} \right)^{\beta_{ROI}} \tag{21}$$

where the value in parenthesis on the right hand side represents the atmospherically corrected sum of FRP measured by SEVIRI in the 5° cell averaged over the n preceding timeslots available in one hour (where $n = 4$, typically) and the factors α and β are power law parameters calculated separately for each of the four LSA SAF geographic regions shown in Fig. 2. Equation (22) therefore converts aggregate SEVIRI-derived FRP measures into that which would have been measured by MODIS when viewing the area within the centre 2/3rds of its swath. The exponent β was functionally intended to allow for the fact that SEVIRI-to-MODIS ratios of FRP are generally lower during periods of reduced fire activity (Freeborn et al., 2014a). However, the predictive abilities of this formulation proved to be statistically no more skilful than a linear formulation, so β was fixed at 1.0 and α derived using a weighted least squares linear best fit to the median values of the training dataset (Fig. 20). Final values of α used in the FRP-GRID product are shown in Table 5, and since the value for the European LSA SAF region was found statistically insignificantly different from that of North Africa it was assigned the same value since many more fires were available in North Africa to derive a more robust relationship.

The uncertainty (σ_G) on the derived gridded FRP was specified as:

$$\sigma_G = \sqrt{\sum_{k=1}^{n} \left(\frac{\partial G}{\partial k}\right)^2 \sigma_k^2} \qquad (22)$$

where k represents the terms in Eq. (22) contributing to the uncertainty in G, namely the coefficient α and the mean FRP measured by SEVIRI in the grid cell over a one hour summation period. Expanding this expression:

$$\sigma_G = G \sqrt{\left(\frac{\sigma_{\alpha_{\text{ROI}}}}{\alpha_{\text{ROI}}}\right)^2 + \left(\frac{\sqrt{\sum_{i=1}^{p} \sigma_{\text{FRP},i}^2}}{\sum_{t=1}^{n} FRP_{\text{SEVIRI},t}}\right)^2} \qquad (23)$$

where $\sigma_{\alpha_{\text{ROI}}}$ is the uncertainty in the regression coefficient (Table 5), p is the number of active fire pixels detected by SEVIRI in the grid cell during the hour, and $\sigma_{\text{FRP},i}$ is the uncertainty associated with the individual active fire pixel i given by Eq. (19) and stored in the FRP-PIXEL products.

Whilst accumulating SEVIRI active fire pixels detected during each hour, the algorithm used to create each FRP-GRID product also adjusts the summed FRP to account for cloud cover, which may have obscured fires, by normalising by the hourly-averaged cloud cover fraction. This procedure is similar to that performed for MODIS by Giglio et al. (2006) and in Global Fire Assimilation System (GFAS) of the CAMS (Kaiser et al., 2012). It is important to stress that the bias and cloud-cover adjustment procedures implemented during FRP-GRID processing are purely statistical in nature, and are aimed at reducing the impact of regional scale biases occurring when data are accumulated over multiple time-slots. Importantly, the cumulative FRP detected by the original FRP-PIXEL products is obtainable from the FRP-GRID product, so that the user can remove, adjust, or apply their own bias corrections should they prefer. Many users may wish simply to focus on use of the FRP-PIXEL product itself.

7   LSA SAF FRP product access and file structure

7.1   Product data access

Users can access the LSA SAF FRP-PIXEL and FRP-GRID products from the following three sources:

i. In real time via EUMETCast using very low-cost Digital Video Broadcast (DVB-S2) technology to receive multiple EO datasets and products (http://www.eumetsat.int/website/home/Data/DataDelivery/EUMETCast/index.html). EUMET-Cast primary transmissions is via Eutelsat's Eurobird-9 satellite (in Ku band) and can be received across most of Europe, and is relayed via Eutelsat's Atlantic Bird 3 (in C band, covers Europe and Africa) and SES New Skies' NSS-806 (in C band, covers both Americas). EUMETCast corresponds to the EUMETCAST contribution to the wider GEONETcast service, a near real time, global network of satellite-based data dissemination systems designed to distribute space-based, airborne and in situ data, metadata and products, led by Eumetsat in Europe (services in Europe, Africa and South America), the Chinese Meteorological Administration (CMA) in the Asia-Pacific region (FengYunCast), and NOAA in the Western Hemisphere (GEONETCast Americas). FRP-PIXEL product dissemination on GEONETcast is described at www.eumetsat.int/website/home/Data/Products/index.html.

ii. In real time via FTP. In this case users should contact the LSA SAF (helpdesk.landsaf@meteo.pt) to register for an automatic push or pull file service.

iii. Offline via FTP or website, via registration at the LSA SAF (http://landsaf.meteo.pt/). Data are free of charge but registration is again required.

An FRP product Algorithm Theoretical Basis Document (ATBD), User Manual, and Validation Report are also available from the LSA SAF web site.

7.2 FRP-PIXEL product files

All FRP products from the aforementioned sources are stored in the HDF5 file format. A new FRP-PIXEL product (both the List and Quality Product files) is delivered every 15 min for each of the four LSA SAF geographic regions, with file names constructed according to the following convention:

HDF5_LSASAF_MSG_FRP_ListProduct_⟨Area⟩_YYYYMMDDHHMM.h5

HDF5_LSASAF_MSG_FRP_QualityProduct_⟨Area⟩_YYYYMMDDHHMM.h5

Where ⟨Area⟩, YYYY, MM, DD, HH and MM respectively denote the geographical region (Euro, NAfr, SAfr, SAme), and the year, month, day, hour and minute of the data acquisition. The time specified in the filename refers to the relevant image acquisition start time (with SEVIRI scanning South to North as described in Sect. 2).

Since the FRP-PIXEL List Product file stores outputs (e.g. FRP, FRP uncertainty, active fire pixel location etc.), algorithm information (e.g. size of the background window) and input data (e.g. IR3.9 and IR10.8 brightness temperatures) at the pixel locations of detected active fire pixels only, it is typically only some kilobytes in size. The full list of variables is detailed in the FRP Product User Manual (PUM) available on the LSA SAF web site (landsaf.meteo.pt) and many users will be content to use only this (very small) product file. The FRP-PIXEL Quality Product files are significantly larger (~ 0.05–0.2 Mb), since they store values at all SEVIRI pixels whether a fire is detected or not, but the additional information (e.g. on why an active fire was not recorded at a certain ground locations) can be extremely useful, for example for emissions modelling and when comparing to other datasets e.g. (Freeborn et al., 2014a; Georgiev and Stoyanova, 2013) and is used with the FRP-based Global Fire Assimilation System (Kaiser et al., 2012). Both List and Quality Product files are mandatory inputs to the algorithm that generates the FRP-GRID product.

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7.3 FRP-GRID product files

Every hour the LSA SAF processing chain generates one FRP-GRID output file (~ 850 Kb) for the entire Meteosat disk, according to the following name convention:

HDF5_LSASAF_MSG_FRP_Frp_Grid_Global_YYYYMMDDSSEE.h5

where YYYY, MM, DD, SS and EE respectively denote the year, the month, the day, the starting and end hour of the analysed period.

Table 4 indicates the content of each FRP-GRID file, where the value of each variable is obtained according to the following formula:

Real_value = Stored_value/Scale_factor

Where the Stored_value is the two byte integer recorded in the FRP-GRID product file. An example of the content of an FRP-GRID product file was shown as Fig. 19. The value stored in each grid cell also includes a code for where no fires have been found, either due to "input data missing" (327671) or "no detected fire in the grid cell" (0).

8 Product comparison and trend analysis

8.1 Comparison to other SEVIRI active fire products

Since Roberts et al. (2005) published the first Meteosat SEVIRI active fire detection algorithm, the LSA SAF FRP-PIXEL product has been joined by other active fire studies using SEVIRI data (e.g. Calle et al., 2006; Amraoui et al., 2010; Roberts and Wooster, 2014), some of which have resulted in routinely generated datasets (e.g. Carvalheiro et al., 2010; Calle et al., 2011). Roberts et al. (2015) performs a detailed performance evaluation of the FRP-PIXEL and FRP-GRID products in comparison to both the MODIS Active Fire and Thermal Anomaly Products and a series of alternative

SEVIRI-derived fire products. Here we briefly demonstrate the large differences that can exist between geostationary active fire products generated from even the same SEVIRI level 1.5 source data, focusing on the FRP-PIXEL and WF-ABBA products. The latter are described by Gonzalo et al. (2009) and are generated using the long-standing WF-ABBA algorithm originally developed for use with the GOES imager (Prins et al., 1998). Figure 21 shows the fire diurnal cycles resulting from simultaneous FRP-PIXEL and WF-ABBA products, and since we know that the FRP-PIXEL product undercounts active fire pixels below the $\mathcal{H}_L$ threshold of Fig. 18, we show both the total FRP-PIXEL fire pixel count at each timeslot, and that from pixels with FRP > 40 MW and > 50 MW. For WF-ABBA we show four diurnal cycles calculated using the different classes of active fire pixel present in the WF-ABBA record: all detections (which is the entire set of active fire pixels identified); filtered detections (which has certain active fire pixels considered less likely to be true active fires removed, primarily those identified only once as an active fire in 24 h); and the set of filtered detections corresponding to only high (Flag 0 to 3) and high-to-medium (Flag to 4) possibility fires. As can be seen, for many imaging slots the operational FTA algorithm used to generate the FRP-PIXEL product detects around twice as many active fire pixels as does the WF-ABBA algorithm, even when using the "all detections" (unfiltered) WF-ABBA data. The unfiltered WF-ABBA data also appear to show some potentially unrealistic temporal patterns, for example in (b) during the early morning of 31 August 2014 a local peak in fire pixel count is present at 7.00 a.m. LT and is quite possibly caused by glint effects. This local peak is reduced and finally removed by the more stringent WF-ABBA filtering, though this filtering also lowers the number of overall fire pixels recorded. Whilst active fire pixels below threshold $\mathcal{H}_L$ of Fig. 18 are certainly undercounted by the FRP-PIXEL product, the FRP-PIXEL data shown here indicates that there remain substantial numbers of active fire pixels successfully detected below 50 MW by the FRP-PIXEL product, and to a lesser extent also below 40 MW, and that this sensitivity to the lower FRP component of the targeted fire regime is important when gaining as full a picture of the daily diurnal cycle as possible from geostationary orbit. Roberts et al. (2015) includes a much

more complete active fire product intercomparison and performance evaluation, but the limited comparison provided here serves to indicate both the highly sensitive nature of the FTA algorithm, and its ability to screen out early morning sunglint induced false alarms without recourse to temporal filtering. Since fires in African landscapes quite often show up in a given pixel only once in a 24 h period (either having moved into a neighbouring pixel as the fire spreads across the landscape, or being detected only occasionally due to the low FRP nature of the fire itself), the ability to perform sensitive and accurate active fire detection without having to filter out fire pixels detected only once during the day offers a useful capability.

8.2 Comparison to MODIS and analysis of active fire trends

The LSA SAF Meteosat SEVIRI FRP products are available since 2008, and in 2015/16 a reprocessing is planned that will generate over a decade of data starting from 2004. Baldassarre et al. (2015) and Roberts et al. (2015) show how these products can be used to support fuel consumption rate estimation for use in high temporal resolution atmospheric modelling of smoke plume dispersion, whilst Freeborn et al. (2014a, c) demonstrate both their complimentarity to MODIS and their ability to discriminate trends in fire behaviour.

In terms of complimentarity with MODIS active fire data, and the fire detectability possible with SEVIRI, Fig. 22 shows the map of (a) MODIS MOD14/MYD14 and (b and c) SEVIRI FRP-PIXEL active fire detections collected over a two week period across a $15° \times 15°$ domain covering Central African Republic (CAR). Figure 22b shows the set of SEVIRI active fire detections made at the MODIS overpass times (within ±6 min of it), and Fig. 22c all SEVIRI detections. The ground distance Δd between the centre of each MODIS fire pixel and the centres of all contemporaneously detected SEVIRI fire pixels was calculated, and the minimum used to identify the nearest temporally coincident SEVIRI active fire pixel for each MODIS active fire pixel. Results indicate that 30, 42, and 53 % of the MODIS active fire pixels had a SEVIRI counterpart detected at the same time and located within 3, 4, and 5 km, respectively. Only 10 % of the

MODIS active fire pixels had the spatially closest, simultaneously detected SEVIRI active fire pixel located more than 20 km away. The same proximity analysis was then repeated, but expanded to include the full set of SEVIRI active fire pixels detected at all timeslots (i.e. those mapped in Fig. 22c). In this case, the vast majority (83, 91, and 95 % respectively) of the MODIS fire pixels had a SEVIRI active fire pixel located within 3, 4, and 5 km. Figure 23a confirms the reverse, that SEVIRI fire pixels detected in each timeslot almost all have a MODIS pixel within 4 km of it (detected anytime within these two weeks). Furthermore, our proximity analysis indicates that fewer than 1 % of the MODIS active fire pixels did not have a SEVIRI counterpart within 20 km. This confirms that, although the FRP-PIXEL product fails to detect a significant proportion of the active fire pixels detected by MODIS when both sensors view the same area at the same time, due to the fall off in active fire detectability below the $\mathcal{H}_L$ threshold shown in Fig. 18, the SEVIRI FTA algorithm does ultimately detect the vast majority of MODIS-detected fires at some earlier or later stage of their lifecycle.

Figure 23b indicates the time difference within which the matching SEVIRI and MODIS detections of the same fire generally occur (with the matched detections taken as the SEVIRI detection with the minimum time difference to the MODIS detection and located within 4 km of it). Overall, 70, 79, and 84 % of the collocated MODIS fire pixels were detected by SEVIRI within 12, 24 and 36 h respectively of the best matched MODIS observation, with the SEVIRI detection more commonly being after the MODIS detection, but quite often occurring before. The 15 min repeat cycle of SEVIRI is well suited for capturing temporal fluctuations in fire behaviour (Roberts et al., 2009a), and is able to capitalize on those opportune moments when a fire does become detectable, notwithstanding the relatively coarse pixel sizes available from geostationary orbit.

Figure 24 shows the full time-series of FRP-PIXEL data over the Central African Republic (CAR), and the mean FRP of the detected active fire pixels shows a periodic variability across the fire season, with extremely low FRP fire pixels dominating outside of the main period of fire activity. Biomass burning is spatially very extensively in the CAR (Fig. 22; Eva and Lambin, 1998; Bucini and Lambin, 2002; Freeborn et al.,

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2014a, c), and from Fig. 24 it is apparent that trends and patterns seen in the active fire pixel count and total FRP are similar, with a clear seasonal cycle and some suggestion of a generally decreasing trend in fire activity in recent years. Freeborn et al. (2014c) recently identified a matching decreasing trend in fire activity metrics across the CAR using a decade of MODIS data, attributing these to a shift in the timing, intensity, and extent of fire activity.

In terms of the FRP-PIXEL products ability to provide information relevant to individual large fire events, Fig. 25 shows an example of high FRP (≥ 200 MW per pixel) fires detected across the Mediterranean in July 2009. At this time a series of wildfires were burning across France, Greece, Italy, Spain, and Turkey (Pausas and Fernández-Muñoz, 2012). Selecting the single fire pixel that corresponds to the intense wildfire that burned close to Sierra Cabrera (SE Spain), the timeseries shows that on 14 July this fire expanded and was burning with a fuel consumption rate of 221 kg s^{-1} (588 MW FRP and the conversion factor of Wooster et al., 2005), before dying out on the 15 July, matching well with news reports of the time (http://en.wikipedia.org/wiki/2009_Mediterranean_wildfires). The same reports indicate that on 23 July the fire flared again, and this second event is also observed in the FRP-PIXEL product time-series, with the FRP reaching almost the same heights seen in the initial blaze (Fig. 25). FRE-estimated total fuel consumption is estimated to have been in excess of 11 thousand tonnes.

9 Summary and conclusion

Satellite-based estimates of FRP, including from the geostationary Meteosat satellites, are increasingly used to support regional and global biomass burning emissions calculations (Remy and Kaiser, 2014; Roberts et al., 2011; Vermote et al., 2009; Zhang et al., 2012; Turquety et al., 2014; Baldassarre et al., 2015). We have provided a detailed description of the algorithms, formats, and information content of the operational SEVIRI FRP products available from the EUMETSAT Land Surface Analysis Satellite

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Applications Facility (LSA SAF), both the FRP-PIXEL product (3 km spatial resolution, every 15 min), and the spatio-temporal summary FRP-GRID product that includes bias adjustments for cloud cover and SEVIRI's inability to detect the lowest FRP fire pixels.

We show that SEVIRI can detect active fire pixels with an FRP down to around 20 MW with the operational geostationary Fire Thermal Anomaly (FTA) algorithm described here, but that active fire pixels with FRP lower than ∼ 40 MW are typically undercounted, hence the requirement for the bias-adjustment factors included in the FRP-GRID product. We show how FRP and FRP uncertainty are derived, and we use scene simulation and analysis of Meteosat-8 "special operations" data to demonstrate that certain of the data pre-processing procedures applied onboard the MSG satellites or in the EUMETSAT Image Processing Facility (IMPF), are non optimum for the active fire application. Standard cloud masking procedures also need to be optimised, since they can otherwise mask smoke, or even active fires, as cloud. We recommend consideration of these issues when designing the pre-processing and cloud masking chains to be used with Meteosat Third Generation, whose sensor has a dedicated low gain MWIR channel to support active fire applications (Just et al., 2014). Comparisons to the WF-ABBA SEVIRI product indicates strong performance of the FTA algorithm, which detects substantially more active fire pixels, both in any particular SEVIRI timeslot and over the full diurnal cycle. The LSA SAF FRP products are therefore well suited to prescribing the typical diurnal cycle of biomass burning regions (Turquety et al., 2014; Andela et al., 2015), and for estimating high temporal resolution wildfire smoke emissions for atmospheric modelling (Baldassarre et al., 2015; Roberts et al., 2015).

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Table 1. SEVIRI spectral bands.

Channel No.	Spectral Band (µm)	Band Characteristics (wavelength, µm) Centre	Min	Max	Main Observational Applications
1	VIS0.6	0.635	0.56	0.71	Surface, clouds, wind fields
2	VIS0.8	0.81	0.74	0.88	Surface, clouds, wind fields
3	NIR1.6	1.64	1.50	1.78	Surface, cloud phase
4	IR3.9	3.90	3.48	4.36	Surface, clouds, wind fields
5	WV6.2	6.25	5.35	7.15	Water vapour, high level clouds, atmospheric instability
6	WV7.3	7.35	6.85	7.85	Water vapor, atmospheric instability
7	IR8.7	8.70	8.30	9.1	Surface, clouds, atmospheric instability
8	IR9.7	9.66	9.38	9.94	Ozone
9	IR10.8	10.80	9.80	11.80	Surface, clouds, wind fields, atmospheric instability
10	IR12.0	12.00	11.00	13.00	Surface, clouds, atmospheric instability
11	IR13.4	13.40	12.40	14.40	Cirrus cloud height, atmospheric instability
12	HRV	Broadband (about 0.4–1.1 µm)	Surface, clouds		

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Table 2. QUALITY FLAG coding stored within the FRP-PIXEL Quality Product files.

Name	Value	Class	Reason
FRP_OUTSIDE_ROIS	−1	FRP NOT Estimated	Pixels that are in the LSA SAF regions (Euro, NAfr, SAfr, SAme) but not in the internal windows considered for processing
FRP_APL_NOTPOT	0	FRP NOT Estimated	Not classed as a potential fire pixel (see Sect. 3.2).
FRP_APL_FRP	1	FRP Estimated	Successful active fire pixel detection confirmed, with FRP estimation derived from unsaturated 3.9 µm channel signal.
FRP_APL_FRP_SAT	2	FRP Estimated (but from saturated IR3.9 pixel)	Successful active fire pixel detection confirmed, with FRP estimation derived with a saturated 3.9 µm channel signal. (see Sect. 6.2).
FRP_APL_CLOUD	3	FRP NOT Estimated	The pixel is classed as cloud contaminated – active fire pixel detection not attempted.
FRP_APL_SUNG	4	FRP NOT Estimated	The pixel is classed as being potentially strongly affected by sun glint due to the sun-land-sensor geometry – active fire detection was not attempted.
FRP_APL_SUNGRATIO	5	FRP NOT Estimated	Possible sunglint due to the SUNGRATIO test failing (see Sect. 3.4)
FRP_APL_NOBCK	6	FRP NOT Estimated	Potential fire pixel detected, but it was not possible to meet the criteria for background window temperature definition, so no active fire could be confirmed.
FRP_APL_BCKNOT	7	FRP NOT Estimated	Potential fire pixel detected – but with a signal insufficiently above that of the background window to be confirmed as a true active fire pixel.
FRP_APL_CLOUDEDGE	8	FRP NOT Estimated	No active fire detection tests were possible because the pixel is close to a pixel classed as water or as cloudy (see Sect. 3.2).
FRP_APL_BADINPUT	9	FRP NOT Estimated	Some input files are not complete or were corrupted.
FRP_APL_NOTPROC	254	FRP NOT Estimated	The pixel has not been processed.

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Table 3. Details of the Meteosat-8 "Special Operations", where SEVIRI observations over Southern Africa were made at a temporal resolution of four minutes under different onboard pre-processing characteristics. All SEVIRI data were provided by the IMPF geometrically located on the SEVIRI projection grid in two ways, using a nearest neighbour scheme and the interpolation scheme.

Date (Sep 2007)	Digital filter applied to SEVIRI observations onboard the Meteosat-8 satellite	IR3.9 Band Saturation Temperature (K) resulting from standard or "low gain" setting
3	Top-hat	335
4	Sinc Function	375
5	Top-hat	375
6	Sinc Function	335
7	Top-hat	335

Table 4. Datasets stored within the FRP-GRID product file at each 5° grid cell (as a 2-D matrix).

Variable	Meaning	Units	Scale factor	Range
GFRP	Grid cell atmospherically corrected, bias-adjusted FRP. Calculated as an hourly average, with the bias-adjustment factors of Table 5 and the cloud cover correction applied.	MW	0.1	> 0
GFRP_RANGE	Max–min difference in the FRP values recorded in the grid cell within the 1 h period	MW	1	> 0
GRIDPIX	Number of SEVIRI pixels in the 5.0° grid cell used for the estimation of the BURNTSURF parameter	p.n.	1	> 0
NUMIMG	Number of SEVIRI images used for the temporal average (max = 4)	p.n.	1	>=0
NUMFIRES	Mean number of fire pixels detected in the grid cell during the 1 h period	p.n.	100	>=0
BURNTSURF	Percentage of pixels in the grid that had an active fire detection within them in the 1 h period	p.n.	100	[0, 100]
LATITUDE	Latitudinal centre of the grid cell	Deg	100	[−90, 90]
LONGITUDE	Longitudinal centre of the current grid cell	Deg	100	[−180, 180]
GFRP_CLOUD_CORR	Factor accounting for cloud coverage in the 5.0° grid box, averaged over 1 h (1 means cloud free). Divide the GFRP value by this value to remove the cloud cover correction.	p.n.	100	[0, 1]
ATMTRANS	Mean atmospheric transmittance in the 5.0° grid cell, taken from the contributing FRP-PIXEL products	p.n.	10 000	[0, 1]
GFRP_ERROR	Total error associated with GFRP, taking into account FRP_UNCERTAINTY from the FRP-PIXEL List Product, as well as the errors associated with the region-specific adjustment factors	MW	1	> 0
GFRP_ERR_FRP	Error in GRP attributed solely to FRP_UNCERTAINTY in the FRP-PIXEL List Product	MW	1	> 0
GFRP_QI	Quality indicator associated with the estimation of GFRP	p.n	100	[0, 1]

Table 5. Value of the weighted least squares (WLS) regression coefficients obtained from the training exercise (Fig. 20) and implemented during the processing of the FRP-GRID product.

LSA SAF Region	Abbreviation	WLS parameter estimates (with standard error)	
		$\alpha\ (\sigma_\alpha)$	$\beta\ (\sigma_\beta)$
Northern Africa	NAfr	1.674 (0.062)	1.0 (0.0)
southern Africa	SAfr	1.464 (0.065)	1.0 (0.0)
South America	SAme	2.057 (0.224)	1.0 (0.0)
Europe	Euro	1.674 (0.173)	1.0 (0.0)

Figure 1. Near simultaneous IR3.9 channel (3.9 µm) imagery of fires in southern Africa from **(a)** SEVIRI and **(b)** MODIS, along with zooms of a sunglint area in two versions of the SEVIRI data, both **(c)** non-geometrically corrected level 1.0 and **(d)** fully pre-processed level 1.5. These image subsets show pixels with elevated MWIR brightness temperatures as bright, and apart from the glint regions almost all of these are caused by actively burning fires. **(a)** and **(b)** show the area surrounding the Okavango delta wetland (around 250 km long). The SEVIRI data were collected at 11:57 UTC on 4 September 2003, soon after the end of the MSG-1 (Meteosat 8) commissioning phase and just over one year after the satellite launch, whilst the matching near-nadir Aqua MODIS image was collected on the same day shortly after (12:05 UTC). The polar orbiting MODIS and geostationary SEVIRI data are not exactly co-registered, but cover approximately the same area. Whilst the increased spatial resolution of the MODIS data is clear and allows more fires to be visually identified via their elevated MWIR signals, many of the fires can also clearly be seen in the SEVIRI imagery. SEVIRI provides 96 images per day (one every 15 min) at a consistent view zenith angle. At this latitude up MODIS provides up to four images per day, though some of these will be at extreme view zenith angles up to 65° under which conditions the MODIS spatial fidelity is far reduced, with each pixel covering approximately the same ground area as does a SEVIRI pixel (Freeborn et al., 2011). The local afternoon imaging time of MODIS Aqua, as used here, is also relatively close to the typical peak of the fire diurnal cycle (Roberts et al., 2009a), but the times of the other MODIS overpasses are significantly distant from this. The SEVIRI images in **(c)** and **(d)** indicate the similarity between sunglint and active fire signals in the MWIR channel, which requires consideration when designing active fire detection algorithms. The effect of the spatial resampling undertaken between the SEVIRI Level 1.0 and Level 1.5 data is also apparent.

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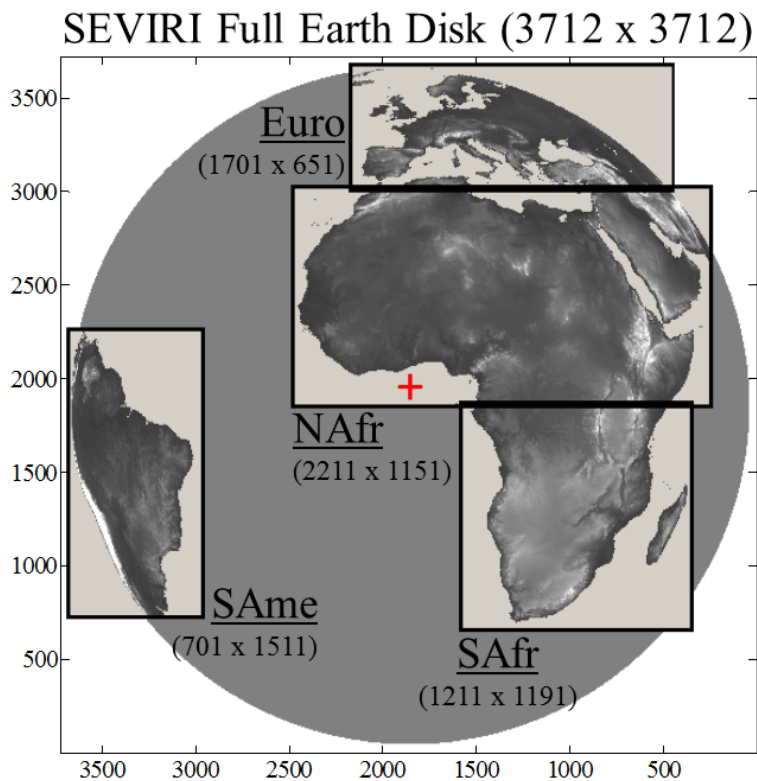
Figure 2. The four regions of the Meteosat disk currently used for deriving the LSA SAF products (shown here as an elevation map). Oceanic areas are not currently processed by the LSA SAF, and for most LSA SAF products information from each geographic region is delivered in separate product files. The location of the sub-satellite point (SSP) is shown as the red cross. Later in 2015 the LSA SAF will switch to delivering full-disk data for most products, including the FRP products described herein.

Figure 3. Example data extracted from the LSA SAF Meteosat SEVIRI FRP-PIXEL product. **(a)** Active fire locations and their FRP as measured on 17 July 2009 over southern Africa. **(b)** The same data but now shown as the diurnal cycle of FRP, binned into 25 MW increments. These data indicate that the individual fire pixel FRP values recorded on this date almost all lay below 150 MW, and that the peak of the diurnal cycle generally occurred earlier in the day for higher FRP fire pixels.
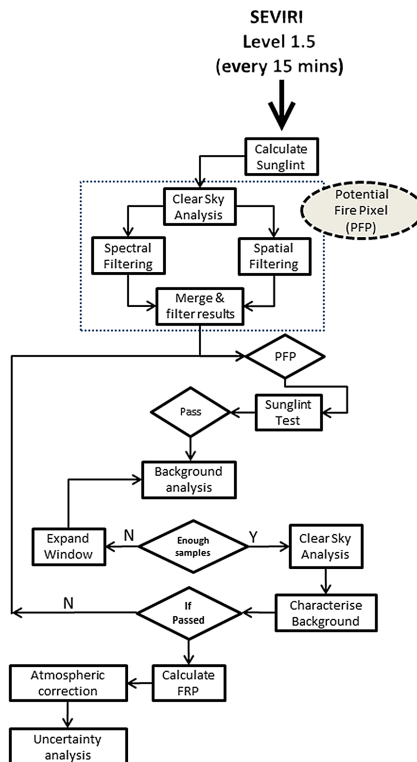
Figure 4. Flowchart illustrating the FRP-PIXEL product processing chain, which uses the operational geostationary "Fire Thermal Anomaly" (FTA) algorithm described herein. The processing chain acts upon the input Level 1.5 data from each SEVIRI imaging slot independently, and the procedures outlined by the blue dotted box are those involved in selection of the potential fire pixels (PFPs). These PFPs are then subject to a series of thresholding procedures based on spatially varying "contextual" thresholds, used to determine whether or not each FPF can be confirmed as a true active fire pixel and have its FRP assessed.
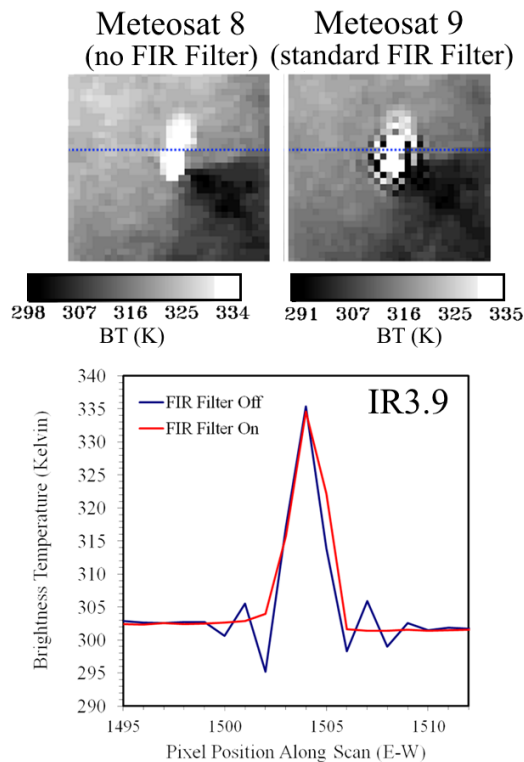
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Figure 5. Illustration of the impact of optimised cloud masking procedures used in the FRP-PIXEL Product processing chain, which are based on an adjusted version of the Meteosat NWC SAF CMa Cloud Mask described in Derrien and Le Gleau (2005). **(a)** SEVIRI Channel 1 (VIS 0.64 µm) image subset acquired at 7 July 2004 15:42 UTC over southern Angola (centred on 11.06° S, 16.63° E) showing a mixture of cloudy and clear sky pixels, and including many fires; **(b)** impact of the CMa Cloud mask on the active fire detection process. "Masked fire" are active fire pixels successfully detected by the FTA algorithm using the adjusted CMA cloud mask, but which would have been masked as cloud if the standard CMa mask brightness temperature difference test ($BT_{3.9} - BT_{10.8}$) had been applied unaltered. "Cloud" are cloudy non-fire pixels detected with this test, and active fires are fire pixels successfully detected by the FTA algorithm with or without the test applied. It is clear that many active fire pixels would have be omitted if the standard CMa cloud mask procedure were applied unaltered within the FRP-PIXEL processing chain. Area of the SEVIRI image subset shown here is approximately 618 km × 468 km.

Figure 6. Simultaneous data collected by the Aqua MODIS and Meteosat SEVIRI instruments over a 1° × 1° region of Central African Republic at 12:00 UTC on 11 January 2009. **(a)** 500 m spatial resolution MODIS Aqua true colour composite, **(b)** MODIS fire mask retrieved from the coincident MYD14 Active Fire and Thermal Anomaly product, **(c)** the status flags (Table 2) retrieved from the coincident SEVIRI FRP-PIXEL quality file, and **(d)** the MODIS cloud mask retrieved from the coincident MYD35 MODIS Cloud Product. The MODIS true colour composite image has been reprojected into geographic coordinates, and this area is shown boxed on the other products (shown in their native image coordinate systems). It is apparent that the geographically widespread, but somewhat transparent, cloud shown in the MODIS colour composite in **(a)** is widely detected by the MODIS MYD35 cloud mask **(d)** and by the adapted CMA Cloud Mask used in the FRP-PIXEL products **(c)**. However, the MODIS cloud mask used in the MODIS fire product **(b)** is specified such that it does not detect such thin cloud and allows fires burning underneath to remain detectable. Far less cloud can be seen to be detected by this mask than by either other the other two masks. Figure adapted from Freeborn et al. (2014a), who go onto confirm the very strong sensitivity of the SEVIRI CMa mask of Derrien and Le Gleau (2005) compared to that of the MODIS Active Fire Product cloud mask.

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Figure 7. Information from European (Euro) region FRP-PIXEL Quality Product for 12:45 UTC, 16 August 2010. **(a)** Full Quality Product, with area shown in **(b)** outlined, and **(b)** spatial subset over the eastern Mediterranean region with southern Italy at far left and the Black Sea far right. The Greek island of Peloponnese, the location of the large fires in August 2007 whose smoke emissions are calculated using the FRP-PIXEL product in Roberts et al. (2015), is at the bottom centre of the spatial subset. The subset illustrates the significant impact of the water proximity mask on the Euro region FRP-PIXEL Product, a class stored within the "Cloud Edge" quality flag (here shown as yellow). The large amount of coastline in the European region typically results in a greater proportion of pixels classified as this class than in the other LSA SAF geographic regions. The Danube river running East–West in the centre of **(b)** clearly highlights the impact of this quality flag. Colour bar represents the classes in Table 2 from −1 ("outside processing region") to +9 ("bad data"), though there are no pixels classed as "bad data" (Class 9) in this subscenscene. The last class has a value of +254 ("not processed") and represents primarily ocean pixels.

Figure 8. Simulated SEVIRI IR3.9 (MWIR) imagery of active fires, shown in comparison to real imagery. Images are scaled with the highest brightness temperature in the images shown white, and the lowest black. x and y axes are in SEVIRI image column and row coordinates. **(a)** is a simulated MWIR view of a 350 MW fire contained within the ground area of a single SEVIRI 3 km pixel (prior to application of the convolved filter shown in Fig. 9). After filter application, the fire signal appears smeared across many pixels, and the result appears similar to typical SEVIRI imagery of an active fire shown in **(b)**, and noting that the dominantly along-scan nature of the smearing may not be so apparent in real SEVIRI imagery due to the pixel geolocation processes performed during the level 1.0 to level 1.5 pre-processing procedures (see Fig. 1b and c). **(c)** and **(d)** show the simulation of larger fires stretching across three 350 MW SEVIRI pixels in the E–W and N–S directions respectively, with the impact of the filtering shown to be dependent upon the fire orientation with respect to the SEVIRI scan process. The simulations were aimed at being indicative only, with a uniform surface temperature, atmospheric transmission and emissivity assumed, and the sub-pixel fire of fixed FRP located at the scene centre.

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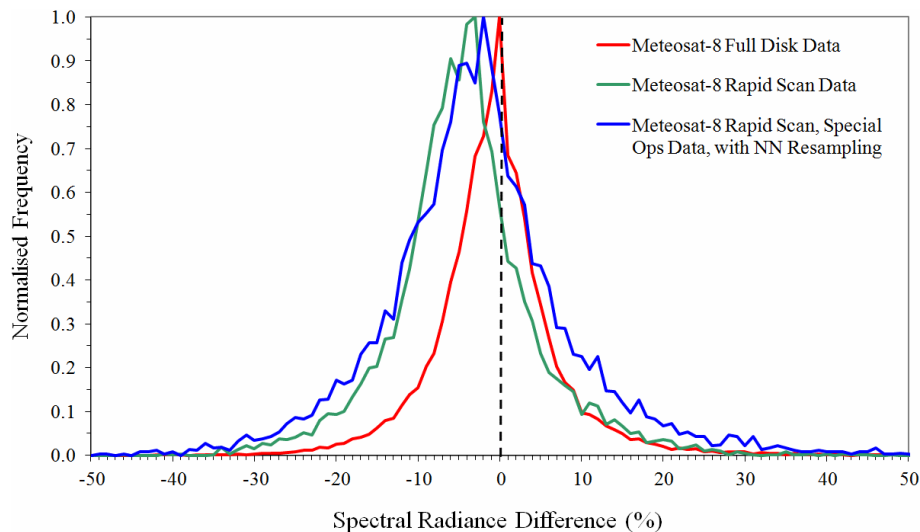Full Screen / Esc

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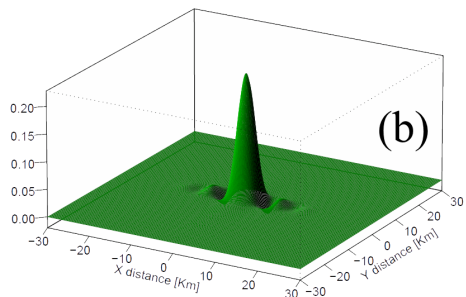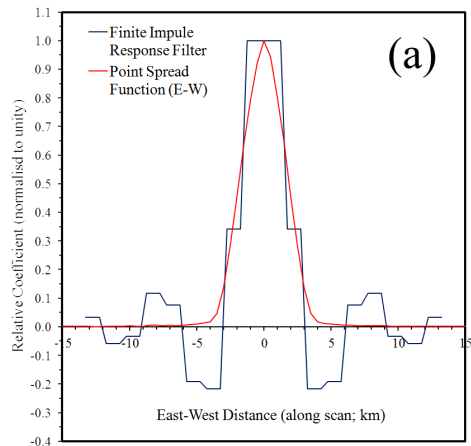
Figure 9. (a) The E–W point spread function of SEVIRI (at sub-satellite point) and the finite impulse response (FIR) function. The latter is applied to Level 1.0 data before conversion to level 1.5. Both are shown here normalised to unity. Note the negative side lobes of the FIR filter. **(b)** Convolution of the FIR filter and the E–W and N–S SEVIRI point spread fuction (PSF) used in the simulation of active fire observations (Fig. 8).

Figure 10. Near simultaneous Meteosat-8 and -9 IR3.9 Imagery of a large, intensely burning (high FRP) fire in southern Africa taken on 3 September 2007 during the Meteosat-8 "Special operations" described in Table 3. Meteosat-8 had the application of the FIR filter removed temporarily during this period (no FIR filter), and the data appear somewhat different to that collected with the normally operating Meteosat-9.

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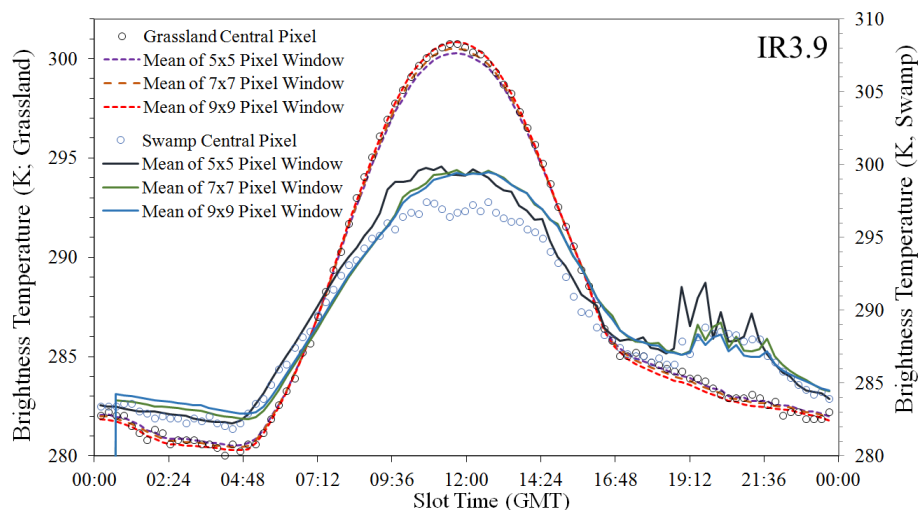
Figure 11. Example test of the ability to estimate the SEVIRI IR3.9 (MWIR) brightness temperature of the central pixel in a 5 × 5, 7 × 7 and 9 × 9 pixel window, using the mean of the remaining "background window" pixels. Results for two different landcover types are shown from the GLC2000 database, grassland (plotted on left hand y axis) and swamp (plotted on right hand y axis).
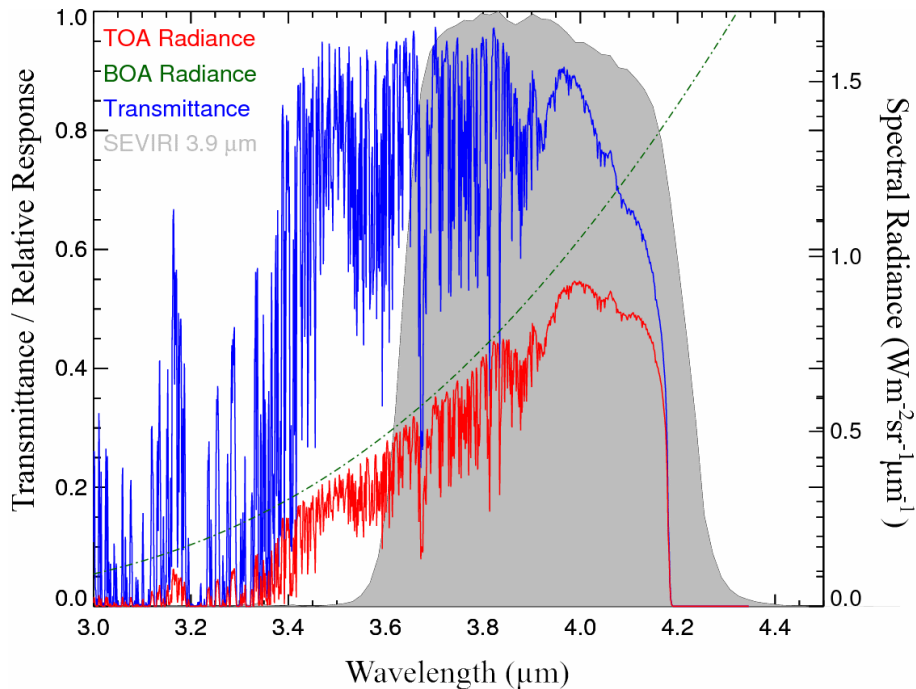
Figure 12. SEVIRI IR3.9 (MWIR) band spectral response function, with example atmospheric transmittance calculated across the 3.0–4.5 µm wavelength range assuming a standard atmosphere (Berk et al., 2005), plotted on the lhs y axis. Also shown, plotted on the rhs y axis, are the bottom-of-atmosphere (BOA) thermal emittance for a 310 K blackbody, along with the top-of-atmosphere (TOA) equivalent after the emitted radiation has passed through the intervening atmosphere to space. Simulations performed using the MODTRAN 5 radiative transfer code (Berk et al., 2005 and the US Standard Atmosphere).

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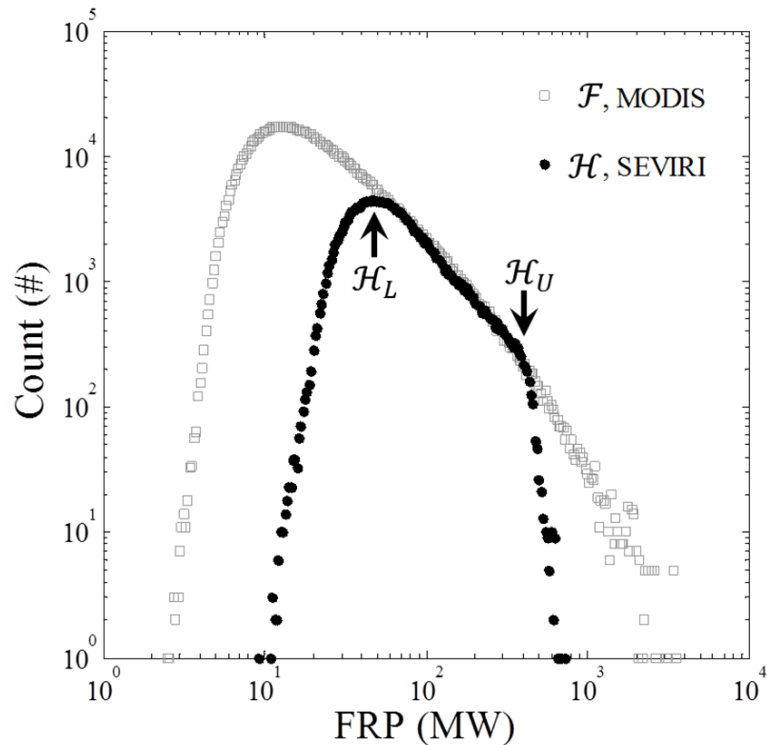Full Screen / Esc

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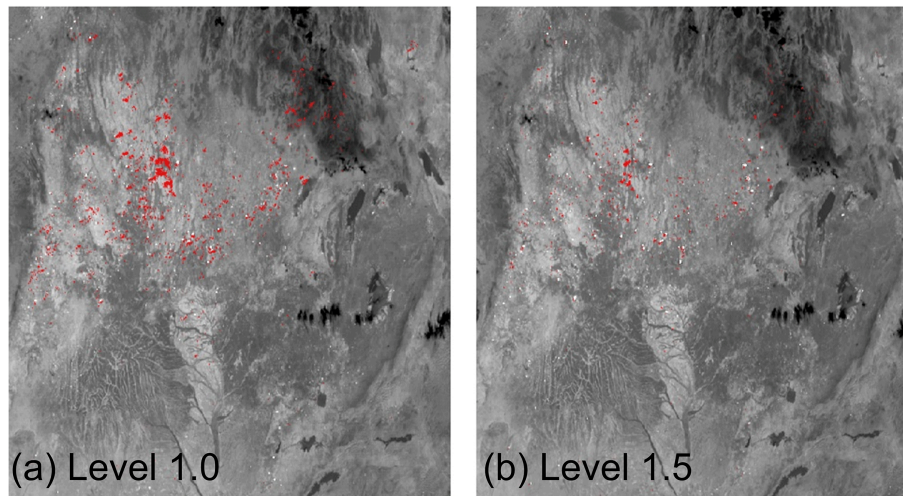
Figure 13. Typically a maximum of only a few percent of active fire pixels are saturated in any particular SEVIRI image, but the exact proportion changes between data pre-processing levels. Here in red we show the spatial distribution of saturated active fire pixels in **(a)** level 1.0 and **(b)** level 1.5 SEVIRI data collected over a 2 day (48 h) period in a region of southern Africa (16 and 17 July 2014). Twice as many pixels are saturated in the level 1.0 across these two days (shown by a 10 bit DN of 1023; $n = 2797$) than are apparent in the level 1.5 data (shown by a maximum brightness temperature recordable in the IR3.9 band; $n = 1390$). The background imagery on which the saturated active fire pixels are displayed is IR3.9 image acquired on the 17 July at 13:00 h (UTC).
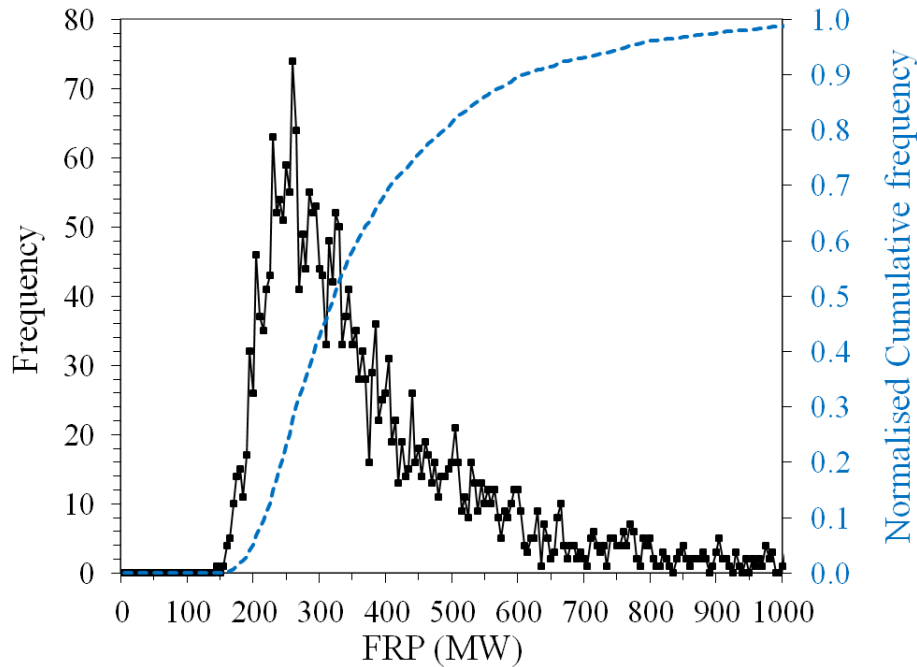
Figure 14. Frequency distribution and normalised cumulative frequency of the FRP recorded at detected active fire pixels that would have been saturated under normal SEVIRI operating conditions, but which remained unsaturated during the low-gain "Special Operation" of the IR3.9 band of Meteosat-8 SEVIRI (Table 3). Pixels with FRP > 1000 MW are shown due to their extremely low frequency, though one pixel with an FRP approaching 2000 MW was seen (see main text).
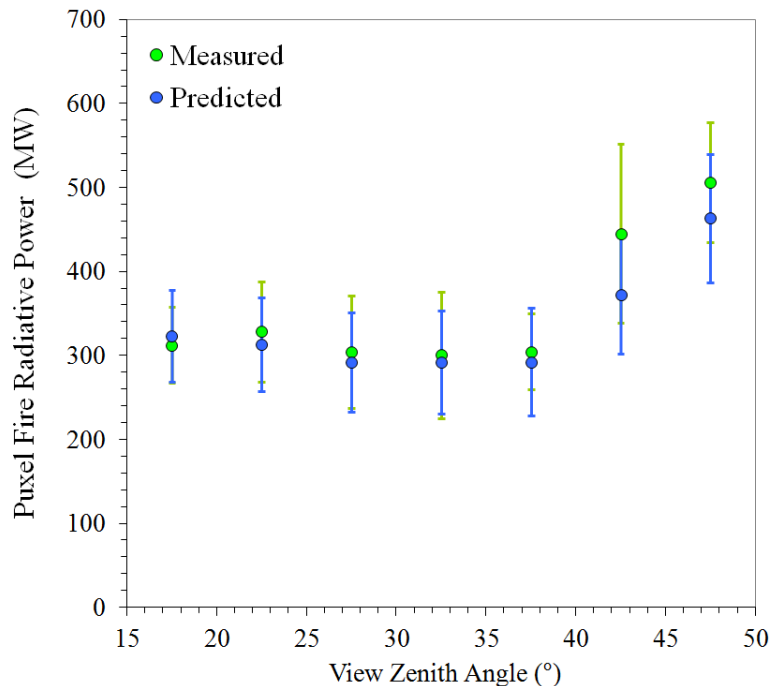
Figure 15. Median FRP values recorded at active fire pixels which would have been saturated had Meteosat-8 SEVIRI been operating in normal gain mode, but which when observed during the low-gain IR3.9 band "Special Operation" of Meteosat-8 SEVIRI (Table 3) were unsaturated. Data are stratified by view zenith angle. Also shown are the ±1 mean absolute deviation from the median, and the predictions of FRP made when the actual fire pixel IR3.9 spectral radiance is replaced with a fixed value of $4.08\,\mathrm{mW\,m^{-2}\,sr^{-1}\,(cm^{-1})^{-1}}$ to represent the case of the adjustment applied to saturated pixels in normal mode level 1.5 SEVIRI data (see Sect. 5 for details).

Figure 16. Comparison of SEVIRI IR3.9 band spectral radiance differences recorded at active fire pixels observed simultaneously by Meteosat-9 operated continuously in standard mode full disk viewing, and Meteosat-8 operated in both standard mode and a number of "Special Operations" modes (Table 3). The red line shows the Meteosat-8 and -9 difference when the former is operated in normal mode, with no time difference between observations, the green line when Meteosat-8 Rapid Scan mode was used, which resulted in time differences of 50–65 s between matched Met-8 and Met-9 observations, and the blue line when Meteosat-8 Rapid Scan data were processed without the FIR filter applied (see Fig. 10) and with a nearest neighbour geometric resampling scheme rather than an interpolation function. From these intercomparisons, estimates of the radiometric uncertainties introduced by the SEVIRI level 1.0 to level 1.5 pre-processing operations were deduced.
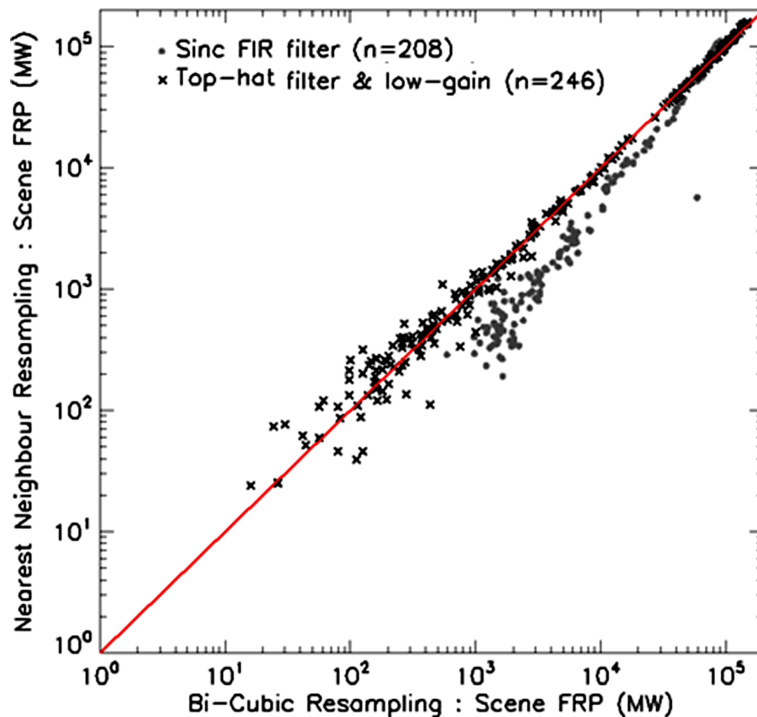
Figure 17. Total scene cumulative FRP (MW) measured by Meteosat-8 across the region of the Rapid Scan observations (3° N to 33° S; Table 3) when data were delivered using different geometric resampling schemes (nearest neighbour and the standard IMPF bi-cubic scheme) and image processing filters (standard Sinc function shown in Fig. 9, and "top-hat" which equates to no significant digital filtering). Data were collected between 3–7 September 2007 during the period of Meteosat-8 "Special Operations" detailed in Table 3.

Figure 18. Frequency-magnitude distributions constructed from coincident active fire pixels detected by SEVIRI, $\mathcal{H}$ (•), and MODIS, $\mathcal{F}$ (□), over the African continent between May 2008 and May 2009. The lower breakpoint of the SEVIRI distribution, $\mathcal{H}_L$, coincides with the decline in SEVIRI's active fire detection performance as the thermal radiance emitted from small and/or lower intensity fires cannot be reliably distinguished from that of the background window, and so many remain undetected. The upper breakpoint, $\mathcal{H}_L$, coincides with the onset of IR3.9 detector saturation. The Level 3 FRP-GRID Product aims to account for the FRP that SEVIRI fails to detect as a result of these sensor artefacts, as well as by that due to cloud obscuration.

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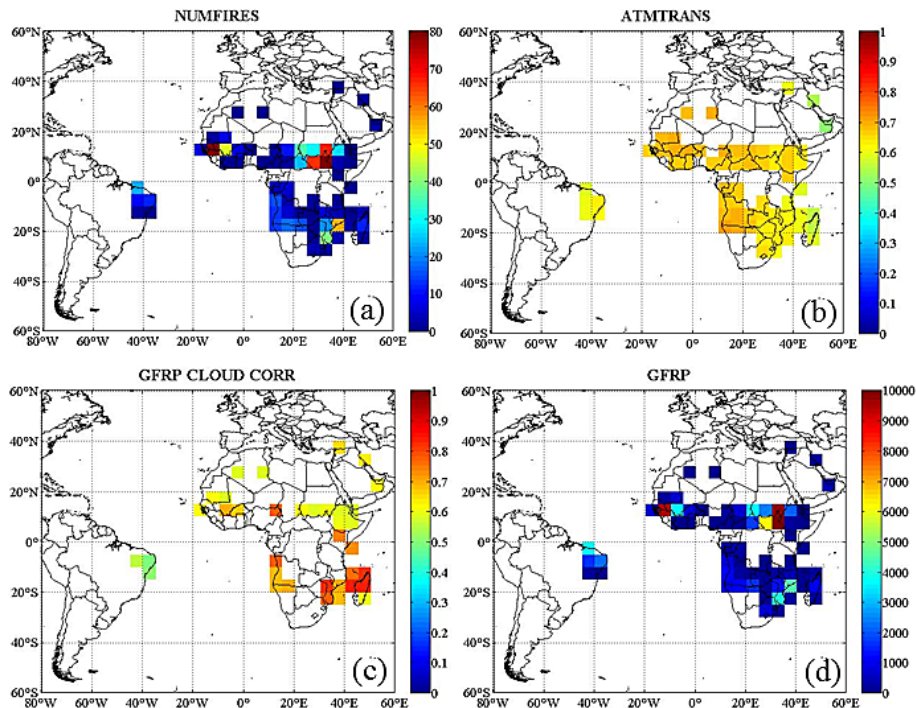
Figure 19. Example of the product contents for a single FRP-GRID product (issued hourly), as recorded on 11 November 2009 at 14:00 UTC, including **(a)** the average number of fires detected per 15 min imaging timeslot, **(b)**, the average atmospheric correction factor, **(c)**, the average cloud correction factor, and **(d)** an estimate of the average FRP that MODIS would have measured during the hour. A full description of all FRP-GRID product fields is provided in Table 4.
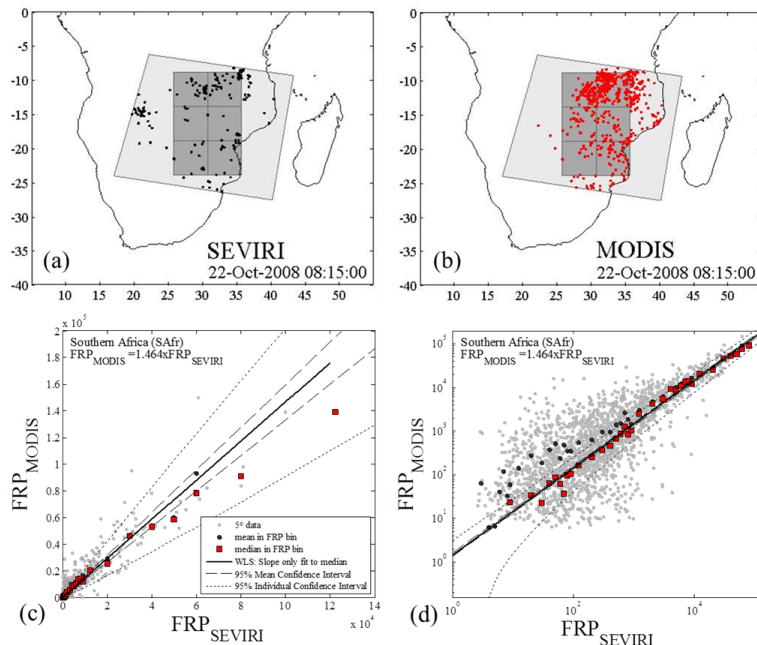
Figure 20. Illustration of the training dataset and the technique used to derive the regional bias adjustment factors used in the FRP-GRID product processing chain, here illustrated for the southern African LSA SAF geographic region. Temporally coincident **(a)** SEVIRI and **(b)** MODIS active fire pixels between 2008 May and 2009 May were accumulated in 5° grid cells strategically located within geographic areas covered by the centre two thirds of the MODIS swath. Shown is one example obtained at 08:15 UTC on 22 October 2008. To achieve a sufficient sample size, SEVIRI active fire pixels were accumulated over an hour, as in the FRP-GRID product. For each LSA SAF geographic region, appropriate SEVIRI-to-MODIS bias adjustment coefficients were determined by performing a weighted linear least squares fit through the median values, shown in **(c)** and **(d)**. The resulting bias-adjustment factors are applied in the FRP-GRID product, and are summarized in Table 5.
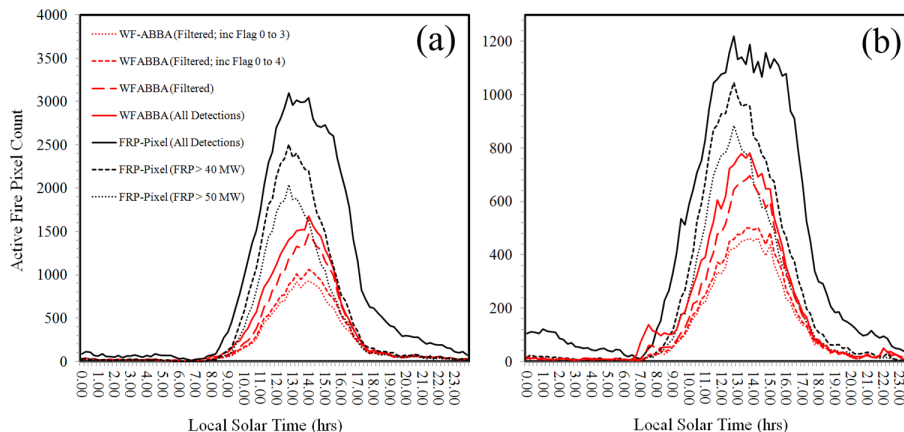
Figure 21. Comparison between FRP-PIXEL product active fire detections made in the southern African geographic region (Fig. 2), along with the those made simultaneously by the WFABBA SEVIRI Fire Product (http://wfabba.ssec.wisc.edu/). Dates are **(a)** 2 August 2014, and **(b)** 31 August 2014, and both are shown in terms of local solar time of detection. For the FRP-PIXEL product, three active fire time-series are shown, all detections; and those only from fire pixels with FRP > 40 MW and > 50 MW, since it is known that significant undercounting of active fire pixels occurs around these limits (i.e. below threshold H_L in Fig. 18). For the WFABBA active fire detections, four versions of the data are shown, all active fire detections; the WF-ABBA "filtered" detections where SEVIRI pixels only detected as an active fire once during 24 h are removed; and the filtered detections keeping only the higher possibility fires (WF-ABBA flags 0 to 3) and high and medium possibility fires (WF-ABBA flags 0 to 4). Details of the WF-ABBA flags can be found at www.ssd.noaa.gov/PS/FIRE/Layers/ABBA/abba.html. On both days and at all timeslots, the full FRP-PIXEL product active fire record (black line) detects substantially greater numbers of active fire pixels than the full WFABBA record (red line).

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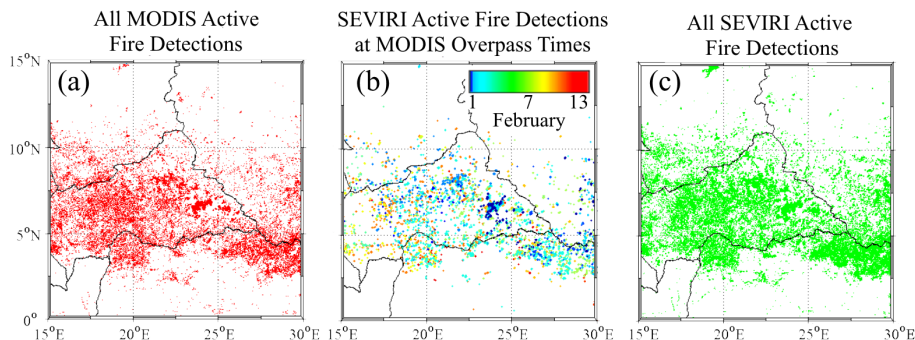
Figure 22. Active fire detections made across Central Africa for a two week window (1–13 February 2004) in February 2004, as detected from **(a)** the MOD14/MYD14 Active Fire products, **(b)** SEVIRI data and the FTA algorithm within ±6 min of the MODIS overpass, and **(c)** all SEVIRI data. In **(b)**, the detected active fire pixels are coloured by day of detection, and it is apparent that fires appear potentially larger and are detected earlier in the east of the region, somewhat matching the detailed analysis presented in Freeborn et al. (2004a, c).

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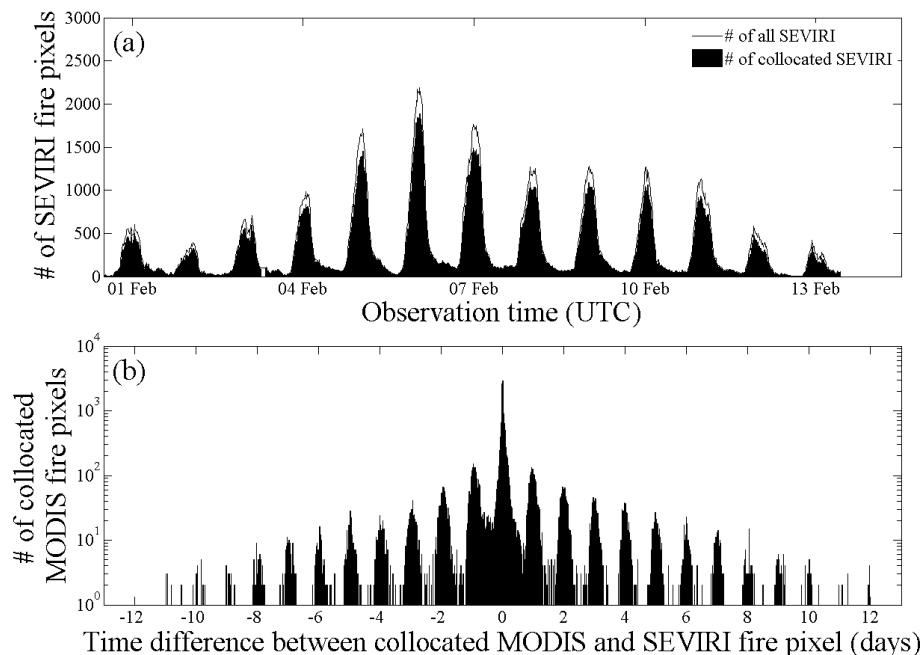
Figure 23. Results of the temporal analysis performed using collocated SEVIRI FTA and MODIS MOD14/MYD14 active fire pixels detected in Central African regions shown in Fig. 22 between 1 and 13 February 2004. In **(a)** is the total number of active fire pixels detected by the FTA algorithm in each SEVIRI timeslot, and the number that were within 4 km of a MODIS active fire pixel detected at any time during the study period. In **(b)** is the number of MODIS active fire pixels detected within 4 km of a SEVIRI fire pixel, expressed as a function of the time difference between the MODIS detection and the most contemporaneous SEVIRI active fire detection. Positive time differences represent a SEVIRI fire detection occurring after the MODIS active fire detection. Note the log scale of the y axis in **(b)**.

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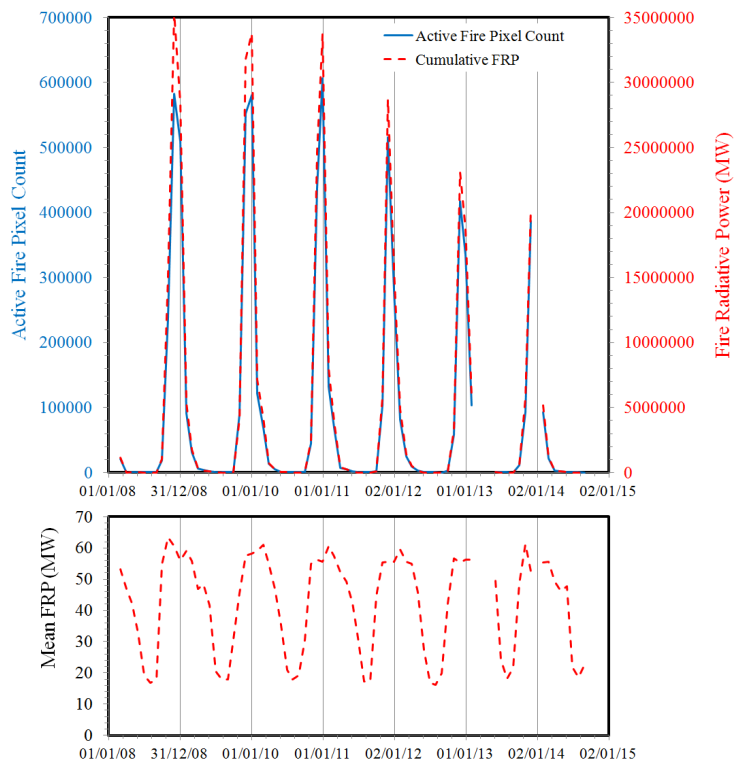
Figure 24. Metrics of monthly fire activity (total monthly FRP, monthly active fire pixel count, and the mean per-pixel FRP) for the Central African Republic (CAR), as extracted from the 2008–2014 time series of FRP-PIXEL products available from the Land Surface Analysis Satellite Applications Facility (LSA SAF; landsaf.meteo.pt).
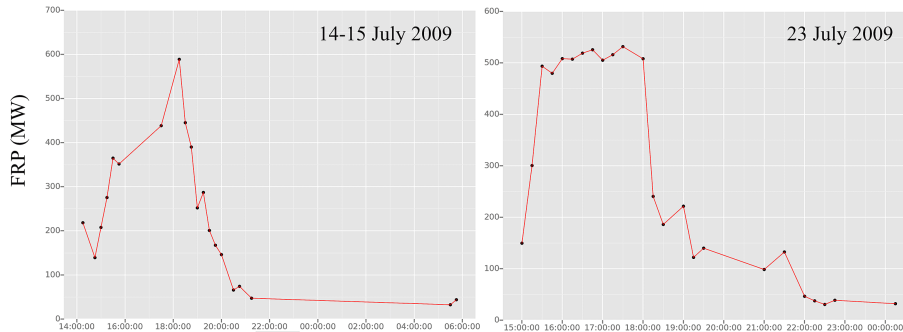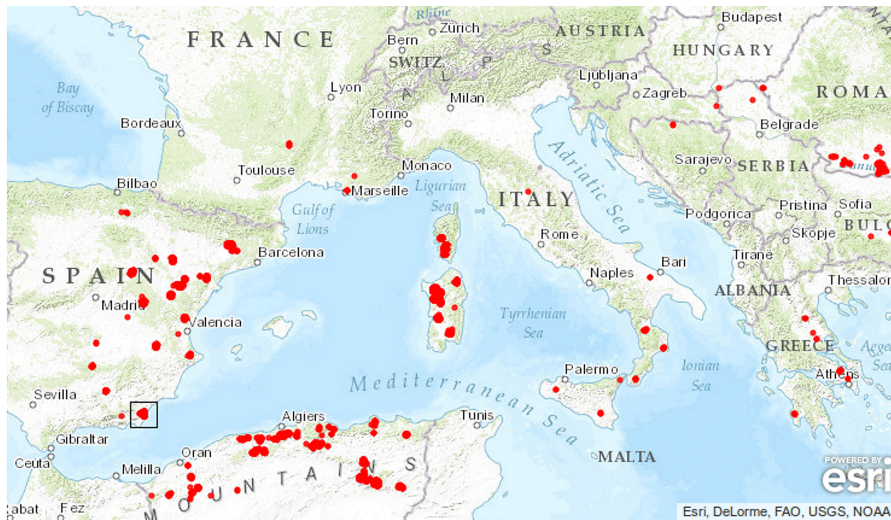
Figure 25. Active fire detections made across parts of Europe and North Africa (4.0° E–35.0° W, 25.0–46.0° N) in July 2009 and stored in the SEVIRI FRP-PIXEL product. Only the locations of active fire pixels with FRP ≥ 200 MW are shown for clarity. The location of the wildfire close to Sierra Cabrera in Span (37.15° N, 1.92° W) is outlined, and its FRP time-series shown.