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Copernicus Climate Change Service

Product Quality Assurance Document

ICDR Sentinel-3 Active Fire & Fire Radiative Power Daytime Products (v1.2)

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Contributors

BROCKMANN CONSULT GMBH
Carsten Brockmann
Grit Kirches
Martin Boettcher

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History of modifications

Version	Date	Description of modification	Chapters / Sections
V1.0	28/02/2023	First version	All
V1.1	21/04/2023	Update to include comments of reviewers	All
V1.2	08/08/2023	Document amended to account for feedback from independent reviewer and finalized for publication	All document: minor changes in the text to fix a few typos and style.
V1.3	31/05/2024	Renaming of the document,	-
V1.4	16/07/2024	Update of figure 3-4, and update of RD-2 and RD-3 reference, addition of summary results in section 4.	3,4
V1.5	31/10/2024	Renaming of the document & update of validation results	4
V1.6	19/11/2024	Document amended to account for feedback from independent reviewer and finalized for publication	All document: minor changes in the text to fix a few typos and style.

List of datasets covered by this document

Deliverable ID	Product title	Product type (CDR, ICDR)	Version number	Delivery date
WP2-ICDR-FRP-DAYTIME-2022-SENTINEL3-v1.2	CDR and ICDR Sentinel-3 AF &FRP v1.2- 2022	ICDR	1.2	31/05/2024
WP2-ICDR-FRP-DAYTIME-2023-SENTINEL3-v1.2	CDR and ICDR Sentinel-3 AF &FRP v1.2- 2023	ICDR	1.2	30/08/2024

Related documents

Reference ID	Document
[RD - 1]	E.U. Copernicus Climate Change Service, 2021, Product Quality Assurance Document (PQAD) CDR and ICDR Sentinel-3 Active Fire & Fire Radiative Power Products, D2.2.16-v1.0_PQAD_CDR-ICDR_FRP_SENTINEL3_v1.0_PRODUCTS_v1.1[1]
[RD - 2]	E.U. Copernicus Climate Change Service, 2024, Algorithm Theoretical Basis Document (ATBD) CDR and ICDR Sentinel-3 Active Fire & Fire Radiative Power Daytime Products, WP2-FDDP-FRP-DAYTIME-2022-SENTINEL3-v1.2_ATBD_v1.4
[RD - 3]	E.U. Copernicus Climate Change Service, 2024, Product Quality Assessment Report (PQAR) CDR and ICDR Sentinel-3 Active Fire & Fire Radiative Power Daytime Products, WP2-FDDP-FRP-DAYTIME-2022-SENTINEL3-v1.2_PQAR_v1.1 – not public available
[RD - 4]	E.U. Copernicus Climate Change Service, 2024, Product Quality Assessment Report (PQAR) CDR and ICDR Sentinel-3 Active Fire & Fire Radiative Power Daytime Products, WP2-FDDP-FRP-DAYTIME-2023-SENTINEL3-v1.2_PQAR_v1.2 - not yet published

Acronyms

Acronym	Definition
AF	Active Fire
API	Application programming interface
ATBD	Algorithm Theoretical Basis Document
CAMS	Copernicus Atmosphere Monitoring Service
C3S	Copernicus Climate Change Service
CDR	Climate Data Record
CMG	Climate Modelling Grid
CSV	Comma-separated values
EC	European Commission
ECV	Essential Climate Variable
EGC	European Grid Conference
EO	Earth Observation
EU	European Union
FRE	Fire Radiative Energy
FRP	Fire Radiative Power
GFAS	Global Fire Assimilation System
LEO	Low Earth Orbit

[1] http://dast.data.compute.cci2.ecmwf.int/documents/satellite-fire-radiative-power/D2.2.16-v1.0_PQAD_CDR-ICDR_FRP_SENTINEL3_v1.0_PRODUCTS_v1.1.pdf

MIR	Middle infrared
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Form
NTC	Non-Time Critical
PUGS	Product User Guide
PQAD	Product Quality Assurance Document
PQAR	Product Quality Assessment Report
S3A	Sentinel 3A
S3B	Sentinel 3B
Sentinel 3	Earth observation satellite series
SLSTR	Sea and Land Surface Temperature Radiometer
SWIR	Short wavelength infrared
VCF	Vegetation Continuous Field

General definitions

Active Fire (AF)

A landscape fire that was actively burning when the satellite observations was made. Satellite 'Active Fire' Products are those that report information on these types of fires using thermal remote sensing techniques. AF pixels are pixels classified as containing one or more actively burning fires when the observation was made.

Fire Radiative Power (FRP)

The rate of radiant heat output from a landscape fire, typically expressed in Watts $\times 10^6$ (MW). FRP is typically very well related to a fires combustion rate (how much material is being burned per unit time) and rate of smoke emission, and hence remotely-sensed FRP measures are commonly used to estimate these terms. At the pixel scale, a satellite product typically is reporting the total FRP from all fires burning within that pixel at the time the observation was made.

Fire Radiative Energy (FRE)

The temporal integral of fire radiative power calculated over the fire's lifetime, equating to the total amount of energy radiated by the fire. FRE is typically used to estimate how much material was burned in a fire and how much smoke was released.

Radiometric Brightness Temperature (BT)

The temperature of a hypothetical blackbody emitting an identical amount of radiation as is being measured in the waveband.

Error of Omission

A type of error where data is erroneously excluded from membership of a class when it should have been included. In satellite AF products this typically means a pixel being incorrectly left out of being classified as an AF pixel, when other data suggest it should have been.

Error of Commission

A type of error where data is erroneously included in the membership of a class when it should have been excluded. In satellite active fire products this typically means a pixel being incorrectly classified as an AF pixel when other data suggest it should not have been.

Satellite Data Processing Levels

- **Level 0** (L0) data are reconstructed, unprocessed instrument and payload data at full resolution, with any and all communications artefacts (e.g., synchronization frames, communications headers, duplicate data) removed.
- **Level 1A** (L1A) data are reconstructed, unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric and geometric

calibration coefficients and georeferencing parameters (e.g., platform ephemeris) computed and appended but not applied to L0 data.

- **Level 1B** (L1B) data are L1A data that have been processed to sensor units (not all instruments have L1B source data).
- **Level 1C** (L1C) data are L1B data that include new variables to describe the spectra. These variables allow the user to identify which L1C channels have been copied directly from the L1B and which have been synthesized from L1B and why.
- **Level 2** (L2) data are derived geophysical variables at the same resolution and location as L1 source data.
- **Level 2A** (L2A) data contains information derived from the geolocated sensor data, such as ground elevation, highest and lowest surface return elevations, energy quantile heights ("relative height" metrics), and other waveform-derived metrics describing the intercepted surface.
- **Level 2B** (L2B) data are L2A data that have been processed to sensor units (not all instruments will have a L2B equivalent).
- **Level 3** (L3) are variables mapped on uniform space-time grid scales, usually with some completeness and consistency.
- **Level 3A** (L3A) data are generally periodic summaries (weekly, ten-day, monthly) of L2 products.
- **Level 4** data are model output or results from analyses of lower-level data (e.g., variables derived from multiple measurements).

Descriptions of data processing levels ranging from Level 0 to Level 4 have been sourced by the following National Aeronautics and Space Administration (NASA) Earth Observation Data website: https://www.earthdata.nasa.gov/engage/open-data-services-and-software/data-information-policy/data-levels

Validation

Validation is essential for providing a high-quality product that is accepted and applied by the user community. The different steps that jointly lead to the achievement of the validation objectives are:

- Internal validation
- Independent product validation and comparison
- User assessment and feedback

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Scope of the document

This Product Quality Assurance Document (PQAD) provides an overview of the product validation methodology for the C3S Daytime Active Fire Detection and FRP products, which comprise the level-2 summary and three level-3 products. The current version of this product suite is 1.2. The products are generated by Brockmann Consult GmbH using data from the Sentinel-3 SLSTR sensor. These data are processed using an active fire detection and FRP retrieval strategy that generates the location, time and strength of the fires burning on the Earth´s land surface when the Sentinel-3 satellite passed over, the fires being detected via their infrared energy signature. The fires must be sufficiently large and/or intensely burning to be detected, and not covered by meteorological cloud at the time of the satellite overpass. The daytime algorithm was designed pre-launch by Wooster et al. (2012) and modified post-launch by Xu and Wooster (2023). The daytime Sentinel-3 Level 2 Active Fire Detection and FRP products issued in non-time critical (NTC) mode are based on an operational implementation of this algorithm, and these Level 2 NTC products provide the source data for the C3S FRP products.

There are four C3S AF & FRP Daytime products generated for each Sentinel-3 satellite. These are firstly, a Level 2 Summary Product providing a text-based summary of the non-time critical (NTC) Sentinel-3 Level 2 Active Fire (AF) Detection and FRP Product data collected over the period of one month across the globe at the locations of each detected active fire pixel. Secondly there are three Level 3 'synthesis products' which each sample the Level 2 Active Fire (AF) Detection and FRP Product data at various spatial and temporal resolutions and provide the ability to adjust some of the metrics for cloud cover variations if desired. Since both Sentinel-3A and -3B have an equatorial crossing time of ~ 10:00 and ~ 22:00, rather similar to that of the Terra satellite carrying MODIS, the C3S FRP products can be intercompared with the AF products generated from Terra MODIS in terms of a quality assessment based on independent data.

Executive summary

Active Fire (AF) and Fire Radiative Power (FRP) are among the Essential Climate Variables provided by the C3S. The C3S AF & FRP products are generated from observations made by the Sea and Land Surface Temperature Radiometer (SLSTR) operating onboard the Sentinel-3 satellites, currently Sentinel-3A and -3B. The SLSTR data are used to generate a Level 2 AF Detection and FRP Product in non-time critical (NTC) mode, which records the location, time, fire radiative power (FRP) and various sensor related characteristics (e.g., view zenith angle) related to fires burning on the Earth´s land surface which are detected via their emitted infrared energy signature. There are four C3S AF & FRP Daytime products for each Sentinel-3 satellites, including one Level 2 FRP Summary Product providing a text-based summary of the Level 2 AF Detection and FRP Product data collected over the period of one month across the globe at the locations of all detected active fire pixels, along with three Level 3 ‘synthesis products’ which each sample the Level 2 AF Detection and FRP Product data at various spatial and temporal resolutions. The Level 3 products also provide information that can be used to adjust the number of detected active fire pixels for variations in the amount of cloud cover blocking the fires from the satellite sensor´s view. The algorithm for the C3S active fire (AF) detection and fire radiative power (FRP) Daytime products are provided in the corresponding ATBD [RD - 2].

This Product Quality Assurance Document (PQAD) provides a detailed description of the C3S FRP product validation methodology, used to assess the four C3S FRP datasets. This is done in part via comparison to independent reference data, which come from AF data products generated from observations made by the MODIS sensor operating onboard the Terra satellite. Terra has a similar equatorial crossing time (10:30 and 22:30) to Sentinel-3 (10:00 and 22:00), and provides data at a similar spatial resolution (500 m to 1 km at nadir; depending on waveband), so broad patterns of fire should agree between the active fire data records derived from the two sensors. The AF products generated from MODIS have themselves been very widely used and subject to comprehensive evaluation. Sometimes, near-simultaneous views of the same fire-affected area are provided by SLSTR and by MODIS, and using such data the AF detection performance of the former can be assessed as the error of commission and omission with respect to MODIS. The FRP retrievals made at the same fires successfully detected by SLSTR and by MODIS can also be compared, and the total FRP in the regions observed near-simultaneously can be used to evaluate the effect of the SLSTR AF detection commission and omission statistics on regional FRP totals. Extending beyond the near-simultaneous views, the spatial pattern, FRP magnitudes and fire season timing (e.g., start, end, duration and peak of the fire season) can be compared between Terra MODIS and the relevant C3S Level-3 FRP products. The Product Quality Assessment Report (PQAR) [RD - 3] detailed the results for the C3S FRP products assessments, ultimately allowing the reporting of various accuracy parameters and assessing the degree of agreement of the products with those of Terra MODIS.

1. Validated Products

There are four C3S FRP products in total, comprising two main different product types: (i) a Level-2 Monthly Global Fire Location and FRP Summary Product, which provides a text-based summary of the Level 2 NTC Product data collected over a one month period across the globe at the locations of all identified active fire pixels, and (ii) three gridded Level 3 'synthesis products' derived at daily, 27-day and monthly intervals. Each of the Level 3 products grids the NTC Level 2 AF Detection and FRP data at different spatial and temporal resolutions, and includes information on fractional meteorological cloud cover, since SLSTR cannot detect actively burning fires under cloud. The number of detected active fire pixels reported in the Level 3 product grids can therefore be adjusted for cloud cover fraction if desired, as is done for example in the Global Fire Assimilation System (GFAS) operated as part of the Copernicus Atmosphere Monitoring Service (CAMS), and relying for its input on FRP data streams (Kaiser et al., 2012). The formats and specifications of each product are detailed in Table 1-1.

Table 1-1: Specifications of the four C3S FRP daytime products.

Product	Coverage		Resolution		Sensor	Projection	Format
	Spatial	Temporal	Spatial	Temporal			
Level-2 Monthly Global Fire Location and FRP Summary	global	03/2022-02/2024	data only at locations of detected AF pixels	monthly with daily resolution	SLSTR	-	CSV
Level-3a Daily Gridded FRP Product	global	03/2022-02/2024	0.1°	daily	SLSTR	Plate-Carrée - WGS 84	NetCDF
Level 3a 27-Day Gridded FRP Product	global	03/2022-02/2024	0.1°	27 days	SLSTR	Plate-Carrée - WGS 84	NetCDF
Level-3 Monthly Summary FRP Product	global	03/2022-02/2024	0.25°	1 month	SLSTR	Plate-Carrée - WGS 84	NetCDF

1.1 Level-2 Monthly Global Fire Location and FRP Daytime Summary Product

The C3S Level 2 Monthly Global Fire Location and FRP Daytime Summary Product provides a text-based summary of the FRP data and other information contained within all Sentinel-3 Level 2 Active Fire Detection and FRP Products issued in non-time critical (NTC) mode collected over the period of one month worldwide, but separated by each Sentinel-3 satellite. Information is provided in the C3S Level 2 Monthly Summary FRP Product at the location of every detected daytime land-based active fire pixel across the globe present in the NTC Level 2 Products. These original Level 2 products are based on radiometrically calibrated near-nadir view scan SLSTR observations. Each scan covers a 1420 km swath of the Earth in a series of visible to longwave infrared spectral bands using view zenith angles from 0° to almost 55°. The most important SLSTR spectral channel is that in the middle infrared (MIR), since this is where active fires are most discernible by day (and by night) against the ambient temperature background (Roberts et al., 2005; Wooster et al., 2012; Giglio et al., 2016). This is also the channel that provides the spectral radiance observations used to calculate the FRP of landscape fires (Wooster et al., 2003; 2005). Sentinel-3 SLSTR possesses two MIR channels, 'S7' and 'F1', to enable the measurement of brightness temperatures (BTs) that are both close to or at those measured over ambient surfaces temperature (using S7), or which are greatly elevated above ambient due to the presence of active fires (using F1). The use of these two channels in the derivation of the Sentinel-3 Level 2 Active Fire Detection and FRP Products issued in non-time critical (NTC) mode is described in detail in Xu et al. (2020).

With two Sentinel-3 satellites operating concurrently, the global daytime revisit time provided by SLSTR in the near-nadir view scan includes two days with one satellite, and one day with two satellites (Donlon et al., 2012). Imaging frequency increases at higher latitudes due to orbital convergence, and it even doubles if both daytime and night-time passes are included.

The C3S Level 2 Monthly Global Fire Location and FRP Daytime Summary Product stores the latitude, longitude, FRP, date, time and associated data of each detected AF pixel present in the original Level 2 Products. Separate summaries of the data records coming from the S3A and S3B satellites are put into the corresponding text type file stored in CSV format.

1.2 Level 3a Daily Gridded AF & FRP Daytime Product

The Level 3a Daily Gridded AF & FRP Daytime Product file stores daily summarised data from the NTC Level 2 Active Fire Detection and FRP Products collected worldwide, doing so on a global 0.1° resolution grid, but separated by each Sentinel-3 satellite. The grid cell size is approximately 10 km × 10 km at the equator and decreases in area latitudinally away from the equator.

1.3 Level 3a 27-Day Gridded AF & FRP Daytime Product

The Level 3a 27-Day Gridded AF & FRP Daytime Product builds on the Level 3a Daily Gridded AF & FRP Daytime Product by collating and summarising 27-Days of daytime data at the same 0.1° resolution, separated by each Sentinel-3 satellite. Since AF detection performance changes with pixel area and thus view zenith angle (Freeborn et al., 2011), this time interval is selected to match the standard Sentinel-3 orbital repeat cycle (Donlon et al., 2012) which results in the SLSTR near-nadir scan view zenith angle to an imaged Earth surface location being essentially repeated every 27 days.

1.4 Level 3 Monthly Summary AF & FRP Daytime Product

The Level 3 Monthly Summary AF & FRP Daytime Product builds on the Level 3a Daily Gridded Product by collating and summarising the information contained therein over a calendar month, but now on a reduced spatial resolution grid of 0.25° to match that of the MODIS Climate Modelling Grid (CMG) active fire products.

Figure 1-1 shows the gridded global daytime AF pixel count and total FRP variables extracted from the global datasets stored in the C3S Sentinel-3 Level 3 Monthly Summary AF & FRP daytime Product of March 2022 (with both the Sentinel-3A and -3B data shown). Total FRP is calculated as the summary of all FRP recorded at a grid cell size of 0.25°.

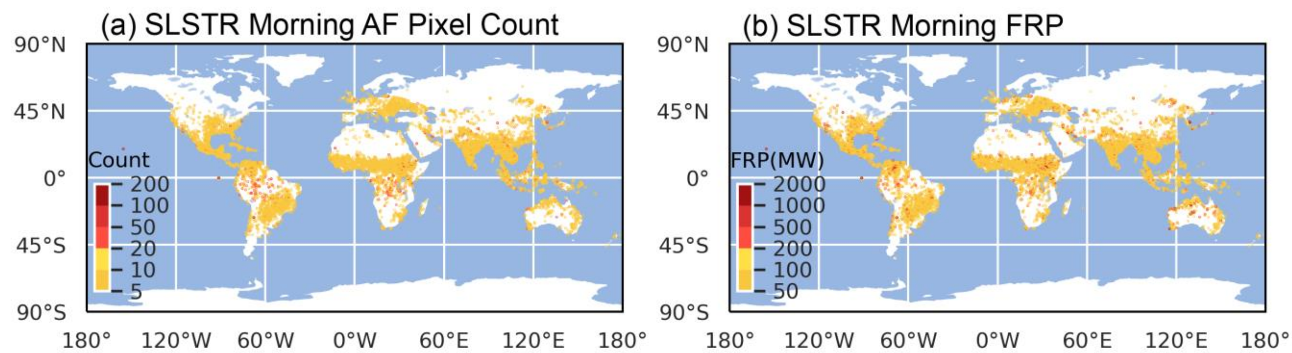

Figure 1-1: Monthly global map of (a) active fire pixel count and (b) total FRP, both derived from data held within the C3S Level 3 Monthly Summary AF & FRP Daytime Product of March 2022. Data shown are from SLSTR on board both Sentinel-3A and -3B in this case. Grid cell size is 0.25°.

2. Description of Validating Datasets

The non-time critical (NTC) Sentinel-3 Level 2 Active Fire (AF) Detection and FRP Products are the data source used to generate the C3S Level 2 Summary and Level 3 AF & FRP Daytime products. The Sentinel 3 Level 2 FRP products are subject to continuing quality checks and evaluation. These quality checks include dedicated airborne validation activities and intercomparisons with AF detection and FRP data coming from other satellite-based sensors, including from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor onboard the Terra satellite which has a similar overpass time to Sentinel-3 at certain locations and on certain dates as detailed below. Since their first iteration in 2000, these MODIS AF products have been used to help address a very broad range of scientific questions concerning fire characterisation and the role of biomass burning within the Earth system (e.g. Wooster and Zhang, 2004; Ichoku and Kaufman, 2005; Giglio et al., 2006; Ichoku et al., 2008; Freeborn et al., 2011; Kaiser et al., 2012; Archibald et al., 2013; Hantson et al., 2013; Peterson and Wang, 2014; Sembhi et al., 2020; Zhang et al., 2018).

2.1 Reference Data Generation

MODIS provides radiometrically calibrated and geo-coded remote sensing observations of the Earth in 34 spectral bands over a 2330 km swath, including at times similar to those of the SLSTR sensor onboard Sentinel-3. Terra MODIS' data are used to generate the pixel-level MOD14 MODIS Active Fire and Thermal Anomaly products (Giglio et al., 2016). The latest Collection 6 MOD14 products are used as the reference data for the C3S FRP product evaluation. From the granule-level MOD14 Level 2 MODIS AF products, a series of summary products are generated., including the MODIS Climate Modelling Grid (CMG) AF products (Giglio et al., 2006), primarily intended for use in regional and global modelling. MODIS has a 16-day repeat cycle, and these CMG products are generated on a 0.25° spatial resolution grid – either every calendar month (MOD14CMQ) or every eight days (MOD14C8Q). An example of the corrected AF pixel count layer (CorrFirePix) from the MOD14CMQ product for January 2001 is shown in Figure 2-1.

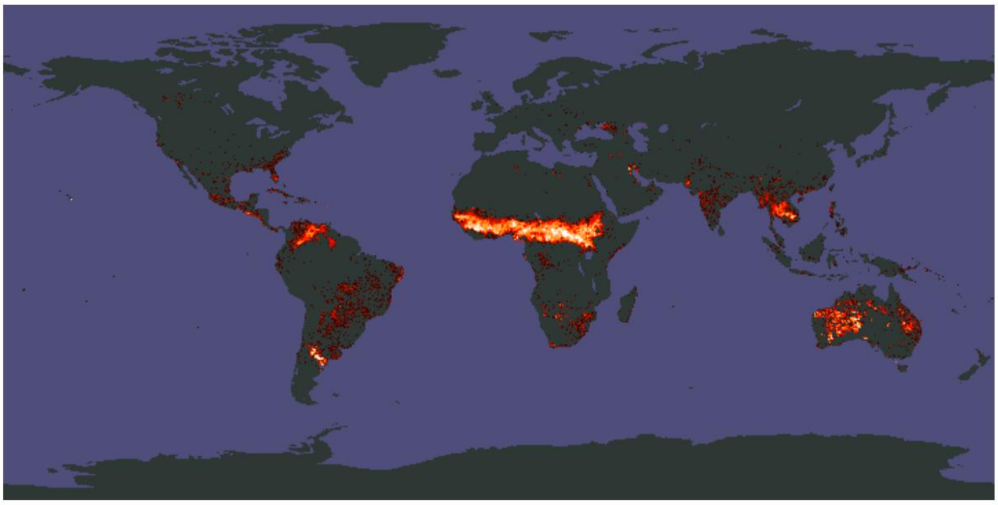

Figure 2-1: Global 'corrected active fire' (AF) pixel count data layer ('CorrFirePix') extracted from the January 2001 Terra MODIS MOD14CMQ monthly Climate Modelling Grid (CMG) AF product.

3. Description of Product Validation Methodology

3.1 Level 2 Active Fire Detection and FRP Performance Assessment with Terra MODIS

3.1.1 Internal Validation

The NTC Level 2 Sentinel-3 AF detection and FRP Products are summarized and stored in CSV format in the C3S Level 2 Monthly Global Fire Location and FRP Summary Products. Thus, the first validation step (internal validation) in the evaluation of the C3S FRP products is comparison of both the C3S Level 2 Monthly Summary Products and the Level 3a Daily Gridded FRP Products to the information contained within the set of NTC Level 2 Sentinel-3 AF detection and FRP Products from which they are derived. This 'verification' of the data contained in the C3S Level 2 Monthly Summary Product and the C3S Level 3a Daily Gridded FRP Product underlies the evaluation of all the C3S FRP products, since all C3S FRP products are derived from the same NTC Level 2 FRP Product datasets.

3.1.2 Independent Validation

The second (independent) validation step is comparison of the C3S products to the similar MOD14 products generated from Terra MODIS. As detailed in Section 2 (Description of Validating Datasets), at certain areas and times both sensors collect near-simultaneous data at a similar pixel resolution (~ 1 km at the near nadir point). With MOD14 as the comparison dataset, the C3S Level 2 Monthly Global Fire Location and FRP Summary Product AF detection errors of omission and commission can be calculated with respect to MODIS, as well as the degree of FRP agreement under two conditions - (i) when both sensors view the same individual fire cluster at almost the same time (e.g., within ± 6 minutes, following Xu et al., 2017; 2020; 2021), and (ii) when both sensors view the same larger land surface region within the same time interval. In these comparisons, in addition to requiring near simultaneous-views, MODIS data can be restricted to those with a scan angle maximum of ±30° to avoid geometric issues associated with the MODIS 'bow-tie' effect (Freeborn et al., 2011; 2014a; Xu et al., 2020; Xu & Wooster, 2023). This restriction limits the MODIS pixel area to a maximum of 1.7 km^2. To match this the SLSTR data can also be restricted to those with an S7 pixel area maximum of 1.7 km^2 (the matching SLSTR F1 pixel area maximum at this scan angle is 1.2 km^2). To facilitate the inter-comparison, MODIS AF pixels are re-projected to the SLSTR Level 1b projection data grid, and Sentinel-3 AF errors of omission with respect to MODIS evaluated by considering whether an SLSTR AF detection was present within a 7 ×7 pixel window centred on each MODIS AF pixel location (following satellite AF product intercomparison methodologies adopted by Freeborn et al., 2014a; Xu et al., 2017; 2020; 2021).

Matching SLSTR and MODIS example data are shown in Figure 3-1. In this case S3 SLSTR detected a total of 47 AF pixels, with 44 (94%) of these present in the MODIS AF product, and 3 (6%) not (area boxed in green in Figure 3-1b). MODIS detected a total of 48 AF pixels, most detected by SLSTR and of those missed ~ 80% were small fires located near water or cloud edges (see an example in the yellow boxed area of Figure 3-1c). A per-fire based FRP analysis of the data contained within the C3S Level 2 Monthly Summary FRP Product is conducted to intercompare its FRP values to those provided by MODIS of the same view viewed near-simultaneously. In this case a 'fire' is taken as comprising a set of a spatially contiguous (or near-contiguous) AF pixels, since the two sensors may not detect exactly the same AF pixels. This intercomparison provides an estimate of the level of agreement in FRP when both sensors identify the same fire at almost the same time. The regional analysis extends this type of per-fire comparison, now intercomparing the total FRP identified across an area observed near simultaneously by SLSTR and by MODIS. The regional analysis indicates the effect of any AF detection errors of omission or commission on the regional-scale FRP total. These types of methodologies are common in satellite AF product intercomparisons (e.g. Freeborn et al., 2014a; Roberts et al., 2015; Xu et al., 2017; 2020; 2021).

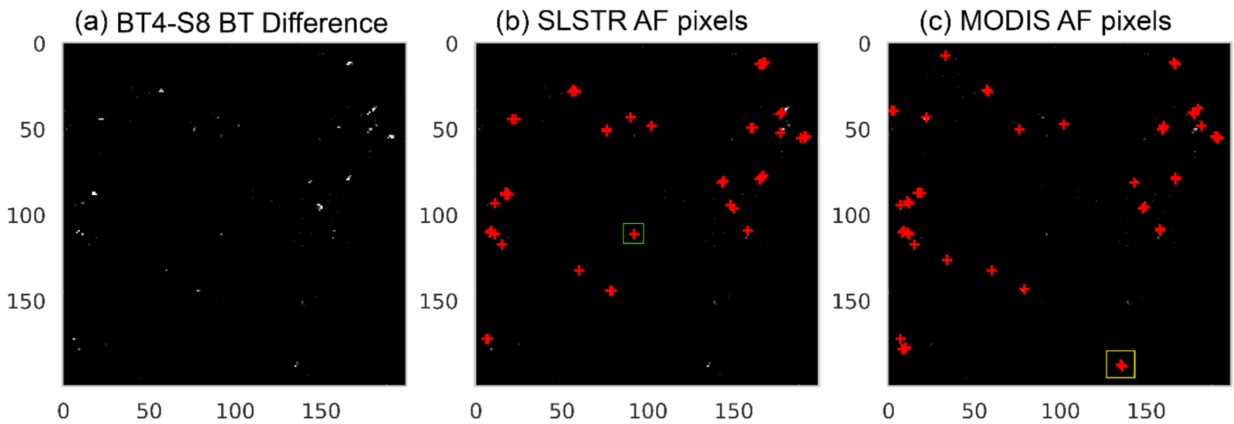

Figure 3-1: Comparison between near-simultaneous S3 SLSTR and Terra MODIS active fire (AF) data near Lake Rukwa in Tanzania, Southern Africa, based on the methodology detailed in section 3.1. The SLSTR image subset covers 200 km × 200 km and was collected at 07:51 UTC on 6th Aug 2020, and the matching MODIS data at 08:00 UTC. (a) SLSTR MIR Brightness Temperature (BT) difference between BT4 and S8 channel and where higher BT difference are depicted as brighter pixels. (b) Same as (a) but with the SLSTR AF detections overlain. (c) Same as (a) but with near-simultaneous MODIS AF detections (yellow boxed area - example of a fire only identified in the MODIS data; green boxed area in (b) - example of a fire only identified in the SLSTR data).

3.2 Fire Pattern & FRP Magnitude Analysis

Whilst the performance of the C3S Level 2 Monthly Global Fire Location and FRP Daytime Summary Product can be best assessed against near-simultaneous MOD14 product files, the three C3S Level-3 gridded FRP Products can be best evaluated via analysis of their spatio-temporal patterns and comparison to those in the wider set of MOD14 data expected to show similar patterns. Similar intercomparisons made between the Sentinel-3 SLSTR and Terra MODIS AF data records are also expected to form the basis of transfer functions used to blend these data together to develop a long-term AF data record spanning from the early 2000's and across the Sentinel-3 lifetime.

Figure 3-2 shows a visual comparison between the spatial pattern of daytime AF and FRP data retrieved from SLSTR observations made by Sentinel-3A and -3B in March 2022 compared to that from Terra MODIS. Very similar spatial patterns are seen, indicating a wide degree of broad agreement despite the MODIS data including all daytime observations and not only those collected near-simultaneously with SLSTR. A similar comparison of AF pixel counts shows that the SLSTR product includes more AF detections than does MOD14 (Xu and Wooster, 2023), but the grid-cell FRP totals shown in Figure 3-2 are similar between the two records because the additional AF pixels that SLSTR detects in many of the grid cells are dominated by low FRP values.

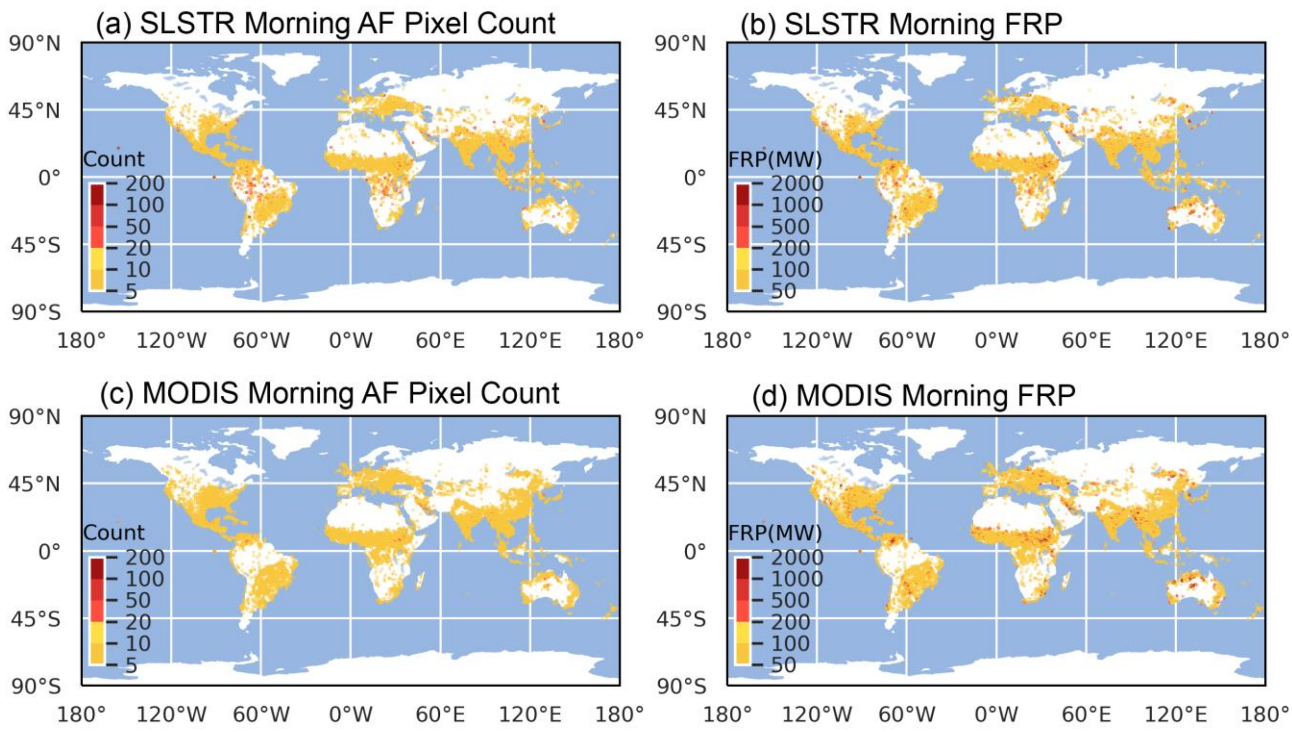

Figure 3-2: Total AF & FRP of daytime actively burning fires detected within 0.25° grid cells using all SLSTR onboard Sentinal-3A and -3B (a and b) and Terra MODIS (c and d) data of March 2022.

3.3 Fire Season Metrics

The C3S Level 3 Gridded AF & FRP Daytime Products are intended primarily for large scale analysis of fire patterns, seasonality, anomalies and trends. Such characteristics help define regional 'fire regimes' which help describe the role of landscape fires in an area, and under this broad definition, their physical attributes such as fire frequency, size, intensity, type and timing. Fire regimes may alter with changing climate and with human activity associated with e.g., landuse management and landuse change (Moritz 2009; Flannigan et al., 2009; Archibald et al., 2013; Hantson et al, 2015). Characterizing past and current fire regimes has historically been performed by analysing field data such as charcoal records, fire-scar networks and fire occurrence databases. However, the regular and continuous information on landscape fires that can be provided by EO satellites is increasingly being used to determine certain fire regime characteristics (e.g., Chuvieco et al., 2008; Freeborn et al., 2014b). Fire seasonality is a key characteristic of a region´s fire regime. The C3S Level 3 gridded FRP Products are well suited to determine fire seasonality, as are the existing MODIS MOD14 products and their MOD14CMQ and MOD14C8Q Climate Modelling Grid (CMG) summaries. To evaluate the C3S Level 3 Gridded FRP Products, we will derive fire regime seasonality characteristics from them and compare these to the same metrics derived from the MOD14 data used to create the MOD14CMQ and MOD14C8Q products. We will also directly intercompare the AF detection and FRP patterns present in the matching monthly temporal resolution C3S Level 3 Monthly Summary FRP Product and MOD14CMQ Products.

In terms of fire season, the start and end of the fire season for a grid cell or region can be defined as the times when the total FRP in the region exceeds certain percentages of the total FRP of the whole year , as illustrated for two grid cells in the Central African Republic in Figure 3-3 (Freeborn et al., 2014b). The exact percentage thresholds can be altered as desired (in Figure 3-3 the values of 10% (start) and 90% (end) are used). A key advantage of this cumulative approach is that it does not rely on a single threshold of active fire 'amount' being exceeded at any particular time-step (Freeborn et al., 2014b). This means it can be meaningfully and successfully applied in both (a) areas showing both short, intense periods of fire activity characterized by a clear peak above a threshold value (e.g. grid cell WGC in Figure 3-3), and (b) areas with far longer but less intense fire seasons (e.g. grid cell EGC) where the absolute amount of fire activity can fluctuate and may sometimes drop below any pre-defined threshold. Once the start and end of the fire season are derived, the fire season duration can then be defined as the difference between them, whilst the fire season peak can be defined as that time when maximum fire activity is reached (Freeborn et al., 2014b). We will derive these fire season metrics from the C3S Level 3a Daily Gridded AF & FRP Daytime products, and compare them to those same metrics derived from the daytime MODIS data of the same period.

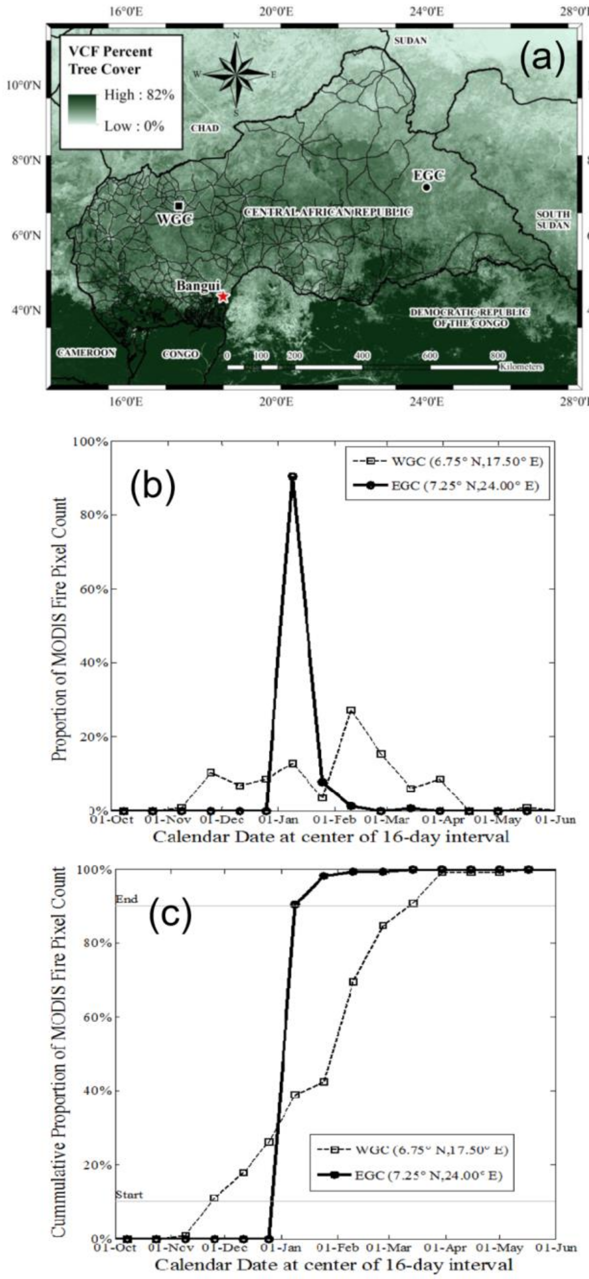

Figure 3-3: Fire season data for the Central African Republic (CAR). (a) Map showing the locations of the western and eastern grid cells (labelled WGC and EGC) whose data is analysed in (b) and (c), superimposed on percent tree cover characterized according to the 500 m Global Land Cover Facility (GLCF) Version 3 of the Collection 4 Vegetation Continuous Field (VCF) product (major road networks are also superimposed). Normalized seasonal profiles of (b) MODIS active fire (AF) pixel counts and (c) cumulative distributions of MODIS AF pixel counts for two 0.05° grid cells at 16-day temporal resolution. Seasonal profiles are generated from 10 years of aggregated observations, and the locations of the example grid cells, referred to as the western and eastern grid cells (WGC and EGC), are shown in (a). The peak of the fire season is represented by the maxima shown in (b). The 10th and 90th percentiles of the cumulative AF pixel counts are shown in (c) to demonstrate the start and end of the fire season, whilst the duration is the difference between these dates.

Fire season metrics derived from the C3S Level 3a Daily Gridded AF & FRP Daytime Product files will be compared to those derived from MOD14 data gridded to the same 0.1° spatial resolution grid. The comparisons can be made per-grid cell, per biome or per region (e.g., see regions in Figure 3-4a), and also both in terms of AF detections (as in Figure 3-3), but also with FRP. As Sentinel-3 satellites have been reported to have the capability of detecting from three to five times more AF when compared with MODIS while the total FRP of the fire cluster and regions is very close for both sensors (Xu et al., 2020), the fire season driven from FRP will be more similar than the ones calculated using number of AF. Therefore, we focus on fire season from FRP for quality assessment. The most appropriate level of geographic comparison will be determined in part from the number of AF pixels present within the data (too few in a grid cell and the statistical analysis will be less meaningful and a larger concatenation of the data from multiple grid cells or over a region or biome will be required). As an example at the global scale, Figure 3-4b shows monthly global total FRP (03/2022- 03/2023)as derived from Sentinel-3A, -3B and Terra MODIS gridded global products All three products show a very similar temporal development at this global scale.

The C3S Level 3a 27-Day Gridded AF & FRP Daytime Product is simply the accumulation of twenty-seven C3S Level 3a Daily Gridded FRP Products, so its evaluation will simply focus on verifying the correctness of the lower temporal resolution statistical summary derived from the former data (i.e., internal validation/verification).

The C3S Level 3 Monthly Summary FRP Product will be compared to the MODIS MOD14CMQ product. Since the monthly temporal resolution is potentially too low for comparing the precise fire season start and end, the comparison will focus also on the degree of spatio-temporal FRP pattern agreement, defined by several metrics such as the statistical summaries (mean, standard deviation, etc), coefficient of determination (r^2) and the slope of the linear best fit.

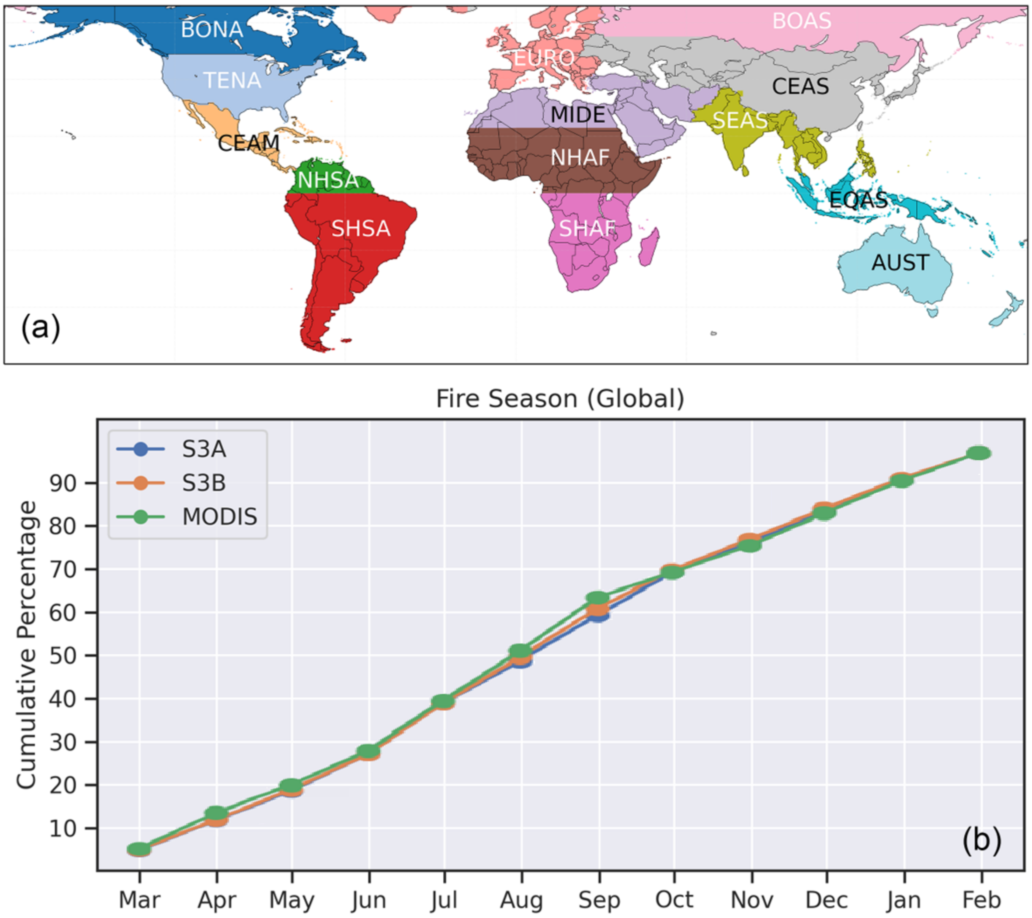

Figure 3-4: Fire seasonality metrics. (a) Global regions used in the Global Fire Emissions Database (Van der Werf, 2017), and (b) example of global monthly total FRP (03/2022 – 02/2023) as derived from all fires across all regions in (a) using Sentinel-3A, -3B and Terra MODIS. The abbreviations are as follows: Boreal North America (BONA); Temperate North America (TENA); Central America (CEAM); NH South America (NHSA); SH South America (SHSA); Europe (EURO); Middle East (MIDE); NH Africa (NHAF); SH Africa (SHAF); Boreal Asia (BOAS); Central Asia (CEAS); SE Asia (SEAS); Equatorial Asia (EQAS); Australia & New Zealand (AUST).

4. Summary of validation results

The corresponding Product Quality Assessment Reports (PQAR) [RD - 3] provide a detailed description of the C3S FRP product verification and validation results from the four C3S AF & FRP daytime datasets of March 2022 to February 2024. Therefore, only a brief summary is included here.

The verification and validation results from the four C3S AF & FRP daytime datasets of March 2022 to February 2024 based mostly on the inter-comparison to corresponding data retrieved from MODIS onboard Terra (since this instrument has a similar equatorial overpass time to SLSTR). For the daytime data analysed, very similar spatial patterns are seen between the S3A and S3B datasets and MODIS, indicating a broad degree of agreement despite the majority of the MODIS daytime observations data not being collected near-simultaneously with those of Sentinel-3 SLSTR. The comparison of AF pixel counts between the sensors shows that the Sentinel-3 product generally includes more AF detections than does MODIS, but that the grid-cell FRP totals are similar between the two records since the additional AF pixels detected by SLSTR mostly consist of low FRP pixels located at the edge of fire clusters, and which are at least in part offset by some single pixel fires that MODIS detects but SLSTR does not. Furthermore, the additional pixels are generally of low FRP magnitude.

A comparison of global data collected by MODIS Terra at almost the same time as SLSTR (within +/- 6 minutes) and within a view zenith angle maximum of 30 degrees, indicates that the C3S daytime Level-2 Summary FRP product shows ~ 70% of MODIS-identified active fire (AF) pixels having a matching Sentinel-3 AF pixel detection. Conversely, of the Sentinel-3 AF pixel detections present the same dataset, ~ 84% had a matching MODIS AF pixel detection. Directly comparing the FRP of AF clusters imaged near simultaneously by Sentinel-3A, -3B and by MODIS Terra in March 2022 also indicates a strong degree of agreement though one that is slightly worse than for the night-time products. This is expected as a result of the source Level 2 Sentinel-3 FRP products performing less well in detecting the lowest FRP fires by day compared to MODIS, whereas by night the Sentinel-3 products perform slightly better than MODIS. This in turn is a result of the different active fire detection strategies used by day and by night, because of the differing daytime and night-time saturation status of the SLSTR ‘S7’ middle infrared band that is so important for active fire detection.

At the global scale, the fire season begins and ends at similar months according to the different data sources, and therefore the duration is also very close. However, there are some discrepancies between SLSTR and MODIS in terms of the peak of the global fire season. The Sentinel-3 product analysis reports a fire season peak in July 2022, whilst MODIS shows a peak in September 2022. For the year of 2023, the Sentinel-3 product analysis reports a fire season peak in July 2023, whilst MODIS shows a peak in October 2023. For all the GFED regions, ~ 25% of the 14 regions have 100% agreement for all the four fire season metrics analysed, whilst ~ 80% have a difference of one month or very occasionally more. Almost all the regions have a difference in the metrics of less than two months.

Based on two years´ S3A, S3B and Terra MODIS data covering March 2022 to February 2024, the C3S products and those from Terra MODIS show good levels of agreement. This is both at the scale of individual fires and simultaneously observed regions, as well as in the regions defined by the global fire emissions database (GFED) and globally. For example, the FRP of AF clusters imaged near simultaneously by Terra MODIS in March 2022 and by SLSTR indicates a strong degree of agreement, as evaluated previously, detailed in Xu et al. (2023). Furthermore, the fire season metric agrees between the C3S Level 3a monthly FRP product and MODIS globally, for all the four fire season metrics analysed, whilst ~ 80% have a difference of one month or very occasionally more.

Overall, we find that our comparison of two years´ global Daytime C3S FRP products coming from S3A and S3B, and two years´ matching data from Terra MODIS, show a strong degree of agreement (data from March 2022 to February 2024). With Terra MODIS likely reaching its end of life in the coming years (sometime within the next 1 to 2 years)2, the C3S FRP products are likely to provide the morning and evening AF data record required to continue this important ECV into the coming decades. Longer-term comparisons like those conducted herein will provide the information required to mesh together the long-term MODIS and SLSTR time-series into a single compatible ECV for long-term trend analysis.

[2] https://terra.nasa.gov/2022/06

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Copernicus Climate Change Service

ECMWF - Robert-Schuman-Platz 3, 53175 Bonn, Germany

Contact: https://support.ecmwf.int/