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Copernicus Climate Change Service

Product Quality Assurance Document

ICDR Sentinel-3 Active Fire, Fire Radiative Power Night-time Products & Gas Flare Products (v1.2)

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This document is an evolution of the document (D2.2.16-v1.0_PQAD_CDR-ICDR_FRP_SENTINEL3_v1.0_PRODUCTS_v1.1 [RD - 1]). It has been updated by the consortium in collaboration with the former partners - Prof. M. Wooster & Dr. W. Xu.

History of modifications

Version	Date	Description of modification	Chapters / Sections
V1.0	30/11/2022	First version	All
V1.1	23/06/2023	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.
V2.0	31/12/2023	Update of the document to include validation of 2022 and finalized for publication	All
V3.0	09/12/2024	Document amended to add the description of the validation methodology regarding the gas flare products	All
V3.1	08/01/2025	Document amended to account for feedback from independent reviewer and finalized for publication	All

List of datasets covered by this document

Deliverable ID	Product title	Product type (CDR, ICDR)	Version number	Delivery date
WP2-FDDP-FRP-NIGHTTIME-2021-SENTINEL3-v1.2	CDR and ICDR Sentinel-3 AF &FRP v1.2- 2021	ICDR	1.2	30/06/2023
WP2-ICDR-FRP-NIGHTTIME-2022-SENTINEL3-v1.2	CDR and ICDR Sentinel-3 AF &FRP v1.2- 2022	ICDR	1.2	31/12/2023
WP2-ICDR-FRP-NIGHTTIME-2020-2023-SENTINEL3-v1.2	CDR and ICDR Sentinel-3 AF &FRP v1.2- 2020 - 2023	ICDR	1.2	31/10/2024

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 Night-time Products, WP2-ICDR-FRP-NIGHTTIME-2020-2023-SENTINEL3-v1.2_ATBD_v2.0 (not yet published)
[RD - 3]	E.U. Copernicus Climate Change Service, 2024, Product Quality Assessment Report ICDR Sentinel-3 Active Fire & Fire Radiative Power Night-time Products", E.U. Copernicus Climate Change Service, Document ref: WP2-ICDR-FRP-NIGHTTIME-2020-2023-SENTINEL3-v1.2_PQAR_v3.0 (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
KMZ	Keyhole Markup Zipped
LEO	Low Earth Orbit
LWIR	Long-Wave Infrared

[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
Suomi-NPP or SNPP	Suomi-National Polar-Orbiting Operational Environmental Satellite System Preparatory Project
SWIR	Short wavelength infrared
UTM	Universal Transverse Mercator
VCF	Vegetation Continuous Field
VIIRS	Visible Infrared Imaging Radiometer Suite

General definitions

Active Fire (AF)

A landscape fire that was actively burning when the satellite observations were 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 fire´s 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.

Brightness Temperature (BT)

The temperature of a hypothetical blackbody emitting an identical amount of radiation as 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 cited from 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

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

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

Scope of the document

This Product Quality Assurance Document (PQAD) provides an overview of the product validation methodology for the C3S Night-time Active Fire Detection and FRP Products, including the Level-2 Monthly Global Summary Product and three Level-3 'synthesis' Global Gridded Products (version 1.2), and the matching C3S Night-time Gas Flare Products which have the same basis but only store information related to gas flares rather than all high temperature detections. These C3S products are generated by Brockmann Consult GmbH using observations made by the Sea and Land Surface Temperature Radiometer (SLSTR) sensor operating onboard the two operational Sentinel-3 satellites. All the C3S products are based on the Non-Time-Critical (NTC) Level 2 Active Fire Detection and FRP products, which themselves are derived from SLSTR Level 1b data are processed using an active fire detection and FRP retrieval algorithm that, based primarily on infrared energy emission signatures, generates the location, time and strength of fires burning when the Sentinel-3 satellite passed over. 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. This document describes validation methods for the C3S Night-time Active Fire Detection and FRP Products and matching Gas Flare Products, whilst a separate document deals with the C3S Day-time Products.

There are four types of C3S Night-time Active Fire Detection and FRP Products generated from the observations made by each Sentinel-3 satellite, and each are generated for the thermal infrared-derived 'active fire' hotspots and the shortwave infrared-derived gas flares. The four C3S Night-time Active Fire Detection and FRP Products include a Level 2 Summary Product providing a text-based summary of the 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. In addition there are three Level 3 'synthesis products' which each grid the information contained within the Level 2 Active Fire (AF) Detection and FRP Products at various spatial and temporal resolutions. The thermal infrared derived gridded products also provide information to users that can be used to adjust certain of the metrics for cloud cover variations if desired. The C3S 'active fire' hotspot products are all derived from thermal infrared channel observations made by the SLSTR sensor and converted to active fire data stored in the FRP_in.nc file of the Level 2 C3S Night-time Active Fire Detection and FRP Product files. The C3S 'gas flare' products are all derived from shortwave infrared channel observations made by the SLSTR sensor and converted to active fire data stored in the FRP_an.nc file of the Level 2 C3S Night-time Active Fire Detection and FRP Product files.

Since both the Sentinel-3A and -3B satellites have an equatorial crossing time of ~ 10:00 and ~ 22:00, rather similar to the historical overpass time of the Terra satellite carrying MODIS, these night-time C3S AF & FRP products can be intercompared to the somewhat similar products generated by NASA from Terra MODIS. This provides a quality assessment of the C3S products, based on an independent and similarly-timed dataset. Since Terra MODIS has a similar overpass time to SLSTR, we focus here on Terra MODIS data for validation purposes in relation to the C3S active fire products, and the Visible Infrared Imaging Radiometer Suite (VIIRS) NightFire products for validation purposes in relation to the C3S gas flare products. Even though the overpass times of the Suomi-National Polar-Orbiting Operational Environmental Satellite System Preparatory Project (Suomi-NPP or SNPP) satellites carrying VIIRS are many hours different from those of S3A and S3B, because gas flares tend to persist the VIIRS NightFire product represents the most effective dataset with which to compare to the C3S Gas Flare Products.

Executive summary

Active Fire (AF) and Fire Radiative Power (FRP) are two Essential Climate Variables (ECVs) covered by datasets provided by the C3S.The C3S FRP products are generated from observations made by the Sea and Land Surface Temperature Radiometer (SLSTR) operating onboard the two operational Sentinel-3 satellites, currently Sentinel-3A and -3B (2024). The SLSTR data are used to generate a Level 2 AF Detection and FRP Product in 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 - detected via their emitted infrared energy signature. There are four C3S AF & FRP Night-time 'Active Fire' Products for each Sentinel-3 satellite derived from SLSTR thermal channel observations, and four matching C3S Night-time Gas Flare Products derived from SLSTR shortwave infrared channel observations. Each set of four includes one Level 2 FRP Summary Product providing a text-based summary of the Level 2 Product data collected over the period of one month across the globe at the locations of all detected active fire pixels (or in the case of the gas flare products on the Level 2 gas flare data), along with three Level 3 'synthesis products' which each grid the same Level 2 data at various spatial and temporal resolutions. The Level 3 AF & FRP Night-time Active Fire 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) Night-time products and the matching Gas Flare Products are provided in the corresponding ATBD [RD - 2].

This Product Quality Assurance Document (PQAD) provides a detailed description of the product validation methodology used to assess the four night-time C3S AF Detection & FRP Products, and the four night-time C3S Gas Flare Products. This validation is conducted in part via intercomparisons to independent reference data, which in the former case come from AF data products generated from observations made by the MODIS sensor operating onboard the Terra satellite, and in the latter from the VIIRS NightFire Products. Terra has a similar equatorial crossing time (~ 10:30 and ~ 22:30) to Sentinel-3 (~ 10:00 and ~22:00), and also provides observations made at a similar spatial resolution (500 m to 1 km at nadir). Therefore, the spatial-temporal patterns of fire detected by the C3S and

MODIS Terra products should broadly agree. The AF products generated from MODIS have themselves been very widely used and evaluated, and near-simultaneous views of the same fire-affected area are often provided by SLSTR and by MODIS. Using such “matchups”, the AF detection performance of the C3S products can be assessed via, for example, error of commission and omission statistics with respect to the already well-validated MODIS active fire products. The FRP values of the same fires successfully detected by SLSTR and by MODIS can also be compared to confirm that when both sensors detect the same fire at the same time, they measure approximately the same FRP. Also the total FRP in a region observed by the two sensors near-simultaneously can be used to evaluate the effect of an SLSTR AF product detection performance difference to MODIS on regional FRP totals. Prior to this intercomparison, a product verification occurs whereby the data contained in the C3S Level 2 Monthly Summary Active Fire Detection and FRP Products is compared to the set of Level 2 products from which it is derived. Extending beyond the comparison of the near-simultaneous view data from SLSTR and MODIS, 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 AF Detection & FRP products to determine how similar the results of these types of analyses are from the two product types. For the C3S Level-3 Night-Time Gas Flare Products, a similar verification process and then intercomparison analysis is conducted against the VIIRS NightFire Product Data. The corresponding Product Quality Assessment Report (PQAR) will describe in detail the results for the C3S FRP products assessments, whose methods are detailed herein.

1. Validated Products

There are eight C3S FRP products in total, comprising two main different product types:

(i) Level-2 Monthly Global Summary Product, which provides a monthly text-based summary of the global information derived at the locations of all identified active fire pixels in the Level 2 NTC Level 2 AF Detection and FRP Product. The Summary Product information is held in two separate product files;

a. Level-2 Monthly Global Fire Location and FRP Night-time Summary Product.
b. Level-2 Monthly Global Gas Flare Night-time Summary Product.

(ii) Three gridded Level 3 Active Fire (AF) and FRP 'synthesis products' & three gridded Level 3 Gas Flare 'synthesis products' – each derived at daily, 27-day and monthly intervals.

Each of these Level 3 products grids the NTC Level 2 AF Detection and FRP data at a different spatial and temporal resolution, and some include information on fractional cloud cover for reference since SLSTR cannot detect actively burning fires under cloud. The number of detected active fire pixels reported in the Level 3 product grids can also be adjusted by the user for cloud cover fraction if desired, as is done for example in the FRP-based Global Fire Assimilation System (GFAS) operated as part of the Copernicus Atmosphere Monitoring Service (CAMS) (Kaiser et al., 2012). The formats and specifications of each product are detailed in Table 1-1.

Table 1-1: Specifications of the eight C3S FRP products.

Product	Coverage		Resolution		Sensor	Projection	Format
	Spatial	Temporal	Spatial	Temporal			
Level-2 Monthly Global Fire Location and FRP Summary	global	03/2020-02/20203	data only at locations of detected AF pixels	monthly with daily resolution	SLSTR	-	CSV
Level-3a Daily Gridded AF & FRP Product	global	03/2020-02/2023	0.1°	daily	SLSTR	Plate-Carrée - WGS 84	NetCDF
Level 3a 27-Day Gridded AF & FRP Product	global	03/2020-02/2023	0.1°	27 days	SLSTR	Plate-Carrée - WGS 84	NetCDF
Level-3 Monthly Gridded AF & FRP Product	global	03/2020-02/2023	0.25°	1 month	SLSTR	Plate-Carrée - WGS 84	NetCDF

Product	Coverage		Resolution		Sensor	Projection	Format
	Spatial	Temporal	Spatial	Temporal			
Level-2 Monthly Global Gas Flare Summary	global	03/2020-02/20203	data only at locations of detected gas flare pixels	monthly with daily resolution	SLSTR	-	CSV
Level-3a Daily Gridded Gas Flare Product	global	03/2020-02/2023	0.1°	daily	SLSTR	Plate-Carrée - WGS 84	NetCDF
Level 3a 27-Day Gridded Gas Flare Product	global	03/2020-02/2023	0.1°	27 days	SLSTR	Plate-Carrée - WGS 84	NetCDF
Level-3 Monthly Gridded Gas Flare Product	global	03/2020-02/2023	0.25°	1 month	SLSTR	Plate-Carrée - WGS 84	NetCDF

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

The C3S Level 2 Monthly Global Fire Location and FRP Night-time Summary Product provides a text-based summary of the main FRP data and other information contained within the Sentinel-3 Level 2 Active Fire Detection and FRP Products issued in 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 Global Fire Location and FRP Summary Night-time product at the location of every detected night-time land-based active fire pixel across the globe that is present in the NTC Level 2 Products FRP_in.nc file – which correspond to those detected using thermal radiometric measurements (See the Copernicus Sentinel-3 SLSTR Land User Handbook). These detections mostly relate to actively burning landscape fires, but can also be volcanoes, gas flares or other industrial heat sources.

The original Level 2 NTC Level 2 AF Detection and FRP Products are based on analysis of Level 1b radiometrically calibrated observations present in the visible to longwave infrared spectral channels made in the near-nadir view scan of the SLSTR, which images the Earth across a 1420 km swath using a scanner that operates with view zenith angles from 0° out to almost 55°. For the C3S Level 2 Monthly Global Fire Location and FRP Night-time Summary Product, 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 in almost all operational FRP products generated today – including those from MODIS to which the C3S products are compared (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 at or close to those typically measured over ambient surfaces (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 NTC mode is described in detail in Xu et al. (2020). It should be clarified however that the 'active fire pixels' are detected using primarily data in the SLSTR MWIR and Long-Wave Infrared (LWIR) spectral channels, and that the FRP is retrieved from the MWIR radiances. These AF pixels can, as we have already said, be related to volcanoes, gas flares or other industrial heat sources as well as landscape fires – but by far the vast majority are related to landscape fires and it is relatively common to ignore the contribution of other phenomena when analysing such data.

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

The C3S Level 2 Monthly Global Fire Location and FRP Night-time Summary Product stores the latitude, longitude, FRP, date, time and associated data of each detected AF pixel present in the original Level 2 Products FRP_in.nc file. 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 Night-time Product

The Level 3a Daily Gridded AF & FRP Night-time 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. As with the Level 2 Summary Product discussed above, these Level 3 data are based on the thermal-channel derived information coming from the FRP_in.nc files present in the Level 2 products.

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

The Level 3a 27-Day Gridded AF & FRP Night-time Product builds on the Level 3a Daily Gridded AF & FRP Daytime Product by collating and summarising 27-Days of night-time 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. These Level 3 data are also based on the thermal-channel derived information coming from the FRP_in.nc files present in the Level 2 products.

1.4 Level 3 Monthly Summary AF & FRP Night-time Product

The Level 3 Monthly Summary AF & FRP Night-time 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. These Level 3 data are also based on those coming from the FRP_in.nc files present in the Level 2 products.

Figure 1-1 shows the gridded global night-time AF pixel count and total FRP variables extracted from the global datasets stored in the C3S Sentinel-3 Level 3 Monthly Summary AF & FRP Night-time Product of August 2020 (with only the Sentinel-3A data layers shown). Total FRP is calculated via the multiplication of the AF pixel count and mean FRP data layers stored in the Level 3 product file, which is recorded at a grid cell size of 0.25 degrees.

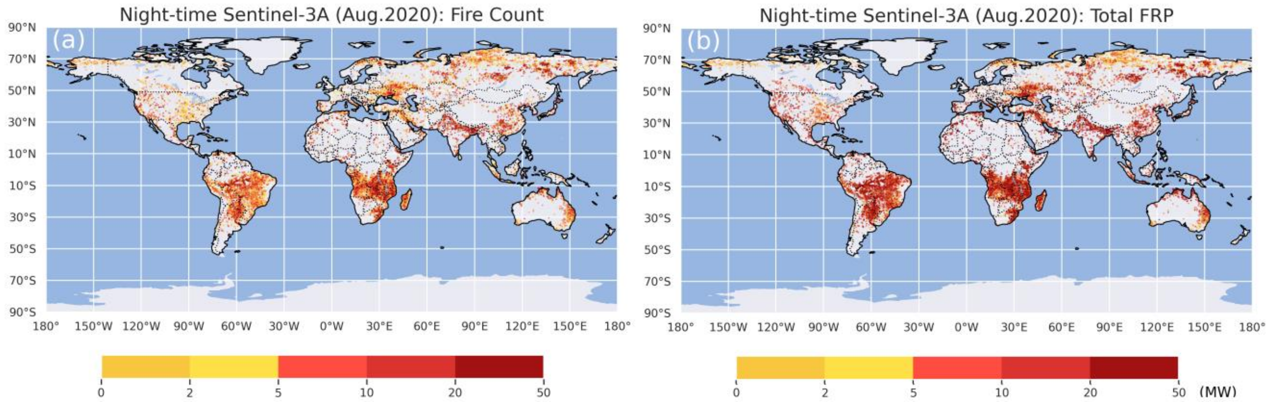

Figure 1-1: Monthly global map of (a) active fire pixel count and (b) total FRP, both derived from data held within the C3S Level 3 Monthly Summary AF & FRP Night-time Product of August 2020. Data shown are from Sentinel-3A in this case, with the product file also containing the same data from Sentinel-3B. Grid cell size is 0.25°.

1.5 Level-2 Monthly Global Gas Flare Night-time Summary Product

The C3S Level 2 Monthly Global Gas Flare Night-time Summary Product provides a text-based summary of the main FRP data and other information contained within the Sentinel-3 Level 2 Active Fire Detection and FRP Products issued in NTC mode collected over the period of one month worldwide, but separated by each Sentinel-3 satellite. Whilst the Level-2 Monthly Global Fire Location and FRP Night-time Summary Product is derived from information stored within the NTC Level 2 Products FRP_in.nc file, the Level 2 Monthly Global Gas Flare Night-time Summary Product is derived from information stored in the NTC Level 2 Products FRP_an.nc file – which represents night-time land-based active fire pixels across the globe who are detected and have their FRP quantified using radiances measured detected with the SLSTR SWIR channels (See the Copernicus Sentinel-3 SLSTR Land User Handbook). Whilst in the Level 2 product these SWIR detections mostly relate to actively burning landscape fires, but can also be volcanoes, gas flares or other industrial heat sources – the C3S Level 2 Monthly Global Gas Flare Night-time Summary Product attempts only to include those related to gas flares. It does this using the spectral radiance ratio measured over the detected AF pixel in the S5 and S6 SLSTR spectral channels, held within the original Level 2 FRP product files. As detailed in Fisher and Wooster (2019), this spectral radiance ratio can be used to separate gas flares from many other high temperature phenomena due to the fact that gas flares are typically hotter and have a higher value of this ratio than (typically cooler) vegetation fires. However, gas flares are highly sub-pixel targets at the scale of the SLSTR observations, so any difference in the point spread function of the S5 and S6 spectral bands may affect the value of this ratio, as will any inter-band spatial misregistration. To minimise such impacts, the L2 summary product algorithm follows the strategy adopted by Zhukov et al. (2006) for sub-pixel hotspot analysis, and performs calculation of this spectral radiance ratio metric on a 'fire cluster' basis - rather than at the level of individual active fire pixels. The metric is used to classify each cluster, and thus each AF pixel within it, as a gas flare or not based on thresholding of the S5-to-S6 spectral radiance ratio. Only pixels classified as gas flares are passed to the next stage of the algorithm, which is a temporal persistence test that requires at least one gas flare detection a month to occur for a period of three months to have the AF pixel classified as a confirmed gas flare.

With two operational Sentinel-3 satellites operating concurrently, the global night-time equatorial revisit time provided by SLSTR in the near-nadir view scan whose data are used to generate the Level 2 products upon which this Summary Product depends includes two days with one satellite, and one day with two operational satellites (Donlon et al., 2012). Imaging frequency increases at higher latitudes due to orbital convergence. The C3S Level 2 Monthly Global Gas Flare Night-time Summary Product stores for each confirmed gas flare the latitude, longitude, SWIR-derived FRP, date, time and associated data of each detected AF pixel confirmed as a gas flare and present in the original NTC Level 2 Products FRP_an.nc files. 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.

1.6 Level 3a Daily Gridded Gas Flare Night-time Product

The Level 3a Daily Gridded Gas Flare Night-time 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. The Product stores for each grid cell information related to the SWIR-derived FRP and other associated data of each detected AF pixel confirmed as a gas flare and present in the original NTC Level 2 Products FRP_an.nc files.

1.7 Level 3a 27-Day Gridded Gas Flare Night-time Product

The Level 3a 27-Day Gridded Gas Flare Night-time Product builds on the Level 3a Daily Gridded Gas Flare Daytime Product by collating and summarising 27-Days of night-time 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. The Product stores for each grid cell information related to the SWIR-derived FRP and other associated data of each detected AF pixel confirmed as a gas flare and present in the original NTC Level 2 Products FRP_an.nc files.

1.8 Level 3 Monthly Summary Gas Flare Night-time Product

The Level 3 Monthly Summary Gas Flare Night-time Product builds on the Level 3a Daily Gridded Gas Flare 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. The Product stores for each grid cell information related to the SWIR-derived FRP and other associated data of each detected AF pixel confirmed as a gas flare and present in the original NTC Level 2 Products FRP_an.nc files.

Figure 1-2 shows gridded global data extracted from the Sentinel-3A C3S Sentinel-3 Level 3 Monthly Summary Gas Flare Night-time Product of July 2023. Total FRP is calculated via the multiplication of the AF pixel count and mean FRP data layers stored in the Level 3 product file, which is recorded at a grid cell size of 0.25 degrees.

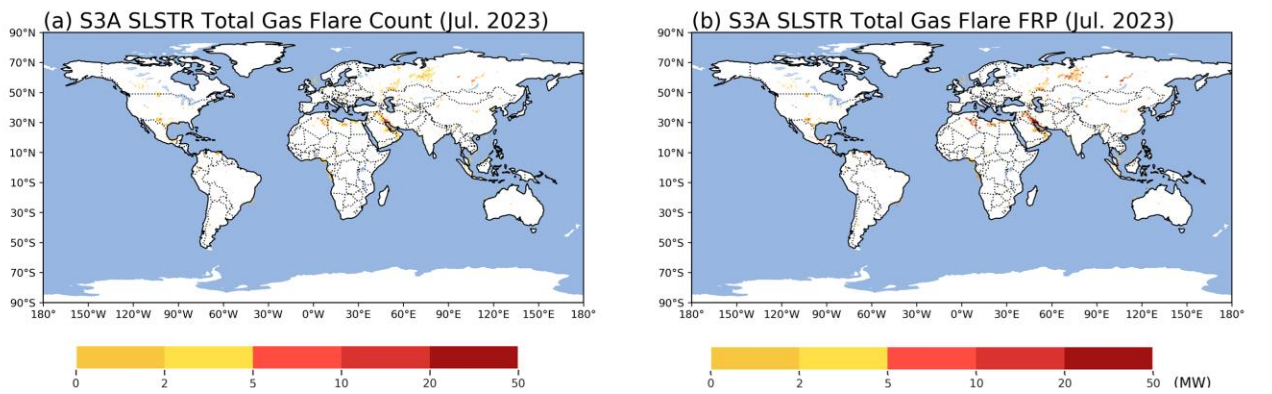

Figure 1-2: Monthly global map of (a) active fire pixel count for pixels identified as gas flares, and (b) total FRP of these gas flare pixels, both derived from data held within the C3S Level 3 Monthly Summary Gas Flare Night-time Product of July 2023. Data shown are from Sentinel-3A in this case, the products from Sentinel-3B are stored in separated file. Grid cell size is 0.25°. The data in these Level 3 Gas Flare Monthly Summary Files ultimately come from the original NTC Level 2 Products FRP_an.nc files that store information derived from the SLSTR SWIR bands.

2. Description of Validating Datasets

The 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 Night-time 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 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 MODIS AF & FRP Product

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. Since Terra MODIS lowered its orbit and it overpass time started drifting significantly in 2022 as it prepared for its end of life in 2026, we focus here on Terra MODIS data from before that period.

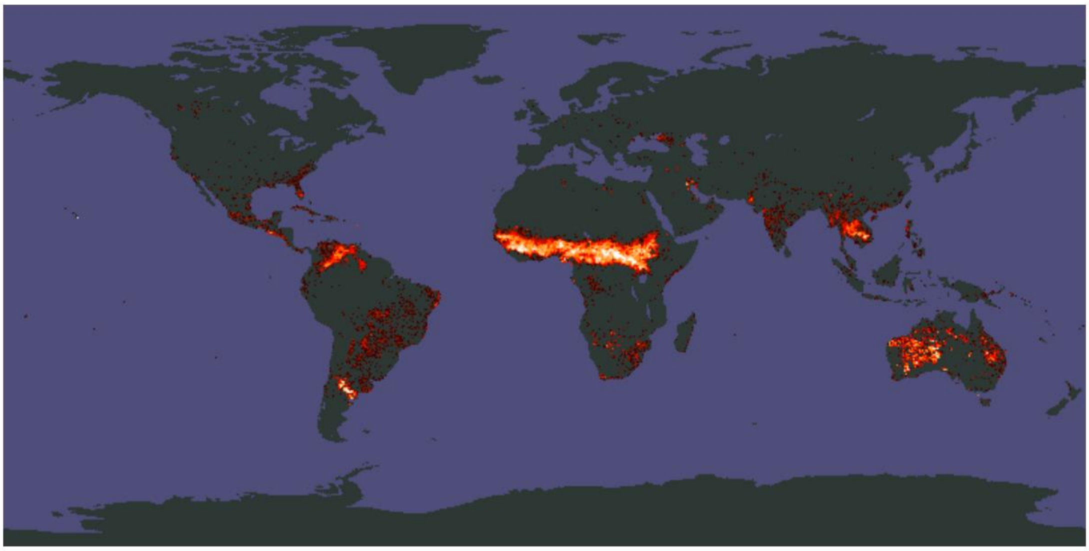

Figure 2-1: Global 'corrected active fire' (AF) pixel count data layer ('CorrFirePix') extracted from the January 2001 Terra MODIS MOD14CMQ monthly Climate Modelling Grid (CMG) AF product.

2.2 VIIRS NightFire product

The C3S Level 3 Gas Flare Products are best intercompared to the VIIRS NightFire product, which is the first global, long-term Earth Observation-based gas flaring dataset, leveraging the low-light imaging capability of the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor. VIIRS is carried on the Suomi-NPP satellite, and the subsequent NOAA polar orbiting satellites as well. The VIIRS NightFire product aims to detect and characterize gas flares globally, providing insights into flaring activity and supporting efforts to reduce flaring emissions (Zhizhin et al.,2021).

The NightFire algorithm operates on night-time multispectral VIIRS observations, including those in the VIIRS shortwave infrared (SWIR) bands. It uses a Planck fitting approach using multi-band spectral radiance measures to estimate the effective flaring temperature (in Kelvin) and area (in square meters) of sub-pixel hot targets. Gas flares are identified by thresholding this temperature—generally those detections exceeding 1,400 K are assumed to be flares —and their persistence in detection. These dual criteria help ensure that the algorithm reliably differentiates gas flares from transient or non-flaring heat sources, allowing for highly accurate detection. From these parameters, the radiative power output of the flares, also referred to as Fire Radiative Power (FRP) in the context of landscape fires, can be calculated using Stefan's Law.

Since 2012, VIIRS has provided annual global surveys of gas flare sites, taken from the NightFire products thresholded at 1,400 K, with nightly data accessible in CSV and Keyhole Markup Zipped (KMZ) formats. These datasets support both longitudinal studies and real-time assessments, enabling scientists to analyse flaring trends and their implications on a global scale. Validation studies have corroborated the robustness of the VIIRS NightFire methodology, showing a strong correlation with reported flaring data, with some regions achieving an R^2 value as high as 0.92. This high correlation values achieved in the validation underscores the reliability of the VIIRS gas flare product for research and policy applications (Zhizhin et al.,2021). Figure 2-2 below shows one year of the global gas flare data mapped from the VIIRS NightFire product of 2012.

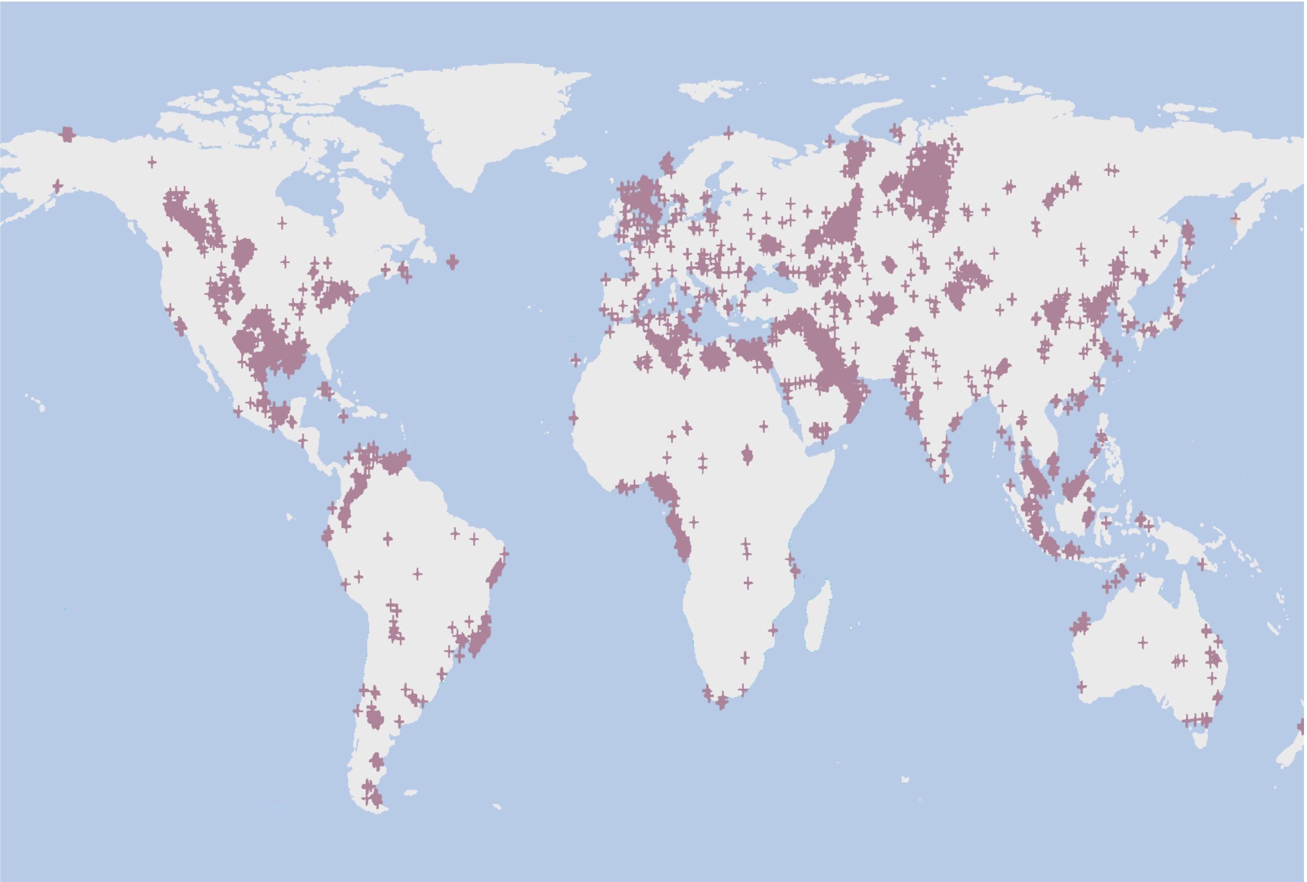

Figure 2-2: Global gas flares (red areas) detected in 2012 as present in the VIIRS NightFire products of that year.

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 (and specifically the data stored within the FRP_in.nc file of those products).

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 km². To match this the SLSTR data can also be restricted to those with an S7 pixel area maximum of 1.7 km² (the matching SLSTR F1 pixel area maximum at this scan angle is 1.2 km²). 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).

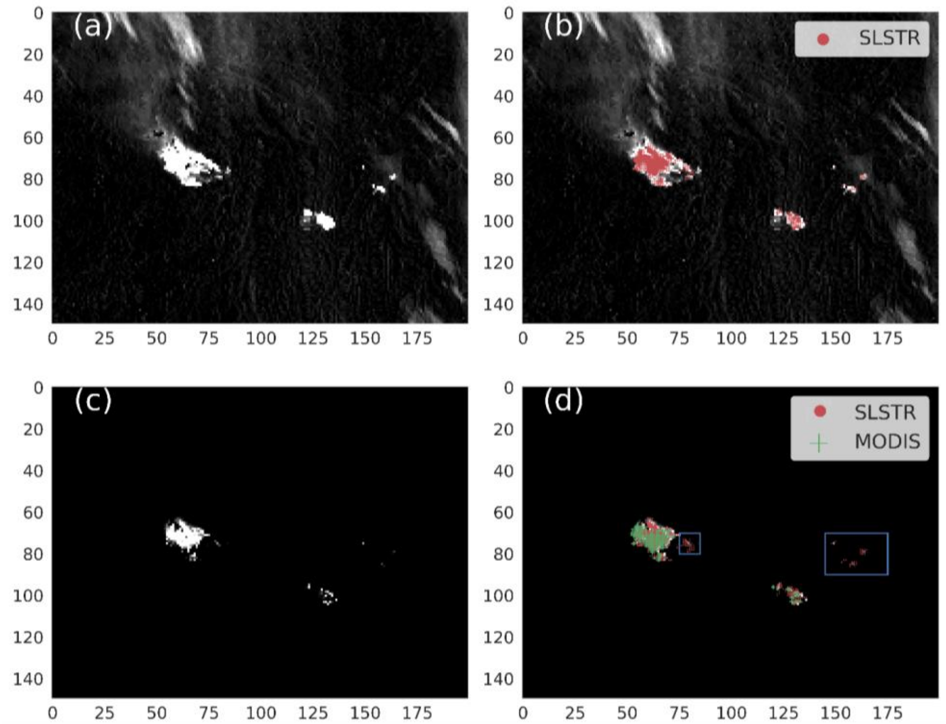

Figure 3-1: Comparison between near-simultaneous night-time observations of the same fire made by Sentinel-3A SLSTR and Terra MODIS. The location is that of the Fort McMurray wildfire in Alberta, Canada. The SLSTR image subset covers 200 km by 150 km and was collected at 04:56 UTC on 6th May 2016, with the matching MODIS data collected at 05:00 UTC. The intercomparison is based on the methodology outlined in Section 3.1. (a) SLSTR MIR-LWIR Channel (S7 – S8) Brightness Temperature (BT) difference image, where higher BT differences are depicted as brighter pixels. (b) Same as (a) but with the SLSTR AF detections overlain with a one pixel offset for clarity. (c) SLSTR S6 (SWIR) channel data matching (a), and (d) the same as (c) but with SLSTR AF detections superimposed as red '…' and near-simultaneous MODIS AF detections as green '+' (both with one pixel offsets for clarity). In (d), the blue rectangle highlights the AF pixels detected by SLSTR but missed by MODIS. Example taken from Xu et al. (2020).

Matching night-time SLSTR and MODIS example data are shown in Figure 3-1. In this case SLSTR identifies all AF pixels detected in the MOD14 product (a total of 283), plus an additional 67 AF pixels that remained undetected by MODIS. The additional AF pixels detected by SLSTR are either isolated single pixel detections, or pixels lying at the edges of clusters of detected AF pixels. Figure 3c also shows that at night many fires clearly show up in the 500 m spatial resolution SLSTR SWIR band recorded in the sensor´s 'S6', confirming that the AF detections based on the MIR channel data are the result of real fires and not false alarms (since there should be very few false alarms in SWIR-detected AF pixel data at night; Xu et al., 2020). 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 of a set of a spatially contiguous (or near-contiguous) AF pixels, sometimes termed a fire pixel 'cluster', since the two sensors may not detect an identical set of AF pixels even when both view the same fire at the same time. This 'cluster-based' 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).

3.2 Fire Pattern & FRP Magnitude Analysis

The performance of the C3S Level 2 Monthly Global Fire Location and FRP Night-time Summary Product can be best assessed against near-simultaneous MOD14 product files generated from Terra MODIS observations. In contrast, the three C3S Level-3 gridded FRP Products can be best evaluated via analysis of their spatial-temporal patterns. Comparison to those in the wider set of MOD14 data are 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 night-time AF and FRP data retrieved from SLSTR observations made by Sentinel-3A and -3B from March 2020 to Feb 2021 compared to that from Terra MODIS. Very similar spatial patterns are seen, indicating broad agreement despite the MODIS data including all night-time observations – including some not 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, 2020), 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.

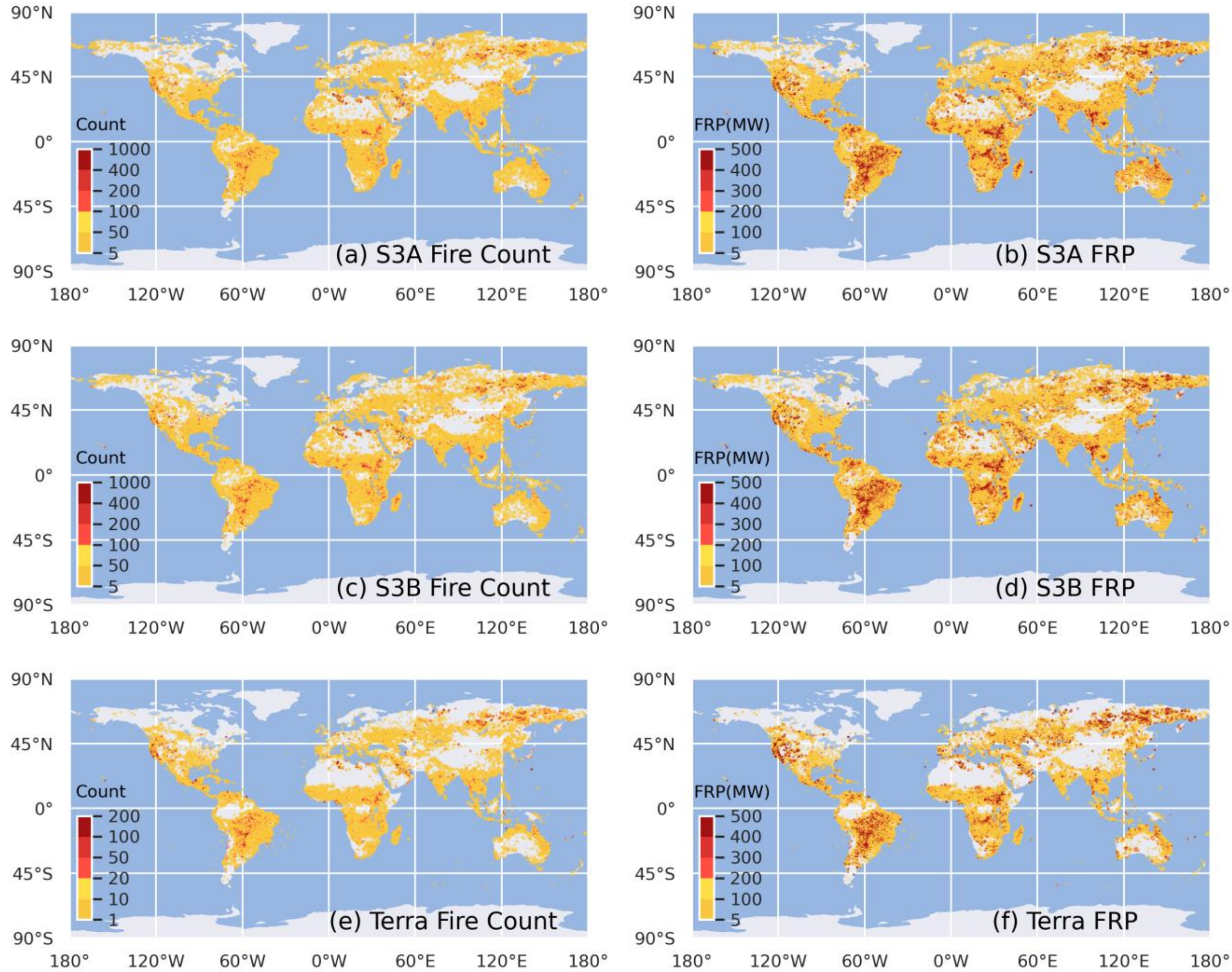

Figure 3-2: Total active fire (AF) pixel count and total FRP of fires detected within 0.25° grid cells from March 2020 to February 2021 using all Sentinel-3A, -3B SLSTR and Terra MODIS data. Note the Terra MODIS active fire pixel count has a scale which is 5 times smaller than that of S3A and S3B due to the lower number of AF pixels the former sensor typically detects.

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, and the C3S Level 3 gridded FRP Products are well suited to its determination, 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 time when the total FRP in the region exceeds a certain percentage of the total FRP of the whole year respectively, 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% and 90% 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 and FRP Night-time products and compare them to those same metrics derived from the night-time MODIS data of the same period.

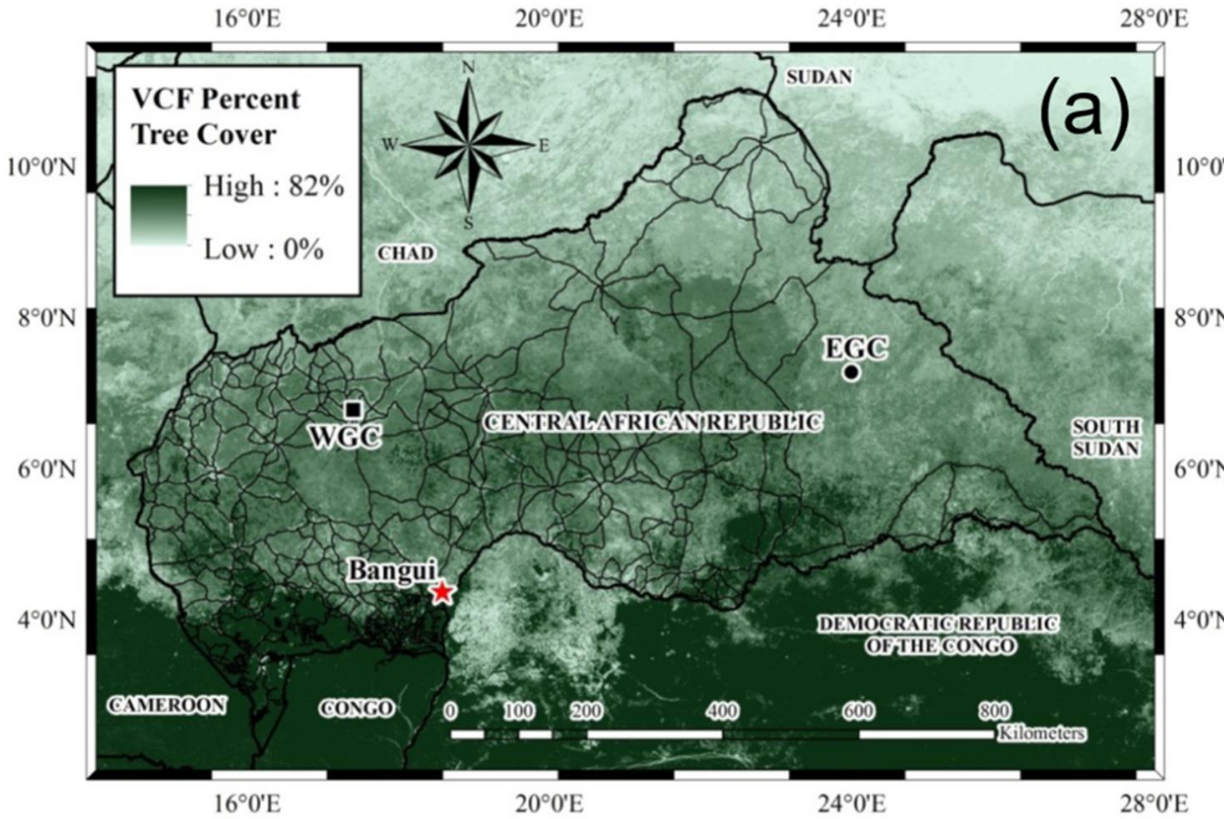

Figure 3-3: Fire season data for the Central African Republic (CAR) - Map showing the locations of the western and eastern grid cells (labelled WGC and EGC) whose data is analysed in (Figure 3-4), superimposed on percent tree cover characterized according to the 500 m Global Land Cover Facility (GLCF) Version 3 of the Collection 4 Vegetation Continuous Field (VCF) product (major road networks are also superimposed).

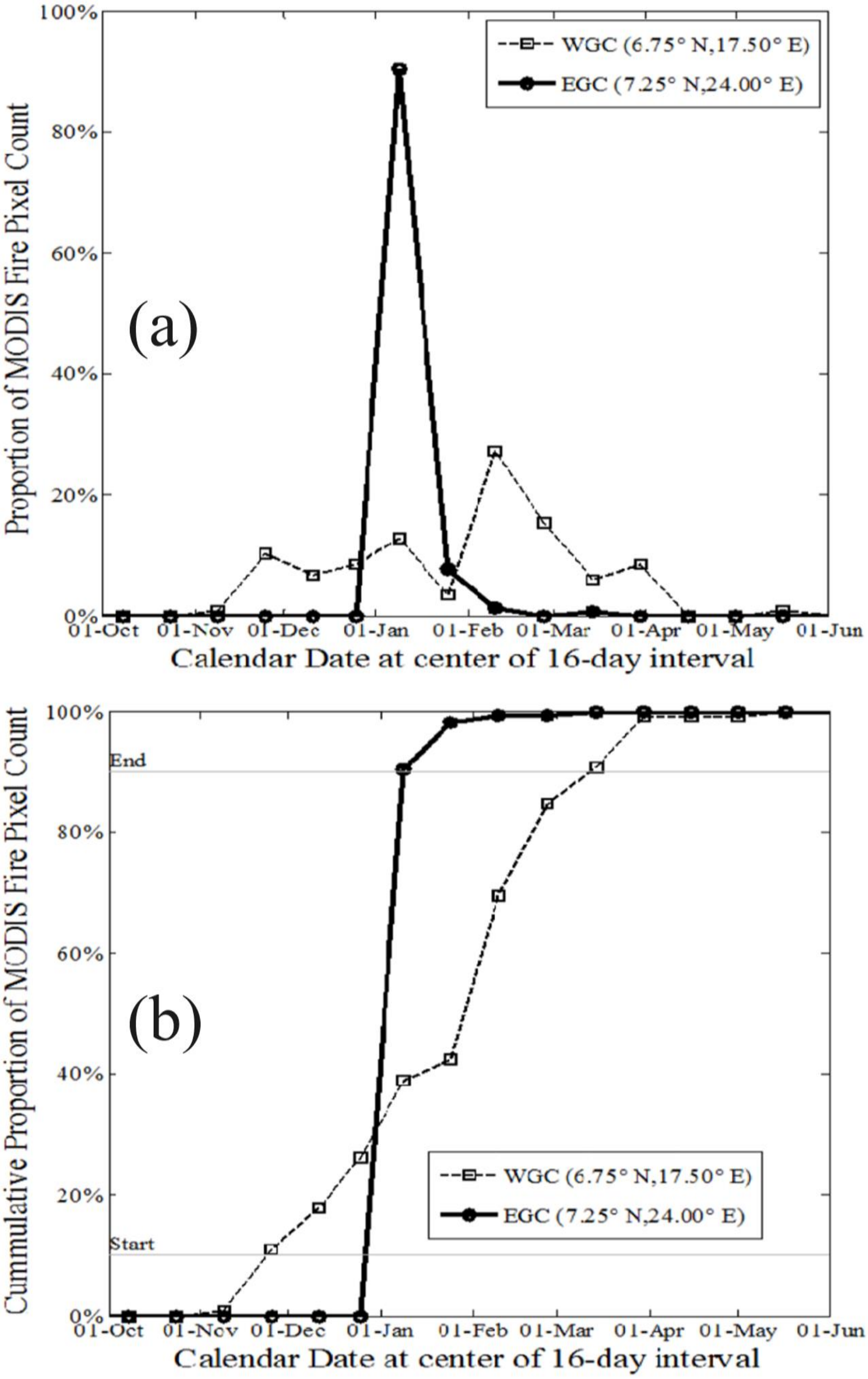

Figure 3-4: Fire season data for the Central African Republic (CAR) - Normalized seasonal profiles of (a) MODIS active fire (AF) pixel counts and (c) cumulative distributions of MODIS AF pixel counts for two 0.05° grid cells at 16-day temporal resolution. Seasonal profiles are generated from 10 years 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 (Figure 3-3). The peak of the fire season is represented by the maxima shown in (a). The 10th and 90th percentiles of the cumulative AF pixel counts are shown in (b) 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 Night-time 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 3-5a), and also both in terms of AF detections (as in Figure 3-3 & Figure 3-4), but also with FRP. As Sentinel-3 satellites have been reported to have the capability of detecting from three to five times more AF pixels that does near simultaneous MODIS data - while the total FRP of the fire cluster and regions is very close for both sensors (Xu et al., 2020), the fire season metrics derived from FRP data will be more similar than the ones calculated using numbers of AF pixels. Therefore, we focus on deriving fire season information from FRP data for this 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 3-5b shows monthly global total night-time FRP 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 such metrics as the statistical summaries (mean, standard deviation, etc.), coefficient of determination (r^2) and the slope of the linear best fit.

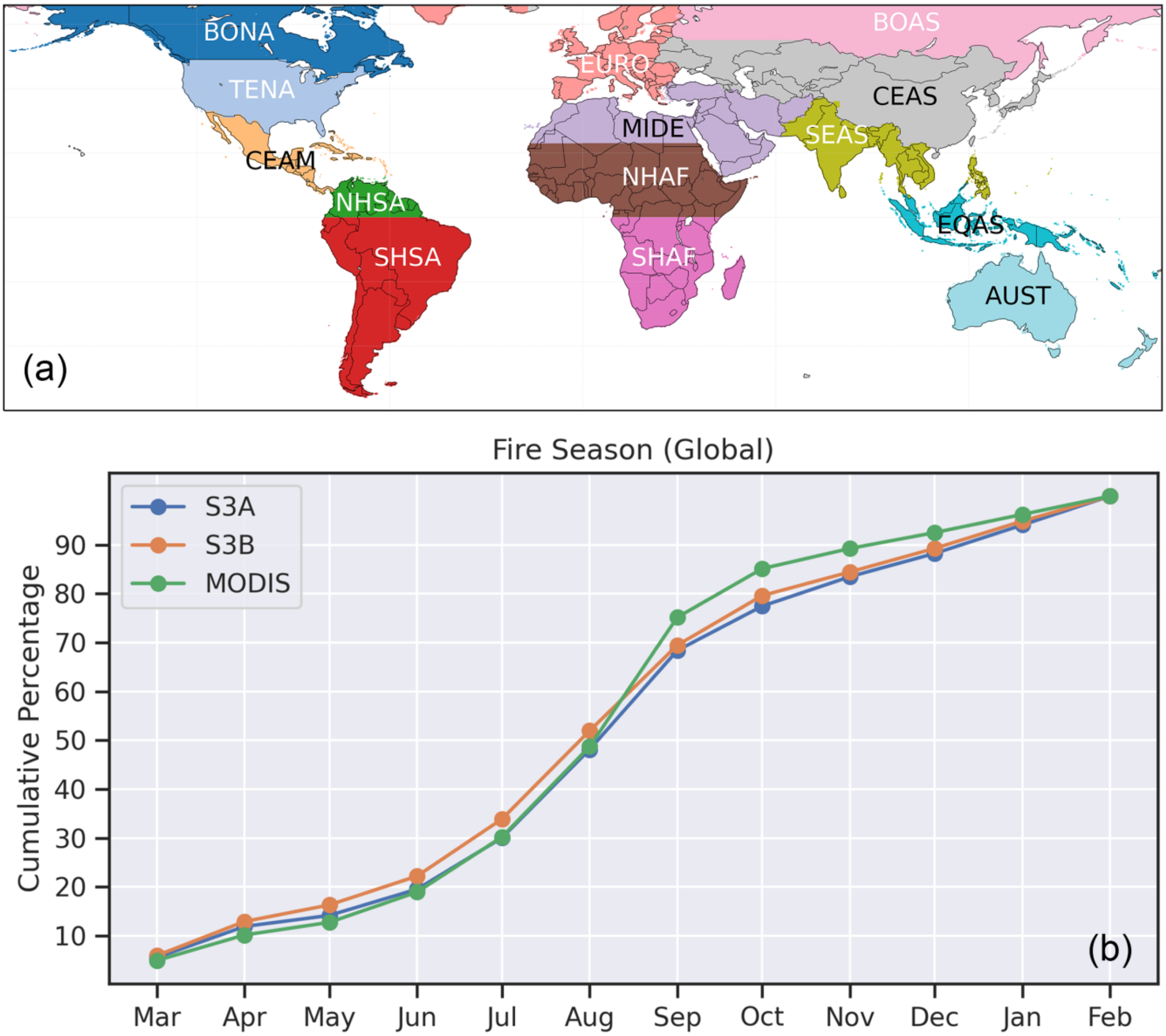

Figure 3-5: Fire seasonality metrics. (a) Global regions used in the Global Fire Emissions Database (Van der Werf, 2017), and (b) night-time global monthly total FRP as derived from all fires across all regions in (a) using Sentinel-3A, -3B and Terra MODIS (The abbreviation of the names is as follows: 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 and New Zealand (AUST).

3.4 C3S Product Gas Flare Performance

3.4.1 Internal Validation

Similar to the NTC Level 2 Monthly AF detection and FRP Summary Products, the C3S Level 2 Monthly Global Gas Fire Summary Products store their information in CSV format. Thus, the first validation step (internal validation) in the evaluation of these C3S Gas Flare products is comparison of both the

C3S Level 2 Monthly Gas Flare Summary Products and the Level 3a Daily Gridded Gas Flare Products with 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 Gas Flare Summary Product and the C3S Level 3a Daily Gridded FRP Product underlies the evaluation of all the C3S Gas Flare products, since all C3S FRP products are derived from the same NTC Level 2 FRP Product datasets (and specifically the data stored within the FRP_an.nc file of those products).

3.4.2 Independent Validation

The independent validation of the S3 SLSTR Gas Flare data is conducted using the VIIRS NightFire products described in Section 2.2. The comparison of data from the S3 and VIIRS gas flare products involves a systematic spatial analysis using a grid-based approach. Initially, both datasets are aggregated to a 0.25-degree global grid over a one-month to one-year period. For each grid cell, the presence of a gas flare is binary-coded, where cells containing at least a single gas flare pixel detection are assigned a value of 1, and this unity value remains regardless of the actual pixel detection count. The assessment of the degree of agreement between the two products employs a spatial window technique. For each SLSTR gas flare pixel detection, a 3x3 cell window centred on the detection is examined and if at least one VIIRS gas flare pixel detection exists within this window, the detection is classified as an agreement between the two products. This approach accounts for potential minor geolocation differences and the different spatial resolution characteristics of the two sensors.

Commission errors are identified through a reciprocal analysis of both datasets. For SLSTR gas flare pixel detections, any detection without a corresponding VIIRS detection in its 3×3 window is classified as a commission error. Similarly, VIIRS gas flare pixel detections without corresponding SLSTR detections in their respective 3×3 windows are marked as omission errors. This approach enables a quantitative assessment of the spatial agreement between the two gas flare datasets whilst also accounting for the differing technical and operational characteristics of both sensor systems. As such the method provides a robust framework for evaluating the relative performance and complementarity of SLSTR and VIIRS gas flare detection capabilities, remembering that the original VIIRS NightFire product contains all hot-spot detections made and that these are reduced to only those of the gas flares using thresholding of the effective hotspot temperature and the persistence of detection, as detailed in Section 2.2.

Figure 3-6 shows the spatial co-location analysis between VIIRS and SLSTR gas flare pixel detections in July 2023. The intercomparison reveals strong agreement between the data coming from the two instruments. Of the 1,850 total VIIRS gas flare pixel detections, 83.8% (1,551) were co-located with an SLSTR detection, while only 16.2% (299) were unique to VIIRS, indicating an SLSTR omission error of 16.2%. Similarly, for SLSTR's 1,571 total gas flare pixel detections, 92.0% (1,446) were co-located with VIIRS detections, with just 8.0% (125) being SLSTR commission errors with respect to VIIRS. This high degree of correspondence between the two instruments (>80% co-location rate for both) suggests robust detection capabilities and suggests a good reliability of gas flare identification from both satellite systems, considering for example that the VIIRS and SLSTR instruments observe the same location at a very different time of the night when cloud cover (through which gas flares cannot be detected) may also be quite different.

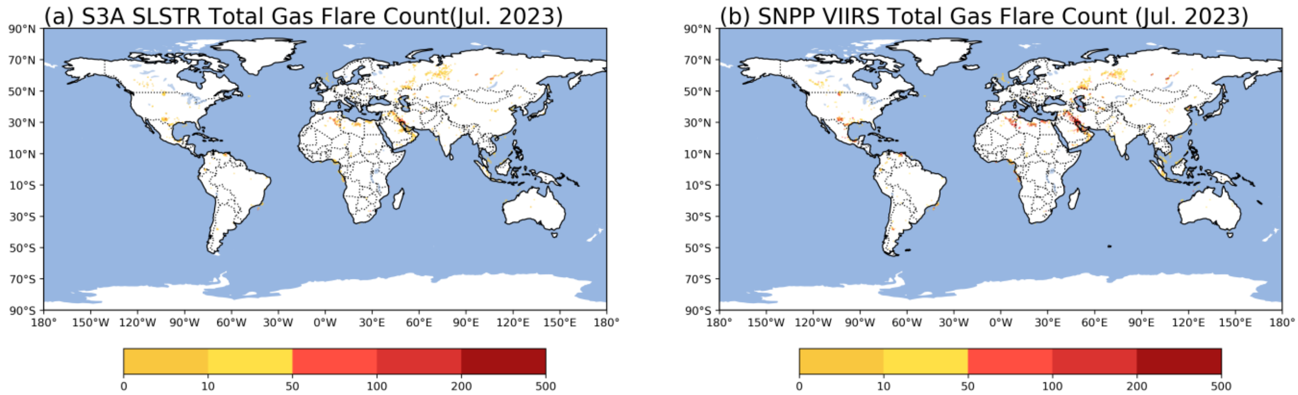

Figure 3-6: Comparison of global gas flare pixel detections made by (a) Sentinel-3A SLSTR and (b) SNPP VIIRS in July 2023, based on data held within the C3S Level 2 Monthly Gas Flare Summary Products and the matching set of VIIRS NightFire products respectively.

4. Summary of validation results

The detailed results of the validation assessment are described in the PQAR [RD - 3], therefore only a very brief summary is provided here.

In terms of the NTC Level 2 Sentinel-3 AF detection and FRP Products, very similar spatial patterns are seen in the data generated from S3A, 3B and Terra MODIS. This indicates a broad degree of agreement, even though the majority of the MODIS data night-time observations are not collected near-simultaneously with SLSTR. The comparison of AF pixel counts shows that the SLSTR product includes many 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 (due to its enhanced sensitivity to night-time active fire detections compared to MODIS) are mostly of low FRP.

In comparison to the global data collected by Terra MODIS at almost the same time (within +/- 6 minutes) and within a view zenith angle range of 0 to 30 degrees, the C3S Night-Time Level-2 Summary FRP Product shows 95% of MODIS-identified active fire (AF) pixels have a matching Sentinel-3 AF pixel detection, representing an apparent SLSTR product omission error compared to MODIS of 5%. Conversely, of the Sentinel-3 AF pixel detections present the same dataset, only 63% had a matching MODIS AF pixel detection. This confirms the greater sensitivity of the SLSTR AF product to night-time active fires when compared to MODIS, as reported by Xu et al. (2020). Directly comparing the FRP of AF clusters imaged near simultaneously by SLSTR on Sentinel-3B and by Terra MODIS in Jan 2019 also indicates a strong degree of agreement between the FRP values (r^2=0.91). The slope of the ordinary least squares (OLS) line of best fit exceeds 1.0 (at 1.08) primarily because SLSTR quite often detects some low FRP AF pixels at the edge of an active fire cluster that MODIS does not detect, and thus the former provides a slightly higher FRP measurement. Similarly, the comparison between regions observed simultaneously by SLSTR on Sentinel-3B and Terra MODIS indicates a strong degree of agreement (r2=0.95) and a slope of 1.16, again due to SLSTR being able to detect some low FRP AF pixels that MODIS does not.

Comparison of the C3S Night-time Level 3a Daily FRP product and MODIS, both globally in terms of FRP, and in almost all 14 geographic regions defined for use by the Global Fire Emissions Database, shows a good degree of agreement. Globally the coefficient of variation (r^2) between the FRP measured by S3A and by Terra is 1.00, and the slope of the ordinary least squares linear best fit is 1.06 to 1.07. The corresponding correlation coefficient between S3B and Terra is 1.00 and the slope is 1.07 to1.08. For the GFED regions, the coefficient of variation (r^2) between S3A and MODIS ranges from 0.76 to 1.00, and the slope from 0.60 to 1.15. Between S3B and MODIS the same metrics are 0.83 to 1.00 and 0.69 to 1.13 respectively. Comparisons between the Night-time Level 3 Monthly Summary FRP product and MODIS show similar results to those obtained with the C3S Daily product, but with lower temporal fidelity. The fire season metric of 'peak of the fire season' also agrees between the C3S Level 3a Daily FRP product and MODIS. For the C3S Level 3 Monthly Summary FRP Product the fire season metrics of start, peak, end and duration of the fire season agree very well with those derived from MODIS. Globally, the differences between each of these metrics for each satellite is maximum one month. For all the GFED regions, >20% of the 14 regions have 100% agreement for all the four fire season metrics analysed, >70% have a difference of only one month, and almost all the regions have a difference of less than two months.

Based on four years´ S3A, S3B and Terra MODIS data covering March 2020 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 geographic 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 Jan 2019 and by SLSTR on Sentinel-3B as recorded in the Level 2 Summary AF Detection and FRP product indicates a strong degree of agreement, as evaluated previously in Xu et al. (2020). Furthermore, the fire season metric of 'peak of the fire season' agrees between the C3S Level 3a Daily FRP product and MODIS globally, and out of the 14 GFED geographic regions, ten regions show a fire season peak identical to within a month as derived via the data from each sensor. Further statistical intercomparisons between the C3S FRP products and MODIS also show a strong degree of agreement. Overall, we find that our comparison of ~ four years of global C3S AF Detection and FRP products coming from night-time S3A and S3B observations with two years of matching data from Terra MODIS, show a strong degree of agreement. With Terra MODIS likely reaching its end of life in the next few 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 shown here will provide the data required to mesh together MODIS and SLSTR data into a single compatible time-series for long-term trend analysis that will continue far beyond the lifetime of Terra MODIS.

As for the C3S Gas Flare Products, Fisher & Wooster (2018) have already shown a strong agreement between the shortwave infrared-derived FRP present in the SLSTR products and that derived via Planck function fitting to multiband VIIRS data and stored in the NightFire products (Figure 2-10). These two datasets align along a 1:1 line, demonstrating minimal bias (μ = 0.5 MW) and low scatter (σ = 1.6 MW). Here we have compared the C3S Gas Flare products with the VIIRS NightFire product over one year (2023), with both datasets being based on night-time observations (albeit not made at the same time of the night). Very similar spatial patterns are shown in terms of the location and also the number of 0.25° global grid cells affected by gas flaring (C3S product 2183 cells; VIIRS NightFire 2067 grid cells). The C3S product registered 1,964 grid cells that had gas flares where VIIRS also recorded flares, whilst VIIRS recorded 1,863 cells with gas flares where the C3S product also recorded them. The C3S product has 219 unique gas flare grid cells not captured by VIIRS, whilst the NightFire product identified 204 unique grid cells not captured by C3S. Overall, SLSTR achieved a 90.0% detection confirmation rate with VIIRS, whilst VIIRS achieved a very 90.1% detection confirmation rate with C3S. The nearly identical co-location rates of approximately 90% and complementary omission rates of 10% between the two products demonstrate their high degree of consistency, especially considering the completely different overpass time of SLSTR and VIIRS.

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

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