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Observation operator and detection limits for MODIS and VIIRS Fire Radiative Power products

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Abstract

We analyze the MODIS and VIIRS active-fire Fire Radiative Power (FRP) products and suggest an approximation for the FRP detection limit as a linear function of a pixel area and develop analytical observation operators for both pixel-level and gridded FRP products. We have shown that the collection-6.1 of MODIS has the FRP detection limit at 3.7 MW in case of a nadir retrieval at a clear-sky night. For a daytime sideview, it reaches as high as 40 MW. For VIIRS, the smallest fire reliably detected at night is 0.5 MW. Application of the developed operators for the cross-mapping the MODIS and VIIRS datasets at the pixel/granule level confirmed their consistency. Applying the grid-level operators alongside satellite overpass and weather data, we generated global maps of fire detection probabilities, revealing regional variations. As a global average, probability of detection of powerful fires is 78% for MODIS (88% for VIIRS). Variations between regions are large: in some equatorial areas this probability is less than 30% for MODIS (40% for VIIRS).

Key words: Fire Radiative Power, MODIS, VIIRS, observation operator, sensitivity, detection limit

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1. Introduction

Vegetation fires have long been recognized as one of the most-powerful phenomena affecting the lifecycle of forest and grassland ecosystems, a strong source of atmospheric pollutants, and a significant climate factor (Crutzen et al., 1979; Kollanus et al., 2017; Buchholz et al., 2022; Khabarov et al., 2016; Chowdhury et al., 2025). Since fires are a global phenomenon, satellite observations are the natural way of their systematic monitoring. Two types of products are the most-important in this respect: burnt-area scars left by recently occurred fires (Chuvieco et al., 2019) and active-fire products, such as Fire Radiative Power (FRP) and Temperature Anomaly (TA), which rely on a thermal fingerprint of active fires (Ichoku and Kaufman, 2005; Kaiser et al., 2012; Kaufman et al., 1998; Parrington et al., 2025). Both types of products have their strong and weak points (Archibald and Roy, 2009; Roy et al., 2008; Schroeder et al., 2014a; Vilar et al., 2015; Zubkova et al., 2023). This work concentrates on active-fire products.

Observations of active fires produce two types of data: hot spot counts (Arino et al., 2012; Li et al., 2001) and fire radiative power FRP (Kaufman et al., 1998; Ichoku and Kaufman, 2005; Schroeder et al., 2014b; Giglio et al., 2016, 2021; Schroeder, 2020a, 2020b; Xu and Wooster, 2023). The key strength of the FRP - based approach is that the data characterizes the fire intensity at the moment of the observations. It allowed to construct operational global fire information systems (Kaiser et al., 2012; Wiedinmyer et al., 2011; Sofiev et al., 2009; Chen et al., 2022), build injection-height models (Freitas et al., 2007; Sofiev et al., 2013, 2012; Rémy et al., 2017; Li et al., 2022), and estimate characteristic diurnal cycle of the fire activity (Soares et al., 2015; Sofiev et al., 2013).

A limitation of the active-fire data is a tendency to miss a substantial fraction of fires – a so-called omission error. Thus, (Schroeder et al., 2008) used Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) at 30 m spatial resolution to provide a “ground truth” dataset for the MODIS algorithm. They produced summary

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statistics indicating that 50 to 100 ASTER fire pixels (corresponding to 5%-10% of area of a 1 km pixel) are necessary to trigger the MODIS fire detection with >80% probability. The uncertainty in the estimate was associated with the fraction of the pixel area covered by trees. No quantitative estimation of the FRP detection limit was provided.

A fire can be missed if its radiative power is below the detection limit of a given instrument/algorithm. This threshold, in turn, depends on the overall contrast of the scene, i.e., the size of the burning area, the size of the pixel, background temperature of non-burning areas around the burning pixel. A larger pixel means stronger averaging and lower contrast. We are aware about only one study so far that quantified the dependence of the minimum strength of the observable fire on the pixel size (Maier et al., 2013), which considered MODIS Collection 5 for Australia.

Among the key reasons for omission error of low-orbit satellites is a cloud obscuration during the satellite overpass. This error is milder for geostationary-based instruments, such as SEVIRI, GOES, and HIMAWARI (Roberts and Wooster, 2008; Schroeder et al., 2007; Schultz et al., 2008; Xu et al., 2017) because they can provide information for a specific location several times per hour, thus avoiding some clouds. However, the problem still exists: the effect of cloud obscuration was studied for Brazilian Amazon (Schroeder et al., 2007) showing the GOES omission error of 11% of fire counts during the considered episode.

Utilization of any observational data in numerical models requires a procedure that relates the observed quantities and the ones computed by the model. It has been shown (Bocquet et al., 2015) that the model-measurement comparison should be performed in the observational space, i.e., the modelled quantities should be converted to the observed ones using an Observation Operator, hereinafter OOp (Bocquet et al., 2015; Carrassi et al., 2018). In principle, every type of observation requires own OOp, but in many cases the modelled quantities are considered to be close enough to the observed ones for

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assuming the identity OOp. For satellite data, this is practically never the case, therefore sophisticated operators have been developed targeting radiance as one of the primary remote-sensing variables (Evans, 2007; Greenwald et al., 2004, 2002; Kostka et al., 2014). Such operators involve radiative transfer models and provide a sufficiently accurate mapping of the model data to variables observed by the satellite instrument. It is also possible to construct simpler operators converting the model output to an intermediate remote-sensing variable, which is deemed accurate. For instance, (Banks et al., 2012) developed an OOp for the remote-sensing ocean color synthetic measurement at the water surface, whereas the key step in the OOp for OMI NO_2 column data is accounting for the instrument averaging kernel (Boersma et al., 2011).

An identity operator has been used for the FRP data so far (Kaiser et al., 2012), and we are not aware about any non-trivial OOp developed for the FRP retrievals.

The objectives of the current work are: (i) to quantify the detection limit of individual MODIS (collection 6.1) and VIIRS (collections 2 and 2.1) retrievals of FRP and to suggest a unified analytical approximation as a function of pixel size; (ii) to suggest an observation operator for gridded MODIS and VIIRS FRP products; (iii) to apply the developed OOp to quantify the omission error over the globe and estimate the probability of fire detection by MODIS and VIIRS during the fire season as a function of the location, (iv) to demonstrate the OOp application to mapping the level-2 MODIS and VIIRS FRP products.

The paper is organized as follows. The next section 2 describes the input data of the assessment, section 3 introduces the study methodology, derives the sensitivity of the FRP products, detection limit, and OOp formulations; section 4 presents the results of the OOp application: global maps of the MODIS and VIIRS omission error and application of pixel-level OOp to cross-mapping the MODIS and VIIRS pixel-/granule-level FRP retrievals. These are discussed in section 5.

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2. Input data

2.1. MODIS Fire Radiative Power and supplementary products

The MODIS dataset used in this study consists of the level-2 (L2) Fire Radiative Power retrievals MOD14 and MYD14 from the instrument onboard Terra (2000-2023) and Aqua (2002-2023) satellites respectively. Hereinafter, the common notation will be MxD14. The L2 products were downloaded from Atmosphere Archive & Distribution System (LAADS) Distributed Active Archive Center (DAAC) (https://ladsweb.nascom.nasa.gov/, visited 12.10.2025, (Giglio and Justice, 2021a, 2021b). The data after 2023 were not used to avoid impact of the TERRA constellation exit maneuvers.

The MODIS L2 products are organized in granules, i.e., chunks of data collected during 5 minute intervals. Each MxD14 granule contains a field of flags for every pixel in a granule indicating if a detection was possible or not (cloud obscuration, failed retrieval, sun glint, water surface etc.) and a list of overheated pixels with FRP, geolocation, position in the swath, pixel size, etc. The geolocation of non-overheated pixels was picked from the MODIS cloud products MxD35 collection 6.1 (MODIS Atmosphere Science Team, 2017a, 2017b).

The key variables used in the assessment are: (i) the pixel-wise FRP expressed in megawatts throughout the paper; (ii) quality flags of MxD14, (iii) geolocation information of individual pixels of MxD35.

The FRP retrievals were censored by removing ~0.6% of pixels with unphysically strong FRP, $P_p > 500$. Secondly, the first months of MODIS Terra operations, until November 2000, were removed entirely due to known problems with the sensor (Giglio et al., 2021). No other filtering was applied.

2.2. VIIRS Fire Radiative Power products

The VIIRS data from the instruments onboard SUOMI-NPP (2012-2024) and NOAA-20 (2018-2024) satellites were obtained from the same NASA LAADS DAAC Earth Data server as the MODIS products.

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We used VNP14IMG and VJ114IMG (Giglio, 2024a, 2024b) for FRP, locations of detected overheated pixels, and the detection mask, and VNP03IMG and VJ103IMG products (VIIRS Calibration Support Team (VCST), 2021a, 2021b) for pixel geolocation. The corresponding common notations hereinafter are Vxx14 and Vxx03. The date before February 2012 were discarded to avoid suspiciously large number of fires reported in the first days of the instrument operation. No other filtering was applied.

3. Methodology

3.1. Size of a MODIS and VIIRS pixel

MODIS and VIIRS fire radiative power algorithms are based on thermal contrast of the fire pixel and its surroundings and are sensitive to the pixel area at the surface. An approximate formula for the pixel size calculations has been suggested by Ichoku and Kaufman (2005) with a reference to Masahiro Nishihama (pers. comm. 2004) and the MODIS Algorithm Technical Basis Document ATBD (Nishihama et al., 1997). A ground pixel size along the scan ΔS and the satellite track ΔT directions are functions of the scanning angle θ and the basic orbit parameters:

$$\Delta S = R_e s \left[\frac{cos\theta}{\sqrt{(R_e/r)^2 - sin^2\theta}} - 1 \right] \quad (1)$$

$$\Delta T = rs \left[cos\theta - \sqrt{(R_e/r)^2 - sin^2\theta} \right] \quad (2)$$

where R_e=6378.137 km is radius of Earth, r=R_e+h, h is altitude of the orbit (705 km for MODIS), p is pixel nadir size (1 km for MODIS), s=p/h=0.0014184397 (MODIS), and scanning angle θ is determined by the pixel number i in the scan line consisting for MODIS of totally N=2030 pixels:

$$\theta_i = s\left(i - \frac{N+1}{2}\right) \quad (3)$$

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Since these formulas have no instrument-specific parameters, they can also be applied to VIIRS with h=825.2 km, N=*6400* non-aggregated pixels, s=0.375 km (Schroeder et al., 2014b; Wolfe et al., 2013). Accuracy of this approximation has been verified against the instrument look-up table (W. Schroeder, pers.comm., 2022) and showed the error not exceeding 0.2% for all variables of (1) - (3).

3.2. Swath geometry

Formulas (1) - (3) describe the features of the MODIS and VIIRS swaths (Figure 1). The total width of the MODIS scan over the Earth surface is ~2063 km, and the pixel area varies from 1 km^2 in nadir view at θ = 0 up to 9.66 km^2 at the edge of the swath at θ = 55°, where pixels are of 2 km × 4.8 km size (Figure 1 a). Despite so wide range of sizes, about 40% of the swath is covered by pixels with A_p < 2 km^2 and only 20% - by pixels with A_p > 6 km^2 (Figure 1 b,c).

MODIS has 10 detectors in the track direction (Nishihama et al., 1997). The growing size of the pixels towards the edge of the swath means that the neighboring swaths partly overlap along the track direction (Figure 1 d, see also Figure 3-1 of (Nishihama et al., 1997) for MODIS). The overlap along the track is significant: near the swath edge it can reach 50% of the pixel area, i.e., the edges of swaths are observed twice.

The VIIRS swath geometry is generally similar but with peculiarities. To limit the pixel size growth along the scan direction, individual pixels of both I- and M-bands are aggregated as 3 × 1 (three scan-direction samples by one track-direction sample), 2 × 1, and 1 × 1 for the scan angles of 0°-30°, 30°-45° and 45°-55°, respectively (Figure 1, (Schroeder et al., 2014b)).

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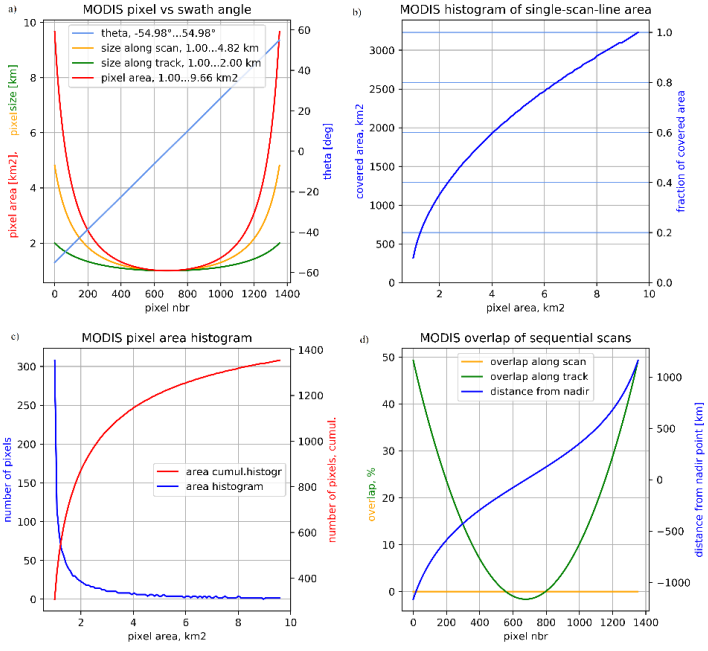
MODIS swath geometry



VIIRS swath geometry

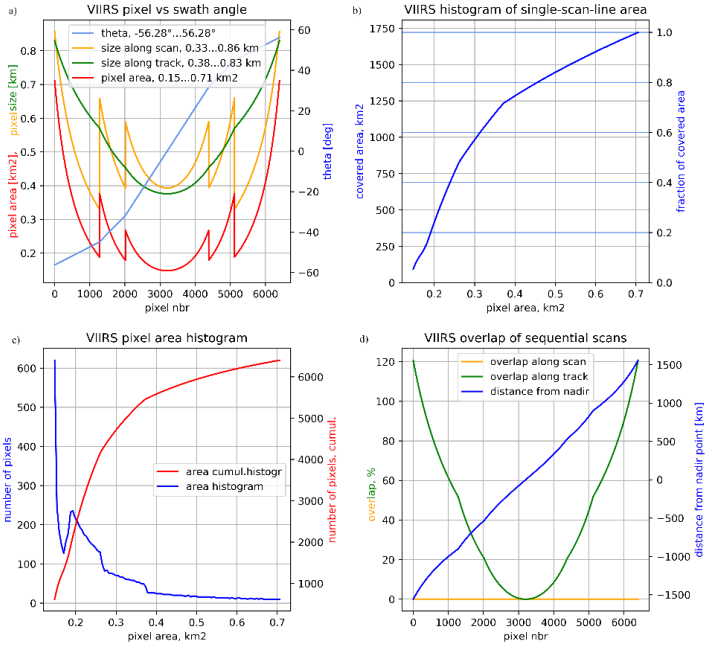


Figure 1. MODIS and VIIRS swath geometry. Panels: a) linear sizes, area, and viewing angle along the scan; b): fraction of swath covered by pixels smaller than the given area; c): distribution of pixel area; d): overlap of pixels along the track and along the scan.

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A singe VIIRS sensor has 32 I-band sensors in the track direction, and subsequent scans substantially overlap at high scan angles leading to up to a triple coverage at the edge of the swath. To reduce the redundancy and to limit the amount of data to transfer, data readings from two and four I-detectors from the top and bottom of the arrays (the largest scan angles) are not transmitted in the 2 × 1 and 1 × 1 aggregations zones, respectively (a "bow-tie deletion"). The current study used data of the I-band detectors, which provide ~375m nadir pixel size (Wolfe et al., 2013), and explicitly accounted for the pixel aggregation and the bow-tie deletion (Figure 1).

3.3. Pixel-wise and gridded statistics of retrievals

Since all considered satellites are on sun-synchronous orbits and because the fires are heavily influenced by the local diurnal cycle, the analysis was performed in local solar time (LST). Two types of statistics were computed: for individual pixels and for gridded data.

3.3.1. Pixel-wise detection limit

The pixel-wise assessment was performed independently for MODIS and VIIRS. Since it was made with regard to the pixel area (not viewing angle), there was no difference between the procedures, only numerical constants were instrument-specific. For individual pixels, the following classification flags were adopted throughout the computations: missing data, cloud, sun glint, non-fire, fire. Areas outside the swath were considered missing.

The pixel detection limit was computed as follows (Figure 2, Figure 3). The retrievals of each instrument were aggregated to four 2-D distribution density functions: for daytime, nighttime, and whole-day FRP $\pi_f(A_p, P_f)$, and for the whole-day number of fire pixels $\pi_n(A_p, P_f)$. Here, A_p is pixel area, P_f is fire radiative power registered by an individual pixel at a single overpass. The obtained distributions are shown in Figure 2 and Figure 3 for MODIS and VIIRS, respectively.

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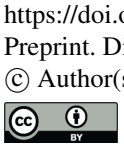

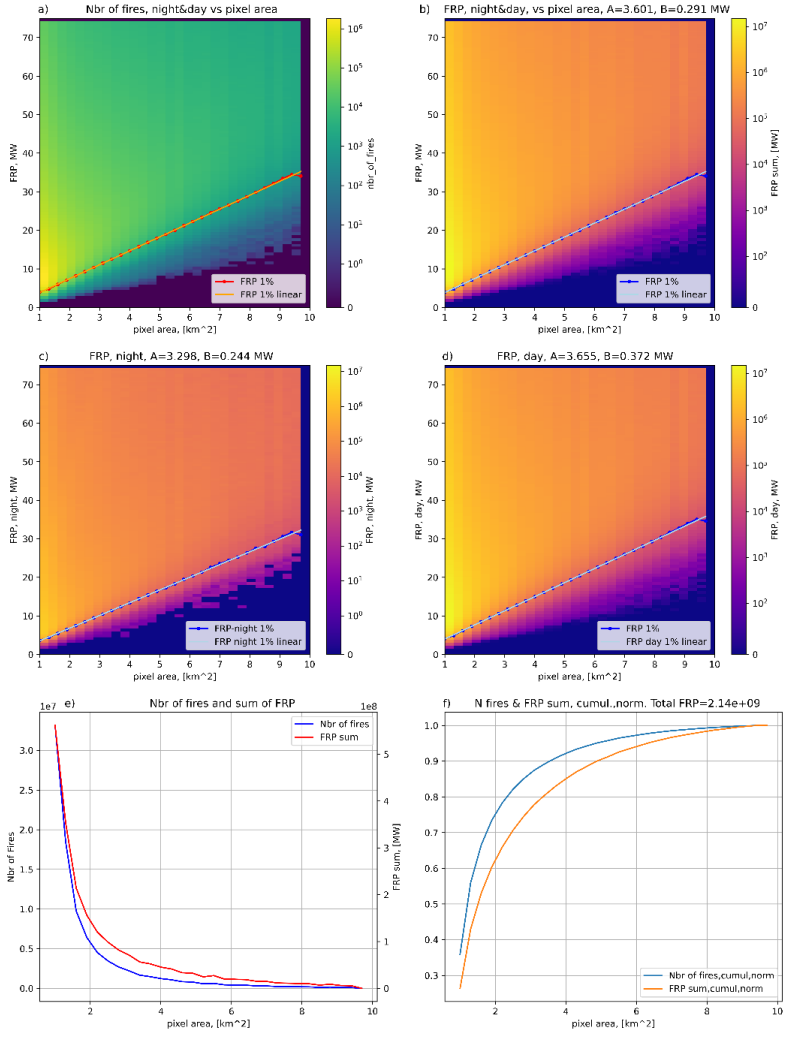

174

175 *Figure 2*. Distribution of the fire pixels detected by MODIS below 75 MW (arbitrarily taken cut-off allowing to see the peaks of
176 the distributions and detection limits) as a function of a pixel size and FRP. Panel a) Total number of fire pixels for all
177 overpasses, b) Total FRP of all overpasses, c) Total FRP registered by night-time overpasses; d) Total FRP registered by day-time
178 overpasses; e) Total FRP and number of fire pixels of the specific area, all FRP values counted (no upper limit); f) same as e) but
179 cumulative. Panels a)-d): red dots represent the 1%-tile for each pixel area whereas the orange lines on top of them represent
180 the corresponding linear approximations, which slope A and intercept B are shown in the panel titles.

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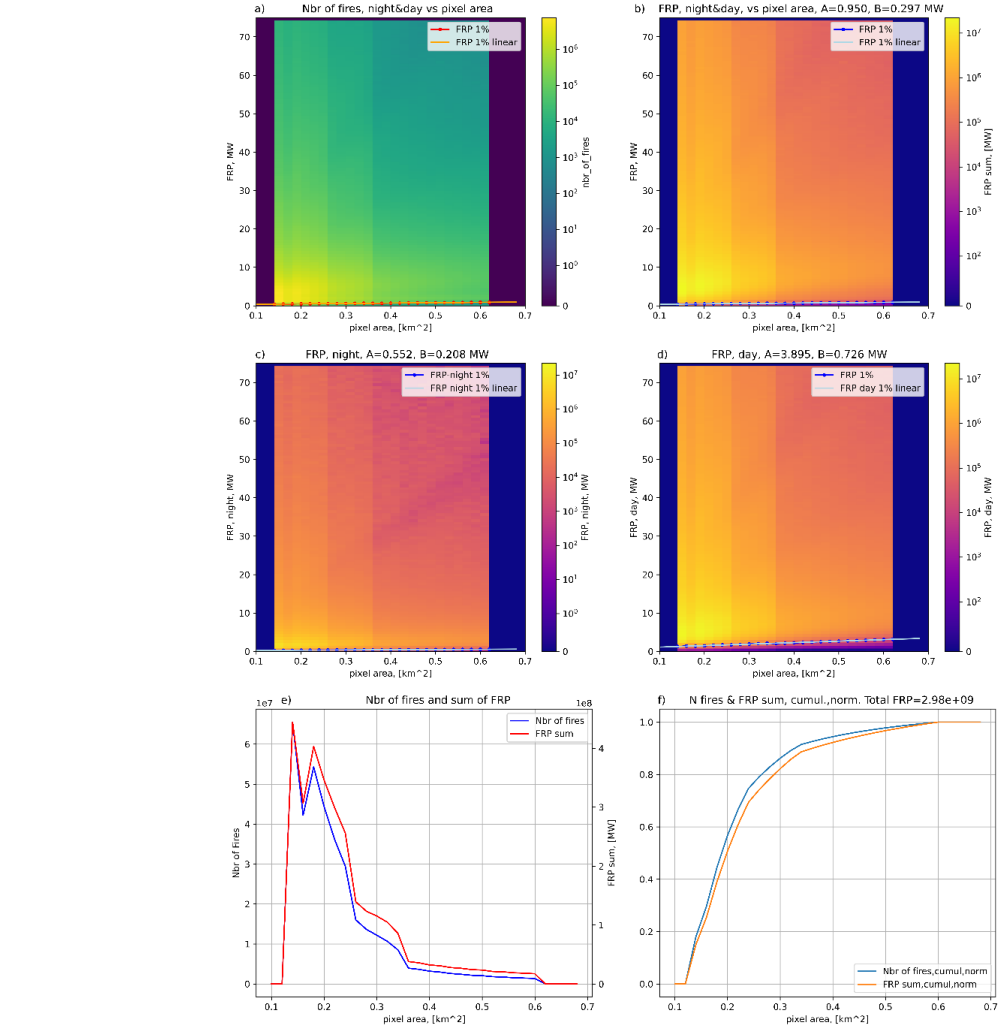

181

182 *Figure 3.* Distribution of the fire pixels detected by VIIRS as a function of the pixel area and detected FRP. Same panels as for
183 *Figure 2*. Panel a) Total number of fires for all overpasses, b) Total FRP of all overpasses, c) Total FRP registered by night-time
184 overpasses; d) Total FRP registered by day-time overpasses; e) Total FRP and the number of fires registered by the pixels of the
185 specific size, all FRP values counted (no upper limit); f) same as e) but cumulative. Panels a)-d): red dots represent the 1%-tile
186 for each pixel area whereas the orange lines on top of them represent the corresponding linear approximations, which slope A
187 and intercept B are shown at the panel titles.

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Detection limit identification was based on the vertical cross-sections of the FRP distribution densities $\pi_f(A_p, P_f)$ (Figure 2, Figure 3) for each specific pixel size (Figure 4 for MODIS and Figure 5 for VIIRS). The noise in the curves for large FRP is due to the low number of fires falling into the corresponding FRP ranges. The left sides of the curves in panels a) and b) of Figure 4 and Figure 5 can be approximated by a rising logistic function, shifted downward and cut at zero to remove the very small FRP values from the fit and then rescaled to reach max of 1.0:

$$P_{tot}(P_f) = P_0 + \frac{1}{a - c_o} max\left(0, \frac{a}{1 + e^{-r_p(P_f - D_p)}} - c_o\right) \quad (4)$$

Here, P_{tot} is total FRP registered for the corresponding range of P_f, P_0 and a are coefficients of the fit, D_p is the mid-point of the rising sigmoid curve, [MW], and r_p is rate of the function rise, [MW^{-1}], c_o is cut-off. Their values are given under each panel of Figure 4 and Figure 5. As one can see, the shifted logistic-function approximations turned very accurate for all curves (if the noise is smoothed, $r^2 > 0.95$ in all cases and normalized RMSE < ~0.1%).

From the Eq. (4), the definition of the detection limit naturally comes as the position of the midpoint D_p of the rising logistic function. For fires of such power, the total FRP registered by the instrument with the pixels of the corresponding size is half of the histogram max value for that size. It corresponds to ~50% of fires of this intensity missed by the instrument. Dependence of D_p and r on the pixel area A (panel c), $D_p(A_p)$, is a linear function of the pixel area (correlation coefficient > 0.999):

$$D_p = \begin{bmatrix} \infty & for\ pixel\ flagged\ as\ missing \\ \lambda_{lst} A_p + \mu_{lst} & for\ \ pixel\ \ with\ a\ valid\ \ retrieval \end{bmatrix} \quad (5)$$

The coefficients λ_{lst}, μ_{lst} of the Eq. (5) are shown in Figure 4c and Figure 5c and summarized in Table 1 for MODIS and Table 2 for VIIRS. The dependencies of the sigmoid max slope on pixel size are well approximated by hyperbolas.

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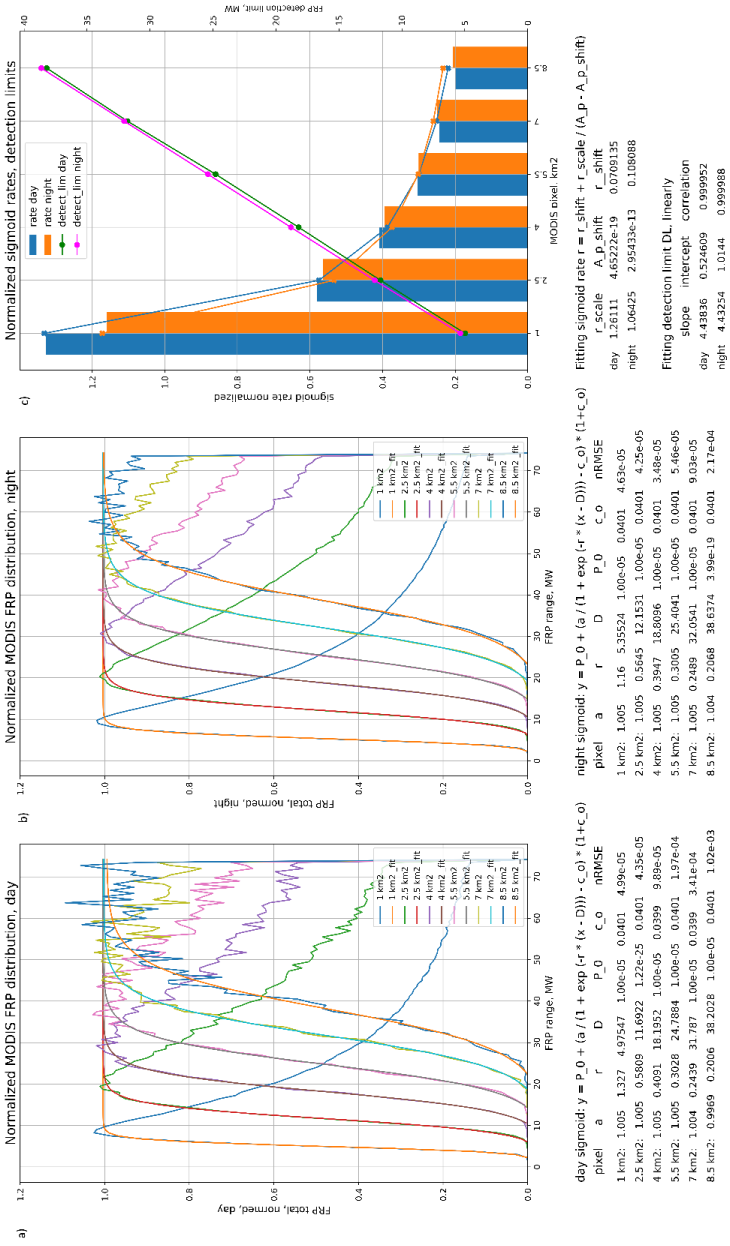

207

208 *Figure 4*. Definition of the detection limit as a function of pixel area via the normalized FRP distribution. Colored broken lines at
209 panels a) and b) are the normalized vertical cross-sections of the panels c) and d) of the *Figure 2*, for day and night retrievals,
210 respectively. All curves have been normalized to their smoothed max values. The rising part of each curve is approximated by a
211 sigmoidal function with parameters shown under the panel. Panel c): broken lines show FRP values corresponding to 0.5-level
212 of the corresponding sigmoidal function of the panels a) and b) – the detection limit for the specific pixel size; bars: slope of the
213 sigmoid at those points.

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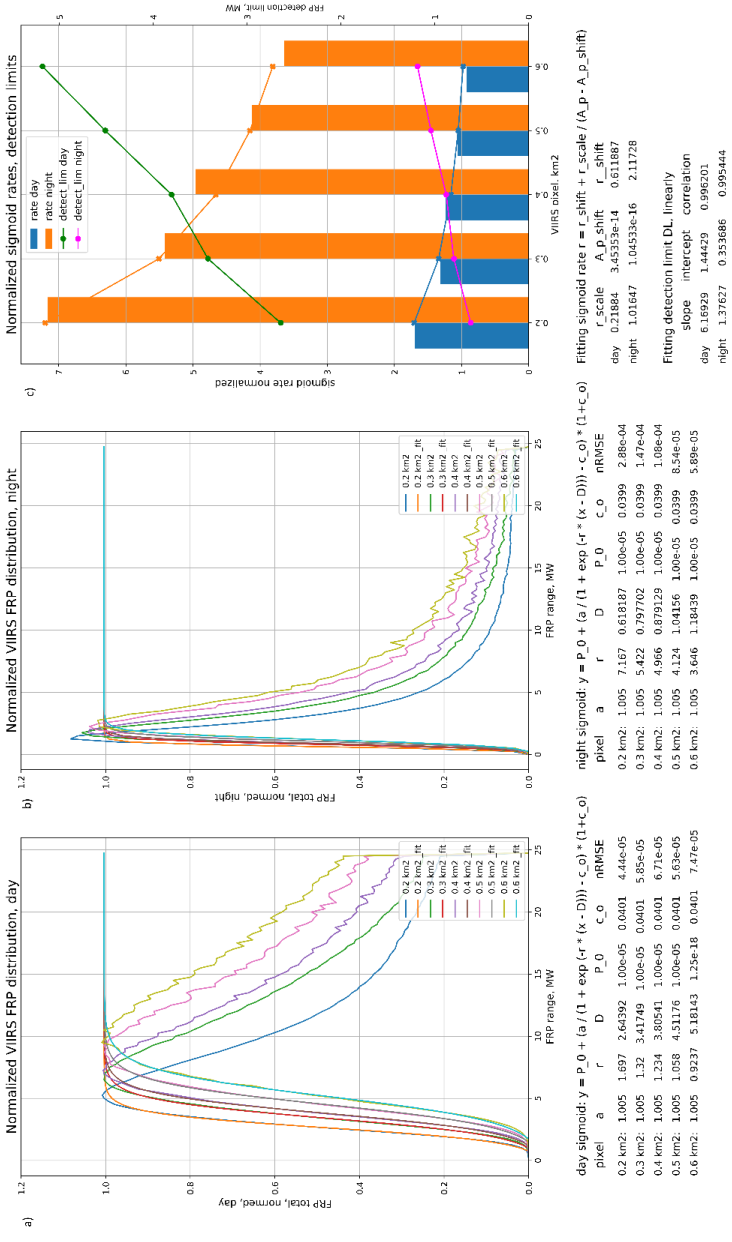

Fitting sigmoid rate r = r_shift + r_scale / (A_p - A_p_shift)

	r_scale	A_p_shift	r_shift
day	0.21884	3.45353e-14	0.611887
night	1.01647	1.04533e-16	2.11728

Fitting detection limit DL, linearly

	slope	intercept	correlation
day	6.16929	1.44429	0.996201
night	1.37627	0.353686	0.995444

night sigmoid: y = P_0 + (a / (1 + exp (-r * (x - D)))) - c_o) * (1+c_o)

pixel	a	r	D	P_0	c_o	nRMSE
0.2 km2:	1.005	7.167	0.618187	1.00e-05	0.0399	2.88e-04
0.3 km2:	1.005	5.422	0.797702	1.00e-05	0.0399	1.47e-04
0.4 km2:	1.005	4.966	0.879129	1.00e-05	0.0399	1.08e-04
0.5 km2:	1.005	4.124	1.04156	1.00e-05	0.0399	8.54e-05
0.6 km2:	1.005	3.646	1.18439	1.00e-05	0.0399	5.89e-05

day sigmoid: y = P_0 + (a / (1 + exp (-r * (x - D)))) - c_o) * (1+c_o)

pixel	a	r	D	P_0	c_o	nRMSE
0.2 km2:	1.005	1.697	2.64392	1.00e-05	0.0401	4.44e-05
0.3 km2:	1.005	1.32	3.41749	1.00e-05	0.0401	5.85e-05
0.4 km2:	1.005	1.234	3.80541	1.00e-05	0.0401	6.71e-05
0.5 km2:	1.005	1.058	4.51176	1.00e-05	0.0401	5.63e-05
0.6 km2:	1.005	0.9237	5.18143	1.25e-18	0.0401	7.47e-05

Figure 5. Definition of the FRP detection limit as a function of pixel size via the normalized FRP distribution for VIIRS. Panels are the same as in *Figure 4*. Colored broken lines at panels a), b) are the normalized vertical cross-sections of the panels c) and d) of the *Figure 3* for day and night retrievals, respectively. All curves have been normalized to their smoothed max values. The rising part of each curve is approximated by a sigmoid function with parameters shown under the panel. Panel c) broken lines: FRP values corresponding to 0.5 levels of the corresponding sigmoid function of panels a) and b) – the detection limit for the specific pixel size; bars: slope of the sigmoid at those points

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Table 1. Coefficients for the pixel-wise MODIS Observation Operator, Eqs. *(5)* - *(7)*

	Day: $\phi < 90°$	Night: $\phi \geq 90°$
λ_{lst} (slope), [MW km^{-2}]	4.44	4.43
μ_{lst} (intercept), [MW]	0.52	1.01
r_0 (shift), [MW^{-1}]	0.07	0.11
r_1 (scale), [km^2 MW^{-1}]	1.26	1.06
c_0 (cut-off)	0.045	0.045

Table 2. Coefficients for the VIIRS pixel-wise Observation Operator, Eqs. *(5)* - *(7)*

	Day: $\phi < 90°$	Night: $\phi \geq 90°$
λ_{lst} (slope), [MW km^{-2}]	6.17	1.38
μ_{lst} (intercept), [MW]	1.44	0.35
r_0 (shift), [MW^{-1}]	0.61	2.12
r_1 (scale), [km^2 MW^{-1}]	0.21	1.02
c_0 (cut-off)	0.05	0.05

Figure 4c and Figure 5c show that the slope of the rising sigmoid of the Eq. (4) is a hyperbolic function of the pixel size:

$$r_p = r_0 + \frac{r_1}{A_p - A_0} \quad (6)$$

For other coefficients, as follows from the fitting coefficients in Figure 4a,b and Figure 5a,b, the very small value of P_0 can be neglected, and the coefficient a set to 1.0.

Finally, replacing P_f with a model-predicted P_{mdl}, we obtain the observed FRP P_{obs} as a function of predicted P_{mdl}, thus concluding the pixel-wise observation operator $\Xi_{pix}(P_{mdl})$:

$$P_{obs}(P_{mdl}) \triangleq \Xi_{pix}(P_{mdl}) = \frac{P_{mdl} * 1}{1 - c_o} max\left(0, \frac{1}{1 + e^{-r_p(P_{mdl} - D_p)}} - c_o\right) \quad (7)$$

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3.3.2.Grid-cell-wise detection limit

This section introduces the OOp for models operating on a regular grid and with a regular time step. The grid cell size d is assumed to be significantly larger than the MODIS or VIIRS pixels. The grid-cell FRP $P(i,j)$ is a sum of FRPs of pixels in this cell: $P(i,j) = \sum_{(i,j)} P_f$. Evidently, the grid-cell fire detection is determined by the highest P_f – that very pixel has the highest chances to be noticed by the satellite. A mean fraction of the strongest fire pixel in the grid cell, $\gamma(d,P) = \overline{P_f/P}$, can be found from MODIS and VIIRS statistics as a function of $d \wedge P$ (Figure 6).

As seen from Figure 6, for grids coarser than 0.5°, γ depends only on total FRP $P(i,j)$: the curves corresponding to different d coincide. For fine grids, γ is larger reaching unity when grid cell size becomes similar to that of individual pixels. We approximated this 2-D dependency as follows:

$$\gamma = 1 - \left[1 - \left(\frac{P_2 - P_1}{P(i,j) - P_1} exp\left(\frac{d_1}{d}\right)\right)^{k_1}\right]^{k_2} \quad (8)$$

Here, d is grid resolution, d_1 is its empirical scaling, P_1, P_2, are FRP scaling constants, [MW], k_1, k_2 are dimensionless empirical constants. Both MODIS and VIIRS FRP retrievals can be approximated with this formula (Figure 6). The only difference is that VIIRS detects almost four times more small fires than MODIS, thus reducing the contribution of the strongest fire pixel by approximately 50%.

For a clear-sky grid cell, it is natural to use an area-weighted spatial average of detection limits over the pixels in the cell and account for the fraction of the largest fire in the total FRP:

$$D_{clr_{sky}}(i,j) = \frac{\sum_{p\in(i,j)} D_p A_p}{\gamma \sum_{p\in(i,j)} A_p} \quad (9)$$

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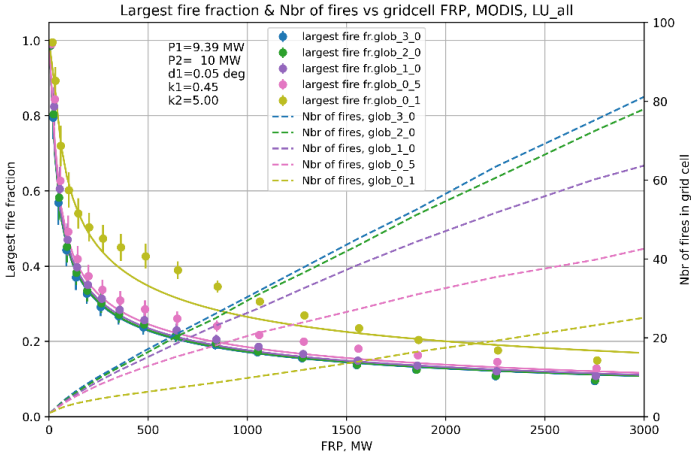
a)



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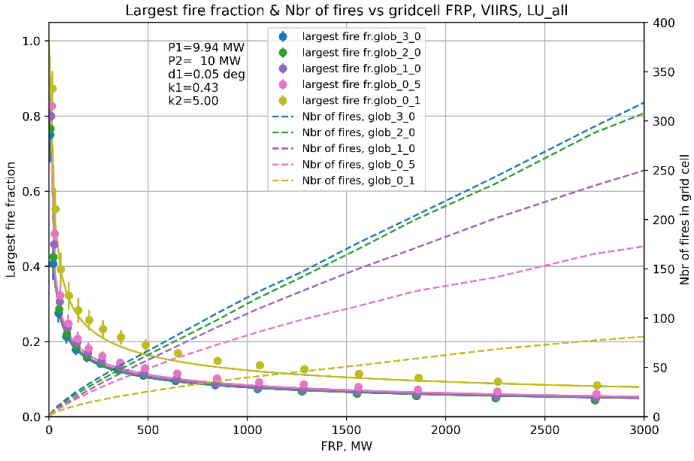

Figure 6. A mean fraction γ of the largest fire pixel in the total grid-cell FRP *P,* as a function of *P*. Calculated from MODIS 2000-2023 time series (panel a) and VIIRS 2018-2024 (panel b) as a function of grid-cell FRP for different grid resolutions *dx*. Fitting curves are computed from the Eq.*(8)* with the coefficients shown at the plot. Charts and dots are slightly shifted horizontally to reduce overlapping.

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For accounting for the partial obscuration of the grid cells, the following rules have been applied:

- for a grid cell *(i,j)*, the gridded fire radiative power is $P(i,j) = \sum P_f$ – a sum of all pixels within the grid cell *(i,j);*
- a fraction of the grid cell retrieved area, β_{ret}, is calculated from the pixel state flags as a fraction of the cell covered with pixels flagged as fire or non-fire, (i.e. not missing, cloudy, or sun-glint)

The grid-cell detection limit D_g is computed as a sum of the clear-sky detection limit D_{clr_sky} (9) and a term inversely proportional to β_{ret}, thus approaching infinity for a fully cloudy grid cell. Formally, it can be written as follows:

$$D_g(i,j) = \frac{\sum_{p\in(i,j)} D_p A_p}{\gamma \sum_{p\in(i,j)} A_p} + P_{max}\left(1 + exp\left(\frac{\beta_{ret}(i,j)}{\sigma_{ret}}\right)\right)^{-1} \quad (10)$$

The summation in the first term is taken over all non-missing MODIS pixels *p* of the grid cell *(i,j)*, P_{max} is a large FRP value, e.g., 10 GW, and σ_{ret} is a width of the transition range of the logistic function, e.g., 0.1. With such parameters, the second term is practically zero for β_{ret} > 0.3 but quickly grows approaching 5 GW if the grid cell has fewer valid pixels. The very high but still finite detection limit for cloudy scenes is taken to avoid numerical problems at the implementation stage.

With D_g from (10), the observed grid-cell FRP $P_{obs}(i,j)$ can be computed similarly to the pixel-wise OOp:

$$P_{obs}\left(P_{mdl}(i,j)\right) \triangleq \Xi_{grd}\left(P_{mdl}(i,j)\right) = \frac{P_{mdl}(i,j)}{1 + e^{-r_g\left(P_{mdl}(i,j) - D_g(i,j)\right)}} \quad (11)$$

The sigmoid slope r_g can be calculated as an area-weighted mean value for the pixels in the grid cell or simply taken as a prescribed instrument-specific constant representing a “typical” swath geometry (Table 3). Additional uncertainties due to this simplification are much smaller than those of the cloud-related term in the Eq. (10).

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Table 3. Suggested "typical" slope r_g for Eq. (11)

	Day: $\phi < 90°$	Night: $\phi \geq 90°$
r_g MODIS, [MW km^{-2}]	0.5	1.2
r_g VIIRS, [MW km^{-2}]	1.5	15

3.4. Thin clouds and smoke obscuration

In the above derivations, it is assumed that fire is either obscured by a cloud or not. However, the cloud can be thin, or a fire can be dimmed by its own smoke or other aerosols. The satellite would then process the pixel like a non-obscured one, but the signal strength would be lower. Denoting aerosol column optical depth AOD at the wavelength of the fire detection (4 μm for MODIS and VIIRS) as τ_4, one should replace the model-predicted FRP P_{mdl} with $P_{\widetilde{mdl}}$ in (7) and (11):

$$P_{\widetilde{mdl}} = P_{mdl} \exp(-\tau_4) \quad (12)$$

All other terms remain the same. This approach should be considered as indicative because aerosol obscuration will impact the retrieval at other wavelengths too reducing its accuracy.

3.5. Application of the OOp for comparison of the satellite datasets

The OOp has been developed for projecting a model-predicted FRP onto the observational space, but it can also be used for projecting one FRP dataset onto another. A complexity, however, is that the OOp implies a space-time co-location of the datasets, which is impossible for the low-orbit satellites. For instance, the accurate spatial co-location of MODIS AQUA and VIIRS Suomi NPP retrievals is straightforward, but their retrieval times differ by 1-2 hours. Different cloud patterns can be accounted for by symmetric OOp application: the MODIS OOp is applied to VIIRS FRP retrievals, the VIIRS OOp is applied to MODIS retrievals, and the obtained datasets compared:

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(13) $\Xi_{pixMODIS}(P_{VIIRS})$ vs $\Xi_{pixVIIRS}(P_{MODIS})$

Here, $\Xi_{pix}(P)$ is the pixel-wise OOp, Eq. (7).

4. Examples of the OOp applications

4.1. Application of grid OOp to retrieve cloud obscuration statistics

The cloud-related term in Eq. (10) leads to a space-dependent probability of missing a fire regardless of its intensity. A rough estimate of such probability is a mean of β_{miss} for a particular region, averaged over the satellite overpasses (Figure 7a, mean cloud cover for the MODIS overpass hours). However, the average cloud cover should be considered as the upper estimate of β_{miss} because fires tend to occur in dry periods when the cloud cover is lower than the annual mean.

A way to account for the mutual anticorrelation of clouds and fire occurrences is to calculate the mean cloud cover only during a fire season in the region. A quantitative criterion can be the non-zero sum of FRP for the surrounding area of, for instance, 1°×1° (Figure 7b for MODIS and Figure 7c for VIIRS).

Due to anticorrelation between cloud cover and detection probability, the missing fractions in Figure 7b,c, being more realistic than the mean cloud cover of Figure 7a, probably underestimate the omission error, thus being the lower estimate of the omission probability.

The results in Figure 7 depend on the arbitrarily selected size of the inspected area around the cloudy grid cell. Calculations with the different inspected areas showed that, e.g., doubling it to 2° × 2° adds ~10% to the omission probability of Figure 7 b, c. Further expansion eventually leads to the same map as that of Figure 7a (for MODIS). However, a wide search is not justified: already 200 km is too large as a correlation distance for regional fires. A smaller size was not efficient: the map becomes patchy. Therefore, 1° can be considered optimal.

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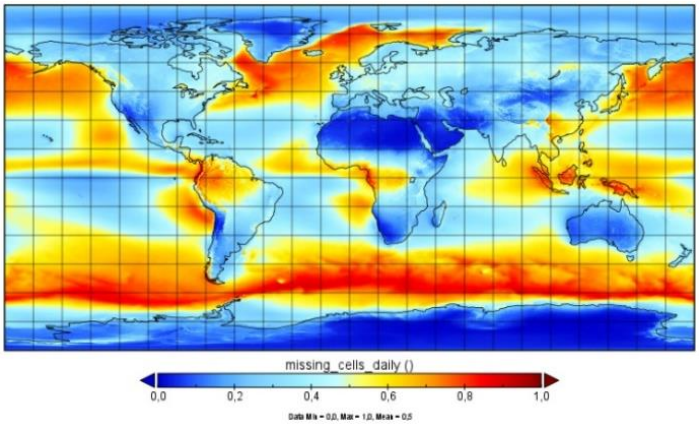

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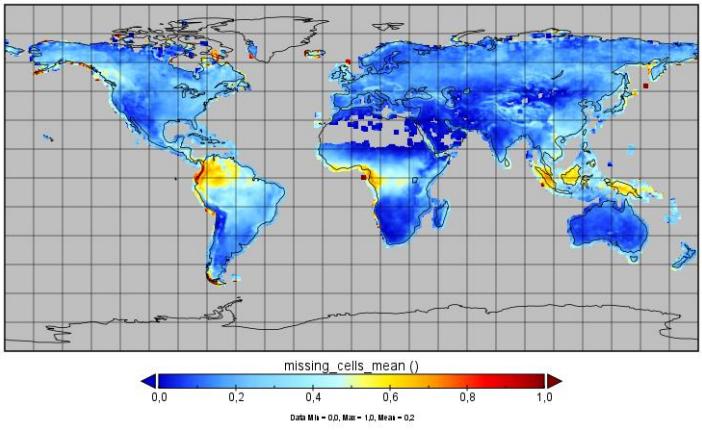

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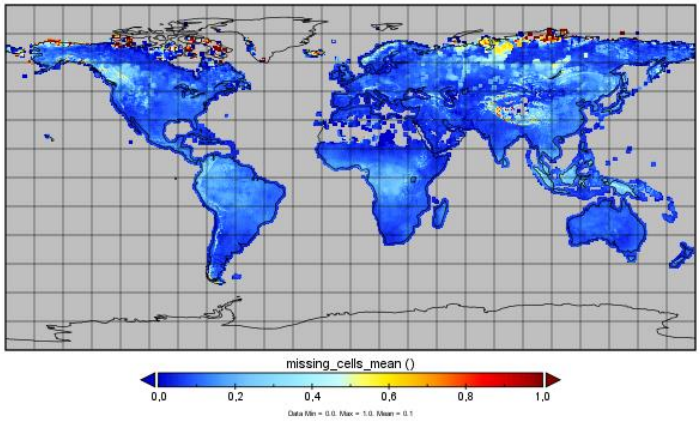

c)

Figure 7. Mean fraction of missing pixels due to cloud obscuration of MODIS, 2000-2020, and VIIRS, 2018-2024.10. Panel a) mean over all MODIS overpass times, b) mean over hours when non-zero FRP registered by MODIS anywhere in 1° × 1° square centered around the grid cell, c) mean over hours when non-zero FRP registered by VIIRS anywhere in 1° × 1° square centered around the grid cell.

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The maps of Figure 7 suggests that, even during the fire seasons, the omission error of low-orbit satellite instrument like MODIS or VIIRS is typically within 20-40% for most fire-prone regions, with VIIRS showing 10-20% lower omission error than MODIS. In equatorial regions, omissions can be much higher: the fraction of missed fires can exceed 60% for MODIS and 40% for VIIRS.

The lower omission error of VIIRS may be due to (i) higher resolution, (ii) higher sensitivity, as shown in the discussion below, (iii) specificity of the overpasses, which occur in the middle of day when cloudiness may be at its daily lowest level. Another peculiarity of VIIRS is a very high omission in Arctic, where MODIS shows the “usual” 40%. This is caused by the high sensitivity of VIIRS: it detects more fires in partly cloudy conditions and outside the main fire season. Clouds during these periods then contribute to the VIIRS omission error, whereas MODIS misses them altogether and thus does not consider these times as fire-prone at all.

4.2. Application of OOp to relate VIIRS and MODIS observations

The pixel-wise OOp was applied to the MODIS AQUA and VIIRS SNP FRP retrievals for a full year of 2020, taken as an example. The procedure followed the symmetric approach (13). The outcome (example in Figure 8) expectedly showed that VIIRS registered ~30% more FRP than MODIS (panels a), b) Figure 8) due to its lower detection limit. Application of MODIS-based OOp zeroed pixels with small FRP resulting in a 1.5 times lower granule total (panel d). Accounting for the differences in cloudiness via application of VIIRS OOp to the MODIS fire pixels led to ~30% reduction of the total FRP, thus leaving only those locations that were visible for both satellites (panel c).

Analysis of the whole year 2020 brought over 40,000 MODIS AQUA granules with fire pixels registered by at least one instrument. Total FRP retrieved by MODIS and VIIRS within these granules was 128 TW and 177 TW, respectively. Symmetric application of $\Xi_{pixVIIRS}(P_{MODIS})$ and $\Xi_{pixMODIS}(P_{VIIRS})$ lead to 88 TW and 106 TW, respectively. This is illustrated in Figure 9, which compares VIIRS retrievals before and

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343 after the MODIS OOp application (P_{VIIRS}, blue dots and $\Xi_{pixMODIS}(P_{VIIRS})$, orange dots) with the MODIS

344 FRP processed by the VIIRS OOp ($\Xi_{pixVIIRS}(P_{MODIS})$, x-axis in Figure 9).

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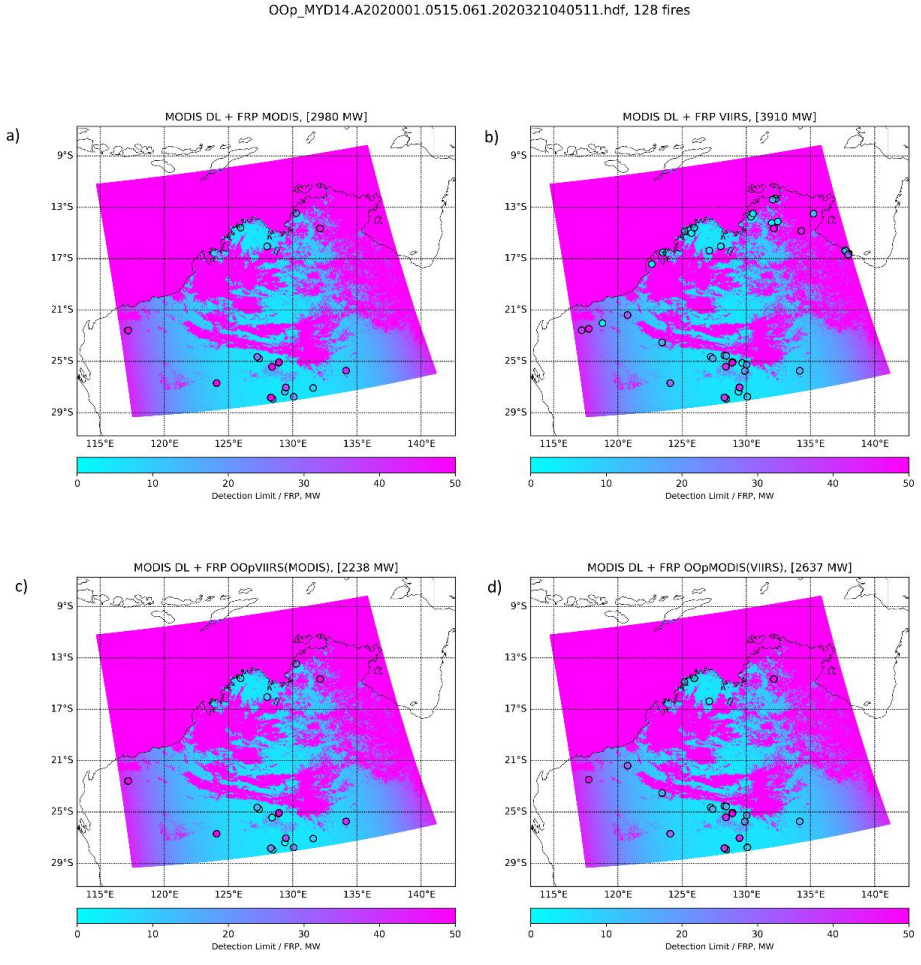

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347 *Figure 8.* MODIS and VIIRS fire retrievals for a MODIS AQUA granule over North-East Australia, 1.1.2020, 5:15 UTC, [MW].
348 Background in all panels is MODIS detection limit accounting for larger pixels at the swath edges and cloudiness. Upper panels
349 show MODIS and VIIRS FRP retrievals that fell into that granule, lower panels present the $\Xi_{pixVIIRS}(P_{MODIS})$and
350 $\Xi_{pixMODIS}(P_{VIIRS})$, respectively.

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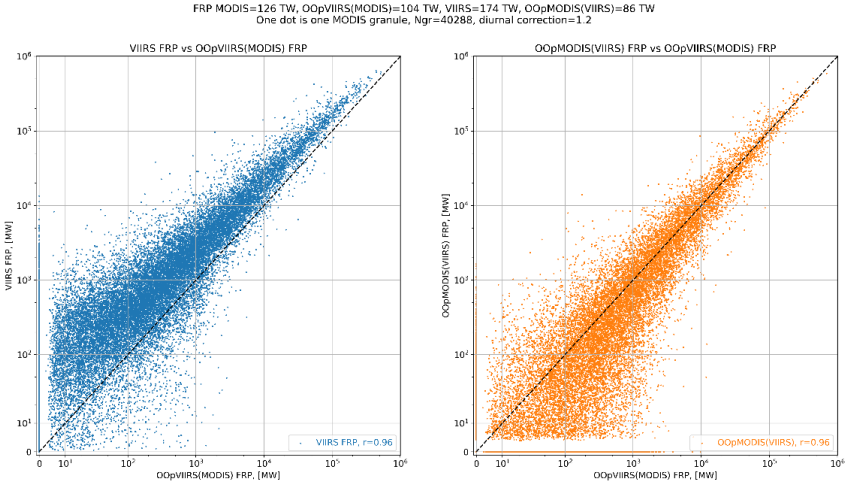

Figure 9. Summary of P_{MODIS} (blue) and $\Xi_{pixMODIS}(P_{VIIRS})$ (orange) for 2020. Each dot represents the total FRP of fires that fell to a single MODIS AQUA granule. Granules that did not have VIIRS coverage (missing or corrupted VIIRS granules) and granules with no fires in both instruments are filtered out. A diurnal variation correction factor 1.2 is applied to VIIRS retrievals (see Discussion section).

The OOp-processed datasets match closely: the initial 38% difference, VIIRS registering more FRP, turns to 20% more OOp-processed FRP of MODIS. This 20% difference originates from different overpass times of the satellites (see the discussion section below), so accounting for it results in a close match of the OOp-processed datasets (Figure 9).

5. Discussion

5.1. Features of the pixel-wise detection limit and OOp of MODIS and VIIRS FRP retrievals

The first percentiles of the distribution densities $\pi_f(A_p, P_f)$ and$\pi_n(A_p, P_f)$ (Figure 2, Figure 3) (the red-dots and orange regression lines) are linear functions of the pixel area for both MODIS and VIIRS, with

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correlation coefficient >0.99. For both satellites, the 1st percentile of the nighttime FRP is lower than that of daytime, for all pixel sizes, with the difference being larger for VIIRS than for MODIS.

The panels e) and f) of the figures show that the smallest pixels register most of the FRP and the total number of fires. For MODIS, 50% of fires are from 1 – 1.2 km^2 area pixels while the fraction of the swath covered by such pixels is about 20% (see the swath geometry in Figure 1b, c). For VIIRS, pixels < 0.3 km^2 occupy 60% of the swath area but provide ~90% of fire detections.

5.2. Previous assessments of the MODIS/VIIRS omission error and sensitivity to small fires

The results reported above can be compared with case studies presented in literature. For instance, the cloud obscuration of fires in Brazilian Amazon (Schroeder et al., 2007) led to the omission error of 11% for GOES geostationary fire products. This estimate expectedly differs from the MODIS / VIIRS statistics (Figure 7): e.g., the mean cloud cover of MODIS overpasses over that area is 0.4 - 0.7. For fire seasons, Figure 7b suggests the omission error from 0.2 - 0.6 for MODIS and 0.1-0.3 for VIIRS. The difference from the value of (Schroeder et al., 2007) refers to the ability of geostationary satellites to follow the fire over time thus avoiding some clouds. As follows from the comparison, it can about-half the omission error, at a price of 16 times lower resolution (GOES sub-satellite pixel was 4km × 4km), with the corresponding loss of small- and mid-sized fires.

The only study reporting the dependence of the fire detection probability on the pixel size was made for MODIS Collection 5 by (Maier et al., 2013) for Australia. The study suggested that fires with FRP < 3.6 MW are never detected (practically no fires were recorded up to 5 MW) whereas the frequency distribution of FRP is significantly disturbed already at 15 MW. According to the FREEVAL study (Schultz et al., 2008), the minimum-FRP detection threshold for MODIS Collection 4 was about 7 – 10 W m^{-2} (7-10 MW for 1 km^2 pixel). This is in agreement with the predicted sensitivity limit of 10 – 20 W m^{-2} of (Kaufman et al., 1998). Finally, our earlier estimates made for Collection 5 (Soares et al., 2015) pointed

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out that noticeable distortions of the FRP distribution start at 15 W m^{-2}. Except for (Maier et al., 2013), none of these works referred to the pixel size and the overpass time, and should therefore be attributed to the smallest nadir pixel of MODIS, 1 km^2. These numbers are about-twice higher than the limit obtained above for Collection 6, which confirms the better detection of small fires in Collection 6 in comparison with the earlier Collections.

The dependence of the detection limit on the pixel size is dictated by the geometry of the instrument and the basic principle of the temperature-contrast based fire detection, leading to qualitatively similar dependencies obtained by (Maier et al., 2013) and in the current work. Among the differences, one can notice an almost-perfect linear relation of the detection limit in the current study in contrast to a "saturation" noticed for large viewing angles by Maier et al, who attributed it to the randomly selected 1% threshold. However, in the current study, there is no saturation for 1% threshold either (Figure 2 and Figure 3). A more probable reason is an insufficient number of fire detections in the large-pixel size range: only 57.2 thousand events were counted in the Maier et al analysis vs ~90 million cases for MODIS in this study. Should this saturation be ignored, the detection limit for the largest pixels at the edge of the swath would exceed 55 MW for Collection 5, compared to 42 MW / 39 MW for day/night overpasses for Collection 6 in this study.

5.3. Comparison with sensitivity and detection probability of SEVIRI

The sensitivity of SEVIRI has been evaluated within the FREEVAL project (Schultz et al., 2008). That study concluded that "SEVIRI should be able to confidently detect actively burning fires whose FRP reaches a minimum of around 100 MW, and in certain cases may be able to detect fires whose FRP is even lower than this, down to around 50 MW." That theoretical conclusion was supported by the fire histogram, which manifested strong disturbances at FRP ~50 MW, with detection limit being around 40 MW for the sub-satellite pixels. This result corroborates very well with the current assessment because the smallest

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412 SEVIRI pixel is 3 km × 3 km, which corresponds to the edge of MODIS swath with the 42 MW detection
413 limit. Therefore, the lowest detection limit of SEVIRI (sub-satellite fires) is close to the highest detection
414 limit of MODIS at the edge of its swath.

415 Comparison with VIIRS is not unequivocal. Schroeder et al. (2014b) related the fire size and temperature
416 to the probability of VIIRS to detect it and concluded that a small (1.5m radius) but hot (1000K) fire can
417 be noticed at night. In a qualitative agreement with that prediction, a histogram of VIIRS FRP data
418 (Figure 3) suggests ~0.7 MW detection limit at night in the center of the swath.

419 5.4. Comparison of MODIS and VIIRS

420 A direct comparison of the detection limit formulas and coefficients for MODIS and VIIRS (Table 1, Table
421 2, Figure 10) reveals both the effect of the pixel size on the detection limit and the difference between
422 the instruments and processing algorithms: VIIRS is about 3x more sensitive than MODIS for comparable
423 pixel size of ~ 1km^2 at night, but about 25% less sensitive during day (within 5% for the first percentile).

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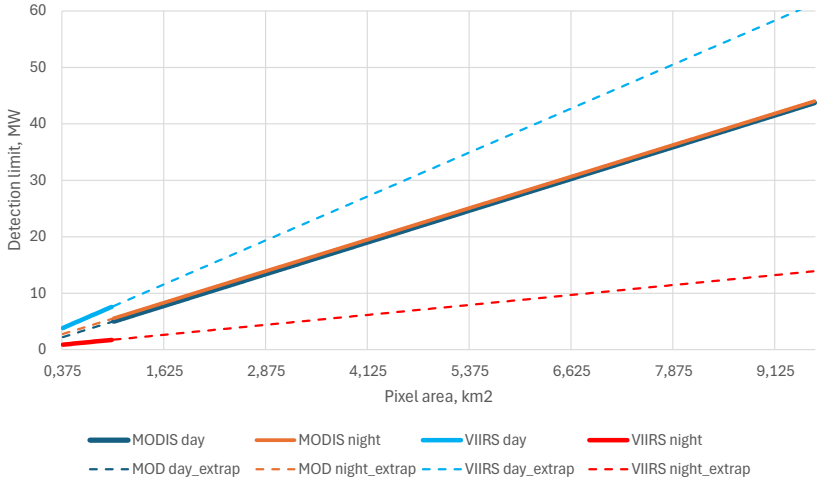

425

426 *Figure 10. MODIS and VIIRS detection limits as functions of pixel sizes. Solid lines denote the actual pixel size range of the*
427 *instruments, whereas dashed lines show their extrapolation to cover the whole size range 0.375 km² – 9.6 km².*

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Application of the OOp-s matches the datasets (Figure 8, Figure 9): the remaining difference of 23% between the $\Xi_{pixMODIS}(P_{VIIRS})$ and $\Xi_{pixVIIRS}(P_{MODIS})$ is a result of the later overpasses of AQUA, which registers most fires around 13:00-14:00 local time, compared to 12:00-13:30 of SNP. The absolute peak of fire intensity, however, was estimated at 14:00-15:00 from the geostationary SEVIRI retrievals (Soares et al., 2015), practically independently from the land use type. According to those calculations (see Fig.5 there), the difference between SNP and AQUA observations corresponds to ~20% higher total FRP for MODIS AQUA (depending on actual retrieval times, the difference is within 0%-50% range), which closely matches the 23% difference between OOp-processed FRPs (this correction is applied to the scatterplots in Figure 9).

5.5. Implications for atmospheric composition assessment

A substantial fraction of fires missed by MODIS and VIIRS, either due to cloud obscuration or finite detection limit, can lead to inconsistencies in the fire retrievals. The first problem is that the satellites register more fires in centres of the swaths than at their edges. Moreover, the orbits shift every day with revisit time of 16 days. As a result, application of an atmospheric composition model with such fires as input would lead to appearing / disappearing fire detections, missing plumes, and incorrectly reproduced episodes.

The second issue is more general. The atmospheric models are calibrated and evaluated against a variety of independent observations, and mean bias of predicted concentrations is one of critical parameters. Many assessments of non-anthropogenic emissions rely on inverse problem solutions (a.c.a. top-down emission inventories). Having a fraction of fires missing, the emission inversion algorithm may tend to offset the bias due to missing fires by exaggerating the emission factors for the observed ones. Such artificial increase might partly explain the factor of 3.4 between the top-down and

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bottom-up approaches to PM emission from fires, as noted in earlier studies (Kaiser et al., 2012; Soares et al., 2015). Conversely, missing fires lead to distorted pollution patterns and lower correlation with observations. In the inverse problems context, lower model-measurement correlation leads to under-estimation of optimized emission fluxes (Sofiev et al., 2024).

One of possible ways to rectify the problem of the omission error is to construct fire prediction models capable of assimilating the observed fires and extrapolating the burning state to the areas not observed due to clouds or below-detection-limit. The vital part of such exercise would be the FRP observation operator constructed in this paper.

6. Conclusions

Detection limits of Fire Radiative Power (FRP) products of two low-orbit satellites, MODIS and VIIRS, have been identified and related to size of the observation pixels. Two types of observation operator (OOp) for FRP retrievals have subsequently been constructed: for individual pixels of the satellite retrievals, and for gridded representation of the FRP fields. The key parameter for the pixel-level OOp is the size of the observation pixel, which solely determines the detection limit as a linear function of the pixel area, with different coefficients for day / night and MODIS / VIIRS retrievals. For gridded representation, the fraction of the largest fire-pixel in the total grid-cell FRP and cloud cover are also important. The probability of detecting even a powerful fire can be as low as 30% for regions with a dense cloud cover. Fires can also be overshadowed by thin clouds or fire smoke attenuating the irradiance and reducing the retrieved FRP.

Application of the OOp-s confirmed their internal consistency: OOp-processed MODIS and VIIRS retrievals, with a correction to the different overpass times, showed a close match of the retrieved FRP.

The detection limits of the FRP products of MODIS Collection 6.1 are 5.7 MW / 3.7 MW for day- / night-time overpasses for the smallest-size pixels in the middle of the swath (about-half of those earlier

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reported for Collection 5). For VIIRS Collection 2, these are 3.7 MW and 0.7 MW, respectively. Finite detection limit leads to an omission of small fires.

The suggested formulations were developed for MODIS and VIIRS, but can also be used, with refitted coefficients, for other low-orbit and, potentially, geostationary instruments.

7. Code and data availability

Code of the observation operator and its coefficients identified for MODIS and VIIRS are available from the GitHub public repository: https://github.com/fmidev/FRP_OOp and from Zenodo archive https://doi.org/10.5281/ZENODO.18339604 (Sofiev and Kouznetsov, 2026).

8. Author contribution

MS developed the concept, performed data analysis, and wrote the paper; RK participated in the concept development, contributed to data analysis and edited the paper.

9. Competing interests

The authors declare that they have no competing interests

10. Acknowledgements

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