

1 **LSA SAF Meteosat FRP Products: Part 2 - Evaluation and**
2 **demonstration for use in the Copernicus Atmosphere Monitoring**
3 **Service (CAMS)**

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19 **ABSTRACT**

20
21 Characterising the dynamics of landscape scale wildfires at very high temporal resolutions is
22 best achieved using observations from Earth Observation (EO) sensors mounted onboard
23 geostationary satellites. As a result, a number of operational active fire products have been
24 developed from the data of such sensors. An example of which are the Fire Radiative Power
25 (FRP) products, the FRP-PIXEL and FRP-GRID products, generated by the Land Surface
26 Analysis Satellite Applications Facility (LSA SAF) from imagery collected by the Spinning
27 Enhanced Visible and Infrared Imager (SEVIRI) on-board the Meteosat Second Generation
28 (MSG) series of geostationary EO satellites. The processing chain developed to deliver these
29 FRP products detects SEVIRI pixels containing actively burning fires and characterises their
30 FRP output across four geographic regions covering Europe, part of South America and
31 northern and southern Africa. The FRP-PIXEL product contains the highest spatial and
32 temporal resolution FRP dataset, whilst the FRP-GRID product contains a spatio-temporal
33 summary that includes bias adjustments for cloud cover and the non-detection of low FRP

34 fire pixels. Here we evaluate these two products against active fire data collected by the
35 Moderate Resolution Imaging Spectroradiometer (MODIS), and compare the results to those
36 for three alternative active fire products derived from SEVIRI imagery. The FRP-PIXEL
37 product is shown to detect a substantially greater number of active fire pixels than do
38 alternative SEVIRI-based products, and comparison to MODIS on a per-fire basis indicates a
39 strong agreement and low bias in terms of FRP values. However, low FRP fire pixels remain
40 undetected by SEVIRI, with errors of active fire pixel detection commission and omission
41 compared to MODIS ranging between 9 - 13% and 65 - 77% respectively in Africa. Higher
42 errors of omission result in greater underestimation of regional FRP totals relative to those
43 derived from simultaneously collected MODIS data, ranging from 35% over the Northern
44 Africa region to 89% over the European region. High errors of active fire omission and FRP
45 underestimation are found over Europe and South America, and result from SEVIRI's larger
46 pixel area over these regions. An advantage of using FRP for characterising wildfire
47 emissions is the ability to do so very frequently and in near real time (NRT). To illustrate the
48 potential of this approach, wildfire fuel consumption rates derived from the SEVIRI FRP-
49 PIXEL product are used to characterise smoke emissions of the 2007 'mega fire' event
50 focused on Peloponnese (Greece) and used within the European Centre for Medium-Range
51 Weather Forecasting (ECMWF) Integrated Forecasting System (IFS) as a demonstration of
52 what can be achieved when using geostationary active fire data within the Copernicus
53 Atmosphere Monitoring Service (CAMS). Qualitative comparison of the modelled smoke
54 plumes with MODIS optical imagery illustrates that the model captures the temporal and
55 spatial dynamics of the plume very well, and that high temporal resolution emissions
56 estimates such as those available from geostationary orbit are important for capturing the sub-
57 daily variability in smoke plume parameters such as aerosol optical depth (AOD), which are
58 increasingly less well resolved using daily or coarser temporal resolution emissions datasets.
59 Quantitative comparison of modelled AOD with coincident MODIS and AERONET AOD
60 indicates that the former is overestimated by ~20 - 30%, but captures the observed AOD
61 dynamics with a high degree of fidelity. The case study highlights the potential of using
62 geostationary FRP data to drive fire emissions estimates for use within atmospheric transport
63 models such as those implemented in the Monitoring Atmospheric Composition and Climate
64 (MACC) series of projects for the CAMS.

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1. INTRODUCTION

1.1. Biomass Burning Emissions and Meteosat SEVIRI FRP Products from the LSA SAF

Biomass burning emissions databases derived from Earth Observation (EO) satellite data, such as the widely used Global Fire Emissions Database (GFED; van der Werf *et al.*, 2006; 2010), typically follow the approach proposed by Seiler and Crutzen (1980) and estimate fire emissions via the multiplication of burned area (m^2), fuel load (kg m^{-2}) and combustion completeness (unitless, 0-1) estimates. Emissions databases developed in this manner have been widely applied to deliver wildfire emissions of trace gases and aerosols for use in atmospheric transport models (Mu *et al.*, 2011; Tsyro *et al.*, 2007). However, whilst excellent for many applications, some limitations of this ‘burned area’ based approach are that it works only after the fire event, cannot be applied in near real-time, and has a relatively low temporal resolution that provides little or no information on the variability of the emissions during the fire itself. All these maybe limitations when modelling certain aspects of fire emissions transport and generally preclude use of the approach in real-time atmospheric monitoring or forecasting systems (Reid *et al.*, 2004). The companion paper to this work, Wooster *et al.* (2015) describes the geostationary Meteosat SEVIRI Fire Radiative Power (FRP) products being generated operationally by the EUMETSAT Land Surface Analysis Satellite Applications Facility (LSA SAF; <http://landsaf.meteo.pt/>). This type of geostationary active fire product offers an alternative route to biomass burning emissions estimation based on assessments of the thermal energy being radiated away from fires, and can do so in near real-time with frequent updates whilst the fires are still burning, though there are also some limitations caused mainly by fires having too low a fire radiative power remaining undetectable with the relatively coarse spatial resolution SEVIRI observations (Roberts and Wooster, 2008). Whilst Wooster *et al.* (2015) describe the methodologies and algorithms used to produce the LSA SAF Meteosat FRP products, and their information characteristics, the purpose of the current work is to (i) provide a full evaluation of the product compared to other real-time active fire products derived from the same SEVIRI observations, (ii) to provide a product validation via comparisons to the widely used and higher spatial resolution (albeit lower temporal resolution) MODIS active fire detections, and (iii) to demonstrate how the product can be used as a high temporal resolution biomass burning emissions driver

101 within a case study that exploits components of the prototype CAMS
102 (<http://www.copernicus-atmosphere.eu/>)

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104 ***1.2. Satellite Earth Observation Active Fire Products***

105 Active fire products that are based on detecting the thermal radiation being emitted by
106 landscape scale fires have been available for over three decades from numerous polar orbiting
107 and geostationary satellites (Prins *et al.*, 1994; Prins *et al.*, 1998; Matson, 1981, Justice *et al.*,
108 1998; Giglio, 2003b). In addition to simple detection, Dozier (1981) first demonstrated the
109 additional potential to estimate a fire's subpixel effective temperature and fractional area, and
110 this approach has been applied in the Wildfire Automated Biomass Burning Algorithm
111 (WFABBA) to data from the Geostationary Operational Environmental Satellite (GOES) for
112 over two decades (Prins *et al.*, 1994). Building on this idea, the FRP route to characterising
113 active fires and estimate wildfire emissions was first proposed by Kaufman *et al.* (1996). The
114 FRP approach is based on the understanding that the amount of heat produced by burning a
115 fixed mass of biomass is relatively invariant to vegetation type (Jenkins *et al.*, 1998). By
116 measuring the component of this "heat of combustion" that is radiated away from the surface,
117 the amount of vegetation being burned per second can then be estimated (Wooster *et al.*,
118 2003; Wooster *et al.*, 2005; Freeborn *et al.*, 2008). An advantage of the FRP approach for
119 estimating smoke emissions to the atmosphere is that it is based on a direct remotely sensed
120 observation, and a large number of polar and geostationary satellite instruments have the
121 requisite midwave infrared (MWIR) waveband required to estimate FRP using the MIR
122 radiance approach of Wooster *et al.* (2003; 2005). The Moderate Resolution Imaging
123 Spectroradiometer (MODIS) instruments onboard the Terra and Aqua satellites have been
124 providing FRP measurements since 2000 and 2002 respectively (Kaufman *et al.*, 1998; Giglio
125 *et al.*, 2003b) and is currently supported by the Visible Infrared Imaging Radiometer Suite
126 (VIIRS) onboard Suomi-NPP (Csiszar *et al.*, 2013) and the soon-to-be-launched Sea and
127 Land Surface Temperature Radiometer (SLSTR) onboard Sentinel-3 (Wooster *et al.*, 2012).
128 Geostationary instruments, such as the Geostationary Operational Environmental Satellite
129 (GOES) imager (Xu *et al.*, 2010), are also providing FRP measurements at much higher
130 temporal resolution but at lower spatial resolution and coverage, and those from the Meteosat
131 SEVIRI instrument (Wooster *et al.*, 2015) are the target of the current work.

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133 ***1.3. Wildfire Emissions Datasets from FRP Observations***

134 Information on the fuel consumption totals required to build wildfire emissions inventories
135 have already been developed using FRP data derived from polar-orbiter (Vermote *et al.*,
136 2009; Ellicott *et al.*, 2009; Kaiser *et al.*, 2012) and geostationary satellite EO data (Pereira *et*
137 *al.*, 2011; Roberts *et al.*, 2011). A limitation associated with the former is their intermittent
138 observation of the diurnal fire cycle, which needs to be characterised in order to estimate
139 daily Fire Radiative Energy (FRE; the temporal integration of FRP). MODIS typically
140 provides around four daily observations depending on latitude which, when accumulated over
141 a sufficiently long time period, have been exploited to model the diurnal fire cycle and
142 estimate total emissions over 8-day or longer periods (Vermote *et al.*, 2009; Ellicott *et al.*,
143 2009). Geostationary FRP datasets provide much higher observation frequencies, and thus
144 unparalleled data on the diurnal fire cycle (e.g. Roberts and Wooster, 2007; Roberts *et al.*,
145 2009;), and Zhang *et al.* (2012) illustrate one way such data can be used to develop a near
146 global biomass burning emissions dataset at hourly type temporal resolutions. However, a
147 limitation of geostationary data is their coarse spatial resolution, which results biases in
148 regional-scale FRP and FRE due to the omission of small and/or low intensity wildfires
149 (Roberts *et al.*, 2005; Xu *et al.*, 2010). Freeborn *et al.* (2009) addressed this issue by
150 synthesising a ‘virtual’ FRP product via the integration of both geostationary and polar-
151 orbiter FRP data, maintaining the high temporal resolution of geostationary data whilst
152 simultaneously adjusting them for the active fire detection biases using the higher spatial
153 resolution MODIS measurements. Roberts *et al.* (2011) blended geostationary FRP data with
154 MODIS-derived burned area information to meet a similar objective.

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156 Perhaps the most obvious advantage FRP-based biomass burning emissions inventories offer
157 over a burned area based inventory is their near real-time capability, since the thermal
158 radiation being emitted by the active fires is being sensed whilst the fire is actually burning,
159 rather than somewhat after the event. As a result, FRP-derived emissions estimates are being
160 increasingly applied to characterise wildfire emissions for use in near real time atmospheric
161 transport models. Sofiev *et al.* (2009) use MODIS FRP measurements to characterise
162 particulate matter (PM) emissions using the method proposed by Ichoku and Kaufmann
163 (2005), and the dispersion of the resulting emissions are propagated using the System for
164 Integrated modeLLing of Atmospheric coMposition (SILAM) dispersion model. In this
165 approach, the diurnal variation of emissions is specified as being 25% greater than the daily
166 mean during the day, and 25% less than the mean during the night. Kaiser *et al.* (2009a;
167 2012) developed the Global Fire Assimilation System (GFAS) to prescribe wildfire emissions

168 for use in the CAMS, potentially calculating the FRP density emitted by actively burning
169 fires (mW m^{-2}) using a variety of FRP measurements from different spacecraft. However, in
170 the NRT version of GFAS used currently only FRP measurements from MODIS are used.
171 The FRE density (J m^{-2}) is estimated by temporally integrating the MODIS-derived FRP
172 density using a Kalman filter. Most recently, Turquety *et al.* (2014) used SEVIRI FRP
173 measurements from the LSA SAF products to prescribe the fire diurnal cycle for the
174 APIFLAME European fire emissions model, and Baldassarre *et al.* (2015) used both the LSA
175 SAF SEVIRI FRP products and other active fire products to simulate the emissions and
176 emissions transport of a large fire in Turkey.

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178 This manuscript provides a detailed evaluation of the Meteosat SEVIRI FRP products
179 available from the LSA SAF, both the full resolution FRP-PIXEL product and the reduced
180 resolution FRP-GRID product, both available in near real time and in archived form
181 (<http://landsaf.meteo.pt/>), and provides a detailed example of their use in characterising
182 wildfire emissions and its atmospheric transport at high temporal resolution. Section 2
183 provides a brief product summary, and readers are referred to the companion paper (Wooster
184 *et al.*, 2015) for a more detailed description of the algorithms used to derive the information
185 from the raw SEVIRI level 1.5 observations. Sections 3 describes a detailed inter-comparison
186 of the LSA SAF SEVIRI FRP-PIXEL product with both the MODIS active fire products
187 (Giglio *et al.*, 2003), and three alternative active fire products also derived from SEVIRI
188 observations: namely the WFABBA (Prins *et al.*, 1998), Fire Detection and Monitoring
189 (FDeM; Amraoui *et al.*, 2010) and Active Fire Monitoring (FIR) product (Joro *et al.*, 2008).
190 Section 4 evaluates the specific performance of spatio-temporal summary ‘FRP-GRID’
191 product available from the LSA SAF, which incorporates statistical adjustments for SEVIRI’s
192 regional FRP biases, whilst Section 5 describes use of the FRP-PIXEL product for
193 parameterising wildfire emissions at high temporal resolution within the ECMWF Integrated
194 Forecasting System (IFS) atmospheric chemistry and transport model that is used to deliver
195 the CAMS (<http://www.copernicus-atmosphere.eu/>).

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197 **2. METEOSAT SEVIRI FRP PRODUCTS FROM THE EUMETSAT LSA SAF**

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199 The Spinning Enhanced Visible and Infrared Imager (SEVIRI) onboard the Meteosat Second
200 Generation (MSG) series of satellites acquires observations every 15 minutes over the Earth’s
201 disk centred on West Africa, including in MWIR and long-wave infrared (LWIR) wavebands.

202 Data collected in these wavebands enables the detection of active fires using the type of
203 algorithms detailed in Li *et al.* (2001), and this has been exploited for the development of a
204 number of geostationary active fire products based on SEVIRI observations. One of these is
205 the Meteosat SEVIRI FRP-PIXEL family of products that has been produced operationally
206 since 2008 by the European Organisation for the Exploitation of Meteorological Satellites
207 (EUMETSAT) LSA SAF (<http://landsaf.meteo.pt>). The LSA SAF Meteosat SEVIRI FRP
208 product suite currently contains two components; (i) the FRP-PIXEL product which records
209 active fire information at the full temporal and spatial resolution of SEVIRI, and (ii) the FRP-
210 GRID product that provides a spatio-temporal summary of the FRP-PIXEL product, along
211 with statistical adjustments for cloud cover and for the regional biases caused by the lowest
212 FRP fires being undetectable with SEVIRI.

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214 **2.1 FRP-PIXEL Product Summary**

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216 The Level 2 FRP-PIXEL product provides information on the spatial location, thermal
217 properties, atmospherically corrected FRP and uncertainty of pixels containing actively
218 burning fires every 15 minutes over Europe, North and South Africa and part of South
219 America (Figure 1), based upon an extended version of the geostationary Fire Thermal
220 Anomaly (FTA) active fire detection algorithm of Roberts and Wooster (2008) and a set of
221 FRP estimation routines that are together fully detailed in Wooster *et al.* (2015). The structure
222 of the FRP-PIXEL product is also detailed in Wooster *et al.* (2015), and follows the heritage
223 of the MODIS active fire products (Giglio *et al.*, 2003) but separated into two discrete files,
224 (i) the FRP-PIXEL ‘Quality Product’ file, a 2D dataset that provides information on the status
225 of each SEVIRI pixel in the geographic region under study (e.g. whether it is a cloud, water,
226 or land pixel, whether it has been classed as containing an active fire etc; Wooster *et al.*,
227 2015), and (ii) a smaller ‘List Product’ file that provides detailed information of pixels in
228 which active fires have been detected (e.g. including the pixel MWIR and LWIR brightness
229 temperatures, FRP, FRP uncertainty, latitude and longitude, and some of the metrics derived
230 during algorithm application such as background window size and estimated MWIR band
231 atmospheric transmissivity).

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233 **2.2 FRP-GRID Product Summary**

234 The Level 3 FRP-GRID product is a spatio-temporal summary of a series of FRP-PIXEL
235 products. At the regional scale, the FRP-PIXEL product provides a minimum estimate of the
236 FRP being emitted from landscape fires due to (i) the inability of SEVIRI to detect the lowest
237 FRP active fire pixels (Roberts and Wooster, 2008; Freeborn *et al.*, 2014a) and (ii) the fact
238 that the assessment of the highest FRP fires suffer from some effects of pixel saturation and
239 other SEVIRI-specific observation characteristics (Wooster *et al.*, 2015). In order to try
240 mitigate these impacts on regional FRP estimation, the LSA SAF processing chain generates
241 the Level 3 FRP-GRID product by temporally accumulating active fire pixels and associated
242 information from the maximum of four FRP-PIXEL products obtained each hour, grids this
243 information within 5.0° grid cells, and applies a set of regional bias adjustment factors.
244 Wooster *et al.* (2015) describe the procedures in full, and an evaluation of the resulting
245 product performance is presented in Section 4 herein.

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247 **3. FRP-PIXEL PRODUCT PERFORMANCE EVALUATION**

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249 Here we validate the SEVIRI FRP products using MODIS active fire data. The relatively
250 high spatial resolution of MODIS' active fire observations (1 km at nadir), and the high
251 saturation temperature of its MWIR channel (~ 500 K), coupled with its better than daily
252 availability from two platforms (the Terra and Aqua satellites), ensure that the MODIS active
253 fire product (Kaufman *et al.*, 1998; Giglio *et al.* 2003) is the standard against which
254 geostationary active fire products are compared when performing product evaluations (Xu *et*
255 *al.*, 2010; Schroeder *et al.*, 2014; Roberts and Wooster, 2014). Here we use near-
256 simultaneously recorded Collection 5 MODIS active fire detections (MOD14 from Terra and
257 MYD14 from Aqua) as the basis of our LSA SAF SEVIRI FRP Product performance
258 evaluations. For completeness, we also include a series of other SEVIRI active fire products,
259 derived using different algorithms and methods to the LSA SAF FRP products, within the
260 same comparison.

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262 **3.1 SEVIRI FRP-PIXEL and MODIS Active Fire Product Intercomparison**

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264 **3.1.1 Methodology**

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266 The FRP-PIXEL product is generated in separate files for the four LSA SAF geographic
267 regions whose boundaries as shown in Figure 1 (Wooster *et al.*, 2015). We conducted the
268 FRP-PIXEL product performance evaluation using one week of operational FRP-PIXEL data
269 collected by Meteosat-9 in each of the LSA SAF regions, together with the matching MODIS
270 MOD14 and MYD14 products. The FRP-PIXEL products of each region were derived from
271 672 separate SEVIRI imaging slots taken every 15 minutes over a 168 hour period in 2008,
272 with the timing of the products for each geographic region being that corresponding to its
273 peak fire period; December in Northern hemisphere Africa, and August in the remaining
274 three regions. Freeborn *et al.* (2014a) previously performed an evaluation of the FRP-
275 PIXEL product over the Central African Republic (CAR), finding that the products active fire
276 detection errors of commission reduced greatly (from 24% to 9%) when the MODIS active
277 fire detections being used as the independent data source were limited to a $\pm 18.6^\circ$ scan angle.
278 This is due to the increasing pixel area of MODIS with increasing scan angle, which results
279 in MODIS itself showing progressively greater active fire errors of omission towards the scan
280 edge (Freeborn *et al.*, 2011). When comparing large-scan angle MODIS data to active fire
281 detections made from SEVIRI, it may well be that MODIS actually misses fires that the
282 SEVIRI FRP-PIXEL product actually correctly detects, but in the absence of any other
283 information a SEVIRI-to-MODIS performance evaluation would record this as a SEVIRI
284 commission error. Therefore, to mitigate against the impact of MODIS' decreasing ability to
285 detect low FRP pixels as MODIS scan angle increases, yet balance this with the need to
286 maintain sufficient data in our intercomparison, MODIS observations are limited to those
287 within $\pm 30^\circ$ scan angle within which MODIS' pixel area increases up to a maximum of 1.7
288 km² from the nadir 1 km² size (Freeborn *et al.*, 2011). For each LSA SAF geographic region
289 we compared the active fire detections made by MODIS within this scan angle limit to the
290 active fire pixels present in the FRP-PIXEL product subsets covering the same area and
291 collected at the closest matching time (generally this will be within ~ 6 minutes of the
292 MODIS overpass). To deal with the differing MODIS and SEVIRI pixel sizes, we remapped
293 the MODIS active fire data to SEVIRI's imaging grid. SEVIRI's per-pixel point spread
294 function (PSF) at the sub-satellite point extends more than 5 km radially from the pixel centre
295 (Wooster *et al.*, 2015), so following the approach of Freeborn *et al.* (2014a) we evaluated
296 active fire detection performance using the presence of an active fire pixel within a 3×3
297 pixel window centred on the active fire pixel under investigation within this grid as a
298 matched detection. For SEVIRI errors of commission we searched for the presence of a

299 matching MODIS pixel for each SEVIRI active fire pixel studied, whilst the reverse analysis
300 was conducted for SEVIRI errors of omission.

301

302 When undertaking the SEVIRI-to-MODIS FRP intercomparison, this was conducted on a 'per
303 fire' basis by clustering the MODIS and SEVIRI per-pixel FRP measurements for the same
304 fire into 'fire pixel clusters' on the basis of spatial closeness (e.g. Zhukov *et al.*, 2006;
305 Roberts and Wooster; 2008; Xu *et al.*, 2011). The MODIS FRP measurements were derived
306 using the same MIR radiance approach to FRP derivation as is used for SEVIRI (Wooster *et*
307 *al.*, 2005; 2015), and as will be employed in the forthcoming Collection 6 MODIS Active fire
308 products (L. Giglio, *pers comm.*). We atmospherically corrected these MODIS FRP estimates
309 using the same procedure applied when generating the FRP-PIXEL product, detailed in
310 Wooster *et al.* (2015), based on an atmospheric transmission look-up-table (LUT) developed
311 using the MODTRAN5 and RTMOM atmospheric radiative transfer models (Berk *et al.*
312 2005; Govaerts, 2006) and ECMWF forecasts of total water column vapour (interpolated
313 from an original spatial and temporal resolution of 0.5° and 3 hours). Generally, the
314 adjustment for the MWIR atmospheric transmission made to the SEVIRI FRP data was larger
315 than that for MODIS, because the SEVIRI MWIR spectral band used in FRP derivation is
316 significantly wider than that of MODIS and extends into spectral regions having much lower
317 atmospheric transmission (Wooster *et al.*, 2015).

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319 **3.1.2 Results**

320 The results of our SEVIRI-to-MODIS per-fire active fire detection intercomparison are
321 detailed in Table 1, Columns 3 and 4. Taking the north African (NAfr) LSA SAF region as
322 the first example, this is closest region to the Meteosat sub-satellite point and therefore offers
323 the highest degree of SEVIRI spatial detail and smallest pixel area. We find that 65% of
324 MODIS' active fire detections made within this region had no corresponding SEVIRI-
325 detected active fire within the closest matching (in time) FRP-PIXEL product file. This
326 'active fire error of omission' rate is higher than the 54% found previously by Roberts and
327 Wooster (2008) over the same geographic area, but using the prototype SEVIRI FTA
328 algorithm, a different period satellite (Meteosat-8) and different time period. The reverse
329 analysis showed that 9% of the Meteosat-9 FRP-PIXEL product active fire pixels had no
330 matching MODIS active fire pixel, a very similar commission error to that found by Roberts
331 and Wooster (2008) for the prototype SEVIRI FTA algorithm over the same North African
332 region.

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334 SEVIRI FRP-PIXEL product active fire detection performance metrics for the other three
335 LSA SAF geographic regions are also shown in Table 1, and indicate a substantially
336 increased active fire omission error in South America and Europe compared to the two
337 African regions. This is in part due to SEVIRI's increased pixel area and greater view zenith
338 angle (and thus greater atmospheric attenuation) over the former two regions which are
339 further from the Meteosat sub-satellite point (SSP). South America and Europe have a mean
340 view zenith angle of 59° and 54° respectively and this significantly raises the minimum per-
341 pixel FRP detection limit in these areas (Figure 1), meaning a greater proportion of lower
342 FRP landscape-scale fires fail to be detected by SEVIRI in comparison to the African
343 regions.

344

345 Figure 2 and Table 1 (Column 5) present the results of the SEVIRI-to-MODIS per-fire FRP
346 intercomparison. Again taking north Africa as an example, on a per-fire basis there is a strong
347 correlation between the FRP measures made by SEVIRI in this region and by MODIS
348 (Figure 2; top left) with over half (53%) of the SEVIRI-to-MODIS matchups having an FRP
349 difference less than 20%. In fact, a strong level of agreement exists for all regions in terms of
350 a low FRP bias between the two datasets, but there is significant scatter. Overall, we find that
351 57% of the FRP-PIXEL products per-fire FRP measures are within 20% of those of MODIS,
352 and this level of agreement remains consistent even when limiting the comparison to fires
353 with $FRP > 50$ MW to ensure we focus on the FRP range where SEVIRI does not clearly
354 underdetect active fires (e.g. Wooster *et al.*, 2015). This suggests that the degree of variability
355 seen between the near-simultaneous measures of per-fire FRP provided by SEVIRI and
356 MODIS is not driven only by active fire pixel errors of omission (e.g. by SEVIRI failing to
357 detect some of the low FRP fire pixels making up a fire cluster), but maybe impacted by other
358 aspects of the FRP measurement process coming from:

359 i) uncertainty in the ambient background signal used to calculate the FRP for each
360 fire pixel with SEVIRI and MODIS data (Wooster *et al.*, 2003; 2005; Zhukov *et*
361 *al.*, 2006; Wooster *et al.*, 2015);

362 ii) the ± 6 minute time difference between corresponding MODIS and SEVIRI
363 observations of the same fire, during which changes in the active fire
364 characteristics that determine the fires FRP may occur;

- 365 iii) the uncertainties present in the MODIS FRP measures coming from the sub-pixel
366 location of the fire with respect to the sensor instantaneous field of view, recently
367 been characterised by Freeborn *et al.* (2014c), and with SEVIRI also from certain
368 image processing operations conducted during the production of SEVIRI level 1.5
369 data (Wooster *et al.*, 2015).
- 370 iv) effects of sensor saturation of SEVIRI's MWIR channel at high FRP fire pixels.

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372 To place the magnitude of the scatter seen in Figure 2 between the SEVIRI FRP-PIXEL
373 product's FRP measures and those from the MODIS MOD14 and MYD14 products into
374 context, during the recent Freeborn *et al.* (2014c) study, multiple MODIS FRP measurements
375 of the same fires made almost simultaneously ($\ll 1$ sec difference) in consecutive MODIS
376 scans were compared and some large scan-to-scan differences found. An approximately
377 normally distributed percentage difference between the two FRP measures, with a mean close
378 to zero but a standard deviation of 26.6% was determined from a large dataset of such
379 matchups (Freeborn *et al.*; 2014c). Further investigation showed that the scan-to-scan
380 differences were largely controlled by the differing sub-pixel location of the fire within the
381 different MODIS scans, a subject previously indicated as potentially significant with regard
382 to FRP observations made by the BIRD Hot Spot Recognition Sensor (HSRS; Zhukov *et al.*,
383 2006). Freeborn *et al.* (2014c) also showed that the scatter reduced as fire clusters containing
384 increasing numbers of active fire pixels were compared, since the sub-pixel location effects
385 would increasingly cancel out as more pixels were included in the instantaneous scan-to-scan
386 FRP inter-comparison. Nevertheless, given the degree of scatter found between even almost
387 totally simultaneous MODIS FRP observations of the same fire made at the same scan angle
388 and pixel area by Freeborn *et al.* (2014c), it is unsurprising that higher levels of scatter arises
389 when comparing FRP data from different sensors (Figure 2; Table 1), where pixel areas, scan
390 angles and imaging time differences are all somewhat greater. Nevertheless, our results
391 indicate that when the FRP-PIXEL product and the MODIS active fire products both detect
392 the same fire, the FRP reported by the two products show small biases. Over the four LSA
393 SAF regions, 391 individual active fire 'clusters' detected by MODIS and SEVIRI were
394 compared and 76% (298 fire clusters) had an FRP within 30% of that measured by MODIS.
395 Given the uncertainties on per-fire FRP retrievals, the LSA SAF target accuracy of the FRP-
396 PIXEL product is specified as, on a per-fire basis, 70% of the SEVIRI-retrieved FRP values
397 being within 50% of those simultaneously measured by MODIS. Therefore, the FRP-PIXEL

398 product significantly exceeds this specification, and actually approaches that specified by the
399 LSA SAF 'optimal accuracy' definition (70% of retrieved SEVIRI-retrieved FRP value being
400 within 20% of the MODIS-derived value on a per-fire basis).

401

402 Whilst our per-fire FRP inter-comparison has indicated a comparatively low degree of FRP
403 bias between the FRP-PIXEL and MODIS MOD14/MYD14 FRP records of the same
404 successfully detected active fires, there remains a significant degree of regional-scale FRP
405 underestimation by the FRP-PIXEL product due to the inability of the coarser SEVIRI
406 observations to detect the lowest FRP component of a regions fire regime (Roberts and
407 Wooster, 2008). Therefore when data from both the MOD14/MYD14 and near-simultaneous
408 matching FRP-PIXEL products covering the same area (i.e. the area covered by MODIS
409 within a $\pm 30^\circ$ scan angle) are compared, SEVIRI reports a lower cumulative 'regional' FRP
410 than does MODIS (Table 1, Column 6). This effect is directly related to SEVIRI's
411 aforementioned active fire errors of omission, an effect that is magnified in geographic
412 regions in which SEVIRI mostly observes at higher view zenith angles. Figure 3 again uses
413 the example of the North African region, where the slope of the linear of best fit to the
414 regional FRP totals recorded near simultaneously in the FRP-PIXEL product and the MODIS
415 active fire products is 0.65. This indicates the relatively small, but certainly not insignificant,
416 impact of the FRP-PIXEL products active fire errors of omission in this region, which is that
417 closest to the Meteosat sub-satellite point (SSP) and thus in which the FRP-PIXEL products
418 active fire errors of omission are lowest (Table 1). Regional FRP underestimation increases
419 away from the SSP, and appears particularly extreme in the European LSA SAF geographic
420 region in our inter-comparison. This is in part a result of a large proportion of active fires
421 being present in Eastern Europe during our inter-comparison period, where the SEVIRI view
422 zenith angle exceeds 60° . With respect to regional FRP characterisation, the performance of
423 the FRP-PIXEL product for southern European fires, which lie relatively close to the
424 Meteosat SSP, is likely to be much closer to that of the North African geographic region.
425 Section 5 includes study of the August 2007 Greek Fires as a case study example of fires in
426 this region.

427

428 **3.2 Inter-comparison of Alternative SEVIRI Active Fire Products**

429 Since the launch of Meteosat Second Generation in 2002, a number of studies have used
430 different algorithms to study active fires with SEVIRI observations (e.g. Calle *et al.*, 2009;
431 Amraoui *et al.*, 2010). This has led to certain other routinely generated SEVIRI active fire

432 products being available, in addition to the LSA SAF FRP-PIXEL product focused upon
433 herein. These alternative SEVIRI-based products include the Wildfire Automated Biomass
434 Burning Algorithm (WFABBA, version 6.5) product (based on the WFABBA fire detection
435 algorithm of Prins *et al.*, 1998), the Fire Detection and Monitoring (FDeM) product (Amraoui
436 *et al.*, 2010), and the Active Fire Monitoring (FIR) product (Joro *et al.*, 2008), each of which
437 essentially generate active fire pixel detections from SEVIRI level 1.5 data as does the FTA
438 algorithm used within the FRP-PIXEL product processing chain (Wooster *et al.*, 2015).

439

440 **3.2.1 Methodology**

441 We assessed the active fire detection performance of the FRP-PIXEL product in comparison
442 to the three main alternative SEVIRI active fire products, and to the MODIS
443 MOD14/MYD14 active fire products using the SEVIRI-to-MODIS intercomparison
444 methodology detailed in Section 3.1. The inter-comparison was conducted using all available
445 FRP-PIXEL products collected over the southern African LSA SAF geographic region in
446 August 2014 (a total of 2959), a month when fires are highly prevalent in southern Africa.
447 For comparison we collected all the available files from the alternative SEVIRI active fire
448 data products, a total of 2949 for WFABBA (Prins *et al.*, 1998), 2963 for FDeM product
449 (Amraoui *et al.*, 2010), and 2914 for FIR (Joro *et al.*, 2008). Due to various data collection
450 and processing issues, not all products were available for all SEVIRI source scenes, as is
451 evident from the slightly different (max 1.5%) number of products in each case. Also, each
452 product has different classes of output, and the FIR product for example classifies fire pixels
453 as either active fires or potential active fires. In this comparison we focus on only confirmed
454 active fire detections. Similarly, the WFABBA product 'filters' active fire pixels detected only
455 once in a 24 hour period and classes them less likely to be fires, aiming to reduce the number
456 of false alarms detected and minimise effects due to sunglint. In our analysis of the
457 WFABBA active fire product we therefore include four variations of the WFABBA dataset.
458 These are the inclusion of all fire detections, all the WFABBA 'filtered' detections (where
459 pixels only detected once during 24 hrs are removed) and the WFABBA 'filtered' detections
460 keeping only 1) the high probability fires (WFABBA flags 0 to 3) and 2) high and medium
461 probability fires (WFABBA flags 0 to 4).

462

463 For comparison to the SEVIRI-derived active fire products we used 544 Collection 5 MODIS
464 MOD14/MYD14 active fire products, acquired over southern hemisphere Africa. To facilitate
465 comparison with the SEVIRI products, we subset the SEVIRI products to cover the same area

466 as the MODIS products and selected the set of temporally coincident MODIS active fire
467 pixels that matched with SEVIRI active fire products in time (± 6 minutes). The MODIS
468 active fire pixels were remapped to SEVIRI's imaging grid and had their FRP
469 atmospherically corrected using the same approach as detailed in Section 3.1 to match the
470 methodology used to generate the FRP values within the FRP-PIXEL product. SEVIRI's per-
471 pixel point spread function (PSF) at the sub-satellite point extends more than 5 km radially
472 from the pixel centre (Wooster *et al.*, 2015), so following the approach of Freeborn *et al.*
473 (2014a) we evaluated the SEVIRI-derived active fire detection performances against the
474 presence of MODIS active fire pixels within a 3×3 pixel window centred on the SEVIRI
475 active fire pixel under investigation. Again, as with Section 3.1 the comparison was restricted
476 to MODIS active fire detections made within a $\pm 30^\circ$ scan angle (Freeborn *et al.*, 2014a).

477

478 **3.2.2 Results**

479

480 The MOD14/MYD14 products contained 286,000 active fire detections during August 2014
481 over the southern African LSA SAF geographic region, and once remapped onto the SEVIRI
482 imaging grid, this equated to 112,576 pixels. Within the specified ± 6 minute MODIS to
483 SEVIRI imaging time limit, the FRP-PIXEL product detects 33,414 active fire pixels and
484 29,037 of these are also detected by the remapped MOD14/MYD14 data. This corresponds to
485 a SEVIRI active fire pixel detection commission error of 13%. Using the same SEVIRI level
486 1.5 data, the WFABBA, FDeM and FIR active fire products detect 13,008, 7664 and 7151
487 active fire pixels respectively, and of these, 12,284, 7260 and 6730 are coincident with a
488 MODIS active fire detection respectively. Hence, the active fire pixel errors of commission
489 are 5.5%, 5.2% and 5.8% respectively for these three SEVIRI-derived products, active fire
490 errors of commission rates around half those of the FRP-PIXEL product. The WFABBA
491 filtered dataset also stratifies active fire detections according to their detection confidence.
492 We analysed the fire detection performance of the WFABBA filtered dataset by just
493 including medium and high probability fires (flags 0-4) and only high probability fires (flags
494 0-3). These filtered WFABBA datasets detect 9736 (flags 0-4) and 8832 (flags 0-3) active
495 fires and of which 9369 and 8496 are coincident with MODIS active fire pixels. This equates
496 to a reduced commission rate of 4 % for both whilst the omission rate increases to 87% and
497 88% respectively.

498

499 A summary of the SEVIRI active fire product intercomparison results is given in Table 2.
500 The ~13% active fire error of commission rate for the FRP-PIXEL product found here and by
501 Freeborn *et al.* (2014a) is higher than the ~8% found by Roberts and Wooster (2008, 2014)
502 using the FTA algorithm prototype. The disparity is in part due to the differing way in which
503 the operational FTA algorithm applies a high-pass spatial filter to screen out certain false
504 alarms from the potential fire pixel set (Roberts and Wooster, 2008). As discussed in the
505 companion paper that describes the fire thermal anomaly (FTA) algorithm in detail (Wooster
506 *et al.*, 2015), the current LSA SAF implementation of the FTA algorithm (whose
507 performance results are reported in Table 2) has some characteristics that are open to being
508 updated, namely whether dynamic or static thresholds are used in the spatial filter applied at
509 the end of the potential fire pixel (PFP) stage, and whether application of the cloud-edge
510 mask is really necessary (see Wooster *et al.*, 2015 for details). We have tested these
511 adaptations using one month of data (July, 2015) collected over the same Southern African
512 region used to perform the evaluation reported in Table 2, and have compared the results to
513 those from contemporaneous MODIS overpasses. Results show that with both adaptations
514 applied, the error of commission of the adjusted FTA algorithm compared to MODIS reduce
515 from the current 14% to 12%, whilst the error of omission remains at 70%. These two
516 adaptations are therefore now being implemented in the operational FTA processing chain.

517

518 The minimum FRP detection limit of an active fire detection algorithm is directly
519 proportional to the pixel area (Roberts and Wooster, 2008; Wooster *et al.*, 2015). If the active
520 fire detection algorithm of Giglio *et al.* (2003) used to generate the Collection 5
521 MOD14/MYD14 MODIS active fire products were applied to SEVIRI level 1.5 imagery, the
522 minimum FRP detection limit at the Meteosat SSP would be 70 - 80 MW, around 10× the
523 minimum FRP detection limit of the MOD14/MYD14 active fire products due to SEVIRI's ~
524 10× larger nadir view pixel area. By contrast, the design of the FRP-PIXEL product attempts
525 to lower the minimum FRP detection limit significantly below this by detecting active fire
526 pixels whose radiometric signals in the MWIR, LWIR and MWIR-LWIR are raised even
527 quite minimally above that of the ambient background (Roberts and Wooster, 2008). By
528 exploiting a variety of spectral and spatial thresholds and contextual processing methods, the
529 FTA algorithm is sometimes capable of detecting SEVIRI active fire pixels having an FRP
530 down to ~ 20 MW at the Meteosat SSP. Nevertheless, statistics show that for active fire
531 pixels below ~ 50 MW the active fire pixel count is underestimated more by SEVIRI
532 compared to the performance above this threshold (Freeborn *et al.*, 2009). However, by

533 restricting our comparison of the FRP-PIXEL product to active fire pixels having FRP \geq 50
534 MW the active fire pixel error of commission of the FRP-PIXEL product fell only slightly to
535 12%, indicating that false alarms are not necessarily dominated by these low FRP fire pixels.

536

537 Whilst our analysis has shown somewhat higher active fire errors of commission for the FRP-
538 PIXEL product compared to the WFABBA, FIR and FDeM products, we find the latter have
539 much higher active fire errors of omission. Figure 4 illustrates the variation seen in active fire
540 pixel detection performance between the different SEVIRI products for one imaging slot (21st
541 August, 2014, 13:15 UTC). In this example, the FRP-PIXEL, WFABBA, FDeM and FIR
542 products detect 1249, 686, 346 and 312 active fire pixels respectively, illustrating a
543 substantial degree of difference. Furthermore, the fire diurnal cycle retrieved using the four
544 products from a single day of data shown in Figure 5 highlights the fact that these differences
545 are maintained over the course of the day, leading to very large variations in the total count of
546 active fires detected on a daily basis.

547

548 When compared to the matching MODIS active fire pixel detections, the WFABBA, FDeM
549 and FIR products contain active fire pixel detections that match 16%, 8% and 5%
550 respectively of the MODIS active fire pixels, whereas the figure for the LSA SAF FRP-
551 PIXEL product is substantially higher at 23%. Georgiev and Stoyanova (2013) previously
552 undertook a limited study of the FRP-PIXEL product performance in south-east Europe, and
553 determined that it provided a marginally higher active fire detection efficiency than did the
554 FIR product. Using a wider area of a region with many more fires covering a wide FRP range
555 we find much larger differences, and indeed the FIR product appears to provide the worst
556 performance of all the four SEVIRI products in terms of its ability to detect active fire pixels.
557 Restricting the FRP-PIXEL active fire detections to those pixels \geq 50MW, the FRP-PIXEL
558 product still detects 9896, 14864, 15896 more active fire pixels that are coincident with
559 MODIS than do the WFABBA, FDeM and FIR products respectively. This corresponds to
560 active fire pixel count differences in excess of \sim 175%, even when limiting the detection
561 regime to an FRP range where all the SEVIRI-derived products should in theory be able to
562 show a reasonably strong performance.

563

564 Our analysis of the operational FTA algorithm's performance has shown an active fire pixel
565 error of omission rate of 77% when comparing the FRP-PIXEL product to simultaneously
566 collected MODIS active fire pixels. This omission error is similar to that previously found by

567 Roberts and Wooster (2014) and Freeborn *et al.* (2014a) for the FTA algorithm, and primarily
568 results from the $\sim 10\times$ larger nadir pixel area of SEVIRI than MODIS. In comparison, the
569 errors of omission for the WFABBA, FDeM and FIR products are significantly greater, at
570 84%, 92% and 95% respectively. Restricting the comparison to those FRP-PIXEL product
571 pixels having a SEVIRI-retrieved FRP ≥ 50 MW, which SEVIRI-based algorithms should be
572 able to detect quite readily, reduces the FRP-PIXEL product active fire pixel error of
573 omission to $\sim 50\%$ in comparison to MODIS.

574

575 In terms of FRP measurements, the ratio between the total cumulative FRP measured within
576 the same southern African geographic region covered by the near-simultaneous FRP-PIXEL
577 and MODIS active fire products is 0.48. This represents a lower underestimate of FRP than
578 might be expected from the FRP-PIXEL omission error rate, and the reason is that the
579 unidentified active fire pixels are predominantly those having low FRP values ($\ll 50$ MW).
580 Restricting the analysis to only those active fires that are correctly identified by both products
581 provides a cumulative FRP ratio of 0.96, showing an excellent agreement in the regional FRP
582 assessment when only active fires successfully detected by both sensors are taken into
583 account. This agrees with the strong-performance in terms of per-pixel FRP assessment seen
584 in Section 3.1.

585

586 Certain previous studies evaluating the FTA algorithm or prototype FRP-PIXEL datasets
587 (e.g. Roberts and Wooster, 2008; Xu *et al.*, 2010; Roberts *et al.*, 2014) have applied an
588 alternative approach when comparing these to MODIS active fire datasets. Rather than the
589 per-pixel approach to inter-comparison applied above, Freeborn *et al.* (2014a) grouped active
590 fire pixels into contiguous clusters based on their spatial closeness to other active fire pixels
591 in the same manner as that described in Section 3.1 for the per-fire FRP intercomparison. To
592 strengthen the link between this work and these previous findings, active fire pixels within
593 each of the active fire products tested were also clustered into spatially contiguous groupings,
594 and the active fire detection errors of commission and omission calculated based on a 'fire
595 cluster' basis instead of for the individual fire pixels. We used a similar strategy for this inter-
596 comparison as used at the pixel scale, specifically searching the surrounding 3×3 pixels for
597 matching active fires in the products to be compared. Using this 'clustering' approach, we
598 found the error rates of the FRP-PIXEL product to be higher than those determined using the
599 per-pixel approach, with errors of commission and omission of 19% and 85% respectively
600 when compared to the matching MOD14/MYD14 products. Again, if only those fire clusters

601 having an FRP ≥ 50 MW are included, these reduce to 18% and 57% respectively,
602 demonstrating in particular a high success of active fire detection in this region of the FRP
603 regime. Using the same approach with the alternative SEVIRI active fire products, we find
604 that the WFABBA products also show slightly higher errors of omission and commission
605 than when examined at the fire cluster scale, now being 7% (commission) and 90%
606 (omission) respectively in comparison to the MODIS product. The error rates for FDeM and
607 FIR products are, however, very similar when examined on a fire cluster basis to the results
608 on a per fire pixel basis, with a commission rate of 6% for both and an omission rate of 96%
609 and 95% for FDeM and FIR respectively.

610

611 **4. FRP GRIDDED Product Evaluation**

612

613 **4.1 Method**

614 Section 2.2 detailed how the LSA SAF SEVIRI FRP-GRID product uses a series of
615 regionally-specific bias adjustment factors (α) to upwardly adjust regional FRP estimates for
616 e.g. the impact of undetected low FRP fire pixels. The aim is to produce an hourly, regional
617 FRP estimate that has minimal bias compared to if MODIS had been able to view the same
618 area at the same time. Full details of the FRP-GRID processing chain are included in Wooster
619 *et al.* (2015). We evaluated the performance of the applied bias adjustments using a
620 validation dataset composed of coincident SEVIRI and MODIS observations collected
621 between May 2008 and May 2009 in each of the four LSA SAF geographic regions.
622 Boundaries of the relevant MODIS level 2 swath products were used to identify all MODIS
623 granules that intersected each region during the year-long study period, and fire pixels subset
624 from the full MODIS ‘MOD14’ and ‘MYD14’ products using six, non-overlapping 5.0° grid
625 cells arranged in the centre of each MODIS granule (Figure 6). Active fire pixels detected by
626 MODIS outside of this region of interest were discarded and not used during the analysis.
627 The sampling design ensured complete coverage of the 5.0° grid cells regardless of the
628 MODIS ground track, and also mitigated the effects of image distortion at the edge of the
629 MODIS swath. All MODIS granules collected during the year-long study period were
630 matched to the most concurrent SEVIRI image, always within ± 6 minutes of each other. The
631 same 5.0° grid cells inscribed within the MODIS granule were then used to clip SEVIRI fire
632 pixels from both (i) the most coincident SEVIRI timeslot, and (ii) the three SEVIRI timeslots
633 immediately preceding the MODIS overpass. Again, active fire pixels detected by SEVIRI

634 outside of this region of interest were not included in the analysis. Entire grid cells were also
635 discarded if three consecutive SEVIRI imaging timeslots could not be retrieved prior to the
636 SEVIRI timeslot concurrent with the MODIS overpass (i.e., if four imaging timeslots were
637 not available). This sampling design not only permitted a genuine comparison of coincident
638 SEVIRI and MODIS observations of FRP, but also mimicked the hourly temporal resolution
639 of the gridded FRP product.

640

641 After the SEVIRI and MODIS fire pixels were spatially and temporally accumulated, half of
642 the concurrent and collocated 5.0° grid cells in each region were used to generate the
643 validation dataset. Relationships between the atmospherically corrected FRP observed by
644 SEVIRI and MODIS were directly compared among the 5.0° grid cells contained within this
645 dataset. Rather than using the instantaneous FRP observed by SEVIRI at the timeslot most
646 concurrent with the MODIS overpass however, the mean FRP generated from the SEVIRI
647 data available over the preceding hour was used instead to correspond more appropriately
648 with the hourly resolution of the FRP-GRID product.

649

650 **4.2 Results**

651 A complete summary of the FRP-GRID product validation results derived from the
652 methodology detailed in Section 3.1 is provided in Table 3. Application of the weighted least
653 squares (WLS) coefficients in northern and southern Africa to the validation dataset yielded
654 unbiased estimates of the instantaneous FRP that would have been measured by MODIS at
655 5.0° spatial resolution (e.g., Figure 7a, Table 3). As expected, however, the region-specific
656 coefficients for South America (Same) and Europe (Euro) geographic regions did not perform
657 as well. Although the adjustment procedure provides an unbiased estimate of the FRP that
658 MODIS would have measured in South America, the coefficient of determination (r^2)
659 indicates that confidence in the predictive capability of the model is limited at this spatial and
660 temporal resolution. As a caveat, however, the validation results in South America and
661 Europe are influenced by observations when SEVIRI did not detect a single active fire pixel
662 within a 5.0° grid cell during the hour. After removing 5.0° grid cells that only contained an
663 active fire pixel detected by a single sensor (i.e., thereby forcing a comparison between
664 observations in which both SEVIRI and MODIS viewed a fire) the r^2 improved to 0.43 in the
665 South America region. Furthermore, by removing a lone outlier improved the correlation

666 coefficient slightly further to 0.55. Likewise for Europe, only including observations in which
667 SEVIRI and MODIS simultaneously detected an active fire pixel yielded an r^2 of 0.31.

668
669 Of course, the linear bias adjustments applied in the FRP-GRID product only capture the
670 underlying macroscopic features of the sensor-to-sensor relationships, and do not account for
671 any temporal variability in the SEVIRI-to-MODIS ratios of FRP induced by diurnal or
672 seasonal fluctuations in fire activity (e.g. as seen in Freeborn *et al.*, 2009). By deriving
673 different regression coefficients for each of the four LSA SAF regions, however, the FRP-
674 GRID algorithm does account for broad spatial differences in the sensor-to-sensor
675 relationships that potentially arise from (i) differences in fire regimes, and (ii) differences in
676 SEVIRI view zenith angles.

677
678 To assess the predictive capability of the bias adjustment factors at broader spatial and
679 temporal scales than simply the hourly/5° spatio-temporal resolution of the FRP-GRID
680 product, the SEVIRI and MODIS validation data were accumulated over weekly intervals
681 and comparisons were performed at scale of the LSA SAF geographic regions. Figure 7b
682 illustrates that in southern Africa, the bias adjustment factors used to generate the FRP-GRID
683 product consistently underestimate the weekly sum of FRP measured by MODIS across this
684 region, and that these results are typical of all four regions (Table 3). Again, this systematic
685 underestimation is partly attributed to the challenge of performing a bias adjustment when
686 SEVIRI does not detect a fire pixel (i.e. the linear bias adjustment coefficient is then applied
687 to an FRP of zero). Nevertheless, the weekly/regional biases shown in Table 3 could in turn
688 be used to adjust the SEVIRI FRP-GRID product measurements to deliver unbiased estimates
689 of the FRP that would have been measured by MODIS at the regional/weekly scale.

690

691 **5. EXAMPLE APPLICATION OF THE LSA SAF METEOSAT SEVIRI FRP** 692 **PRODUCTS IN THE COPERNICUS ATMOSPHERE MONITORING SERVICE** 693 **(CAMS)**

694

695 **5.1 Introduction to FRP-PIXEL Product use in Atmospheric Transport Models**

696 From the FRP-PIXEL product evaluation and inter-comparison conducted in Section 3 it is
697 apparent that the FRP-PIXEL product detects a larger proportion of the ‘true’ landscape-scale
698 fire activity than do alternative SEVIRI-derived active fire products, albeit with a higher

699 commission rate. That evaluation also highlighted the failure of the FRP-PIXEL product to
700 detect many of the actively burning fires that MODIS would detect, particularly the lower
701 FRP fires, resulting in an overall omission rate of 77% over the four geographic regions
702 (Table 1). The degree of difference between geostationary and polar-orbiting active fire
703 products does, however, vary with factors such as geographic location, season and time of
704 day (which all influence the type of fire regime and its subcomponents being sampled),
705 sensor viewing geometry, land cover heterogeneity, fire detection algorithm and the quality
706 of ancillary data such as cloud masks (Freeborn *et al.*, 2014a; Schroeder *et al.*, 2008; Roberts
707 and Wooster, 2014; Xu *et al.*, 2010). Indeed, under some conditions, geostationary active fire
708 datasets compare rather favourably against those derived from polar-orbiting sensors.
709 Georgiev and Stoyanova (2013) analysed a series of short-lived wildfires in south-eastern
710 Europe with the FRP-PIXEL product, and found the higher temporal resolution of SEVIRI
711 resulted in a 50% lower active fire omission rate than did the use of MODIS. Wooster *et al.*
712 (2015) also demonstrate that, taking the Central African Republic as an example, most fires
713 detected by the MODIS are detected by the SEVIRI FTA algorithm, just not necessarily at
714 the same time as the fire is detected by MODIS. Indeed, the high temporal frequencies
715 offered by geostationary observations can enable the diurnal fire cycle and related short-term
716 changes in fire activity to be far better characterised than with polar-orbiting data, and this
717 ability is starting to be exploited to parameterise wildfire emissions in atmospheric transport
718 models.

719
720 One such example is provided by Baldassarre *et al.* (2015), who used the FRP-PIXEL
721 products (Wooster *et al.*, 2015) and the WFABBA SEVIRI products (Zhang *et al.*, 2012),
722 along with MODIS-derived information from the Global Fire Assimilation System (GFAS)
723 inventory of Kaiser *et al.* (2012), to derived biomass burning emissions inputs for simulations
724 of emissions from a large fire in Turkey (Antalya, 2008). The FRP-PIXEL product provided
725 by far the most accurate description of the emissions, both with regard to their spatio-
726 temporal variation and their absolute magnitude. Unlike the MODIS-derived GFAS
727 inventory, the SEVIRI FRP-PIXEL product was able to capture the fires complete life cycle,
728 including the time of peak emissions intensity. And compared to the WFABBA product, the
729 FRP-PIXEL product produced information more consistent with that from MODIS when
730 both SEVIRI and MODIS viewed the Antalya region simultaneously. The simulated smoke
731 plume produced by ingesting the FRP-PIXEL data into the Community Multi-scale Air

732 Quality (CMAQ) atmospheric chemistry model compared far better with observations of
733 MODIS-derived aerosol optical depth (AOD), and with carbon monoxide and ammonia
734 column totals provided by the Infrared Atmospheric Sounding Interferometer (IASI), in
735 particular in relation to the diurnal variability of the fire emissions and the spatial distribution
736 and peak concentrations of the smoke. Please refer to Baldassarre *et al.* (2015) in this
737 Monitoring Atmospheric Composition and Climate (MACC) special issue for further
738 information on the simulation and inter-comparison. Here we provide a second European
739 demonstration of the value of geostationary FRP data in the parameterising of wildfire
740 emissions for use in atmospheric transport models, building on a previous more limited study
741 conducted by Kaiser *et al.* (2009b).

742

743 **5.2 Methodology for modelling emissions and transport of smoke from the 2007 Greek** 744 **'mega fire' event**

745 We use the FRP-PIXEL product as the basis for calculating smoke emissions to the
746 atmosphere from a catastrophic 'mega fire' event that occurred around the Mediterranean, in
747 particular focused on the Greek island of Peloponnese, in August and September 2007. We
748 use these emissions within components of the CAMS modelling systems to simulate the
749 transport and fate of the emitted smoke, ultimately estimating the level of human exposure to
750 high levels of particulate matter (PM_{2.5}). The Peloponnese wildfires occurred after a period
751 of prolonged drought (Gitas *et al.*, 2008), and during a heatwave (Theoharatos *et al.*, 2010).
752 The MODIS burned area product (Roy *et al.*, 2005) indicates they burned across an area of
753 around 1847 km² (Figure 8), a figure in good agreement with burned area reports provided by
754 the local Hellenic fire brigade (1899 km²). The Peloponnese fires predominantly occurred in
755 forested land, both coniferous and broadleaved forest, though some areas of shrublands,
756 grasslands and olive groves were also affected (Veraverbeke *et al.*, 2010; Koutsias *et al.*,
757 2012). Such was their severity that 0.32 Tg (40 %) of the estimated mean annual carbon
758 monoxide (CO) emissions for Greece overall were estimated to have been released by these
759 fires alone (Turquety *et al.*, 2009). The fires contributed greatly to reductions in local air
760 quality, with PM₁₀ values in Athens reaching almost 100 µg m⁻³, double that of the European
761 Union Ambient Air Quality Standard for daily PM₁₀ (50 µg m⁻³). Outside Athens at a
762 background non-urban site, on 24-25th August the PM₁₀ concentration rose to 49 µg m⁻³,
763 significantly up from the 19 µg m⁻³ measured the day before (Liu *et al.*, 2009). Marlier *et al.*
764 (2014) and Reid *et al.* (2009) have already highlighted the potential improvements that high

765 temporal resolution source information can have on the modelling of biomass burning
766 emissions transport, and the exceptional and strongly varying intensity of the Peloponnese
767 fires provides an excellent opportunity to demonstrate this further using SEVIRI-derived FRP
768 observations.

769

770 **5.2.1 Derivation of smoke emissions fields from FRP-PIXEL data**

771

772 FRP-PIXEL data of the European LSA SAF geographic region collected between the 1st
773 August and 13th September 2007 was examined for signals of the fires that occurred around
774 the Mediterranean during July - Aug 2007. Clear FRP signals were apparent from these fires,
775 particularly those on Peloponnese, but it was also evident that the adjusted version of Cloud
776 Mask (CMa) of Derrien and Le Gleau (2005) delivered by the Nowcasting and Very Short
777 Range Forecasting SAF (NWC SAF; www.nwcsaf.org) and used within the FRP-PIXEL
778 product processing chain (Wooster *et al.*, 2015) was identifying some of the extremely thick
779 smoke emitted by these fires as cloud. This is appropriate for studies requiring clear sky
780 observations, but the sensitivity of the algorithm for detecting cloud or smoke contaminated
781 pixels can occasionally result in the omission of fire activity. Since cloud masking is one of
782 the first things conducted within the FRP-PIXEL product processing chain (Wooster *et al.*,
783 2015), misidentification of very thick smoke as cloud prevents fires being identified in these
784 pixels using the FTA algorithm, even though we know that active fires can be quite reliably
785 detected through even quite thick smoke (Petitcolin and Vermote, 2002). This is because
786 smoke particles have a diameter typically much smaller than the wavelength of the MWIR
787 band and so do not act as strong scatterers of the fire-emitted radiation, unlike meteorological
788 cloud (Kaufman and Remer, 1994). Analysis of the raw SEVIRI level 1.5 data, along with the
789 EUMETSAT Meteorological Product Extraction Facility (MPEF) cloud mask (Tjemkes and
790 Schmetz, 1997), confirmed the identification of some areas of thick smoke as cloud by the
791 CMa cloud mask, and also confirmed that the true median percentage cloud cover over
792 Peloponnese was low over the period of the mega fire event (13%). To prevent the masking
793 out of smoke covered fires, which also then impacts surrounding pixels due to the single pixel
794 wide mask that is applied around cloud and water pixels (Wooster *et al.*, this issue), for this
795 particular application we decided to turn off the use of the adjusted CMA cloud mask, and
796 simply relied on the basic cloud masking tests used within the FTA algorithm itself (Wooster
797 *et al.*, 2015). Currently investigations are ongoing to make the cloud masking within the

798 FRP-PIXEL product less sensitive to thin cloud and other atmospheric phenomena through
 799 which fires can still be identified, including very thick smoke (Wooster *et al.*, 2015).

800

801 We then gridded the FRP data from within the FRP-PIXEL product to 0.1° grid cells and
 802 calculated the mean FRP for each cell at an hourly temporal resolution. As with the
 803 operational version of the Global Fire Assimilation System (GFAS; Kaiser *et al.*, 2012), the
 804 FRP density (\tilde{q}_j , Wm^{-2}) for each cell was then calculated by normalising the measured FRP
 805 by the grid cell area (a_j , m^2):

806

$$\tilde{q}_j(d, h) = \frac{1}{a_j} \frac{1}{4} \sum_{k=0,15,30,45} \sum_{i_k \in j} F_{ik}(d, h) \quad (1)$$

807

808 where d, h and k are the date, hour and minute of the SEVIRI observations respectively, $\sum F_{ik}$
 809 is the summation of all FRP measurements within grid cell j .

810

811 The rate of dry matter (DM) fuel consumption (φ [$\text{kg s}^{-1} \text{m}^{-2}$]) was derived from the FRP
 812 density measures of each grid cell (\tilde{q} , Wm^{-2}) following the method described in Wooster *et*
 813 *al.* (2005):

814

$$\varphi(d, h) = c \times \tilde{q}(d, h) \quad (2)$$

815

816 where d is the day, h is the hour and c is the conversion factor that relates fuel consumption
 817 to FRP and which is 0.368 ± 0.015 (kg MJ^{-1} ; Wooster *et al.*, 2005). The approach was further
 818 developed with land cover dependent adjustments by Kaiser *et al.* (2012). However, we
 819 maintain the original fuel consumption estimation and adjust the emission fluxes at the level
 820 of the emission factors, see section 5.2.2.

821

822 **5.2.2 FRP-derived aerosol emissions and atmospheric modelling**

823

824 Ichoku and Kaufmann (2005) first developed an approach to estimate aerosol emissions using
 825 FRP and aerosol optical depth (AOD) measurements using ‘*coefficients of emission*’ that
 826 related FRP to total particulate matter (TPM) as a function of land cover type. The approach
 827 implemented herein calculates emissions using the DM fuel consumption rate φ ($\text{kg s}^{-1} \text{m}^{-2}$):

828

$$\Phi_s(d, h) = \eta_s \times \varphi(d, h) \quad (3)$$

829

830 where Φ_s is the emission flux density ($\text{kg s}^{-1} \text{m}^{-2}$) of species s , d is the day, h is the hour and
831 η is the emissions factor (kg kg^{-1}) given by :

832

$$\eta_s = \alpha(s) \times \kappa_l(s) \quad (4)$$

833

834 where κ_l is the land cover (l) specific emissions factor for species s and α is a constant which
835 is used to adjust bottom-up aerosol emissions estimates to those observed in top-down
836 inventories. A regionally varying bias occurs between bottom-up derived aerosol emissions
837 and MODIS AOD measurements, requiring the former to be adjusted when being used in air
838 quality or climate model simulations (Peterenko *et al.*, 2012). Yang *et al.* (2011) also found
839 smoke emissions ($\text{PM}_{2.5}$) derived using the bottom-up approach was underestimated by a
840 factor of three when compared to MODIS AOD retrievals. Kaiser *et al.* (2012) recommend a
841 global aerosol enhancement by a factor of 3.4 as first-order correction. These values are also
842 broadly consistent with differences of up to a factor of three found by Ichoku and Kaufmann
843 (2005) using satellite observations of FRP and AOD compared to measurements of $c \times \kappa_l(s)$
844 derived from laboratory measurements. Here, we estimate emissions of organic matter and
845 black carbon in exact agreement with Ichoku and Kaufmann (2005) by enhancing their
846 emission factors for Andreae and Merlet (2001) with a factor of 3.1. According to the
847 GFEDv3 land cover dataset, also used for our calculations in GFAS (Kaiser *et al.*, 2012), the
848 fire affected region of Greece is classed as extratropical forest and the emitted species and
849 relevant emissions factors are given in Table 4.

850

851 The atmospheric aerosol model (Morcrette *et al.*, 2008) used within the ECMWF Integrated
852 Forecasting System (IFS) represents smoke aerosols as black carbon (BC) and organic matter
853 (OM), of both hydrophilic and hydrophobic types. Emissions of the latter are approximated
854 by scaling organic carbon (OC) emissions estimates by a factor of 1.5. Other aerosols
855 included in the modelling are sea salt, dust and sulphate aerosols, and advection, convection,
856 diffusion, dry and wet deposition and chemical conversion of these aerosols are simulated,
857 with meteorology nudged to the operational ECMWF analysis every 12 hours. The aerosol
858 abundance however, is based solely on source and sink processes and the atmospheric

859 transport. In this study the IFS model was run with a horizontal resolution of 25 km (T799)
860 and with 91 vertical levels up to 0.01 hPa.

861

862 Smoke emissions from the Peloponnese fires were calculated using Equations 3 and 4, along
863 with the emissions factors given in Table 4. The smoke emissions must be injected into the
864 atmosphere at a particular height, or distribution of heights, and such injection height
865 assumptions can have implications for the resulting spatio-temporal distribution of the
866 emitted species. Leung *et al.* (2007) and Guan *et al.* (2008) demonstrated that use of more
867 detailed plume injection height assumptions resulted in a reduction in near surface CO
868 concentrations, since more plumes were assumed to be lofted above the boundary layer.
869 Paugam *et al.* (2015a) provided a recent review of approaches to estimate smoke plume
870 injection height, including the methods of Sofiev *et al.* (2012) and Paugam *et al.* (2015b) that
871 use FRP measurements to characterise wildfire thermal properties related to plume rise. This
872 research remains at a relatively early stage, but it appears that FRP measures may indeed
873 have a role to play in characterising smoke plume injection height as well as the rate of
874 emission of chemical and aerosol species. Here we retained the commonly used assumption
875 that the calculated smoke emissions are injected into the lowest atmospheric level, since this
876 is generally what has been assumed in the series of MACC projects thus far (Kaiser *et al.*,
877 2012). The CAMS is anticipated to use injections heights from Paugam *et al.* (2015b) in the
878 future.

879

880 **5.3 Results**

881

882 ***5.3.1 Fuel consumption during the Peloponnese Wildfires***

883

884 Figure 9a illustrates the temporal dynamics of total fire FRP (MW) and the equivalent rate of
885 fuel consumption (tonnes s^{-1}), calculated from the MODIS and SEVIRI FRP measurements at
886 their native temporal resolutions. The period of greatest fire activity occurs between the 23rd
887 and 27th August, where the initial active fire detections made by SEVIRI and MODIS occur
888 at 07:57 and 09:00 (UTC) respectively (23rd August). At their most intense, the Peloponnese
889 fires consumed over 15 tonnes s^{-1} of biomass, and such was their intensity that large
890 quantities of fuel ($> 3 \text{ tonnes s}^{-1}$) were consumed even during the night, a period when more
891 landscape typically fires die down quite considerably due to less fire-conducive ambient
892 conditions (Roberts and Wooster, 2007; Roberts *et al.*, 2009). The temporally intermittent

893 MODIS Terra and Aqua FRP measurements broadly capture the pattern seen in the much
894 more frequent SEVIRI data, and are typically much higher in magnitude. On the 25th August,
895 MODIS Aqua (12:05 UTC) detects a total FRP exceeding 180 GW, with the SEVIRI FRP
896 (12:12 UTC) very much lower (38 GW). The large difference mainly derives from the fact
897 that whilst 10% (31) of the MODIS active fire pixels have an FRP >1600 MW and 5% >3000
898 MW, 23% of the 100 active fire pixels detected by the FRP-PIXEL product are in fact
899 saturated in the SEVIRI MWIR channel. Between the 24th and 26th August, when the
900 wildfires were most intense, MODIS made 13 overpasses and the unadjusted SEVIRI
901 observations measured 39% of the total FRP measured by MODIS. This demonstrates the
902 massive scale and intensity of these fires, particularly given that SEVIRI's pixel area at this
903 location is around 14 km².

904

905 Temporal integration of the SEVIRI FRP measurements between the 23rd August and 3rd
906 September indicates an energy release of 4.73 PJ which, following Equation 2, equates to
907 1.74 Tg of combusted fuel, predominantly consumed on 23 - 27 August (Figure 9b). Various
908 burned area estimates exist for the Peloponnese fires, including 1773 km² (Gitas *et al.*, 2008),
909 1628 km² (European Forest Fires Information System, EFFIS; European Commission, 2010)
910 and 1847 km² (Roy *et al.*, 2005; Figure 8). Dividing the SEVIRI-FRP derived fuel
911 consumption with these burned areas provides mean dry matter (DM) fuel consumptions of
912 0.98 kg m⁻², 1.07 kg m⁻² and 0.94 kg m⁻² respectively. Aleppo pine forests occupy around
913 370,000 ha in Greece and are abundant on Peloponnese (Verroios and Georgiadis, 2011).
914 Mitsopoulos and Dimitrakopoulos (2013) assessed 40 stands in this fuel type and found
915 canopy fuel loads to range between 0.63 and 1.82 kg m⁻², estimating a mean of 1.08 kg m⁻².
916 Using the maximum fuel load (1.82 kg m⁻²), the three burned area estimates (1773 km²,
917 1628km² and 1847km²), and assuming a combustion completeness value for forest of 0.6
918 (van der Werf *et al.*, 2006) we calculated a fuel consumption for these fires of 1.94 Tg, 1.77
919 Tg and 2.01 Tg respectively using the standard burned area based approach (Seiler and
920 Crutzen, 1980), which is similar to our SEVIRI-derived estimate of 1.74 Tg. Turquety *et al.*
921 (2009) estimates that 0.32 Tg of CO was emitted during the Peloponnese fires, which using
922 the emissions factors given in Table 4 results in a larger top-down derived fuel consumption
923 3.0 Tg (with a stated uncertainty of ~30%). Due to the aforementioned SEVIRI MWIR
924 channel saturation, the SEVIRI FRP-derived fuel consumption estimate is considered a
925 minimum estimate.

926

927 **5.3.2 Smoke Plume Evolution**

928

929 The Peloponnese wildfires produced huge volumes of smoke that affected regional air quality
930 in the Eastern Mediterranean (Poupkou *et al.* 2014). Figure 10a shows a true colour
931 composite image derived from MODIS Terra imagery acquired on the 26th August 2007
932 (09:35 UTC). The mirrored ‘S’ shaped plume present over the Mediterranean extends across
933 to Tunisia at this time. Figure 10b shows a snapshot of the modelled smoke emissions derived
934 from our use of the FRP-PIXEL product dataset to derive the wildfire emissions, and the use
935 of these within the IFS model (Section 5.2). The modelled smoke emission transport captures
936 the spatial structure of the advected smoke plumes very well, consisting of a series of ‘pulses’
937 of increased AOD that result from the particularly intense emissions during the peak of each
938 diurnal fire cycle. The large region of particularly high AOD on the coast of Libya (L on
939 Figure 10b, and shown in Figure 11a and 11b) results from the intense fire emissions on the
940 25th August, where more than 18 tonnes s⁻¹ of biomass were apparently being consumed at the
941 peak intensity. To the west of the main smoke plume, a thinner plume with a lower AOD is
942 evident emanating from fires in Albania. To the east, a smaller plume resulting from wildfires
943 in Turkey is also captured.

944

945 It is evident from Figure 10 that the modelled smoke plumes are offset slightly compared to
946 the actual plumes observed by MODIS, and this is most evident over the Libyan coast. The
947 difference is believed to result from injecting the smoke plume into the lowest atmospheric
948 level, which is an oversimplification as stated earlier since MISR-derived smoke plume
949 heights acquired on 26th August indicated that the plume closest to the wildfires had a height
950 of 2.5 km (Lui *et al.*, 2009) and CALIPSO lidar observations have detected the plumes at
951 altitudes of 2-3 km on 25th and 26th August (Turquety *et al.* 2009). In contrast, the simulated
952 plumes are located predominantly below 1 km (not shown). Global analysis of MISR data
953 indicates that a large proportion wildfire smoke plume heights remain beneath the boundary
954 layer, although particularly intense fires can inject smoke into the free troposphere (Val
955 Martin *et al.*, 2010; Dirksen *et al.*, 2009; Fromm *et al.*, 2000). Our modelled plume is
956 typically also broader than that observed by MODIS, and covers a larger spatial extent. This
957 may result from the relatively coarse spatial resolution used in the model, and comparisons
958 between our simulation and MODIS AOD estimates made on the 26th August (DOY 238,
959 Figure 11a and b) indicate that whilst the broad magnitude of the modelled smoke emission
960 ‘pulses’ are in good agreement with observations, the simulated plumes AOD appears

961 overestimated compared to MODIS. This suggests some inaccuracies remain in the aerosol
962 source modelling, and for example Garcia-Menendez *et al.* (2014) found modelled PM_{2.5}
963 concentrations are more sensitive to the injection height parameterisation rather than to the
964 emissions vertical distribution, due to the diurnal evolution of the planetary boundary layer
965 and local meteorological conditions.

966

967 **5.4. Impact of Emissions Fields Temporal Resolution**

968 A number of studies (e.g. Chen *et al.*, 2009; Marlier *et al.*, 2014; Reid *et al.*, 2009; Garcia-
969 Menendez *et al.*, 2014) have found that resolving the diurnal variability of fire emissions has
970 important implications when modelling the emissions atmospheric transport. We used our
971 study of the Peloponnese fires to address this issue by reducing the temporal resolution of the
972 SEVIRI FRP-derived emissions density fields, from the original 1-hour to 1-day and then 1-
973 week, the latter two being more representative of the global emissions inventories developed
974 using only observations from polar orbiting instruments (van der Werf *et al.*, 2010; Kaiser *et al.*,
975 2012; Sofiev *et al.*, 2009). The resulting sensitivity to temporal resolution is illustrated in
976 Figure 12a and b, which show modelled AOD (at 550nm) on the 26th August (09:35 UTC)
977 using the emissions prescribed at a daily and weekly temporal resolution. In both cases, the
978 shape of the modelled Peloponnese smoke plume remains broadly consistent with the hourly
979 simulation of Figure 10a, although smoke emissions from neighbouring countries are much
980 less pronounced. The Albanian plume is progressively shorter in Figure 12a and 12b, whilst
981 some plumes (e.g. those from Turkey to Crete) are missing altogether. Source emissions at
982 weekly temporal resolution (Figure 12b) remove the daily variability, resulting in lower
983 aerosol amounts at both the source region and over the entire plume. It is also evident that
984 emissions are being generated at incorrect times when using these reduced temporal
985 resolution source data. For example, the daily and weekly simulations have plumes
986 emanating from southern Italy too early, since fires are in fact in reality just developing in the
987 source region (Figure 12b). Baldassarre *et al.* (2015) provide further evidence of the
988 importance of the high temporal resolution provided by the SEVIRI FRP-PIXEL dataset
989 when modelling smoke transport from individual large fire events.

990

991 **5.5 Comparison of *in-situ* and modelled aerosol optical depth**

992

993 Section 5.4 has indicated that model simulations using hourly smoke emissions fields
994 improve the representation of both the spatial and temporal evolution of the smoke plumes

995 from the main Mediterranean mega-fires of August 2007. However, qualitative comparison
996 to MODIS AOD estimates (Figure 11 a,b) indicated that the plumes modelled AOD was
997 somewhat higher than satellite derived AOD estimates. Over the same time period as the
998 Peloponnese fires, a series of fires occurred on the Algerian coast (Figure 13a) whose plumes
999 were detected by the AERONET (Holben *et al.*, 2001) site at Lecce (Italy; 40.35°N,
1000 18.16°E). Figure 13b and c show the modelled smoke and dust AOD respectively on the 31st
1001 August (00:00 UTC) where the former illustrates the smoke plume extension over the
1002 AERONET site (yellow star symbol). Figure 13d is a temporal profile of AOD recorded (at
1003 500 nm) over Lecce from AERONET observations of total (red circles) and fine mode
1004 (orange circles) AOD, daily averaged MODIS AOD (550 nm) observations (black triangles)
1005 and model simulations of total AOD (blue line). Modelled AOD contributions of smoke
1006 (purple line) and dust (green line) to the total AOD are also shown. The MODIS AOD
1007 estimates are derived through averaging all observations within the model grid cell. The
1008 smoke AOD displays greater short term variability than does the dust AOD, since the
1009 wildfires represent significantly more localised sources than do the regions of dust uplift. The
1010 smoke AOD displays an increase in magnitude from 0.6 to 1.3 between the 31st August and
1011 1st September, which occurs 23 hours prior to the peak FRP (63 GW) of the Algerian fires.
1012 However, between the 27th and 31st August, MODIS detected 330 active fires in southern
1013 Italy (Figure 14) which were greatest in number on the 27th (114) and 31st (110) August and
1014 which are likely to have contributed to the Algerian smoke plume but which may not all be
1015 included in our modelling since the majority (63%) had an FRP <30 MW and so may not be
1016 detected by SEVIRI.

1017

1018 Compared to the daily averaged MODIS AOD, our modelled total AOD is typically
1019 overestimated by ~20% during the overpass of the smoke plume (31st August), but the model
1020 does capture the temporal trend of the observed AOD rather well. The AERONET AOD data
1021 provides a more complete temporal profile than do MODIS' AOD observations, and our
1022 modelled total AOD typically captures these dynamics. However, the onset of increased
1023 AOD due to the Algerian fires (30th August) is captured 8 hours earlier by AERONET than
1024 by our modelled AOD, whilst the descending limb is temporally coincident between datasets.
1025 The former may result from assumptions made regarding the smoke plume injection heights,
1026 or to shortcomings in the simulations due to increased cloud cover over Algeria on the 29th
1027 August. It is also possible that, given the rapid rise in AOD in a three hour period, this is a
1028 localised effect due small, undetected fires in the vicinity of the AERONET station and

1029 which are not represented in our simulation. Between the 28th and 29th August, MODIS
1030 detected 96 active fires (Figure13, red symbols) to the south-west of Lecce and in close
1031 proximity to the smoke plume emitted by the Algerian fires, and these most likely to
1032 contribute to the elevated AOD at this time (Figure 11a and b). In general, the AOD resulting
1033 from the use of the SEVIRI FRP-PIXEL product data and the IFS model is overestimated
1034 compared to AERONET observations by 10 - 40% during the biomass burning plume
1035 overpass, and with a discrepancy of 8 hours at the onset of the plume overpass. Clearly we
1036 will in future aim to further refine the fire emissions parameterisation, which appears
1037 currently to be positively biased relative to the observations. Nevertheless, this case study has
1038 demonstrated the clear value of the high temporal frequency SEVIRI-derived FRP
1039 observations for large, rapidly varying wildfires such as this.

1040

1041 **5.6 Air quality assessment**

1042 The 2007 Mediterranean 'mega fire' event significantly impacted regional air quality, and
1043 fires worldwide are known to have severe health implications for those badly affected by
1044 their emissions. Jacobson (2014) estimated that average annual premature mortalities due to
1045 biomass burning emissions of PM_{2.5} and ozone are of the order of 20,000 (10,000-30,000) and
1046 230,000 (63,000-405,000) respectively, equating to between 5 and 10% of global mortality
1047 due to indoor and outdoor air pollution. One of the primary uses of the CAMS is to forecast
1048 regional air quality across Europe, providing rapid and reliable information directly relevant
1049 to human health issues, and this includes the consequences of wildfire emissions
1050 (Hollingsworth *et al.*, 2008). It is therefore pertinent to assess the significance of our
1051 Peloponnese smoke emissions transport simulations in relation to air quality and human
1052 health, potentially since Mitsakis *et al.* (2014) already estimated that over 2000 people were
1053 admitted to hospitals and medical centres as a direct result of the Peloponnese fire event, and
1054 of these 1100 were due to cardio-vascular and respiratory problems. The World Health
1055 Organisation (WHO) air quality guidelines (WHO, 2006) in particular set a limit of 25 µg m⁻³
1056 for the concentration of fine mode particulate matter (PM_{2.5}) averaged over a 24 hour period.
1057 We estimated concentrations of PM_{2.5} using our simulated OM and BC concentrations in the
1058 lowest modelled atmospheric layer, and calculated the 24-hour running average for
1059 comparison to this WHO threshold.

1060

1061 Figure 15 shows the distribution of 24-hour mean PM_{2.5} concentrations modelled between
1062 23rd August and 3rd September (when the Peloponnese wildfires were at their most intense;

1063 Figure 9a). It is clear that the impacts of the Peloponnese wildfires extend well beyond
1064 Greece's national borders, and indeed resulted in large parts of the Mediterranean region
1065 exceeding the WHO $25 \mu\text{g m}^{-3}$ $\text{PM}_{2.5}$ concentration threshold by significant margins. In fact,
1066 analysis of the spatial distribution of these data with respect to population density (CIESIN
1067 and CIAT, 2005) indicated that, for the region shown in Figure 15, up to 40 million people
1068 might have been subject to $\text{PM}_{2.5}$ concentrations exceeding the WHO guidelines. However, it
1069 should be stressed that this is an upper limit for the exposure, because our study significantly
1070 over-estimates near-surface smoke concentration due to the assumed boundary-layer injection
1071 of the emissions. In particular, surface $\text{PM}_{2.5}$ concentrations in regions reasonably close to the
1072 source that are well above $100 \mu\text{g m}^{-3}$ are very likely to be spurious, and Liu *et al.* (2009)
1073 report elevated non-urban values closer to $49 \mu\text{g m}^{-3}$, albeit still at some distance from source.
1074 Nonetheless, the spatial range of the affected area, and the considerable human health
1075 impacts that these type of large wildfire events can have, highlights the necessity of
1076 modelling their smoke emissions and forecasting their atmospheric transport in the manner
1077 demonstrated here. Through such work, the CAMS and its downstream services aim at
1078 improving emergency preparedness through air quality forecasts. Geostationary FRP data are
1079 likely to be an important component of this system, particularly so as their high temporal
1080 resolution FRP data provides a unique view of the type of individual large "mega fire" event
1081 studied here, that can impact regional air quality so dramatically over short timescales.

1082

1083 **6.0 SUMMARY AND CONCLUSIONS**

1084 This work has provided a detailed performance evaluation of the Meteosat SEVIRI FRP
1085 products available from the LSA SAF, both the full resolution FRP-PIXEL product and the
1086 reduced resolution FRP-GRID product, both available in near real time and in archived form
1087 (<http://landsaf.meteo.pt/>). It has also provided a detailed example of use of the former product
1088 in characterising the smoke emissions from a large European wildfire event whose smoke
1089 significantly affected the Mediterranean region as a whole, and for which we have
1090 demonstrated an ability to simulate the atmospheric transport and human health impacts at
1091 high temporal resolution.

1092

1093 When evaluated against the MODIS MOD14 and MYD14 active fire products, the active fire
1094 pixel detection error of commission of the FRP-PIXEL product is found to be 9% in the
1095 North African LSA SAF geographic region, and increases to higher values particularly in
1096 Europe and South America. The basis of this variation is the combination of SEVIRI's

1097 increasing pixel area with view zenith angle away from the sub-satellite point, and the
1098 relative proportion of lower intensity and/or smaller fires in the various LSA SAF geographic
1099 regions (i.e. their fire regimes). Area-based comparisons indicate that the FRP-PIXEL
1100 product underestimates compared to simultaneously collected MODIS FRP of a region by
1101 between 35 and 89%, with the variation being again dependent upon the above factors.
1102 Underestimation is typically maximised at regions extending towards the edge of the viewing
1103 disk, furthest away from the SEVIRI sub-satellite point. However, comparison of the FRP of
1104 individual fires successfully detected almost simultaneously by both SEVIRI and MODIS
1105 indicates a strong agreement between the two FRP measurements, with the FRP-PIXEL
1106 product meeting its Target Accuracy requirements. We find that 76% of the examined
1107 simultaneously detected fire clusters had an FRP from SEVIRI within 30% of that measured
1108 by MODIS, which given the recent quantification of MODIS' FRP uncertainty (Freeborn *et*
1109 *al.*, 2014c) indicates good performance from the FRP-PIXEL product. Overall, minimal bias
1110 is seen between the per-fire FRP observations made by the two sensors.

1111

1112 When compared against that of other active fire products derived from the same Meteosat
1113 SEVIRI observations, the performance of the operational geostationary fire thermal anomaly
1114 (FTA) algorithm used within the FRP-PIXEL product (Wooster *et al.*, 2015) compares
1115 favourably. During our comparison to MODIS, the SEVIRI WFABBA, FDeM and FIR
1116 products from Prins *et al.* (1998), Amraoui *et al.* (2010) and Joro *et al.* (2008) respectively
1117 have higher active fire errors of omission, varying between 84 and 95%, as compared to the
1118 77% of the FRP-PIXEL product. However, these alternative SEVIRI-derived active fire
1119 products do have lower errors of commission than the FRP-PIXEL product when compared
1120 to MODIS, ranging between 5 and 6% (the FRP-PIXEL product has a 13% commission
1121 error). The FTA errors of commission are currently being reduced by re-inclusion of the
1122 dynamic spatial thresholding parameters described in Section 3.2.2 that were removed from
1123 the operational FTA algorithm for computational speed, but included in the original Roberts
1124 and Wooster (2008) prototype.

1125

1126 The Level-3 FRP-GRID product accumulates a series of FRP-PIXEL products and provides
1127 regional estimates of mean FRP at an hourly temporal resolution and a 5.0° spatial resolution.
1128 These estimates come already adjusted for cloud cover, and for the impact of the low spatial
1129 resolution detection bias that results in SEVIRI failing to detect the lower FRP active fire
1130 pixels. Our evaluation indicates good performance of these bias corrections at the hourly,

1131 5.0° product resolution, but evaluation of accumulated data against summed weekly MODIS
1132 FRP over the four LSA SAF geographic regions indicates that the FRP-GRID product
1133 underestimates total FRP at this scale. This largely results from the difficulty in accounting
1134 for situations where MODIS detects fire activity in a grid cell whilst SEVIRI does not, and so
1135 the bias corrections remain inactive. We provide herein some additional adjustment factors
1136 for those wishing to use the SEVIRI FRP-GRID datasets at this type of scale.

1137
1138 Despite their coarse spatial resolution limitations, the FRP products available from
1139 geostationary satellites offer an unprecedented high temporal resolution for studying wildfire
1140 emissions. This is a key advantage when using such data to parameterise wildfire smoke
1141 emissions within atmospheric transport models (Reid *et al.*, 2009). Here we use a version of
1142 the FRP-PIXEL product to characterise the smoke emissions from the August 2007
1143 Peloponnese wildfires. The resulting emissions fields are used within ECMWF's Integrated
1144 Forecast System (IFS) to model the smoke emissions transport, and in particular the black
1145 carbon and organic carbon aerosols and the resulting aerosol optical depth and PM_{2.5} surface
1146 concentrations. Our results support the findings of other recent studies (e.g. Garcia-Menendez
1147 *et al.*, 2014; Marlier *et al.*, 2014) in that higher temporal resolution smoke emissions
1148 estimates provide increased fidelity in the resulting smoke plume aerial distribution and
1149 optical thickness metrics than do simulations conducted using daily or weekly temporal
1150 resolution data. Visual assessment of the modelled plumes spatial distribution against
1151 simultaneous MODIS optical imagery shows good agreement, but the modelled plume is
1152 slightly offset from the observations which is believed to result from injecting the plume into
1153 the lowest atmospheric layer (whereas in reality it would have been lofted to higher
1154 altitudes). Quantitative comparisons between our modelled AOD and the coincident MODIS-
1155 and AERONET-derived AOD values indicate that modelled AODs are overestimated by ~ 20
1156 - 30%. Further research into model parameterisation (e.g. injection height) and the aerosol
1157 emission factors used is required to investigate this bias, particularly so as it is likely that we
1158 underestimate fuel consumption due to SEVIRI MWIR channel saturation during this
1159 extreme wildfire event. The European Union (EU) has recently signed a delegation
1160 agreement with ECMWF to provide the services implemented in MACC, including the FRP-
1161 based Global Fire Assimilation System (GFAS; Kaiser *et al.*, 2012), in an operational manner
1162 until at least 2020. This includes on-going developments of GFAS which aim at providing
1163 emission estimates with an hourly temporal resolution by combining FRP observations from
1164 both polar orbiting and geostationary satellites. Key pre-requisites are the implementation of

1165 a model for the diurnal cycle of FRP (Andela *et al.* 2015) and a suitable bias correction for
1166 geostationary FRP products to account for the omission of low intensity fires, building on the
1167 simple linear bias corrections applied currently in the FRP-GRID products.

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1205 **8.0 References**

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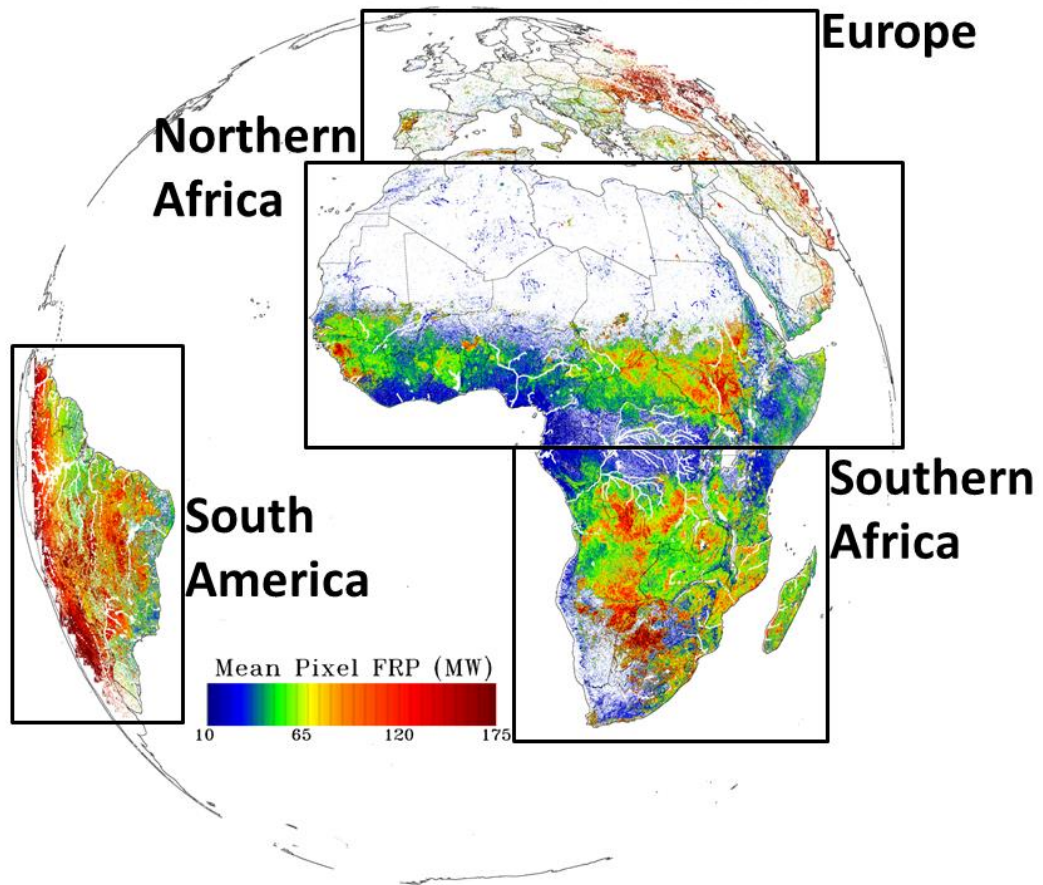
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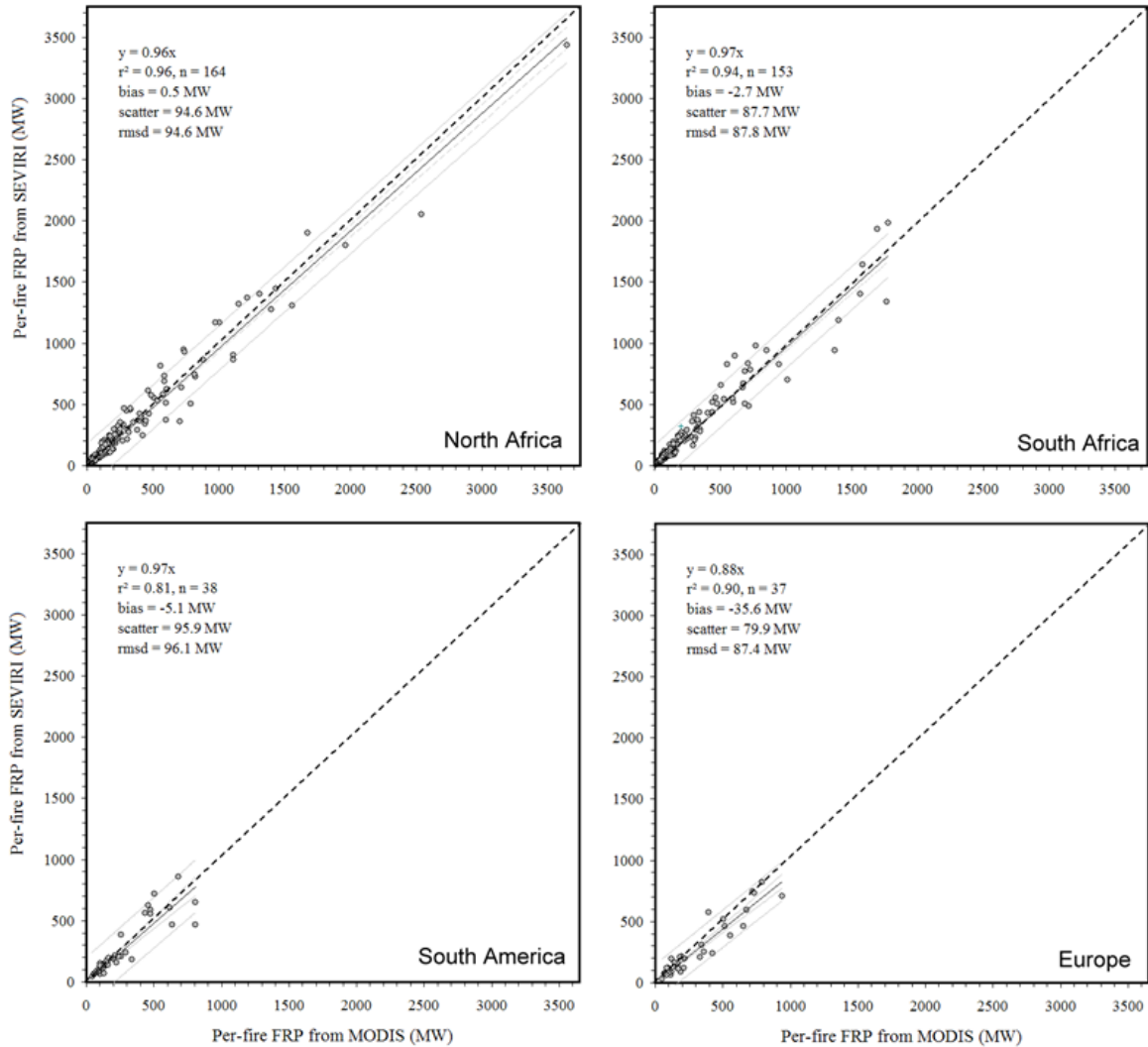
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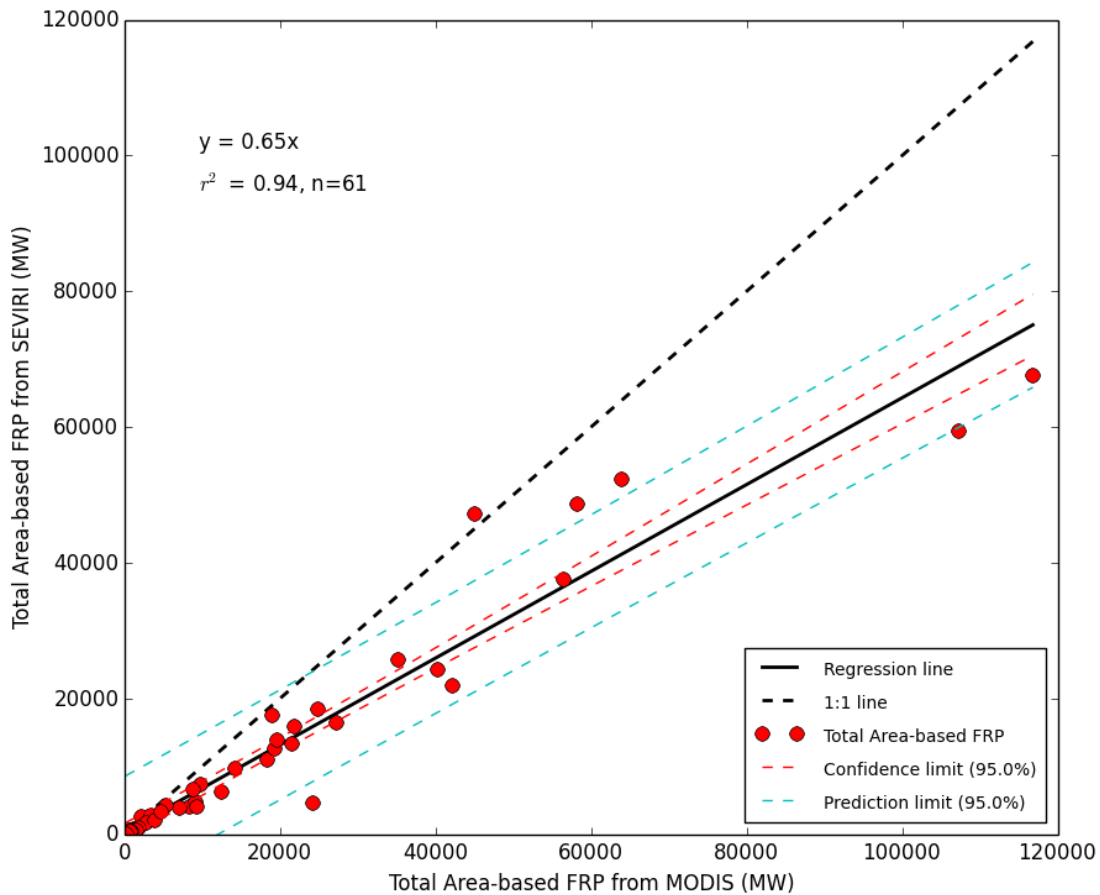
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Figure 1: SEVIRI's imaging disk showing the mean per-pixel FRP (MW) seen in each SEVIRI pixel, calculated using all FRP-PIXEL products available between 2008-2013. Also indicated are the four geographic regions that LSA-SAF SEVIRI products are subset to.

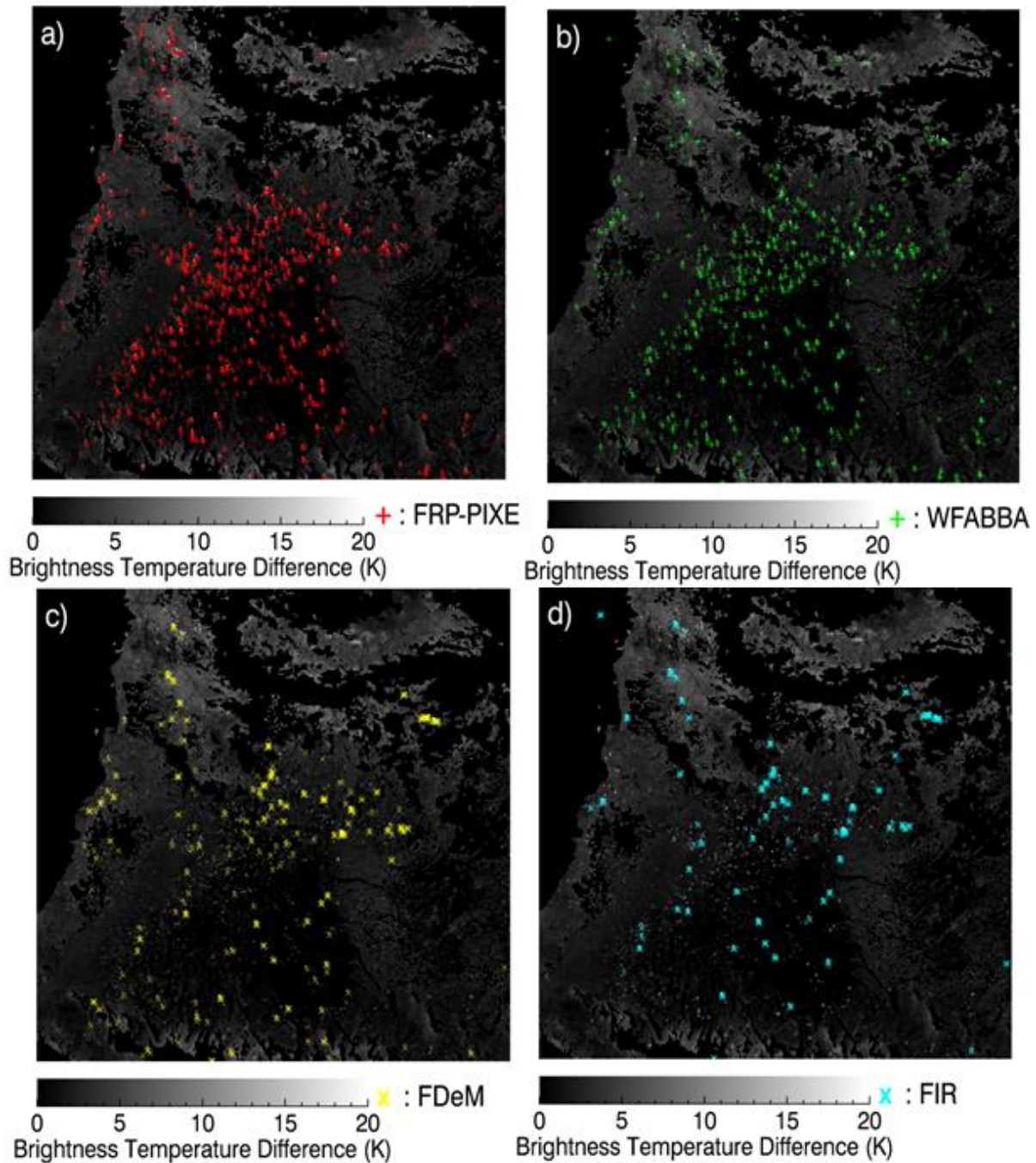


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 1622 **Figure 2:** A comparison of per-fire FRP derived from SEVIRI and MODIS observations of
 1623 fires observed near-simultaneously by each sensor during one week in each LSA SAF
 1624 geographic region (Figure 1). Fires are designated as contiguous clusters of active fire pixels.
 1625 SEVIRI FRP were taken from the LSA SAF FRP-PIXEL product in each case and MODIS
 1626 FRP is taken from the MOD14 product (Collection 5; Giglio *et al.*, 2003). The most radiant
 1627 fires were detected in the northern Africa region (top left), and all regions are displayed on
 1628 the same x- and y-axis scales for ease of comparison.

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 1634 **Figure 3:** Relationship between regional-scale inter-scene FRP derived from all spatially
 1635 matched, contemporaneous SEVIRI and MODIS FRP-PIXEL observations for the northern
 1636 Africa region (1-7 December, 2009). The MODIS swath is taken as the observation area. The
 1637 least squares linear best-fit passing through the origin is shown (bold line), along with the
 1638 95% confidence intervals on the mean (light dotted line) and on the prediction of y from x
 1639 (outermost lines). The 1:1 line is also shown (dashed). SEVIRI tends to generally
 1640 underestimate regional-scale FRP, primarily due to the non-detection of the lowest FRP fire
 1641 pixels, many of which MODIS can detect. However, the degree of underestimation is
 1642 relatively small as described by the slope of the linear best fit to the data.
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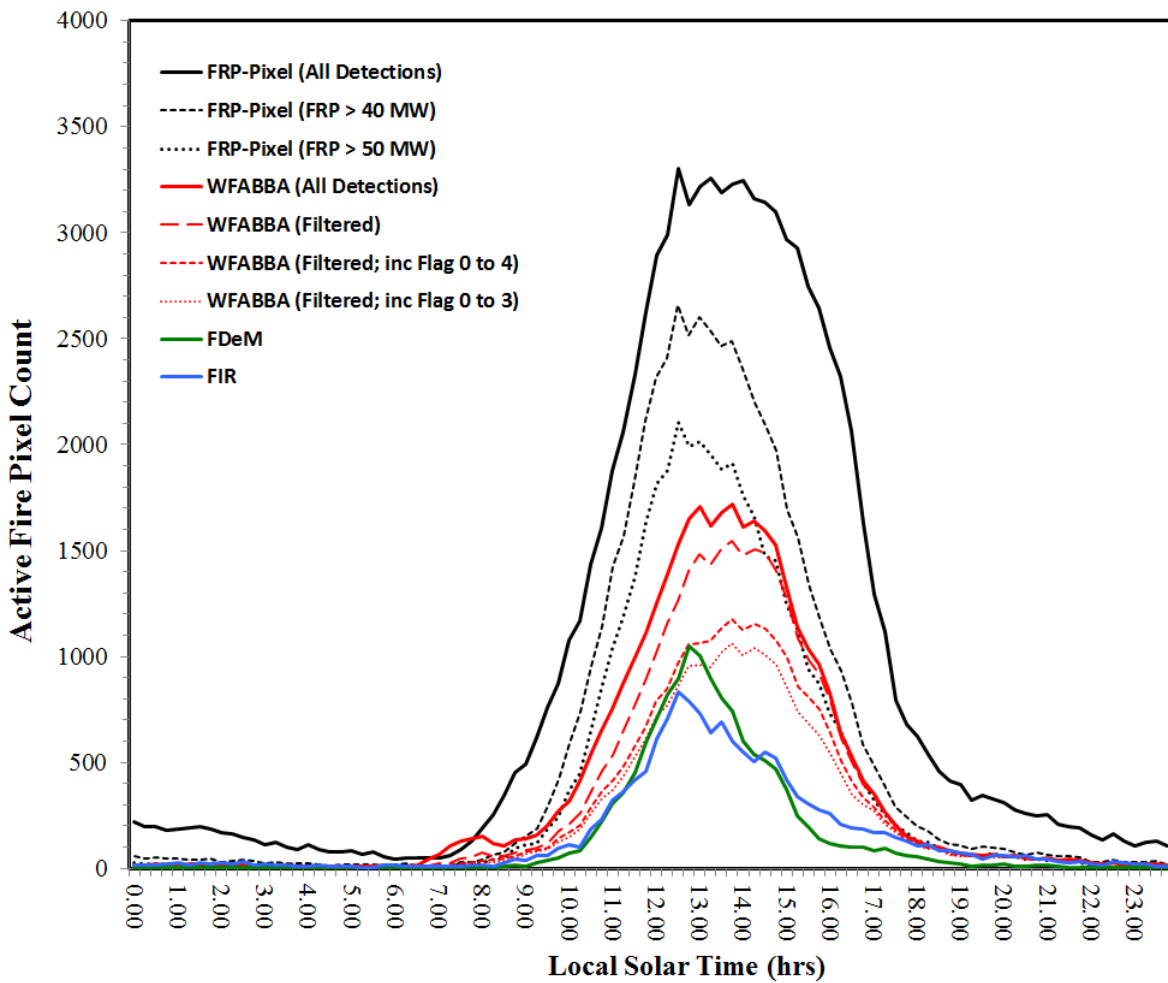


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Figure 4 : Example of the active fire pixel detections contained within the four SEVIRI-derived active fire detection products studied herein (LSA SAF FRP-PIXEL product; Wooster *et al.*, 2015, WF-ABBA; Prins *et al.*, 1998, Fire Detection and Monitoring - FDeM; Amraoui *et al.*, 2010, and FIR Active Fire Monitoring; Joro *et al.*, 2008). The images are produced from a single SEVIRI time slot (13:15 UTC on 21st August 2014) and show the active fire detections made in (a) FRP-PIXEL (1249 active fire pixel detections), (b) WFABBA (filtered version; 686 detections made), (c) FDeM (346 detections) and (d) FIR (312 detections). The underlying greyscale image is the SEVIRI brightness temperature difference image (3.9μm - 10.8μm channels) from the same imaging slot. Water bodies and clouds have been masked out (black). The region shown is that over Angola in the southern African LSA SAF geographic region (Figure 1). It is clear that whilst all the products tend to detect a reasonable number of fires that are comprised on multiple SEVIRI active fire pixels,

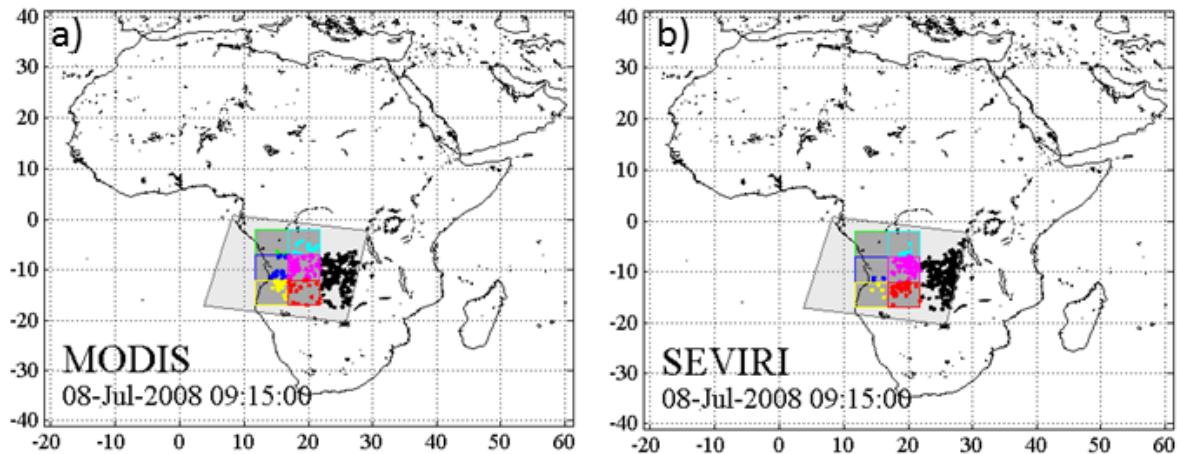
1658 it is the FRP-PIXEL and WF-ABBA products that detect more of the single pixel fires, with
1659 the FRP-PIXEL product dominating in this regard.
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Figure 5: Diurnal cycle of active fire detections present within the four SEVIRI-derived active fire products discussed herein for the LSA SAF southern Africa geographic region (Figure 1) on a single day (30th August 2014). The products are the LSA SAF FRP-PIXEL product (Wooster *et al.*, 2015), Wildfire-ABBA (WFABBA; Prins *et al.*, 1998), Fire Detection and Monitoring (FDeM; Amraoui *et al.*, 2010) and Active Fire Monitoring (FIR; Joro *et al.*, 2008). All confirmed active fire detections made in each product are included here for completeness, and results are shown in terms of the local solar time of detection. For the FRP-PIXEL product, three active fire time-series are shown; 1) all detections, and those only those detections from fire pixels with FRP magnitudes 2) >40 MW and 3) >50 MW since it is known that increasing undercounting of active fire pixels occurs around these limits (Roberts and Wooster, 2008; and companion paper in this issue). For the WFABBA active fire detections, all four versions of the dataset are included 1) all active fire detections, 2) the WFABBA 'filtered' detections where active fire pixels only detected once during 24 hrs are removed; and the WFABBA filtered detections keeping only 3) the high probability fires (flags 0 to 3) and 4) high and medium probability fires (flags 0 to 4). The LSA SAF FRP-PIXEL product detects a total of 89781 active fire pixels over this day, which reduces to 53561 and 39461 when restricted to fire pixels with FRP >40 MW and >50 MW respectively. For WFABBA, the total number of active fire detections is 35759, and the filtered dataset contains 35759 detections which reduces to 30751 and 23957 when WFABBA low and medium probability fire detections are removed. The FDeM and FIR detect only 13477 and 14645 active fire pixels respectively.



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1687 **Figure 6:** Graphical representation of the procedure used to generate the dataset for use in
 1688 evaluating the bias adjustment factors used within the FRP-GRID product. Fire pixels were
 1689 subset from the MOD14 and MYD14 MODIS Active Fire products available between May
 1690 2008 and April 2009 using six 5.0° grid cells centred on the MODIS swath, as illustrated in
 1691 (a). These same grid cells were then used in (b) to subset fire pixels from the SEVIRI full
 1692 Earth disk images acquired at times coincident with the MODIS overpass, as well as from the
 1693 three previous SEVIRI imaging timeslots collected prior to the MODIS overpass.

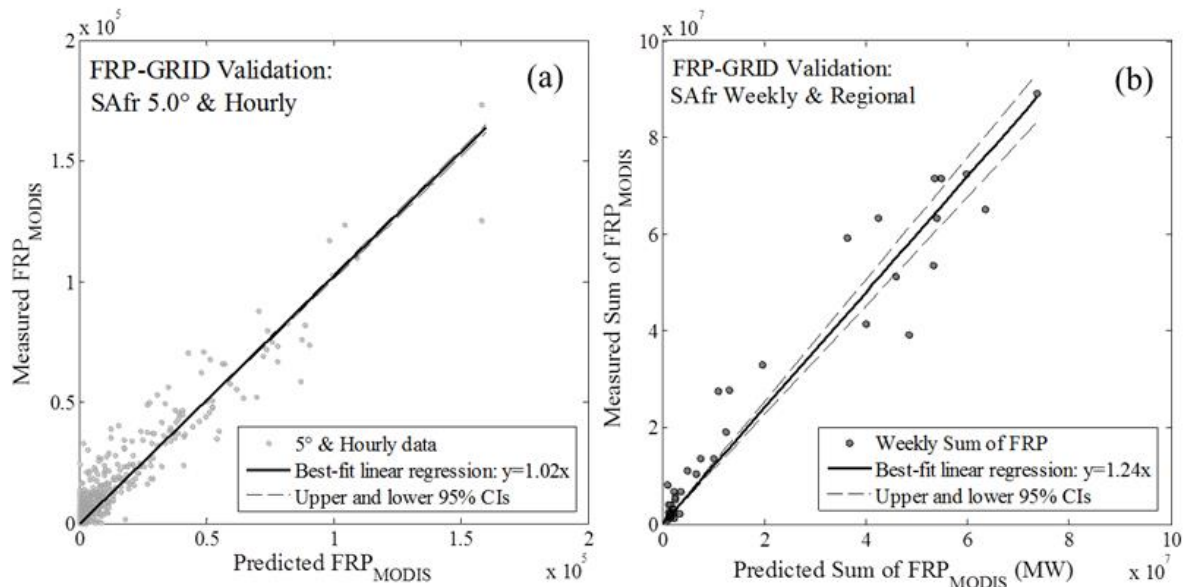
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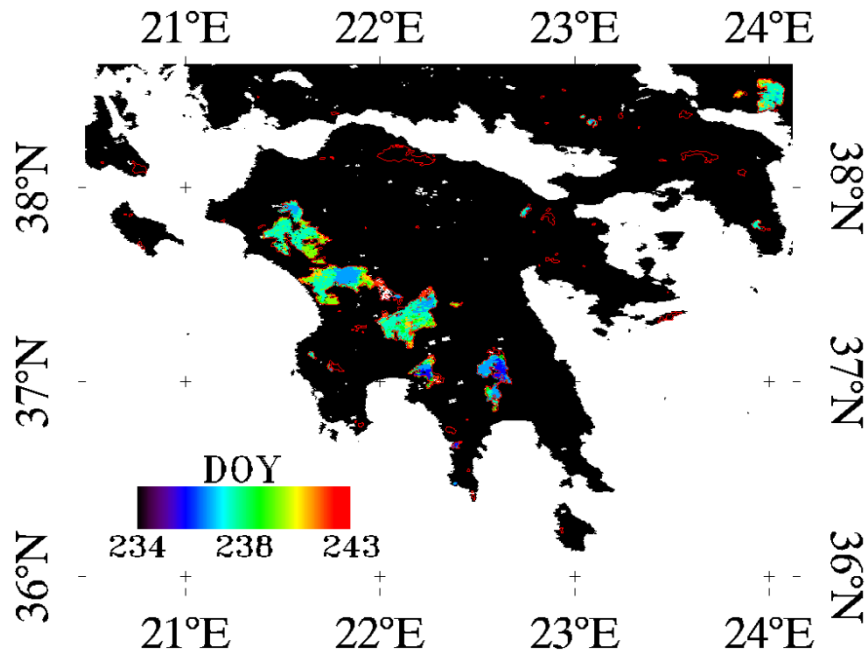
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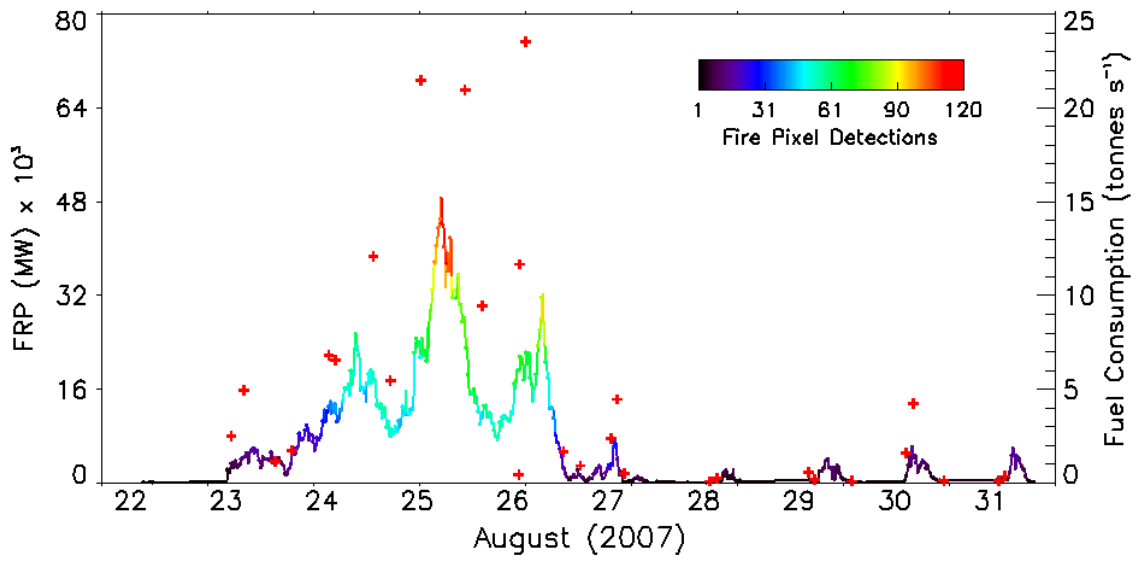
Figure 7: Evaluation of the bias adjustment factors used in the SEVIRI FRP-GRID product. Results are based on coincident SEVIRI and MODIS observations taken between May 2008 and May 2009, collected and matched as shown in Figure 6. The nearly 1:1 relationship between the predicted and measured values of MODIS FRP demonstrates the unbiased nature of the adjustment factor applied at (a) 5.0° grid cell resolution and hourly temporal resolution in the FRP-GRID product, in this case for 5.0° grid cells in southern Africa. In (b) the effect of accumulating observations over weekly intervals and over the entire southern Africa LSA SAF geographic region demonstrates that the FRP-GRID product tends to still deliver a result that underestimates the sum of FRP measured by MODIS at this broader spatiotemporal scale, owing primarily to the numerous observations in which SEVIRI failed to detect at least one active fire pixel in a 5.0° grid cell in which MODIS did successfully detect a fire. Full results of the evaluation exercise for all four geographic regions are presented in Table 3.



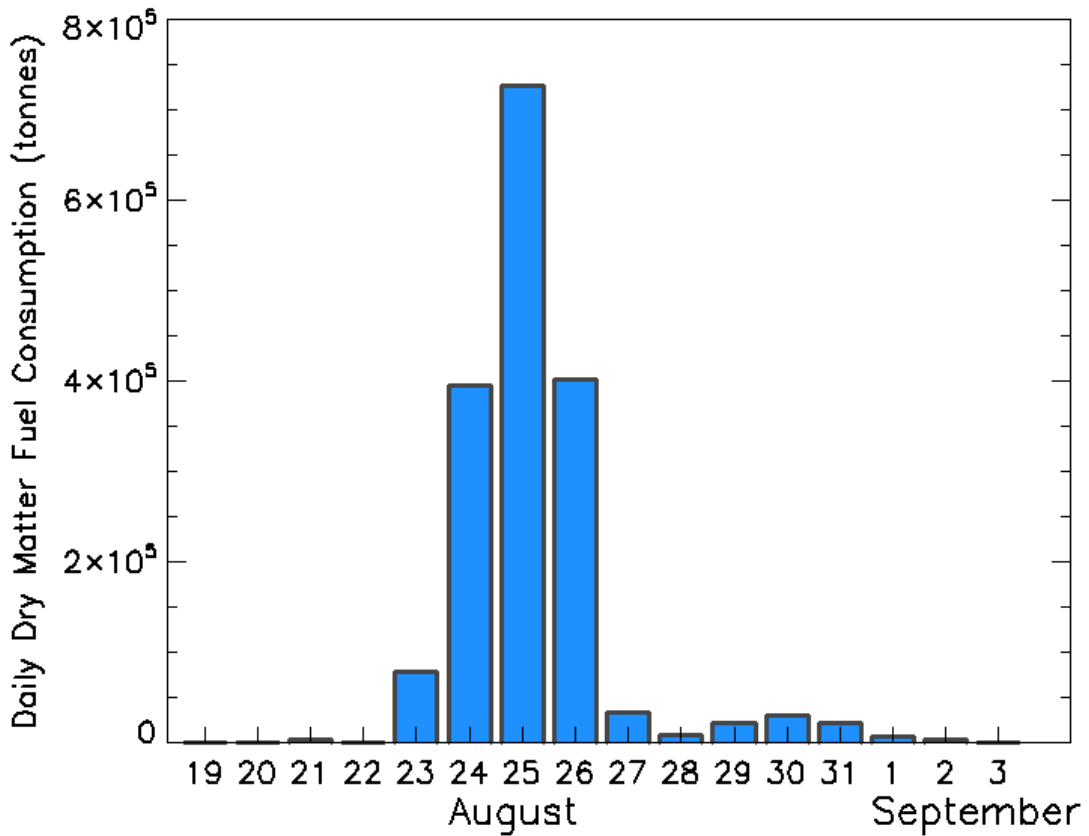
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Figure 8: The Peloponnese wildfires as viewed by the MODIS 500m burned area of Roy *et al.* (2005) collected in August and September 2007 and coloured by day of the year they were detected (DOY). The fires occurred in areas forest, shrublands and olive groves and affected 1847 km² according to these data. Also shown as a red outline are the 2007 burned area perimeters extracted from the European Forest Fire Information System (EFFIS; European Commission, 2010) that encompass 1628 km².

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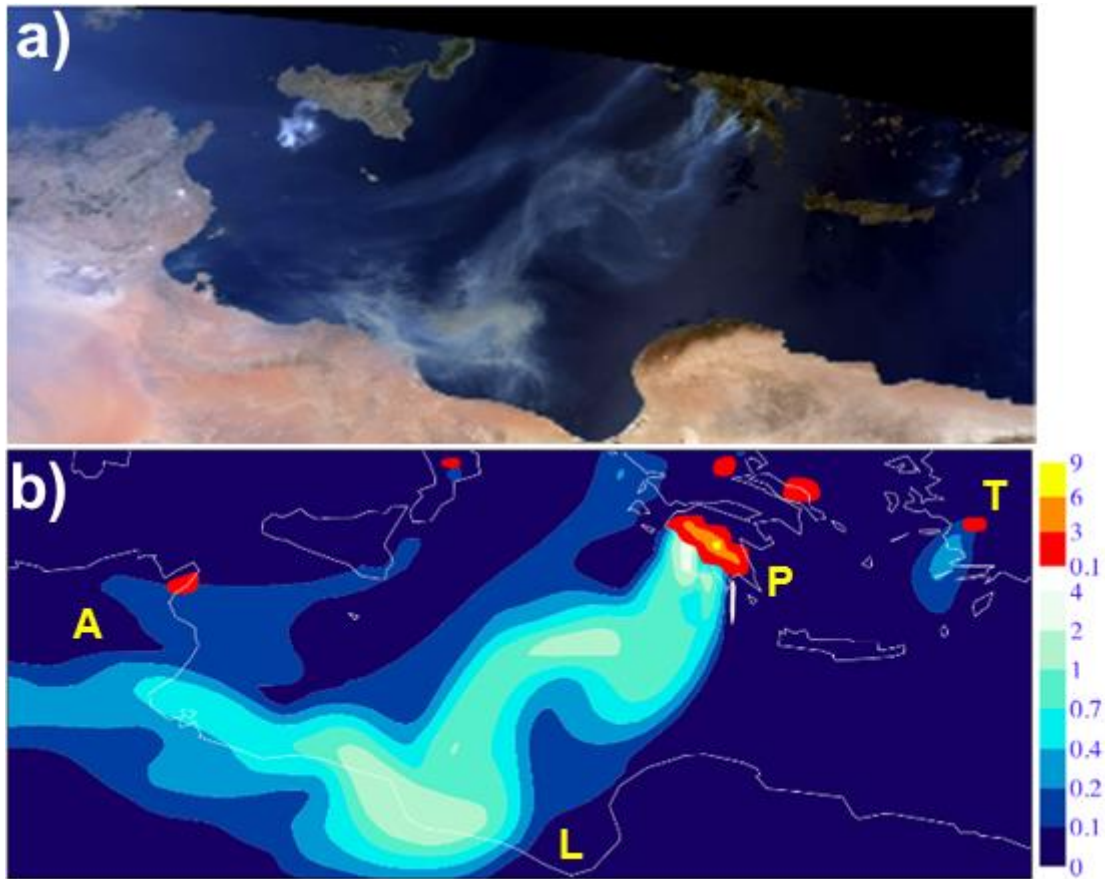
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1751 b)



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1753 **Figure 9:** (a) Time series of atmospherically corrected SEVIRI FRP measures (MW, left
1754 axis) and equivalent fuel consumption rate (tonnes s⁻¹) for the Peloponnese wildfires, as
1755 measured between 22nd and 31st August 2007 using the LSA SAF SEVIRI FRP-PIXEL
1756 product. Also shown are the atmospherically corrected MODIS FRP data collected over the
1757 same time period (red crosses). Note that for clarity of presentation the MODIS FRP measure
1758 recorded on 25th August (12:05 UTC) is not shown as this exceeds 180 GW, and SEVIRI

1759 reaches a far lower value due to strong prevalence of SEVIRI MWIR channel pixel saturation
1760 at this time. (b) Daily total dry matter fuel consumption estimated using the time-integrated
1761 SEVIRI FRP data. We estimate 1.74Tg of fuel was consumed in these fires, the bulk of
1762 which was burned between 24-26th August.
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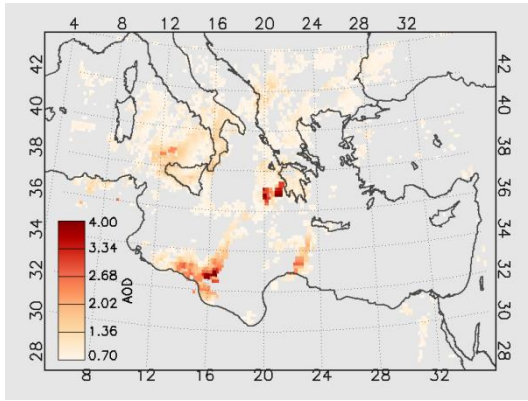


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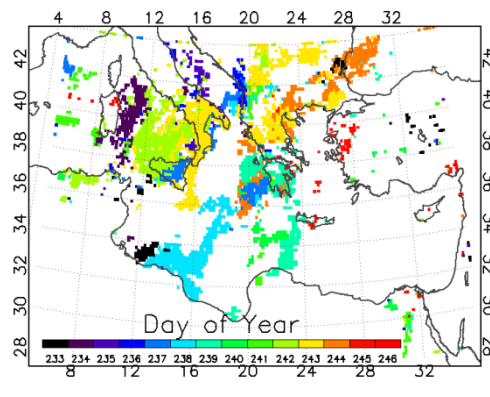
Figure 10: (a) MODIS Terra ‘true’ colour composite derived for August 26th (09:35 UTC) and (b) fire-emitted smoke aerosol optical depth at 550 nm derived using the modelling scheme detailed in Section 5.2 (blue scale) along with SEVIRI-derived FRP-density observations derived from the FRP-PIXEL product [$W m^2$, top, red scale] and interpolated to the atmospheric model grid. The FRP-PIXEL observations indicate the smoke plume sources and highlight the strength of the Peloponnese fires at this time. The Peloponnese (P), Libya (L), Algeria (A) and Turkey (T) are identified. MODIS data source in (a): <http://rapidfire.sci.gsfc.nasa.gov>.

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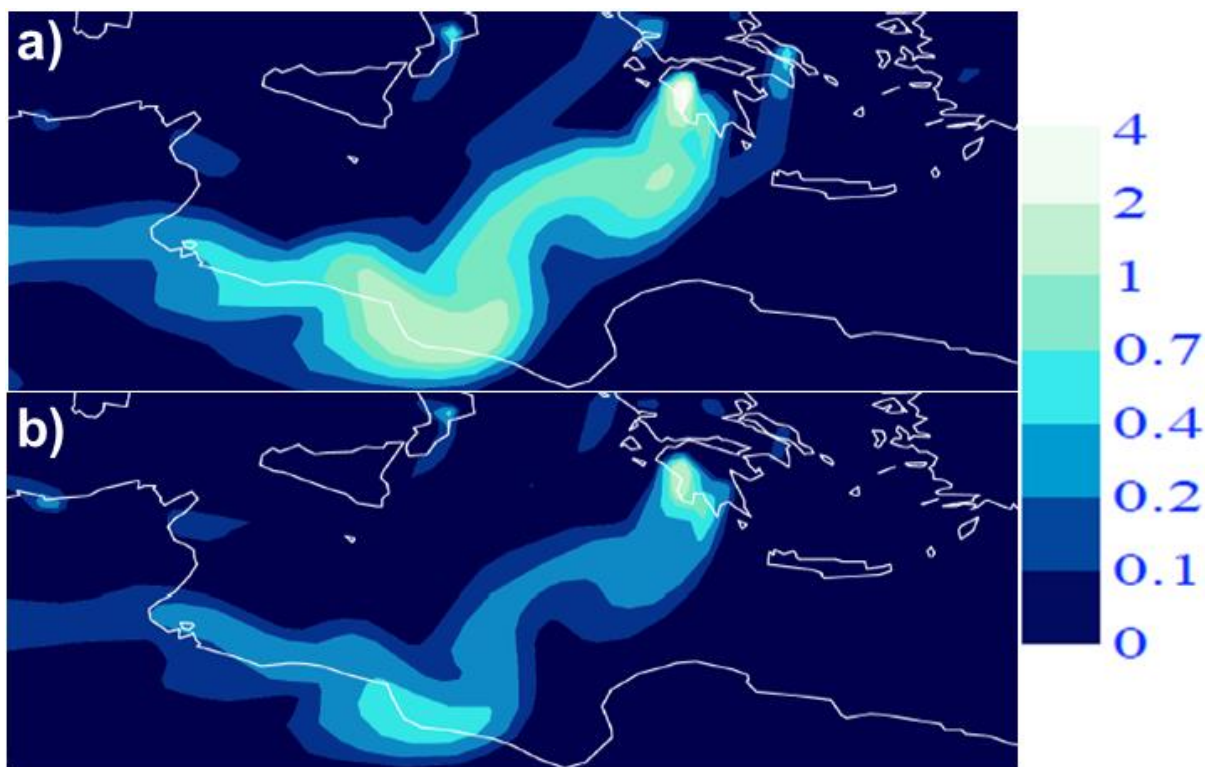


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Figure 11 : Data extracted for the 2007 Mediterranean 'mega-fire' event from Terra and Aqua MODIS Aerosol Optical Depth (AOD) products (a) Maximum value composite of atmospheric Aerosol Optical Depth (AOD) developed using Terra and Aqua MODIS observations (MOD04 and MYD04 products) acquired between the 21st August and 3rd September 2007. Only pixels with an AOD value in excess of 0.7 are shown. (b) Day of the year (DOY) of the highest AOD value shown in (a).

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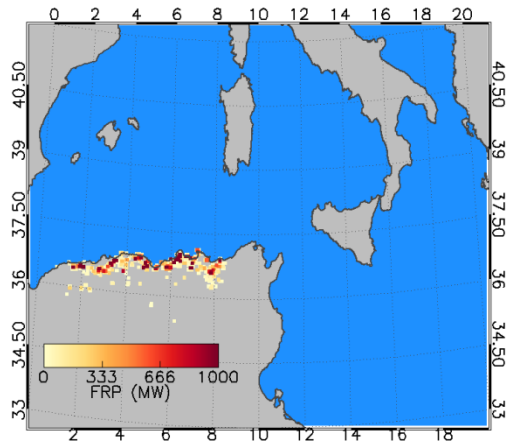
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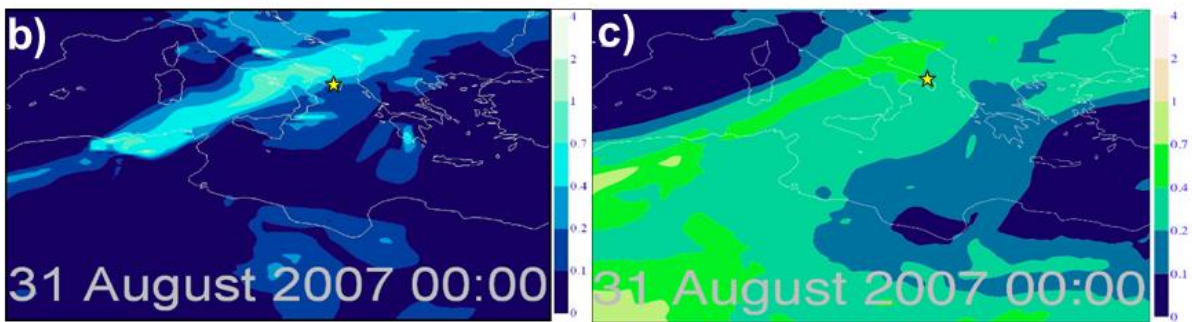
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Figure 12: Modelled smoke plume on the 26th August (09:35 UTC) calculated using (a) daily, and (b) weekly temporal resolution FRP-derived smoke source emissions as described in Section 5.4. The blue scale indicates variations in the modelled smoke aerosol optical depth (AOD) at 550nm. The corresponding modelled AOD obtained using hourly FRP-derived source emissions is shown in Figure 10b.

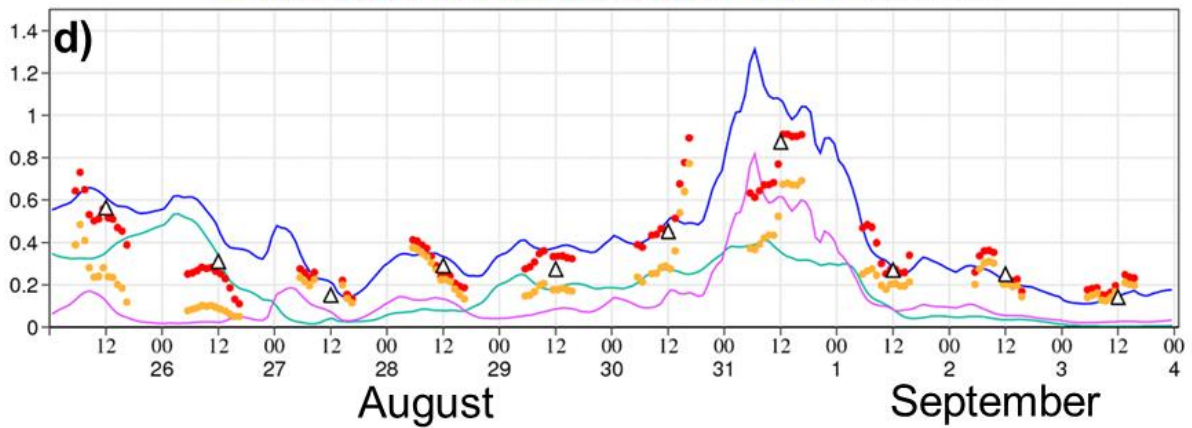
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Comparison of model (eyvo) & MODIS AOT at 550nm and L1.5 Aeronet AOT at 500nm
 FC Total FC Dust FC BC+OM Aeronet Total Aeronet Fine MODIS Total



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1865 **Figure 13:** MODIS FRP from the Algerian wildfires (a) between the 26th August and 4th

1866 September (2007), (b) modelled smoke, and (c) modelled dust aerosol optical depth (AOD) at

1867 550 nm on August 31st 2007 (00:00 UTC). (d) time series of daily averaged MODIS total

1868 AOD observations (open black triangles), the AERONET observations of total (red circles)

1869 and fine mode AOD (orange circles), modelled total AOD (blue line), and its contributions

1870 due to smoke (purple line) and dust (green line). Data sources: MODIS

1871 (<http://disc1.sci.gsfc.nasa.gov>) and AERONET (<http://aeronet.gsfc.nasa.gov>)

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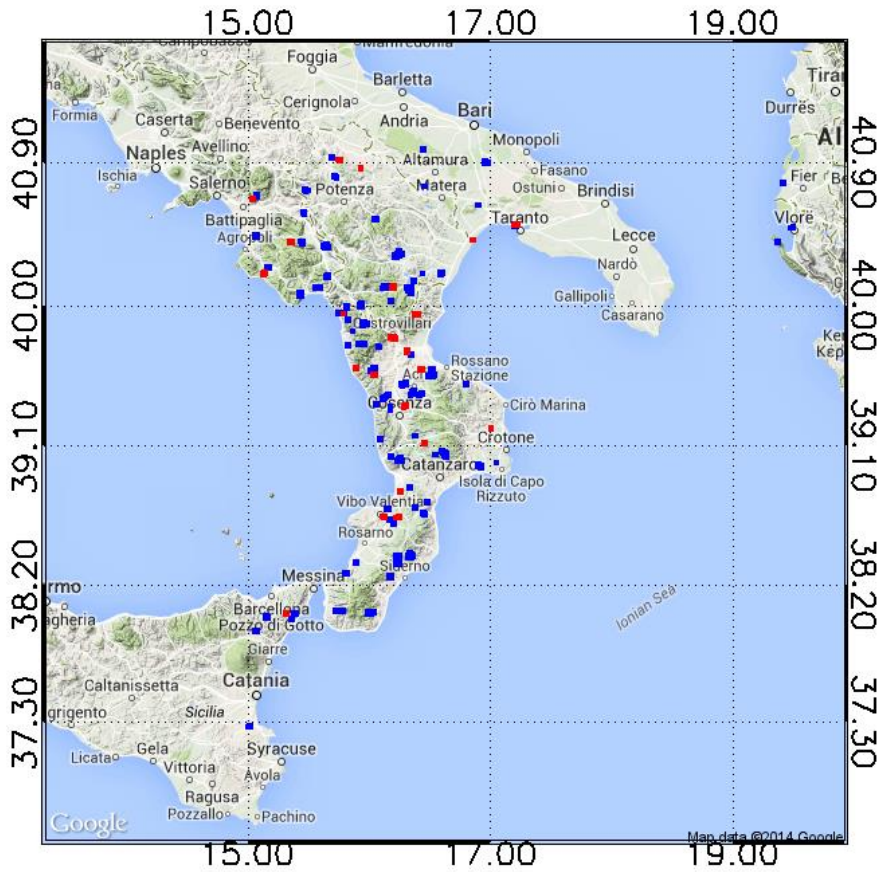
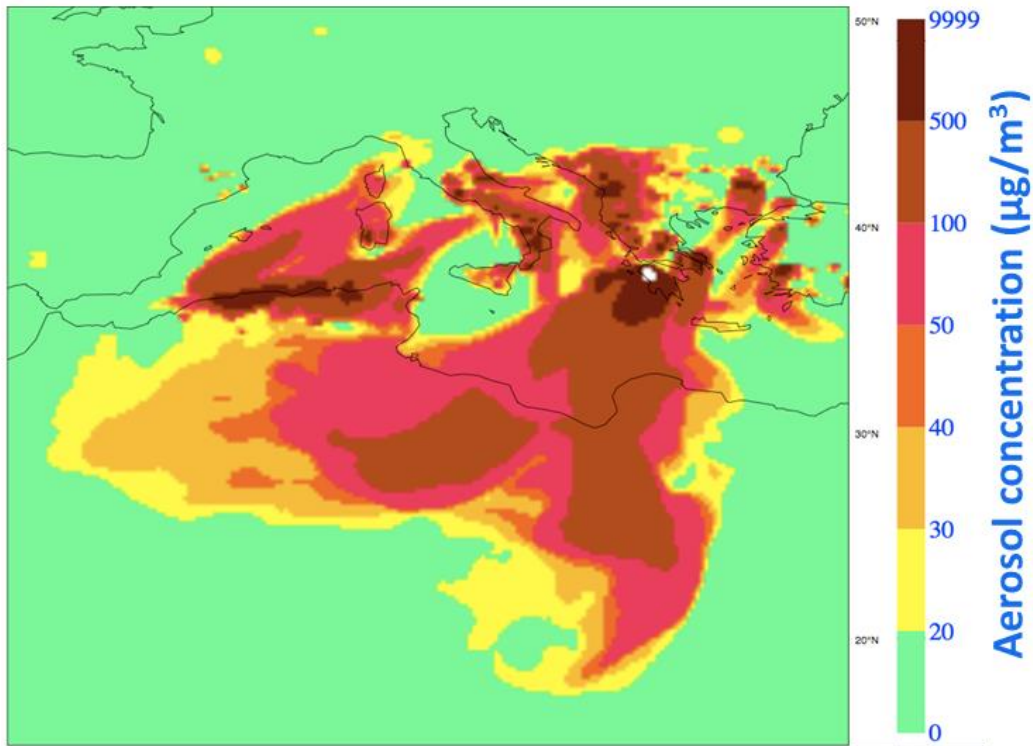


Figure 14 : MODIS active fire detections occurring between the 27 and 31st August (blue symbols) and 28 and 29th August (red symbols). These fires typically occur downwind of the Algerian smoke plume seen in Figure 13, and therefore are likely to have contributed to elevated AOD values detected at the Lecce AERONET site.

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Figure 15: Simulated maximum 24-hour running mean smoke aerosol concentration [$\mu\text{g m}^{-3}$] recorded at the surface between the 23rd August and 3rd September (2007), based on the methodology outlined in Section 5.6. The values are an upper limit due to unrealistically low smoke injection height into the atmosphere. The World Health Organisation (WHO) air quality guidelines (WHO, 2006) set a limit of $25 \mu\text{g m}^{-3}$ for the surface concentration of fine mode particulate matter (PM_{2.5}) averaged over a 24 hour period.

1930 **Table 1:** Performance characteristics of the LSA SAF Meteosat SEVIRI FRP-PIXEL product
 1931 in the four LSA SAF geographical regions, as compared to MODIS active fire product
 1932 (Collection 5 MOD14 and MYD14) collected over the same area and at the same time. Errors
 1933 of omission and commission with respect to MODIS were calculated on a per fire pixel basis
 1934 as described in Section 3.1.1. The per-fire basis results (Column 5) were obtained when
 1935 comparing the total FRP retrieved from MODIS and SEVIRI for fires (defined as a spatially
 1936 contiguous set of active fire pixels) detected by both sensors. The area-based results (column
 1937 6) were derived from comparison of the total FRP measured by all detected fires in a
 1938 matching MODIS and SEVIRI image area, and thus include the influence of non-detected
 1939 low FRP fires by SEVIRI whilst the per-fire comparison results (Column 5) do not.

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LSA SAF Geographic Region	Image Dates (2008)	Active Fire Pixel Detection Omission Error (%)	Active Fire Pixel Detection Commission Error (%)	Slope of linear best fit relationship between SEVIRI-to-MODIS per-fire-based FRP measures	Slope of linear best fit relationship between SEVIRI-to-MODIS Area-based FRP measures
northern Africa	1-8 Dec	65	9	0.96	0.65
southern Africa	19-24 Aug	77	13	0.97	0.53
South America	14-24 Aug	91	39	0.97	0.22
Europe	9-17 Aug	97	30	0.88	0.11

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Table 2 : Summary of active fire pixel detection errors of omission and commission for the four SEVIRI-derived active fire products explored herein (LSA SAF FRP-PIXEL product; Wooster *et al.*, 2015, WF-ABBA; Prins *et al.*, 1998, Fire Detection and Monitoring - FDeM; Amraoui *et al.*, 2010, and FIR Active Fire Monitoring; Joro *et al.*, 2008). Data were collected over the LSA SAF southern Africa geographic region during August 2014, when fire activity is widespread in this area. The MODIS active fire products (MOD14 and MYD14; Giglio *et al.*, 2003) acted as the independent data source for the comparison.

	FRP-PIXEL	WFABBA	WFABBA	WFABBA	WFABBA	FDeM	FIR
		All Detection s	Filtered	Filtered (Flags 0-4)	Filtered (Flags 0-3)		
Number of SEVIRI fire pixels at coincident MODIS overpasses	33414	15610	13008	9736	8832	7664	7151
Number of SEVIRI fire pixels detected by MODIS	29037	14521	12284	9369	8496	7260	6730
Commission error (%)	13	7	6	4	4	5	6
Omission error (%)	77	82	84	87	88	92	95

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Table 3: Summary of the results related to evaluation of the regional bias adjustment factors implemented during the processing of the LSA SAF FRP-GRID product. Slope of the linear best fit between the SEVIRI-predicted regional FRP using the FRP-GRID bias adjustment factors and the FRP measured by MODIS over the same areas are shown, as are the coefficients of determination (r^2), at both 5° and hourly resolution (which is the native FRP-GRID product resolution) and also at a weekly resolution accumulated over the entire LSA SAF geographic region.

LSA SAF Region	Abbreviation	Validation Results: Slope (r^2)	
		5.0° and hourly	weekly and regional
northern Africa	NAfr	1.04 (0.76)	1.15 (0.96)
southern Africa	SAfr	1.02 (0.91)	1.24 (0.97)
South America	SAmE	0.97 (0.34)	1.89 (0.83)
Europe	Euro	1.72 (0.19)	4.94 (0.84)

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2048
2049
2050
2051
2052
2053
2054
2055
2056
2057

Table 4: Trace gas and particulate smoke emission factors (η) for species (*s*) based on extratropical forest fuels, taken from Andreae and Merlet (2001). * The emission factor for BC and OC was derived specifically for use in this study (see main text).

Species	Emissions factor (g kg⁻¹ DM)
Black carbon (BC)	1.7*
Organic carbon (OC)	8.6-9.7
Organic matter (OM)	42*
Total particulate matter (TPM)	17.6±6.4
Fine mode aerosol (PM2.5)	13.0±7.0
Carbon Monoxide (CO)	107±37