ESA Climate Change Initiative – Fire_cci
D1.1 User Requirement Document (URD)

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Summary

This document is the version 5.2 of the User Requirements Document for the Fire_cci project. It refers to Task 1, Work Package 1100. It describes burned area requirements according to the user needs, providing background information to the data provider.

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Document Status Sheet

Issue	Date	Details
1.0	01/12/2010	First Document Issue
2.0	09/02/2011	Restructured and updated Document
3.0	08/07/2011	Full (re)writing of sections 3, 4 and 5
3.1	10/07/2011	Editorial reworking
3.3	26/07/2011	Layout and formal review
3.4	31/08/2011	Layout and formal review
3.5	14/09/2011	Review addressing ESA comments
4.0	26/11/2015	First document for Phase 2 of Fire_cci. Full (re)writing of the document
4.1	15/01/2016	Review addressing ESA comments
5.0	22/09/2016	Revised version of the document
5.1	30/12/2016	Addressing comments of CCI-FIRE-EOPS-MM-16-0128
5.2	20/12/2017	Revised version of the document

Document Change Record

Issue	Date	Request	Location	Details
2.0	04/02/2011	ESA, Fire_cci partners	Whole document	Major editing taking into account review comments by S. Plummer (ESA) and other information and feedback
3.0	08/07/2011	ESA, Fire_cci partners	Sections 3, 4 and 5	Full (re)writing of indicated sections
3.1	10/07/2011	Fire_cci partners	Whole document	Editorial
3.3	26/07/2011	Fire_cci partners	Whole document	Literature review on user requirements and products, layout and formal review
3.4	31/08/2011	GAF	Whole document	Typo and grammar correction, updating references
3.5	14/09/2011	IRD, LSCE, JÜLICH	Whole document Section 3.1	Revision following review comments from Stephen Plummer (ESA), updating references, Data Inter-comparison – separated paragraph introduced
4.0	26/11/2015	MPIC, Fire_cci partners	Whole document	New naming convention for the document New format and layout Full (re)writing of the document

Issue	Date	Request	Location	Details
4.1	15/01/2016	ESA	Sections 1, 2.1, 3, 3.1.4, 3.2, 4.1.1, 4.1.3, 4.1.5, 4.1.6, 4.2, 5.1, 5.2.4, 5.4, 5.4.1, 5.4.2, 5.4.4, 5.4.6, 6.5. Table 1 Section 4.1 Section 5.1 Section 7 Annex 1	Minor changes in the text Minor changes in the line corresponding to Fire_cci The sub-sections of this section were re-ordered New paragraphs added New references added Inclusion of new acronyms
5.0	22/09/2016	MPIC, Fire_cci partners	Section 3 Section 4 Section 4.1.2 Section 4.1.4 Section 4.2 Section 5 Section 6 Annex 2	Updated and expanded; characteristics of burned area products with on-going development are discusses separately from “obsolete” products Updated and expanded. Added description of BB5CMIP6 Added description of FireMIP benchmark system New web of science database query on publications using burned area information Restructured, updated and synthesized Restructured and updated Added annex with commonly used definitions
5.1	30/12/2016	ESA	Section 3.1.5 Section 3.2 Sections 3.3, 5.1, 5.2.6 Section 5.2.8 Sections 6.1, 6.2	Changed the reference of C-GLOPS to GIO-GL1. Sentence added to better interpret the error results, and Figure 1 replaced. Small changes in the text. Last sentence deleted. Information added.
5.2	20/12/2017	MPIC	Sections 1, 3.2, 5.2.12, 5.2.13 Sections 2.1, 4.1.1, 5.2.6, 5.2.14, 6, 6.2 Section 2.4 Section 3.1 Section 4.1.4 Section 4.1.5 Section 5.1 Section 5.2.1 Section 5.2.7 Section 5.2.8 Section 5.3 Section 6.1 Section 6.3 Section 6.4 Annex 2 Annex 3 Annex 4	Text expanded. Small changes in the text. Deleted section of structure of the document. Updated tables, added new sub-sections with new products. Added summary on FireMIP workshop October 2017. Added study by Lehsten et al. (2010). Added GCOS-200 (2016) and update FireMIP requirements, added IBBI 2017 workshop. Update results from user requirement surveys, including Fire_cci product user statistics and the 2017 Fire_cci user workshop survey. Expanded on explanations of what uncertainty characterisation mean. Expanded on quality assurance indicator requirements. Expanded on ongoing user requirement surveys, including GCOS survey. Specified temporal resolution requirements. Added uncertainty characterisation. Specified ancillary data layer requirements. Updated description of measurement uncertainty. Added Fire_cci user survey form. Added 2017 Fire_cci user workshop report

Table of Contents

List of Tables

List of figures

1. Executive Summary

Emissions of greenhouse gases (GHGs) and aerosols from fires are important climate forcing factors, which make the fire emission estimations essential for climate modelling. Fires are also a major factor in land cover changes, species replacement, and hence affect fluxes of energy and water to the atmosphere. Societal implications like air quality, forest management policies, and potential habitat and infrastructure damage are also a growing concern at the international, national and regional level. In this context, spatial and temporal monitoring of fires is of primary importance. Fire activity can be monitored from space through detection of temperature signals from active fires. Furthermore, burned area can be mapped through the post-fire analysis of surface reflectance changes that are caused by the ash and soot deposits remaining after the fire.

A consistent long time series of global burned area is therefore a key variable for climate research and related applications. Burned area data can be used directly to constrain fire perturbation in dynamic vegetation and carbon cycle models, or it can be combined with information on combustion efficiency and available fuel load to estimate emissions of trace gases and aerosols.

This document is the User Requirements Document (URD) for Phase 2 of the Fire_cci project following the terms of reference in the ESA Climate Change Initiative (CCI) Statement of Work [AD-1]. It describes burned area requirements according to the user needs, providing background information to the data provider. This URD is a major adaptation of the Fire_cci Phase 1 URD (Schultz et al. 2011), which provided a detailed assessment of different burned area applications and user communities, desired product characteristics, the expected product quality and means of data delivery. This new update within Phase 2 of the Fire_cci project takes into account newly emerging priorities of international climate assessments, recently released global fire data sets and peer-reviewed publications, and feedbacks from users of the already released Fire_cci burned area products.

The user requirement assessment pinpoints that burned area products have numerous applications in many fields of expertise where ground data are lacking. There is a widespread need for burned area products in climate modelling, especially in dynamic vegetation modelling for applications related to estimation and understanding of the long-term interactions between fire, vegetation, carbon and ultimately climate. For atmospheric chemistry studies the most relevant application of burned area information is for estimating fire emission fluxes. The diversity of applications makes the generation of a specific burned area product accounting for the needs of all user groups rather difficult.

The climate, vegetation and atmospheric chemistry modelling users require long time-series of global burned area observations which are temporally unbiased and which ideally cover several decades. For most application, a spatial resolution of 0.25 degree is sufficient. The preferred temporal resolution of the grid product is monthly or daily. The modellers are interested in burned area products that contain ancillary satellite-derived information on the vegetation type burned, the fuel consumption, the rate of spread, timescale of vegetation recovery and burn patch number and size. Indicators for the impact of fire on vegetation (e.g. fire frontline intensity, fire-induced tree mortality) are also of interest. The combined analysis of several satellite observations will be required to derive such ancillary information; this includes a combined assimilation of different types of products like burned area, fire radiative power and vegetation indices, as well as consistent long-term time series and highest possible accuracy burned area products (wherever helpful those computed from "best stream" of reflectance data extracted from multiple sensors).

Gridded burned area estimates and burned pixel products were the product types most requested by all users. NetCDF, HDF5, and GeoTIFF are the data formats most widely used. Most users request public access to the data products by means that allow for fast and automatized download.

There is a general consensus, however, that existing burned area products suffer from insufficient accuracy. None of the currently available products meets the accuracy target requirements of 15% (error of omission and commission), compared to 30 m observations, defined by the Global Climate Observing System (GCOS) or the threshold omission/commission error margin of 20% expressed by many users. There is a clear demand for extensive product validation that follows internationally agreed procedures. A clear description of the errors, detailing which fire types are commonly missed by the product seems to be a common requirement among users. Error statistics derived from product validation shall ideally be incorporated as a separate data layer into the gridded burned area product. Information on the temporal stability of accuracy is also required. There is a particular increasing demand for a detailed characterisation of small fires missed by most satellite sensors.

Users increasingly request mature uncertainty quantifications in the burned area products. Burned area pixel products shall be provided with burn detection probabilities (p_b) for every pixel and burned area grid products with spatio-temporally explicit uncertainty information attributed to a "best estimate" burned area layer. In contrast to the uncertainty definition used by most product developers in the CCI projects, the burned area users consider the uncertainty information to be a quantitative description of the expected burned area error probabilities as derived from validation. Deriving such products may require a probabilistic characterization of the uncertainty on the input parameters (i.e. reflectances) and the propagation of the uncertainty through the burned area processing chain. To obtain a most likely estimate of burned area for the grid product, a probabilistic aggregation of p_b was favoured over the fixed p_b threshold aggregation approach, which is applied in contemporary satellite-derived burned products.

To promote that burned area products are widely applied and used in an adequate manner, the products shall include mature metadata and be accompanied with a product user guide that provides instructions on how to correctly understand and apply individual product variables.

2. Introduction

2.1. Background

Emissions of greenhouse gases (GHGs) and aerosols from fires are important climate forcing factors, which make the emission estimation due to fire essential for climate modelling and global carbon cycle. Fires are also a major factor in land cover changes, species replacement, and hence affect fluxes of energy and water between the land surface and the atmosphere. Societal implications like air quality, forest management policies, and potential habitat and infrastructure damage are also a growing concern at the national or regional level.

Fire disturbance has been identified as Essential Climate Variable (ECV) by the Global Climate Observing System (GCOS) programme (GCOS 2006, 2011, 2016)[1]. An ECV is a physical, chemical or biological variable that critically contributes to the characterisation of Earth's climate and that can, from a feasibility perspective, be globally observed or derived with current observing systems (Bojinski et al. 2014). For each ECV, GCOS has defined target requirements. These target requirements specify the primary variable(s) to be included in the ECV satellite products and provide detailed specifications on the required accuracy, spatial and temporal resolution and other characteristics (GCOS 2006, 2011, 2016).

Long term, high-quality and traceable ECV data records are essential to advance evidence-based climate research, monitoring and services. To address this need, the European Space Agency (ESA) launched the Climate Change Initiative (CCI) Programme in 2009. The aim is to provide satellite-based climate data records (CDRs) for 13 individual ECVs of which "Fire Disturbance" is one.

GCOS (2010a) states that "Burned area, active fire detection, and Fire Radiative Power datasets together form the Fire Disturbance ECV, (…)". Burned area, as derived from satellites, is considered as the primary variable that requires climate-standard continuity while active fire and Fire Radiative Power are considered as supplementary variables (GCOS, 2011). When combined with burned area, the supplementary variables support quantifications of fuel consumption (and thus carbon release) and fire emissions.

For each ECV, an individual CCI project was launched. The early task for every project was an ECV-specific assessment of the requirements of climate scientists and other users for satellite based CDRs (Hollmann et al. 2013). The results of the assessment conducted during the first Phase of the Fire_cci project (2010 to 2014) are formulated in the User Requirements Document (URD), released in 2011 (Schultz et al. 2011). The results are further synthesized in the peer-reviewed paper of Mouillot et al. (2014).

[1] GCOS is an internationally coordinated network of observing systems and a programme of activities that support and improve this network. It is designed to meet evolving national and international requirements for climate observations. GCOS was established in 1992 as an outcome of the Second World Climate Conference, and is, among others, sponsored by WMO, WMO and UNESCO. GCOS is intended to be a long-term, user-driven operational system capable of providing the comprehensive observations required for monitoring the climate system, detecting and attributing climate change, assessing impacts of, and supporting adaptation to, climate variability and change, application to national economic development, and research to improve understanding, modelling and prediction of the climate system (adapted from the GCOS brochure, available online at http://www.wmo.int/pages/prog/gcos/index.php?name=AboutGCOS, last accessed September 20, 2017).

Phase 1 of the Fire_cci project was completed in 2014. As one key achievement, a new global burned area dataset based on MERIS imagery was developed, validated, produced, assessed and finally publicly released (Chuvieco et al. 2016, Padilla et al. 2014a, 2015, Alonso-Canas and Chuvieco 2015). The Fire_cci MERIS burned area dataset version 3.1 comprised a pixel product at the full spatial resolution of the MERIS images (300 m at nadir) and a grid product at 0.5x0.5 degree spatial resolution. Both cover the years 2006 to 2008.

One of the first tasks of the on-going Phase 2 of the Fire_cci project (2015 to 2018) was to process the full MERIS full resolution (FRS) archive with the newest version of the algorithm. In July 2016, a new version (v4.1) of the Fire_cci MERIS burned area products was released, covering the period 2005 to 2011. Besides algorithmic and other improvements, the new version now provides an increased spatial resolution of the grid product (from 0.5 to 0.25 degree). In December 2017, a newly developed 250-m global MODIS product covering the period 2001 to 2016 is being released. During the current phase of the Fire_cci project, a small fire database for Africa based on Sentinel 1&2 and Proba-V data is also being processed and will be released soon. Furthermore, burned area algorithms for new Sentinel-3 sensors (OLCI and SLSTR) are also being developed. Finally, the uncertainty characterization of all burned area products will be improved and products will be subject to extensive validation.

To ensure that the products generated in in Fire_cci Phase 2 approach the actual user requirements, the URD needs to be regularly revisited and adapted to incorporate evolved user requirements and priorities This URD represents the third and final Phase 2 update of this document.

2.2. Purpose of the document

This User Requirements Document (URD) summarises the user's needs with respect to burned area and other fire disturbance products and the user's expectations on the intended use. The URD serves as the mandate or terms of reference for the design, development and realisation of Fire_cci products. As such, it forms the basis against which success of the products can be measured, and against which compliance can be objectively tested. It is the primary input for establishing the Product Specifications Document (PSD).

As specified in the statement of work of ESA CCI Phase 2 [AD-1], the update needs to capture significant changes in user requirements, evolved product specifications, changed satellite availability and the lessons learnt from Fire_cci Phase 1. The update also needs take into account recent GCOS updates, newly emerging priorities of international climate assessments and recently released global fire data sets as well as specific user requests related to Fire_cci products and activities.

2.3. Applicable Documents

[AD-1]	ESA Climate Change Initiative (CCI) Phase 2 Statement of Work, prepared by ESA Climate Office, Reference CCI-PRGM-EOPS-SW-12-0012, Issue 1.3, date of issue 24 March 2015, available at http://www.esa-fire-cci.org/webfm_send/828

3. Characteristics of global burned area products

The following section summarises the characteristics of available global burned area datasets and provides an overall background for the ESA Fire_cci project.

3.1. Global burned area products: overview

Table 1 summarises the specifications, sensors and algorithms of global, satellite-derived burned area products, which are currently under on-going development or production. Table 2 summarises global burned area products which were produced and released in the first decade of the 21st century and whose production has been discontinued.

Table 1: Overview of global burned area dataset from space-borne remote sensing with on-going production development and production status.
Products marked with * are pre-operational, # provisional and $ not yet released.

Name of burned area dataset	Time span	Sensor/Method	Spatial resolution g=grid p=pixel	Temporal resolution DoB=day of burn	Development purpose	Reference
MERIS Fire_cci v4.1	2005-2011	Hybrid: MERIS reflectances guided by MODIS hotspots	p: 300m g: 0.25d	DoB; Biweekly in 0.25d product	To address GCOS ECV target requirements for climate and dynamic vegetation models	Alonso-Canas and Chuvieco (2015)
MODIS Fire_cci v5.0$	2001-2016	MODIS 250m reflectance guided by MODIS hotspots	p: 250m g: 0.25d	p: DoB; Biweekly in 0.25d product		t.b.d.
GFED4s	1997-present	Aug-2000 to present : MCD64A1 supplemented by small fire burned area (from scaled hotspots)	g: 0.25d	Monthly with scalars for daily and 3-hourly estimations	Atmospheric and bio-geochemical models; analysis of climatic control on fire; land management	van der Werf et al. (2017)
GFED4	1995-present	Aug-2000 to present : MCD64A1 before: scaled ATSR or VIRS hotspots	g: 0.25d	Monthly Daily (from Aug-2000)		Giglio et al. (2013)
MCD64A1 Collection 6	11/2000-present	Direct broadcast algorithm Hybrid: MODIS reflectances guided by MODIS hotspots	p: 500m	DoB	General purpose	Giglio et al. (2009)
GIO-GL1*	1999-present	SPOT VGT; from 04/2014 onwards: PROBA-V	p: 1km	10-day composite with DoB	GHG reporting	Tansey et al. (2008); Tansey et al. (in prep.)
GIO-GL1 300*	04/2014-present	PROBA-V	p: 300m			
BAECV	1984-2015	Landsat surface reflectance change algorithm	p: 30m [only Conterminous US]	16 days Annual summaries	Carbon cycling and climate research, resource and fire management	Hawbaker et al. (2017)
Fused-Landsat$	t.b.d.	Landsat-8 combined with Sentinel-2	p: 10–60m	~ 3 days	General purpose	Roy et al. (2016)
Fire_cci Small Fire Database$	2016	Sentinel-2 and Sentinel-1 data.	p: 20m	DoB	To address GCOS ECV target requirements for climate and dynamic vegetation models	t.b.d.

Table 2: Overview of global burned area datasets from space-borne remote sensing with completed product development and production status.

Name of burned area dataset	Time span	Sensor/Method	Spatial resolution g=grid p=pixel	Temporal resolution DoB=day of burn	Development purpose	Reference
MERIS Fire_cci v3.1	2006-2008	Hybrid: MERIS reflectances guided by MODIS hotspots	p: 300m g: 0.5d	Daily Biweekly	To address GCOS ECV target requirements for climate and dynamic vegetation models	Alonso-Canas and Chuvieco (2015)
GFED3	Jul 1996-Feb 2012	Aug-2000 to present : MCD64A1 before: scaled ATSR or VIRS hotspots	g: 0.5d	Monthly with scalars for daily and 3-hourly estimations	Large scale atmospheric and bio-geochemical models	Giglio et al. (2010)
GEOLAND2	2001-2012	SPOT VGT	p: 1km	10-day		Tansey et al. (2008)
L3JRC	2000-2007	SPOT VGT	p: 1km	DoB	General purpose	Tansey et al. (2008)
GBS	1982-1999	NOAA-AVHRR GAC 8 km data	p: 8km	Weekly, but publicly released product only as climatological fire seasonality map.	Historic records of global fire activity	Carmona-Moreno et al. (2005)
GLOBCARBON	1998-2007	SPOT VGT, ATSR-2, AATSR	p: 1km; g: 10km, 0.25d, 0.5d	p: DoB; g: monthly,	Global carbon cycling and climate models	Plummer et al. (2006)
GLOBSCAR	2000	ERS2-ATSR2	p:1km	DoB		Simon et al. (2004)
GBA2000	2000	SPOT VGT	p:1km, g:0.25d, 0.5d, 1d	Monthly		Tansey et al. (2004)
MCD45A1 V051	04/2000-01/2017	MODIS bi-directional reflectance (BRDF) temporal trends	p: 500m	DoB	General purpose	Roy et al. (2008)
MCD64A1 Collection 5	08/2000-12/2016	Direct broadcast algorithm Hybrid: MODIS reflectances guided by MODIS hotspots	p: 500m	DoB	General purpose	Giglio et al. (2009)

3.1.1. GFED4 and GFED4s

The Global Fire Emission Database (GFED) (van der Werf et al. 2004, 2006, 2010) provides global gridded time series of burned area, fuel consumption and biomass burning emissions. As such, GFED provides the longest global burned area dataset currently available. The latest GFED version, GFED4s, was released in May 2015[2]. The burned area component of GFED4s consists of the GFED4 burned area dataset described in Giglio et al. (2013) and the complementary estimates for burned area by "small" fires described van der Werf et al. (2017). The latter relies on an improved version of the approach described in Randerson et al. (2012).

The GFED4 burned area database provides global, 0.25 degree gridded burned area maps from mid-1995 to the present with monthly resolution. Starting from August 2000, i.e. with begin of the MODIS era, GFED4 burned area time series are also provided in daily temporal resolution. In the MODIS era, GFED4 burned area is built upon aggregated MCD64A1 data (see Section 3.1.2). For the pre-MODIS era, active fire observations from the TRMM VIRS and ERS ATSR sensors were used to estimate burned area, followed by a further correction to ensure consistency with MODIS data.

GFED4 burned area data are distributed in HDF file format via the ftp-server ftp://fuoco.geog.umd.edu. The monthly HDF-files contain seven layers providing an area burned estimate per grid cell and the corresponding uncertainty, the burned area data source and information on the tree density, land and peat cover distribution of the area burned, and on the fire persistence. The uncertainty layer contains an estimate of the one standard deviation (1 σ) uncertainty in monthly burned area. The daily HDF-files have, instead of fire persistence, a layer specifying the uncertainty in the date of burn.

The small fire database contained in GFED4s estimates the burned area from small fires, which fall below the detection limit of the MCD64A1 product. Small fire burned area is estimated by computing the burn ratio between the number of MODIS hotspots inside and outside of 500-m MCD64A1 burn scars (Randerson et al. 2012). Small fire burned area in the pre-MODIS era is estimated from VIRS and ATSR hotspots in an analogous approach. The inclusion of the small fire database increases burned area in GFED4s by around 35% (MODIS era) and 50% (pre-MODIS era), respectively, compared to GFED4.

3.1.2. MCD64A1 Collection 5.1

MCD64A1 refers to the global burned area product, which is generated from MODIS observations from Terra and Aqua using the direct broadcast (DB[3]) burned area mapping algorithm developed by Giglio et al. (2009). The hybrid algorithm combines multi-temporal changes detected in the MODIS 500 m surface reflectance bands with MODIS active fire detections, which are derived from the 1000 m thermal bands.

MCD64A1 Collection 5.1 is provided as monthly, 500 m gridded tiles in the standard MODIS land format, i.e. as HDF file. The files contain five data layers describing the approximate burn date, burn date uncertainty, first and last date of reliable change

[2] http://www.globalfiredata.org/data.html (last accessed December 2017).

[3] Direct broadcast (DB) refers to the capability of the MODIS instrument to immediately broadcast the raw data it collects to regional MODIS DB receiving stations. The DB option opens up the usability of the MODIS data for real-time forecasting and environmental decision making. (http://modis.gsfc.nasa.gov/data/; last accessed August 15, 2016).

detection and a layer containing a categorical quality assessment (QA) indicator[4]. The production of MCD64A1 Collection 5.1 has been ceased in December 2016 due to being superseded by MCD64A1 Collection 6 (see Section 3.1.3). Monthly MCD64A1 tiles are available from the ftp-server of the University of Maryland (via ftp://user:burnt_data@ba1.geog.umd.edu/Collection51/, last accessed November 30, 2017). The MCD64A1 is the basis for burned area estimation included in GFEDv4 (Section 0) for the period 2000 to 2016.

3.1.3. MCD64A1 Collection 6

Similar to its predecessor version, MCD64A1 Collection 5.1 (see Section 3.1.2), the MCD64A1 Collection 6 released in 2017 is a MODIS/Terra+Aqua Direct Broadcast burned area product using the hybrid algorithm developed by Giglio et al. (2009), with some improvements in terms of (a) the algorithm, (b) the use of Collection 6 (versus Collection 5) surface reflectance and active fire input data, and (c) an expanded product spatial coverage. These improvements lead to a reduction in omission errors including a significantly enhanced detection of small burns. They also reduced the uncertainty in the detected date of burn as well as the occurrence of unclassified grid cells (Giglio et al. 2016). The MCD64A1 Collection 6 product is available with a latency[5] of three months from ftp://user@ba1.geog.umd.edu/ Collection6/ (last accessed October 30, 2017).

3.1.4. MCD45A1

MCD45A1 refers to the global monthly, 500m gridded burned area product, which is generated from MODIS observations using an algorithm based on a bi-directional reflectance change detection approach (Roy et al. 2008). This BRDF[6] algorithm is applied on daily 500 m MODIS observations from Terra and Aqua. Before being replaced by MCD64A1 Collection 6, MCD45A1 was frequently denoted as the MODIS "standard" burned area mapping algorithm.

MCD45A1 Science Data Sets (SDS) product is provided as monthly, 500 m gridded tiles in the standard MODIS land format, i.e. as HDF file. The files contain ten layers defining for each 500m pixel the approximate date of burning within a 16-day temporal window, number of observations used in the temporal consistency test and number of which that passed, the largest and second largest number of consecutive missing/cloudy days, the direction in time of burn detection, a layer containing a categorical quality assessment (QA) indicators[4], and surface properties (water, cloud, low NDVI, cloud shadow, high view and solar zenith angle).

MCD45A1 V051 SDS data are available for ordering from the Land Processes Distributed Active Archive Center (LP-DAAC) via http://reverb.echo.nasa.gov (last accessed November 30, 2017). In addition, they are distributed via ftp://user:burnt_data@ba1.geog.umd.edu/Collection51/ (last accessed November 30, 2017) where there are also available in GeoTIFF and Shapefile formats to enhance product usability among broad, interdisciplinary user communities.

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[4] QA gives flags reflecting the confidence of the detection (1= most confident to 4= least confident; 5= detections over agricultural area).

[5] Latency refers to the time delay that the product is produced (and/or publically distributed) beyond real time.

[6] BRDF refers to Bidirectional Reflectance Distribution Function.

MCD45A1 burned area production has been ceased by January 2017 as it is superseded by the Collection 6 MCD64A1 "Direct Broadcast" monthly burned area product.

3.1.5. MERIS Fire_cci v3.1 and v4.1

Guided by the specific requirements of a wide range of end users, the ESA Fire_cci project computed a new global burned area dataset. A new burned area detection algorithm has been developed specifically for the ENVISAT-MERIS sensor. The algorithm combines temporal changes in near infrared (NIR) MERIS corrected reflectances with active fire detections from the standard MODIS thermal anomalies product, following a two-phase algorithm (Alonso-Canas and Chuvieco 2015).

A first version of the global burned area product was released in 2014. Fire_cci version 3.1 covered the period 2006 to 2008 and comprised a pixel burned area product (spatial resolution of approx. 300 m) with date of detection, uncertainty and land cover information. It also included a biweekly grid product at 0.5 degree spatial resolution with 21 auxiliary layers. The product was successfully used for different climate modelling exercises (Chuvieco et al. 2016).

A second version of the Fire_cci burned area product was released in July 2016[7]. In Fire_cci version 4.1, an improved algorithm was applied to compute the time series covering the period 2005-2011. In addition, the spatial resolution of the grid product was increased to 0.25 degree.

Validation of the released Fire_cci product was derived from multi-temporal pairs of Landsat images, following CEOS Cal-Val guidelines. These reference data were generated for the year 2008, selecting the 105 sites from a stratified random sample (see Padilla et al. 2014a, 2015).

3.1.6. MODIS Fire_cci v5.0

A new BA product has been recently released (December 2017) from the Fire_cci project. The product is named MODIS Fire_cci v5.0 and it has been developed by adapting the Fire_cci v4.1 algorithm (Section 3.1.5) to the MODIS 250 m VNIR channels. The global time series of this product covers the period from 2001 to 2016. The product specifications in terms of layers and resolution are basically the same as the Fire_cci v4.1 product. The major exception is a higher spatial resolution of the pixel product (250m versus 300m).

3.1.7. Copernicus Global Land Service burned area product (GIO-GL1[8])

The Copernicus Global Land Service provides global burned area time series from April 1999 to present[9]. This pre-operational service (as of November 2017) uses information from SPOT-VGT (before April 2014) and PROBA-V (from April 2014 onwards). The algorithm basically relies on the L3JRC algorithm described in Tansey et al. (2008), which consist of direct mapping approach that makes use of a temporal index in the near infrared (NIR) channel.

The GIO-GL1 burned area products are distributed via the Copernicus Global Land Service (http://land.copernicus.eu/global/, last accessed November 20, 2017) as two collections: (1) “Burned Area 1km V1” with 1 km spatial resolution and, since April

[7] https://geogra.uah.es/fire_cci/ (last accessed December 12, 2017).
[8] Sometimes also denoted as C-GLOPS.
[9] http://land.copernicus.eu/global/products/ba (last accessed September 20, 2017).

2016, also the (2) "Burned Area 300m V1" collection, i.e. with 300 m spatial resolution. The latter, however, is only produced from PROBA-V available from April 2014.

The GIO-GL1 burned area products are delivered spatially tiled, 10-day composites HDF5 and files contain the day of burn information. The near-real time product is available within 3 days after end of synthesis period. The products have been subject to quality assessments (Tansey and Padilla 2014, Tansey and Arellano 2015).

The accuracy of the PROBA-V burned area generally shows a good performance with global burned area values approximately similar to MODIS burned area. In contrast, the burned area relying on SPOT-VGT exhibited poor accuracy, with commission errors in the northern latitudes in winter and a high probability of omission errors[10].

3.1.8. BAECV

In mid-2017, the U.S. Geological Survey (USGS) has released 30 m spatially resolved annual burned area time series for the years 1984 to 2015 for the conterminous United States, the so-called Burned Area Essential Climate Variable (BAECV) product[11]. The time series rely on imagery from the Landsat archive. The BAECV algorithm was designed to semi-automatically extract burned areas from Landsat scenes "using spatial contagion metrics and region-growing approaches to incorporate the spatial patterns of spectral reflectance among neighbouring pixels, in addition to the pixel-level spectral data to identify burned areas" (Hawbaker et al. 2017). The algorithm creates seasonal summaries for the reflective bands and applies these summaries in the scene-based probability mapping using a gradient boosting tree to predict the probability that any pixel is burned. The boosted regression code allows the model to be trained. The final step consists of applying thresholds to the probability mappings to classify the burned pixels (Hawbaker et al. 2017).

The Landsat archive dates back to 1972 and provides a potential basis for the creation of global high spatial resolution (30 meter) burned area maps. The source code for producing the burned area products from Landsat TM and ETM+ data has been released to the public in March 2016 on https://github.com/USGS-EROS/espa-burned-area (last accessed November 30, 2017), allowing users to produce BAECV burned area time series for other regions of the world.

The validation of the BAECV product over conterminous US was done by comparison with (a) an independent Landsat burned area dataset created primarily by visual interpretation of selected Landsat imagery (VanderHoof et al. 2017a) and (b) burned area processed from 286 high-resolution images collected by QuickBird-2, Worldview-2, GeoEye-1 and RapidEye from DigitalGlobe and Planet (VanderHoof et al, 2017b). VanderHoof et al. (2017a) found for (a) that "BAECV errors of omission and commission for the detection of burned pixels averaged 42% and 33% [...]. Errors of omission and commission were lowest across the western CONUS, for example in the shrub and scrublands of the Arid West (31% and 24%, respectively), and highest in the grasslands and agricultural lands of the Great Plains in central CONUS (62% and 57%, respectively). The BAECV product detected most (> 65%) fire events > 10 ha across the western CONUS". When validating BAECV against (b), VanderHoof et al. (2017b) found that " Errors of omission and commission for burned area averaged 22 ± 4% and

[10] See http://land.copernicus.eu/global/products/ba?qt-ba_characteristics=5#qt-ba_characteristics (last accessed September 20, 2017).
[11] http://remotesensing.usgs.gov/ecv/BA_overview.php (last accessed November 30, 2017)

48 ± 3%, respectively, across CONUS. Errors were lowest across the western U.S. The elevated error of commission relative to omission was largely driven by patterns in the Great Plains which saw low errors of omission (13 ± 13%) but high errors of commission (70 ± 5%)[...]. While the BAECV reliably detected agricultural fires in the Great Plains, it frequently mapped tilled areas or areas with low vegetation as burned."

The BAECV product is provided as annual composites in GeoTIFF raster format containing two raster data layers: (1) a continuous burn probability, and (2) a binary burn classification.[12].

While the Landsat-based BAECV burned area product has much finer spatial resolution than stated in the GCOS target requirements, the product will fail to globally meet the GCOS requirements for temporal resolution due to Landsat’s low revisit interval (~ 16 days), coverage gaps, and cloud cover (Stitt et al. 2011).

3.1.9. Fused Landsat burned area product (only prototype)

Boschetti et al. (2015) developed a methodology to fuse multi-temporal Landsat Enhanced Thematic Mapper plus (ETM+) data with 1 km MODIS active fire detections to map systematically burned areas at 30 m resolution. The fusion aims at overcoming the limitations of the 16 day Landsat temporal resolution. The methodology has been applied over the Western United States and evaluated by comparison with the Monitoring Trends in Burn Severity (MTBS) burned area perimeters that were mapped from manually interpreted Landsat images. They are currently prototyping a combined Landsat-8 and Sentinel-2 product which will allow for global mapping of burned area at 10 to 60 m spatial resolution up to every 3 days (Roy et al. 2016).

3.1.10. GFED3

GFED3, described in Giglio et al. (2010), is the predecessor version of the burned area dataset underlying the Global Fire Emission Database version 4 (GFED4) (see Section 0). The global, 0.5 degree gridded GFED3 burned area data were first released in 2010 as monthly time series starting from 1996. The time series were subsequently updated until February 2012. GFED3 burned area data are distributed as ASCII and HDF files via the ftp-server ftp://fuoco.geog.umd.edu. The HDF-files contain seven layers providing an area burned estimate per grid cell and the corresponding uncertainty, the burned area data source and information on the tree density, land and peat cover distribution of the area burned, and on the fire persistence.

In the MODIS era, there are two main differences between GFED3 and GFED4 burned area versions in addition to the different resolutions: Firstly, while GFED4 relies only on direct mapping burned area, GFED3 burned area is partially estimated from scaling active fire data[13]. Secondly, collection 5.1 of MCD64A1 was used in GFED4 instead of v5.0 in GFED3. Compared to GFED3, GFED4 has partly reduced commission errors and is less affected by the unintentional removal of small agricultural burns and the systematic omission errors in the tropics. Overall, however, the difference in global burned between GFED3 and GFED4 during the overlapping MODIS era time series is small: in terms of the time integral, GFED3 burned area is 0.8% higher than in GFED4.

[12] see https://remotesensing.usgs.gov/ecv/BA_dps.php (last accessed November 30, 2017).

[13] Of the total GFED3 burned area (August 2000 to December 2012), 92 % is derived with from direct mapping and 8 % from scaled hotspots.

3.1.11. Geoland2 burned area product

The Geoland2 burned area product is a further development of the burned area products generated by the Global Burned Area (GBA2000) and L3JRC projects. It relies on burned area directly mapped from SPOT-VGT with the L3JRC algorithm (Tansey et al. 2008), aggregated into a ten-day product with near-real-time dissemination for application on the global scale. The Geoland2 product improves precursor products by including data outside the primary fire season, shortening the preprocessing steps, improving the land-water mask and providing additional years than those available for the previous L3JRC product.

However, global burned area products mapped from SPOT-VGT with the L3JRC algorithm exhibit poor accuracy, with commission errors in the northern latitudes in winter and a high probability of omission errors (Tansey and Padilla 2014[14]). Ruiz et al. (2014), for example, showed that Geoland2 product leads to a five-fold overestimation of burned area in North American Boreal Forest compared to reference data from the forest services. The Geoland2 project ended in 2012 and the access to the Geoland2 burned area product via geoland2 portal[15] has been inactivated. The knowledge gained throughout the Geoland2 burned area project flows into the Copernicus GIO-GL1 burned area product development (see Section 3.1.7).

3.1.12. L3JRC

L3JRC is a global burned area dataset with 1 km spatial resolution covering the period April 2000–March 2007 (Tansey et al. 2008). The product was generated from SPOT VEGETATION (VGT) data by applying a set of regional algorithms based on the previous experience of the GBA2000 product (Tansey et al. 2004). The product is provided as annual GeoTIFF and ASCII files that contain the Julian day at which the burn scar was detected for the first time. The product, which was released in 2008, can be downloaded from http://forobs.jrc.ec.europa.eu/products/burnt_areas_L3JRC/GlobalBurntAreas2000-2007.php (last accessed September 20, 2017). No update to this provisional product release has been made available.

3.1.13. GBS

The Global Burned Surfaces (GBS) dataset was generated from daily, reduced resolution (8 km) NOAA-AVHRR images of the years 1982 to 1999 by applying a multi-temporal multi-threshold change detection algorithms described in Carmona-Moreno et al. (2005). Because of availability and calibration problems of the AVHRR records and omission errors related to the coarse resolution, GBS dataset was approved to be suitable only for qualitative studies. For these reasons, only the derived climatological fire seasonality map with was released in 2006. The GeoTIFF map describes the probability for each 8 km pixel to burn in a given season, with reference to the 1982 to 1999 mean. The GBS seasonality dataset can be downloaded from http://forobs.jrc.ec.europa.eu/products/fire_probability_82-99/global-prob_82-99.php (last accessed September 20, 2017).

[14] see also http://land.copernicus.eu/global/products/ba?qt-ba_characteristics=5#qt-ba_characteristics (last accessed September 20, 2017).

[15] geoland2 Expert Portal http://www.geoland2.eu (inactivated as of August 26, 2016).

3.1.14. Globcarbon

The Globcarbon burned area product was developed by an ESA initiative to provide targeted, long-term, suited land products that can be readily merged into earth system models (Plummer et al. 2006). The fire product builds on the methods and experiences that were developed and gathered during the GLOBSCAR and GBA2000 projects (see Section 3.1.15). Global burned area data were produced by applying two regional GBA2000 algorithms on the 1-km SPOT VEGETATION data, and the GLOBSCAR algorithms on ERS2–ATSR2 and ENVISAT AATSR data. The Globcarbon product covers the period 1998 to 2007 and consists of monthly ASCII files containing burned area estimates at different spatial resolutions (1 and 10 km, 0.25 and 0.5°). Burned area estimates in the 1-km resolution product are provided as a list of the coordinates of all pixels that were detected as a burnt, complemented by information on the date of burn, and the type of sensor and algorithm underlying the burn detection. The product also includes the estimation of different sensors-algorithm combinations, as well as a combination of some of them by union and intersection. Burned area estimates in the lower resolution products are provided as proportion of burnt pixels per grid cell, complemented by a layer reflecting the spatial dispersion of the burnt pixels within the cell.

The latest version of the Globcarbon product, version 2, was released in 2008 and distributed via a web-portal (Arino et al. 2008b). This web-portal has been inactivated in the meantime so that the Globcarbon burned area products are no longer publically accessible.

3.1.15. GLOBSCAR and GBA2000

These two European projects pioneered the development of global burned area algorithms for European sensors in the early 2000s.

The GLOBSCAR burned area product (Simon et al. 2004) was generated from daytime ERS-2 ATSR-2 data with a nominal pixel size of 1 km^2 to produce global monthly maps of burned area for the year 2000. Burned area detection relied on the combination of a contextual and a fixed threshold algorithm. GLOBSCAR was produced as ASCII files containing the coordinates of all pixels, which were detected as a burnt, including information on the date of burn. In addition, files in vector Shapefile format were produced. The product was released in 2002 and distributed via web download. The official download site, however, has been inactivated in the meantime so that the GLOBSCAR products are no longer publically accessible.

The GBA2000 (Global burned area 2000) product, described in Tansey et al. (2004), provides monthly estimates of areas burnt at a global scale for the year 2000. The GBA2000 was generated by applying seven regional algorithms on 10-day composite SPOT-VEGETATION images with a nominal pixel size of 1 km^2. The final version of the GBA2000 product was released in December 2002 and is still accessible online via http://forobs.jrc.ec.europa.eu/products/burnt_areas_gba2000/ global2000.php (last accessed September 20, 2017). The GBA200 product is distributed of monthly ASCII-files of (a) the coordinates of all pixels that were detected as burnt and (b) spatial aggregates (0.25, 0.5 and 1.0 degree). The gridded aggregates provide the total number and the percentage burned in each grid cell. All ASCII files are also provided as Binary files (BSQ format in geographic projection).

Experiences from these GLOBSCAR and GBA2000 projects were later used for the Globcarbon and L3JRC projects.

3.2. Accuracy characteristics of global burned area products

Knowledge on accuracy characteristics of burned area products can be obtained from product validation. Hollmann et al. (2013) defined that "Validation is the comparison of the satellite ECV products with validation data, in order to be able to make statements about the quality of the products. For a CDR, validation includes but goes beyond the calculation of comparison statistics between satellite ECV and the validation data. Such statistics provide information about the accuracy (biases) and precision (scatter) in products." The Committee on Earth Observing Satellites (CEOS) Working Group on Calibration and Validation (WGCV) defines validation as “the process of assessing by independent means the quality of the data products derived from the system outputs” (Justice et al. 2000).

The accuracy of the burned area data is considered as one of its cardinal attributes. Accuracy assessment is always indispensable in data production. In the literature, this accuracy assessment process frequently goes under the name of ‘calibration’, ‘data validation’, ‘accuracy evaluation’, ‘accuracy assessment’ or ‘quality assessment’. Some datasets passed through a thorough accuracy assessment, i.e., spatially explicit quantitative analysis is conducted and commission/omission errors are provided, while for other datasets there are only qualitative statements about data quality provided.

The MCD45A1 and the MCD64A1 Collection 5.1 products have been validated through comparison with high-resolution Landsat imagery (Giglio et al. 2009, Padilla et al. 2014a). While MCD45A1 was validated using around 100 Landsat image pairs selected with probability sampling (Padilla et al. 2014a), validation of MCD64A1 Collection 5.1 is limited to Southern Africa, Siberia, and the western conterminous United States and Florida and uses less than 30 Landsat image pairs (Giglio et al. 2009). The comparison of existing global burned area products for 2008 (MCD45A1, MCD64A1 Collection 5.1, MERIS Fire_cci v3.1, Geoland2) using a statistically designed sample selected the MCD64A1 Collection 5.1 product as the most accurate (Padilla et al., 2015).

From the analysis of global MCD45A1 data of the year 2008 against reference burned area from 102 Landsat images, Padilla et al. (2014a) showed that the overall accuracy (OA) exceeds 97% for all biomes and is 99.7% globally. The accuracy results are less favourable for the burned class. They showed that the MCD45A1 product has estimated commission and omission error rates of 46% and 72% respectively. Commission and omission errors, however, are strongly dependent upon biomes. Compared to the reference data, MCD45A1 detected only 48% of the burned area.

For the MERIS Fire_cci v3.1 burned area product, Padilla et al. (2015) found an overall accuracy on a global scale for the year 2006 of 97%, but with a commission and omission error for the burned class of 64 and 76%, respectively, and a relative bias of -34%. It should be emphasized that errors found in the global burned area products are expected to be high when compared to medium-resolution (Landsat) information, due to the capability of Landsat images to detect small fires that cannot be detected with coarser resolution sensors.

Evaluation of global burned area datasets by comparisons with high resolution burned area datasets highlight their limitations to characterize small fires (Sa et al. 2007), with a threshold of 105 ha for Hawbaker et al. (2008) or 120 ha for Giglio et al. (2009), or low intensity fires, which are frequent in shifting cultivation (Miettinen et al. 2007) or shrubland fires (De Klerk 2008).

Omission and commission errors have been requested early in the burned area product development process (Korontzi et al. 2004) and remain a key variable to account for. For example, spatial accuracy of existing regional burned area products typically range between 70 % and 80% (Kushida et al. 2010, Diagne et al. 2010, Loboda et al. 2007). However, accuracy can fall down to 40% in some biomes (Giglio et al. 2009) or when using coarser resolution sensors (such as NOAA-AVHRR).

Padilla et al. (2015) compared the accuracies of remote sensing global burned area products using stratified random sampling and estimation for 2008 data. While overall accuracy exceeded 99% for all products, burned class accuracy was lower. Burned area commission error ratio was above 40% for all products and omission error ratio was above 65% for all products. Compared to MODIS burned area products, the MERIS Fire_cci v3.1 global burned area estimations exhibited higher errors, but were found better balanced, with less underestimation than those products (but still close to 35%).

As stated by Libonati et al. (2015), the development of an accurate algorithm to detect surface changes caused by fire at the global scale is still hampered by the complexity, diversity, and large number of biomes involved.

Libonati et al. (2015) validated MODIS burned area products over the Brazilian cerrado region with burned area perimeters derived from Landsat imagery. Following the approach developed by Padilla et al. (2014a), the error matrix assumes mixed pixels and the agreement/disagreement between product and reference is computed considering the proportion of burned area from the reference data within the product pixel. The study region covers about 35,000 km^2 and reference maps of burned scars were produced for selected months of the years 2005 to 2010. Libonati et al. (2015) found omission errors in both products were about 8 to 9 times higher than their commission errors (Figure 1). Omission and commission errors were on average roughly 20% higher in the MCD64A1 Collection 5.1 than in the MCD45A1 product. Averaged over 6 years, the omission error was 70% in the MCD64A1 Collection 5.1 product (range of yearly omission errors of 57 to 87%) and 58% (range 22 to 81%) in the MCD45A1 product. Commission errors in both products were on average 6 to 8%, with individual annual values ranging between 2 and 18%. Figure 1 illustrates the inherent strong interannual variability in the individual accuracy measures. Libonati et al. (2015) found that omission errors were largely related to small scars (fires below 100 ha), which could not be detected by the coarse resolution (500 m) of the MCD45A1 and MCD64A1 sensor data. Such small scars contributed around 85% to the total number of fire scars in the study region while large scars (>1000 ha) were rare (close to 1%).

Also Mohler and Goodin (2012) provide evidence of the limited use of MODIS 500 m spatial resolution imagery for mapping burned area in biomes dominated by small fires. Mohler and Goodin (2012) tested a suitable mapping method for burned area in tallgrass prairie in North America by comparing the efficacy of seven combinations of bands and indices from the MODIS sensor using both pixel and object-based classification methods. They showed that that the coarser 500 m spatial resolution bands showed very low performance in mapping the typically tallgrass prairie fires which severely limits their utility. They also showed that scenarios based on the 250 m spatial resolution red and NIR bands outperformed those based on the coarser 500 m spatial resolution bands. The Mohler and Goodin (2012) analysis suggests that 250 m is the minimum spatial resolution that should be used for burned area mapping in tallgrass prairie fires.

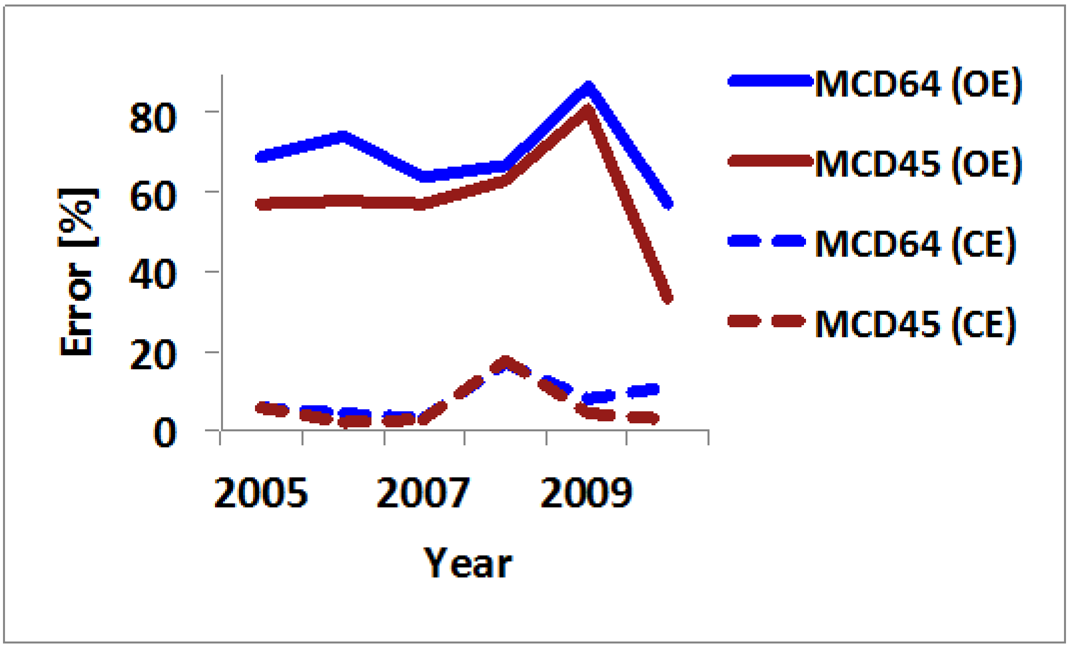

Figure 1: Omission errors (OE) and commission errors (CE) determined for individual years for the MODIS MCD45A1 ("MCD45") and MCD64A1 Collection 5.1 ("MCD64") burned area products for a study region in the Brazilian cerrado (adapted from Libonati et al. 2015).

3.3. Summary of global burned area product characteristics

The mainstream characteristics of the current state-of-the-art global burned area products are:

- Global burned area time series covering up to 15 – 20 years of data. Prior 2000, the time series are derived from scaled active fire data, and not from direct mapping using reflectance change information. Longer time-series of directly mapped burned area using Landsat imagery are currently under development.
- 300, 500 or 1000 m ground resolution of the underlying sensor. Products using sensors with higher spatial resolution (up to 30 m) are currently prototyped.
- Globally gridded product aggregated to 0.25 degree spatial resolution.
- All gridded global burned area products have monthly temporal resolution, except for the biweekly resolution in Fire_cci products. Ancillary products allowing scaling to daily resolution are becoming more common in recent product releases.
- Ancillary layers on vegetation type burned contained in most products.
- Pixel products are provided with day of burn, some of them with complementary uncertainty information layers on the date of burn detection.
- Pronounced omission errors due to method of intercomparison.
- GCOS-154 accuracy requirements currently not met by any global burned area product, as they are target requirements and hence should be challenging.
- Most products suffer from an immature uncertainty and error quantification.
- Most products are made accessible in HDF, NetCDF or GeoTIFF formats via web-transfer (wget, FTP).

4. Applications of burned area products

4.1. A literature review on burned product applications

The following section describes the main uses of burned area products and tries to summarize their requirements in terms of temporal, spatial and thematic characteristics based on identified gaps and failures.

4.1.1. Air quality and atmospheric chemistry modelling

The major application of burned area products in atmospheric chemistry in the context of climate research is the characterisation of fire emission fluxes. Since the early work by Radke et al. (1978), Crutzen et al. (1979) and Seiler and Crutzen (1980) the interest in and recognition of biomass burning as major emission source for trace gases and aerosols has gradually increased to become an important research focus nowadays (Andreae and Merlet 2001, Akagi et al. 2011). Seiler and Crutzen (1980) provided a first estimate of global biomass burning emissions using the following bottom-up approach:

$$M_i = A * AFL * BE * EF_i$$

where **Mi** is the emission of compound **i** (g m^{-2}), **A** is the area burned (m^2), **AFL** is the available fuel dry load (g m^{-2}), **BE** is the burning efficiency, and **EF**$_i$ is the emission factor of compound **i** ($g_i \cdot g^{-1}$).

The underlying burned area data (A) were traditionally derived from burned area information contained in national forest fire assessments (e.g. FAO 2001). However, these assessments were missing for many countries of the world, most notably those in the tropics, and generally did not cover more than 10 years. Furthermore, in many countries, only fires in forested areas are entered in their national fire database; as a result, fires in non-forested areas (e.g. crop-, grass- or shrubland) remain unreported (FAO 2006).

From the 1990’s onwards, atmospheric chemistry studies started to exploit active fire counts provided by satellites to create spatially and temporally resolved fire emissions estimates on a regional to global scale. Emission estimates that rely on fire counts are far less reliable than approaches that are based on burned area maps (Eva and Lambin 1998). Nevertheless, the temporally and spatially resolved fire (“or hotspot”) count products were used as a proxy for burned area because corresponding burned area maps were not yet available by then.

The first global studies in the early 2000s used hotspot information to distribute aggregated best-guess estimates of biomass burning emissions in time and space (Schultz 2002, Generoso et al. 2003, Duncan et al. 2003). The first atmospheric chemistry model studies that appeared took advantage of these new temporally and spatially resolved fire emissions estimates (Chin et al. 2002, Chandra et al. 2002, Martin et al. 2002). Since then, it has become a de-facto standard in atmospheric chemistry models to use biomass burning inventories derived from remote sensing to prescribe trace gas emission fluxes.

In the following years, research activities focussed on approaches to scale hotspot counts to burned area. Burned area was then used to calculate emission fluxes using the Seiler and Crutzen (1980) approach. For example, in the first and second version of the Global Fire Emission Database (GFED) (v1: van der Werf et al. 2003, 2004; v2: van der

Werf et al. 2006), VIRS and ATSR or MODIS hotspot counts were multiplied with scaling factors to obtain global burned area estimates. The scaling factors basically relied on linear regression statistics conducted between hotspot counts and MODIS burned area information available for a limited number of MODIS tiles. The burned area estimates, combined spatially explicit of AFL and BE values from biogeochemical model, are then used to calculate fire emission fluxes.

GFED version 3, released in 2010 (van der Werf et al. 2010), provided the first longer term fire emission inventory (period 1997 – 2009, later expanded to 1996 – 2012) which, to a large part, relies on satellite-derived burned area maps: 92% of the global area burned during the MODIS era (2001 onwards) is directly derived from MODIS burned area maps (Giglio et al. 2010). New versions of GFED, version 4 and 4s, have been released (v4: Giglio et al. 2013, v4s: van der Werf et al. 2017). GFED is widely used in atmospheric chemistry modelling studies to constrain emission fluxes (e.g. v3: Chevallier et al. 2014, Jiang et al. 2015; v4: Berchet et al. 2015, Bauwens et al. 2016, v4s: Bauwens et al. 2016), to study individual air pollution events or transboundary air pollution (e.g. v3: Krol et al. 2013, Aouizerats et al. 2015, v4/v4s: Knorr et al. 2017), or to perform source apportionment analysis (e.g. v1/2: Stravrakou et al. 2009, v3: Chen et al. 2013, v4s: Winiger et al. 2016).

In order to study the impact that climate change-related alterations in wildfire activity and emission rates would have on ozone air quality in North America, Yue et al. (2015) compiled monthly 1x1 degree gridded area burned from 1980 to 2009 for the North American region from interagency fire reports, since satellite burned area products with similar length and accuracy are not yet available.

Future burned area was estimated using the simulated A1B scenario meteorology from 13 climate models under the A1B scenario. Ecoregion-dependent regressions derived from the relationships between the observed annual total area burned and a suite of observed fire weather indices were applied to the simulated meteorology. By this approach, Yue et al. (2015) compiled gridded monthly time series for the mid-21th century. From the gridded area burned data, spatiotemporally resolved fire emissions were calculated. The impact of those emissions on ozone mixing ratios at the mid-21th century was then predicted using the GEOS-Chem chemical transport model (CTM) driven by a general circulation model (GCM).

The dramatic increase in computer power during the last decade enables numerical weather prediction and meteorological modelling at high spatial resolutions (e.g. a few km) and with closely coupled (online or offline) atmospheric chemical transport models (CTM) (Baklanov et al. 2014). Grell et al. (2011), for example, showed that the inclusion of biomass burning emissions into the online coupled regional meteorology chemistry model WRF-Chem had significant impact on weather forecasting because the emissions strongly influenced precipitation and other meteorological quantities. The model study was conducted using model resolutions of 10 km and 2 km and focussed on the 2004 Alaska wildfires. Regionally applied chemical weather prediction models have high demands for accurate fire emission information with high spatial (optimally ~1 km) and temporal (optimally ~ 1 hour) resolution. If used for near-time forecasting, prompt data availability is an additional requirement. As part of CAMS, seven state-of the-art regional air quality models are run daily for the European region (Kukkonen et al. 2012, Marecal et al. 2015). These regional forecast ensemble simulations are routinely performed with a horizontal resolution of 10–20 km, which is well suited to capture the characteristics of air pollution events (Zyryanov et al. 2012).

Finally, as the representation of core processes in atmospheric chemistry model continuously improves, uncertainties in the fire emissions input data – and thus the underlying burned area / hotspot / fire radiative power data – are gaining more importance as predictive constraint. Davis et al. (2015) demonstrated that the uncertainty in input emissions may influence the concentrations predicted by a smoke dispersion model to the same degree as the model's inherent uncertainty due to turbulence.

4.1.2. Coupled chemistry-climate modelling

Since the past decade, researchers are also increasingly using coupled chemistry climate models to investigate the complex interactions between atmospheric chemistry and the climate system on centennial scales (Isaksen et al. 2009, Lamarque et al. 2013, Migliavacca et al. 2013).

Long-term emission estimates from biomass burning and other anthropogenic or natural processes are a key input to these models. Responding to these demands, historical reconstructions of burned area have been compiled, from which gridded, multi-decadal to centennial emission inventories were calculated. These reconstructions typically merge satellite observations of burned area and fire activity, where available, with official fire statistics and extrapolations approaches (Mouillot and Field 2005, Schultz et al. 2008, Mieville et al. 2010, Lamarque et al. 2010).

As an input to the coupled model intercomparison project phase 6 (CMIP6) simulations, a new global fire emission inventory, called BB4CMIP6, has been created and published on the public input4MIPS (input datasets for Model Intercomparison Projects) portal[16] in July 2016. The CMIP6 simulations are expected to support the IPCC Sixth Assessment Report (AR6) as well as other climate assessments (Eyring et al. 2016). The BB4CMIP6 emission inventory is 0.25 degree horizontally gridded covers the period 1750 to 2015 with monthly time steps. BB4CMIP6 has been compiled from combining GFED4s fire emissions with regional proxy observations (charcoal records, visibility observations) and FireMIP model results. The latter comprises simulations with several dynamic global vegetation models (DGVMs) that were coupled with empirical fire or process-based submodels. The simulations are used to estimate burned area and fuel consumption for periods for which no observations of fire activity are available. For benchmarking, FireMIP models require multiple global burned area products (e.g. GFED4, L3JRC, MCD45, and Fire_cci) (Hantson et al. 2016) (see 4.1.4).

In summary, fire emission reconstructions used as boundary condition input of chemistry climate models require global satellite burned area data for (a) direct emission calculation ("GFED approach", see 4.1.1) or (b) for benchmarking DGVM models that are used for emission estimation beyond the satellite fire era. Both applications strongly benefit from an extended temporal coverage and temporal and spatial consistency of global burned area satellite products, while the requirements with respect to spatial and temporal resolutions are low (0.25° spatial and monthly temporal resolution).

4.1.3. Biogeochemical modelling

The estimation of biomass burned by fires has been sometimes approached from spatially explicit vegetation models that simulate plant carbon assimilation and

[16] https://pcmdi.llnl.gov/projects/input4mips/ (last accessed August 12, 2016).

respiration, estimating biomass and litter loads, their water status and the subsequent dynamic and post-disturbance effects. Until the end of the 1990's, major efforts were focused on conceptualising models able to simulate the seasonal and inter-annual variations of these fluxes at the global level based on soil and plant functional parameters, and climate. These models can be divided into dynamic vegetation models and biogeochemical models.

Dynamic vegetation models (DVM) simulate species composition and the seasonal variation in the canopy layer where net primary production (NPP) occurs (see section 4.1.4). In contrast, biogeochemical models are forced by fixed land cover, fire and soils maps and by the fraction of photosynthetically active radiation (FAPAR) intercepted by leaves. The forcing fields generally rely on global estimates derived from remote sensing (Palacios-Orueta et al. 2005). Biogeochemical models are then used for historical short-term studies (over a decade) where changes in land cover are assumed to be not significant at a global scale.

Examples for biogeochemical models are:

- The Carnegie-Ames-Stanford-Approach (CASA) model is a biogeochemical model, which is widely used for studying fire effects on carbon stocks and emissions fluxes. CASA was initially developed for estimating seasonal and inter-annual variability in biosphere/atmosphere exchanges (Potter et al. 1993, Field et al. 1995). It was later on extended by a combustion module, which accounts for fire effects on changes in carbon stocks, direct emissions from combustion and subsequent indirect effects on the decomposition of woody debris resulting from incomplete combustion. Emissions are calculated for the burning of leaves, wood, and litter carbon pools with specific combustion completeness parameters specific to these pools and to the biomes. Combustion completeness is then modified according to soil water content, the driest conditions being the more complete. The combustion module developed for GFED is described in van der Werf et al. (2003); the module developed for historical long term fire emissions is described in Mouillot et al. (2006).
- Biome-BGC (Running et al. 1993) is a biogeochemical model widely used for forest ecosystems, and has a range of global and regional application but has rarely been used in global fire studies (Wang et al. 2011). Fire-BGC (Keane et al. 1989), the stand level forest model designed for fire application is the mostly used BGC derived model implying fires but mostly at the landscape scale.

When applied at global scales, vegetation models require a spatially explicit representation of burned areas as a forced input for calculating combustion. Biogeochemical models require the accurate location and timing of fires for better simulating combustion efficiency and fire emission for further use in atmospheric models. These applications require multi-year burned area datasets as a single year is not relevant due to the high inter-annual variability of biomass burning and the indirect effects of previously burned areas on present fuel biomass. However, model requirements in terms of resolution of the burned area input data are still low as simulations are performed at 0.5° or 1° resolution and on monthly basis.

Fire emissions estimates are also used alongside atmospheric observations to constrain the biogeochemical carbon fluxes in such models (van der Laan-Luijkx et al. 2015).

4.1.4. Dynamic Global Vegetation Models (DGVMs)

DGVMs simulate water, energy and carbon exchanges between the terrestrial biosphere and the atmosphere. Instead of using a fixed land cover derived from global remote sensing (as in biogeochemical models, see section 4.1.3), DGVMs can simulate the global distribution of vegetation dynamically so that land cover (species composition and biomass) is calculated from climate and soil types that allow the germination, growth and survival of species (Sitch et al. 2003). The fire module implemented in DGVMs calculates carbon emissions from combustion as in the biogeochemical models, but it also simulates the potential changes in species composition according to the functional traits associated to resistance to fire and post fire regeneration (Pausas et al. 2004).

Fire information in DGVMs can be inserted from global remote sensing datasets - as in the biogeochemical models for historical fire emission assessments. Fire information in DGVMs can also be computed by a fire risk module, which incorporates the main processes that are required to reproduce fire hazard based on climatic and anthropogenic ignition and fire spread. In this setup, they can be used to simulate the evolution of fire regimes under historical and future climate change scenarios.

The type of fire model embedded in global vegetation models has evolved from simple fire hazard models (Thonicke et al. 2001) to the current state-of-the-art process-based fire models (Andela et al. 2013, Kloster et al. 2010, Lasslop et al. 2014, Li et al. 2013, Pfeiffer et al. 2013, Prentice et al. 2011) and empirical models with optimisation by observation (Knorr et al. 2014; LePage et al. 2014). The majority of fire models explicitly simulate ignitions from natural and human sources, fire propagation, fuel combustion and vegetation mortality, with most process-based fire models operating on daily time step.

Evaluation of complex global vegetation models is time-consuming and non-trivial, and, because different evaluation metrics and reference data are used, the evaluation results are poorly comparable between models. Benchmarking refers to the comprehensive evaluation of multiple aspects of model performance against a standard set of targets using quantitative metrics (Yue et al. 2014a). The Vegetation Model Benchmarking (VMB) system developed by Kelley et al. (2013) allows for an efficient and comparable evaluation how adequately individual processes are represented. It quantitatively evaluates multiple simulated vegetation properties, including vegetation cover distribution and characteristic, runoff and fire regime by computing statistical specific metrics quantifying model performance against observations. The observational benchmarks are derived from remotely sensed 0.5 degree gridded datasets and site-based observations. For fires, annual average gridded GFED3 burned area data are used in the VMB system setup described by Kelley et al. (2013).

In 2014, the "fire model intercomparison project" (FireMIP) was created as an international initiative to compare and evaluate a set of common experiments performed with different global fire models against benchmark target data sets for present-day and historical conditions (Hantson et al. 2016). In addition to an in-depth investigation of modelling processes, FireMIP aims at assessing the historical fire impact on global carbon cycling and vegetation dynamics and at providing an assessment of the reliability of future projections of changes in fire occurrence and characteristics. The systematic evaluation by benchmarking will help to identify and develop improvements in individual models and will potentially guide the further development of vegetation–fire models in general (Hantson et al., 2016).

Two partners (LSCE and IRD) from the Fire_cci project are actively participating in the FireMIP project. The ORCHIDEE-SPITFIRE of LSCE, whose development was financed by the Fire_cci Phase 1 project, is one of the nine fire-enabled DGVMs, which has contributed simulations following the FireMIP protocol.

Most of the DGVM models participating in FireMIP operate on daily time step, with output of fire number, fire size and ultimate simulated burned area. The highest spatial resolution so far is 0.5 degree. In most cases, relevant parameters were adjusted (often a linear scalar to adjust simulated burned area) in order to fit the simulated burned area with the satellite observed burned area. Thus, despite the complex and relatively complete modelling processes, proper parameterization on finer scale or field scale is rather challenging. To some extent, this parameterization is quite highly attached to estimation of contemporary burned area by satellite image retrieval, although this does not impede the models' capacity to investigate historical and future variation of fire activities. In addition, existing mode calibrations are at the best case on monthly scale, very little is known whether models could capture the finer time scale (e.g., diurnal) fire variation and evolution (e.g., fire propagation during consecutive days with limited precipitation).

For benchmarking the FireMIP simulations, the VMB system developed by Kelley et al. (2013) has been specifically adapted. The observational global burned area information included as benchmark data in fireMIPbenchmarking system[17] include GFED4, L3JRC, MCD45A1 and MERIS Fire_cci v4.1 are used. The global burned area benchmark data are standardised to a 0.5 degree common grid, the temporal resolution is monthly (Hantson et al. 2016). The decision for spatial resolution of 0.5 degree as FireMIP default is based upon a sensitivity study, which indicated that spatial resolution had no significant impact on the metric scores quantifying FireMIP model performance (Hantson et al. 2016).

To qualify as benchmark data, satellite observations of burned area must fulfil the quality requirements with respect to (a) spatial coverage (optimal global, except for site-specific data), (b) temporal coverage (multiple years, including information on the seasonal variation), (c) independency from modelling approach that involves calculation of vegetation or fire properties (d) public data availability (Kelley et al. 2013). As for all satellite climate benchmark data, the accuracy of core benchmark observations must be verified against absolute standards and they should meet minimum requirements for accuracy that allow for precise trend estimates (Leroy 2008).

The selection of satellite burned area products to be included as benchmark target data sets is non-trivial. The global burned area products included in the FireMIP benchmarking system differ between each other in terms of spatial and temporal fire patterns and in terms of uncertainties. In addition, all of them systematically underestimate burnt area because of difficulties in detecting small fires (Randerson et al. 2012; Padilla et al. 2015). These types of uncertainties need to be taken into account in model benchmarking – either by focusing on regions or features which are robust across multiple products or by explicitly incorporating data uncertainties in the benchmark scores (Hantson et al. 2016). Additional requirements identified by the FireMIP team are a database providing spatio-temporal information on small fires and a mature uncertainty quantification of the products. Furthermore, for comprehensively benchmarking fire regimes, not only long-term information on the area burned, but also

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[17] http://douglask3.github.io/firemip.html (last accessed August 12, 2016).

information on the number and size distribution of individual fires and on fuel consumption is required.

During the FireMIP meeting in October 2017[18] the participants reinforced their urgent need for long unbiased time series of burned area. Since the FireMIP participants have developed a strong focus on analysing extreme events and interannual variability in regional fire regimes, regional long-term burned area products would also be very beneficial. Improving the model's representation of fuel consumption, which is traditionally computed as the product of fuel load and combustion completeness, is another priority focus and related observational data are urgently required. The participants identified fire-related tree mortality as one of the least constrained aspect of current global fire models, with no existing reference dataset available, and initiated a community effort towards establishing a global tree mortality dataset from observational data. As fire intensity is the basis to parameterise mortality functions in fire models, spatio-temporally resolved information of fire intensity – or proxies of it – are required to evaluate the model performance to accurately predict this quantity. Fire intensity, tree mortality, and fuel consumption, in turn, are dependent on fire size. Hence, spatio-temporally resolved information on fire size distribution is evenly important to the DGVM modelling community.

The on-going advancements in fire modelling have implications for satellite burned area requirements. To allow for proper model validation, high temporal resolution of burned area data is highly desirable as it is crucial to validate the short-term model behaviour. Second, fire patch information is necessary to properly validate the model's capacity to capture fire size distribution, which may be highly related to extreme fire behaviour. This fire patch information may at the same time allow region-specific more in-detail model parameterization, a step forward compared with the current way. Third, high spatial resolution of burned area is important even though most of the models still operate on a rather coarse resolution (best case 0.5-degree). However, finer-resolution spatial gridded burned area data can be still useful for models capable of handling sub-grid level fire activities (e.g., establishing sub-grid new forest cohort after stand-replacing fires). Finally, as fire models are mostly calibrated against contemporary satellite-burned area data, their ability to capture inter-annual variability of fires could be potentially limited by the short time span used for model calibration. The availability of long-term burned area data thus could increase this credibility and, at the same time, allows investigations of long-term fire impacts on the Earth System when burned area data are directly used in the model.

4.1.5. Statistical analysis to identify factors controlling fire activity

Burned area products in combination with climate and other socio-economic data are widely used in statistical analysis pinpointing specific factors controlling global or regional fire patterns. The insights gained are crucial in the development of model parameterisations that realistically describe the core processes driving fire dynamics. Knorr et al. (2014), for example, used three multi-year satellite-based burned-area products in a non-linear statistical model estimate the parameters describing the linkage between population density and fire frequency, including an uncertainty analysis of the estimated parameters. Bistinas et al. (2013) used GFED3 burned area time series to explore the relationship between human population density and burned area at

[18] Hantson S., Notes 4e FireMIP workshop, emailed to firemip@lists.kit.edu on October 26, 2017.

continental and global scales. Andela and van der Werf (2014) used MCD64A1 burned area together with land cover and precipitation data and analysed the driving factors for different burned area trends over northern and southern Africa over 2001-2012. They found that over 51% of the upward trend in burned area in southern Africa could be explained by the change in precipitation. Change in precipitation and expansion of agricultural land collectively explained 44% of the downward trend in burned area in northern Africa.

Hantson et al. (2015a) analysed the drivers of global spatial variations in fire size distribution with a generalized additive model (GAM), using global data on climate, land-cover, human, socioeconomic and vegetation-productivity as explanatory variables. The size of individual fires was computed by grouping temporally consecutive and spatially adjacent MCD45 burned pixels into burned patches. Subsequently, the fire size frequency distribution was described by fitting a power law function to the patches within each 2° grid cell. With only four variables included, the statistical model could explain 53% of the variance in power low exponent. Two of the variables relate to human impacts on the environment (cropland and population density) and two are climatic factors that also have a strong impact on vegetation productivity.

Lehsten et al. (2010) use a data-driven approach to parameterize two dynamic burned area models that are applicable to dynamic vegetation models (DVMs) and Earth system models (ESMs). The parameterization relies on a generalized linear model for burned area obtained when analysing the relationship between observed annual burned area (here MCD45A1) and observational information of certain fire drivers such as climatic factors, vegetation characteristics and population density. The analysis uses a 9-year time series with 1 degree spatial resolution –assuming a spatial scale of one degree as the scale typical for DVMs and ESMs. Identifying and characterising fire driving factors is fundamentally important for developing realistic process-based simulation models of fire occurrence under future climate change scenarios.

More detailed analysis on factors controlling fire activity on a daily time scale have used active fires (MCD145ML) to identify the sociological aspect of fire activity according to weekdays (Pereira et al. 2015), or quantifying fire spread rates (Wang et al. 2014), highlighting the need for accurate pixel-level fire dates in refining global fire processes.

4.1.6. Fire hazard assessment for ecosystem management

Fire has both positive and negative effects on the ecosystems and society, but most commonly it is considered as a natural hazard, as it affects people's lives and properties and ecosystem services. For this reason, fires tend to be avoided. When countries have an active fire suppression policy, fire risk assessment systems are in operation. Accordingly, the identification of the main factors explaining fire ignition and propagation becomes a very relevant research topic. The validation of those fire risk systems requires having accurate fire statistics available. Both fire ignition points and burned areas are required (Ardakani et al. 2011, Chuvieco et al. 2010 and 2014a, Robbins et al. 2008, Trigg and Roy 2007). In savannah for example, identifying climatic or human drivers as well as frequently burned areas requires a fairly good representation of fire contours (Devineau et al. 2010, Archibald et al. 2009). Accurate fire detection information with low spatial shifts is required for fire hazard management in vulnerable areas (Wright et al. 2007, Ressel et al. 2009), such as the implementation of measures promoting fire-free areas where fire sensitive species could be conserved. A special focus should be given to regions undergoing rapid deforestation and where fire is used as major tool for forest clearing. However, several authors point out that separating burning from other types of forest damage in remotely sensed data is particularly difficult in areas where re-burning and understory fires occur (van der Werf et al. 2009, LePage et al. 2008, Pereira 2003, Morton et al. 2011). Particular health risks are associated with the contamination of smoke from wildfires in radioactively contaminated forests (Evangeliou et al. 2015) and the wildland-urban interface.

Fire ignition location and burned area are of interest to fire risk modellers at larger scale who need a conceptual knowledge of processes to be implemented in global fire modules or fire spread/initiation models at global (Thonicke et al. 2010) or regional scale (Anderson et al. 2009). Mapping large fire events in continuous forested ecosystems could contribute to better understanding of their propagation. Requirements here are an accurate timing of fire occurrence on a daily basis and an accurate spatial resolution. Fire return intervals and fire intensity are also very useful to model fire vulnerability, a critical part of fire risk assessment (Chuvieco et al. 2014b)

On the other hand, long time series of fire affected areas are necessary for getting a clear picture of a fire regime with time return intervals much larger than the 15 years available until now, so that most studies, until now had to use a combination of products to get the more accurate and longest time series available (LePage et al. 2008, Bartalev et al. 2007, Bartsch et al. 2009). Providing a single product covering the longest period available would be a major step forward for fire risk assessment.

4.1.7. Early warning fire alert and survey systems

Public awareness and concern with adverse impacts of fire events have increased over the last decades. Concurrently, the public interest of establishing near-real-time fire alert systems has increased (Schroeder et al. 2008, Davies et al. 2009, Zhang et al. 2015). Early warning of fires, optimally followed by fast extinction, are an important means to prevent or mitigate adverse impacts of fires on society and ecosystems. Several early warning fire alert systems, geared towards easy data access and user friendliness, are already in operation. Most of them, however, rely on active fire detection rather than burned area.

For example,

- NASA's Fire Information for Resource Management System (FIRMS)[19]
  FIRMS is part of NASA's Earth Observing System Data and Information System (EOSDIS). It provides near-real-time MODIS hotspots information on a global scale in easy to use formats. Via the FIRMS Web Fire Mapper[20], it allows users to interactively view fire data. As a complementary, UN FAO began offering FIRMS data through its Global Fire Information Management System (GFIMS). In addition, the NASA Worldview tool[21] allows to interactively view the FIRMS NRT product along with other fire-relevant NRT product (e.g. aerosol optical depth measured by MODIS or OMI) as browse imagery.

[19] https://earthdata.nasa.gov/earth-observation-data/near-real-time/firms (last accessed September 20, 2016)
[20] https://firms.modaps.eosdis.nasa.gov/firemap/ (last accessed September 20, 2016)
[21] https://earthdata.nasa.gov/worldview (last accessed September 20, 2016)

- NOAA's Hazard Mapping System (HMS) Fire and Smoke Analysis [22] for continental US

  This system provides near-real-time information on detected hotspots and smoke plumes. The blended, visually quality controlled product relies on data from GOES Imager, NPOESS AVHRR and MODIS (see Schroeder et al. 2008).

- The Global Fire Assimilation System (GFAS)[23]

  GFAS, described in Kaiser et al. (2012), assimilates FRP observations contained in the MODIS Level 2 active fire product (MOD14/MYD14) (Giglio 2013) to provide near real-time global biomass burning emission estimates of various trace species that are required for the operational global atmospheric forecasts of the Copernicus Atmosphere Monitoring Service (CAMS)[24].

- The European Forest Fire Information System (EFFIS)[25]

  EFFIS, described in San-Miguel-Ayanz et al. (2013), is a comprehensive fire information system for Europe implemented since 2003 by the Joint Research Centre of the European Commission. It covers the full cycle of forest fire management, from forest fire prevention and preparedness to post-fire damage analysis. The near-real time fire observation module of EFFIS provides hotspot and burned area observations from MODIS via a public web-mapping interface. The burned area mapping relies on a semi-automated algorithm which combines MODIS 250 m surface reflectance data with MODIS active fires and ancillary information on land cover and media reports on forest fires. Visual interpretation is used to refine the burned area perimeters. The methodology allows mapping burnt areas of about 50 ha or larger. By default, fires in agricultural land as defined by the CORINE land cover map are masked out (Boschetti et al., 2008). Validation of the EFFIS burned area product is still on-going, and has, so far, specifically focussed on a few large fire events in the Mediterranean (San-Miguel-Ayanz et al. 2012). Kalivas et al. (2013) inter-compared EFFIS burned area mapped for the 2005 to 2007 period in Greece with the MCD45A1 MODIS burnt area product. They depict large differences between both products in terms of total burned area and spatial patterns. Annual burned area on non-agricultural land is around 50% higher in EFFIS than in MCD45A1 while the mean fire patch size is around 150% higher. Kalivas et al. (2013) suggest that the difference could be partially linked to EFFIS marking non-burnt areas inside the burnt scar as burned. New methods are being developed to achieve higher accuracies (Sedano et al., 2013).

For early warning fire alert systems to more widely use burned area products would require a timely delivery of burned area maps with low probability of omission. Omission errors could lead to missed alerts with significant consequences. Commission errors would lead to false alerts, but they are generally less damaging if they remain in a reasonable proportion. Additional relevant variables are meteorological predictions and fuel descriptions (Pettinari and Chuvieco, 2016).

[22] http://www.ospo.noaa.gov/Products/land/hms.html (last accessed September 20, 2016)
[23] http://macc.copernicus-atmosphere.eu/d/services/gac/nrt/fire_radiative_power/ (last accessed September 20, 2016)
[24] http://atmosphere.copernicus.eu/ (last accessed September 20, 2016)
[25] http://forest.jrc.ec.europa.eu/effis/ (last accessed September 20, 2016)

The political use of fire detection for survey and penalisation for illegal fires recently emerged in Bolivia (Redo et al. 2011), Indonesia (Harwell 2000) or Malaysia (Zin and Ahmed 2014). This political use of fire information poses particularly high demands on the accuracy of fire detection or, at least, on the clear explanation of uncertainties as any unjustified penalisation due to false alarms or inaccurate locations must be prevented with priority. Fire detection can be used as a proxy for societal conflict in some regions (Bromley 2010) and humanitarian, security or human rights organisations increasingly use of fire detections to plan rapid response efforts (Buatsi and Mbohwa 2014).

4.2. Usage statistics of global burned area product

The scientific use of burned area information over the past three decades was quantitatively analysed by means of a database query of scientific publications referenced in Web of Science. The query searches for the terms "burned area" OR "burnt area" OR "area burned" OR "area burnt" OR “burn scar*” in the topic field (i.e. title, abstract, author keywords and KeyWords Plus) in all publications, which appeared since 1980. Publications in all fields of research are included, except those where the search terms are linking to dermatological publications[26].

By August 2016, the database query identified 1,829 references over the period 1980 to 2015 that deal with burned area information. While there were no to maximally three publications per year before 1991, the rate increased almost exponentially since then, reaching 189 related publications per year in 2015 (Figure 2a). One half of these publications relate to satellite derived burned area information (Figure 2b). Before 2005, most of the publications related to burned area information from satellites refer to AVHRR while the majority is referring to MODIS in the following years. Landsat is mentioned in 27% of the publications related to burned area information and contributes a relatively constant share of the past two decades.

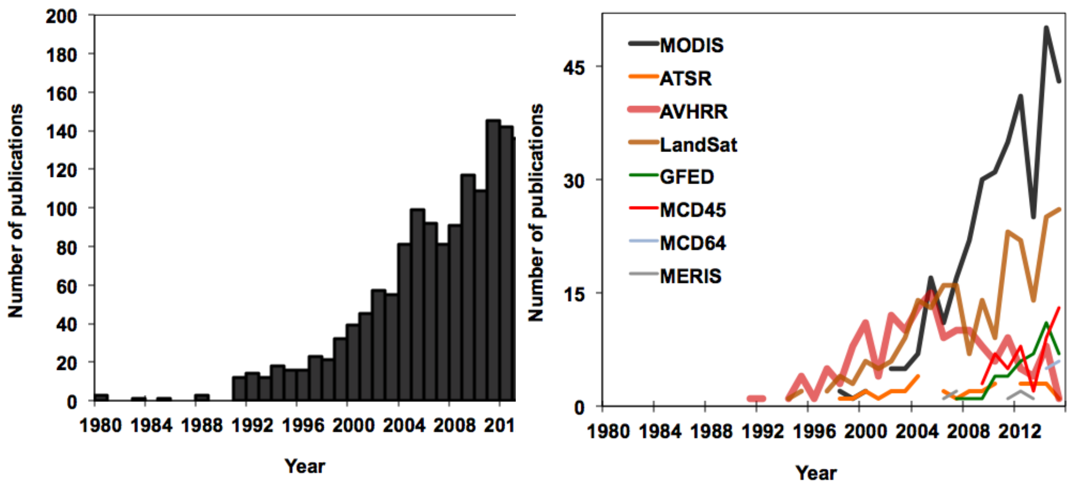


Figure 2: Number of publications references in Web of Science dealing with burned area information (a) total number per year (left) and (b) subset of publications mentioning certain product names (right).

[26] In the latter, burned area refers to skin burns.

Researchers from USA or Canada author 55% of all publications, 34% are authored by researchers from southern Europe (in descending order: Spain, Italy, Portugal, France and Greece) (Figure 3).

A more detailed Web of Science database query on the use of global burned area products was conducted in mid-2011 in the framework of the Fire_cci phase 1 URD (Schultz et al. 2011). The analysis identified 231 references for the 2000 to mid-2011 period, dealing with the developing, validation or use of global burned area products used for global or regional studies and active fire counts. The references are listed in the synthesis table in Annex 2 of the Mouillot et al. (2014) paper.

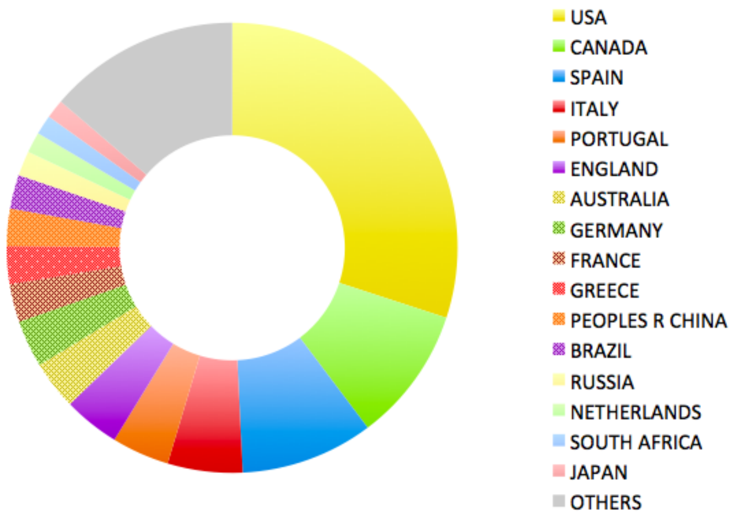


Figure 3: Publications referring to burned area over 1980 to 2015 by based on the country mentioned in the affiliations of the authors.

Figure 4a illustrates that the yearly number of references over the period 2000 to mid-2011 using burned area strongly increased from less than five to 35 in 2010. The majority of these publications (65%) relied on data from the MODIS instruments. At the same time, scientific publications using active fire counts strongly increased (Figure 4b).

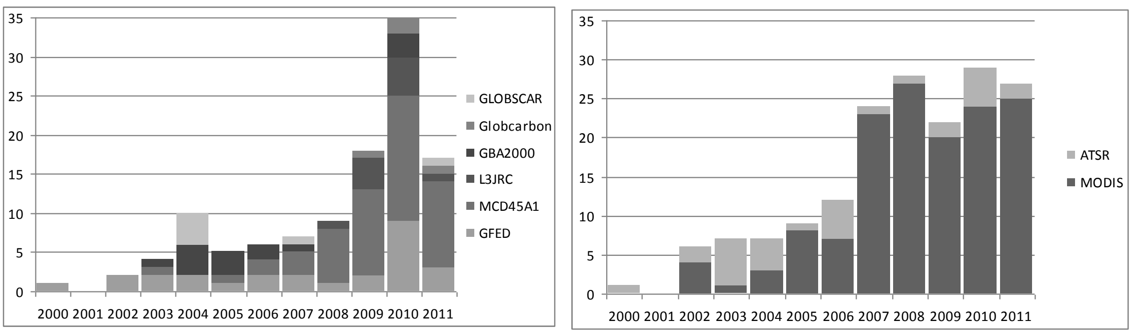


Figure 4: (a) Number of papers references in Web of science database in 2011 using global burned area information classified by input product name (left), and (b) using active fire detection (MODIS MOD or MYD product, and ATSR) (right) (Mouillot et al. 2014).

The literature analysis conducted in 2011 showed that atmospheric chemistry applications constitute the dominant application of burned area products with 20 to 50% of the published studies in the sample. Research applications for fire hazard analysis and forest/ecosystem management actually started later in 2006 and cover a significant end-user group by 2011, implying a wider range of requests than global studies alone.

When classified by geographical regions of product application, 20 to 50 % of the publications before 2006 used burned area products for global studies. Starting with 2006, applications for continental and regional studies predominate more than 80% of the publications. These studies primarily focus on fires in inter-tropical regions. This region actually represents more than 60% of the burned area globally (Mouillot et al. 2006). The region is of particular interest to atmospheric chemistry due to the large amount of carbon and aerosols released from inter-tropical biomes. There is also a significant demand for burned area information for this region for forest management due to the on-going rapid deforestation.

In summary, the analysis of peer-reviewed research publications highlights the increasing use of MODIS-derived products compared to any other products and the importance of these datasets for the tropics where ground data are lacking. The analysis also points out that any set of future burned area products will have to be driven by requirements of the atmospheric community but, at the same time, will have to respond the increasing demand for fire hazard and forest manager.

The literature survey also showed an increase in the number of research publications dealing with small fires, in particular agricultural fires. These low energy fires are poorly characterised in earlier versions of fire products and there is an increasing research interest in developing methods to detect and quantify small fires and to assess their impact on carbon budgets and fire emissions. Randerson et al. (2012) combined 1-km MODIS active fires and 500 m MODIS burned area observations to estimate the contribution of small fires to global burned area and carbon emissions. They showed that accounting for small fires may increase global burned area and carbon emissions by approximately 35%. However, this analysis is not yet validated.

5. User requirements

5.1. Requirements specified by international science programmes

Over the past two decades, several international multi-discipline science initiatives dealing with global fire assessment have specified target requirements for fire observation. Key accuracy targets for future burned area products and desired requirements for new product developments were extracted from the following key programmes and reports (see also Table 3 and Table 4):

- GCOS-92 Implementation plan (GCOS, 2004)

  This plan is the response to the request of the Conference of the Parties (COP) to the UNFCCC to develop a plan identifying implementation priorities and resource requirements in order to ensure that countries have the observational information needed to understand, predict, and manage their response to climate and climate change over the 21st century and beyond. The plan takes into consideration existing relevant global, regional and national capabilities and activities and also provides indicators for measuring its implementation. In total, it recommends 131 Actions to be implemented over the coming five to ten years.

- IGOS Carbon Theme report (Ciais et al. 2004)

  This IGOS Carbon Theme report (Ciais et al. 2004) provides a roadmap to realise an integrated global carbon cycle observation system and specifies in details the observational requirements. The IGOS Carbon or IGCO (Integrated Global Carbon Observation) theme was initiated in 1999 within the framework of the Integrated Global Observing Strategy (IGOS).

- GCOS-107 Systematic observation requirements for satellite-based data products for climate (GCOS 2006)

  This document provides supplemental details to the GCOS-92 Implementation plan. For each ECV, it specifies

  - "target requirements" (spatial and temporal resolution, accuracy and stability),
  - requirements for satellite instruments and datasets,
  - calibration, validation, and data archiving needs,
  - immediate action, partnerships, and international coordination,
  - and benefits the required dataset would bring to different user communities.

  Target requirements are specified as the resolution, accuracy and stability below which there would be no significant additional value for current climate applications from further reductions (GCOS 2011).

- GTOS-68 ECV Fire Disturbance standards report (GTOS 2009)

  This document assesses the status of the development of standards for the fire disturbance ECV. It comprises an overview of the strengths and weaknesses of available global burned area products and provides recommendations regarding standards and methods to be applied in further developments.

- GEO Carbon Strategy (Ciais et al. 2010),

  GEO (Group on Earth Observations) is a collaborative network of over 130 governments and leading international organisations. The purpose of the network was to advance the establishment of Global Earth Observation System of Systems

(GEOSS) by the year 2015. This report sets out a number of key actions that build on a strategy to expand the current observations into a fully integrated observation system measuring the essential parameters and variables.

- GCOS-138 Implementation plan (GCOS 2010a)

  This document is the 2010 update of the Implementation Plan for the GCOS (GCOS-92 2004). It recommends 138 Actions to be implemented over the coming five years.

- GCOS-154 Systematic observation requirements for satellite-based data products for climate (GCOS 2011)

  This document provides supplemental details to GCOS-138. It is an update of its predecessor document, GCOS-107 (GCOS 2006).

- White paper on a NASA Fire ESDR (Justice et al. 2011)

  This notice explores the need for and potential use of a NASA Earth Science Data Record (ESDR) on active fires and burned area. It also identifies the scientific requirements for the satellite fire data.

- ESA CCI Phase 1 Requirements Baseline Document prepared by the Climate Modelling User Group (CMUG 2012).

  The purpose of this document is to assist the CCI projects in focussing on the needs of the climate modelling community and other expert users of climate data. It presents an analysis of their satellite data requirements captured by CMUG through expert interviews. For each ECV, "specific requirements" are synthesized from this analysis. Specific Requirements for the Fire Disturbance ECV are provided for the parameter burned area.

- Response by ESA to GCOS Document (Bojinski and Fellous 2013).

  This document provides a requirement analysis by contrasting the results of the Climate Change Initiative with the GCOS requirements.

- ESA CCI Phase 2 Requirements Baseline Document prepared by the Climate Modelling User Group (CMUG 2015a).

  The document is an update of the Phase 1 CMUG Requirements Baseline Document (CMUG 2012). It describes users' needs with greater detail, taking advantage of a wider range of users interviewed.

- GCOS-200 Implementation plan (GCOS 2016)

  GCOS-200 is an update of the GCOS-138 Implementation Plan and puts a stronger focus on the provision of satellite observations that support adaptation and mitigation measures in a warming climate. The plan suggests 72 actions as the basis for improving the implementation of GCOS. Five of these actions are exclusively assigned to the ECV fire disturbance. These are the (1) the reanalysis of historical fire satellite data, (2) the development of high-resolution fire maps, and the continuation of (3) operational global BA and FRP observations, (4) BA product validation, (5) joint projects involving users of fire disturbance satellite products and the product development community. GCOS-200 also specifies target product requirements for the ECV fire disturbance that data providers should aim to achieve over the next 10 years.

Table 3: Requirements for future burned area products identified from specifications described in international programmes/plans (2004-2010).

Requirements	**IGOS carbon theme (2004)**	**GCOS-92 (2004)**	**GCOS-107 (2006)**	**GTOS-68 (2009)**	**GEO carbon strategy (2010)**
Spatial resolution	<200m	250m (minimum 1km)	250m	GCOS (2006) requirements need to be re-evaluated to be more specific and realistic	
Temporal resolution	1m	1m	1d		
Accuracy [%]: Commission Error		-	5%		
Accuracy [%]: Omission Error		-			
Temporal stability	Continuity		5%		
Period covered		1982-2004; data continuity to the sensors on future satellite series		Long term	As long as possible; starting 1982 with AVHRR
Error characterization				Improved characterisation of missing detections (cloud mask)	
Calibration and validation		CEOS WGCV validation protocols			Apply internationally agreed validation protocol; calibration NIR, VIS, SWIR within 2% over lifetime
Other burned area information	Provide info on ground fires; combine ground observation when possible			Improved documentation	

Table 4: Requirements for future burned area products identified from specifications described in international programmes/plans since 2011.

Requirements	GCOS-154 (2011)	NASA Fire ESDR (2011)	CMUG (2012)	Schultz et al. (2011)	CMUG (2015a)	GCOS-200 (2016)
Spatial resolution	250m	500m+local 30m+aggregated 0.5deg	250m/1km/5km	pixel (sensor's native resolution); grid 0.5/0.1deg	250m/1km/5km	30m
Temporal resolution	1d	2/3d, 1m	1d, 1.5d, 3d	Day of burn (pixel)/1w (grid)	(3h)/ 1d, 1.5d, 3d	1d
Accuracy [%]: Commission Error	15%		Accuracy max. 30/20/10 % error	Threshold/goal: <17%/ <5% error	Accuracy max. 30/20/10/(1) % error	15% (error of omission and commission), compared to 30m observations
Accuracy [%]: Omission Error						
Temporal stability	15%	Consistency	5%	15%	5%	–
Period covered		Long term with AVHRR	5-10 years	Long term	10-20 years	–
Data format	Standardized data format		-	NetCDF plus complementary products	NetCDF-CF	
Error characterization	Error trace ability		-	Characterisation of missing detections (clouds, shadows)	-	Improved uncertainty characterisation
Calibration and validation	Better validation	Calibration NIR, VIS, SWIR	-			Improved validation
Other burned area information	Day of burn		Ancillary layers: land cover or biomass availability	Ancillary layer: land cover, burn severity	Ancillary FRP layer; improved traceability and documentation	FRP, active fires ("hotspots")

Annotations:

(1) The requirements tabulated numerically in GCOS-154 under the heading "accuracy" are indicative of the acceptable overall levels for the uncertainties of product values. The target accuracy requirement is given as 15% (error of omission and commission), compared to 30m observations. Target requirements refer to the maximum performance limit for the observation, beyond which no significant improvement would result for climate applications. It is not specified in GCOS-154 to what spatial or temporal reference the values are referring to. Please note that in the draft version 1.1 of GCOS-154 opened until July 1, 2011, stability was stated more precisely as "temporal stability in annual continental-scale averages" (Schultz et al. 2011).

(2) CMUG states specific requirements for two applications, climate trend monitoring and prescription of model boundary conditions. The specific requirements for both applications are identical expect that the latter may require higher temporal resolution and accuracy (see numbers listed in brackets). It is not defined to what measure of accuracy the specified accuracies are referring to.

(3) In the table, CMUG and GCOS sometimes provide several estimates and then refer to the GCOS objectives "goal" (or "target"), "intermediate" and "threshold". If only a single value is specified in GCOS, it refers to the goal requirement. Goal (or target) refers to the value at which the product development of a given aspect has been exhausted, i.e. further optimizing this value would contribute no significant added value to the product applications in climate research. Threshold refers to the minimum requirement, i.e. the value that has to be met to ensure that data are useful. An intermediate requirement is between 'threshold' and 'goal' which, if achieved, would result in a significant improvement for the targeted application (see also Bojinski and Fellous 2013).

More general requirements with respect to burned area data are expressed by network science initiatives targeting fires in the Earth System.

The Fire Model Intercomparison Project (FireMIP), mentioned in Section 4.1.4, is another on-going integrated research initiative targeting fires in the Earth System Modelling. For the FireMIP simulations, long-term observational global burned area products with coarse (0.5 degree) spatial and daily or monthly temporal resolution are required. Since FireMIP participants have recently developed a strong focus on analysing extreme events and interannual variability in regional fire regimes, regional long-term burned area products would also be very beneficial. Gridded burned area data with resolutions finer than 0.5 degree can be useful for FireMIP models capable of handling sub-grid level fire processes. Other key requirements of FireMIP relating to burned area products are that they are formally validated and that they are publically available. In addition, product stability must be sufficient to allow for precise trend detection. FireMIP members expressed their need for a mature uncertainty characterisation and that spatio-termporally explicit uncertainty information is provided as part of the burned area products. However, FireMIP participants likely understand by this a validation-based, statistical characterisation of the measurement errors rather than an uncertainty characterisation that relies on Bayesian error propagation (see also Annex 4). The FireMIP participants increasingly request complementary data layers providing information on fuel consumption, the effect of fire on vegetation (e.g. as reflected by tree mortality or fireline intensity), the rate of spread, and fire size distribution.

The Interdisciplinary Biomass Burning Initiative (IBBI) has the primary goal to improve atmospheric composition and air quality monitoring through interdisciplinary understanding of the various processes around biomass burning (Kaiser and Keywood 2015). It aims to achieve this by instigating new interdisciplinary research on biomass burning in a series of workshops. During the IBBI workshop in 2014, two informal working groups were formed. One working group agreed on an interdisciplinary effort to improve the representation of chemical ageing of smoke in atmospheric models of different scales. The improvements may contribute to explain the considerable discrepancies between bottom-up emission inventories (used as model boundary condition) and top-down emission estimates (satellite observations of smoke) (Withburn et al. 2015). The second working group agreed to jointly work on the systematic use of paleorecords of fire activity to constrain fire modules in DGVMs, and to include these to compile long-term reconstructions of fire emissions (see BB4CMIP6, in section 4.1.2). The activities of the second working group were integrated in the FireMIP project (see section 4.1.4).

The most prominent current research needs with respect to burned area identified by the IBBI workshop are: (a) approaches to combine burned area information with fire radiative power to better constrain the amount of biomass burned, (b) long-term series of burned area observation and (c) a community database of high-resolution burned area imagery from Landsat for validation of in-depth fire process modelling studies.

The most recent IBBI workshop in 2017 (Keywood et al. 2017) focused on the various on-going U.S. research campaigns, which primarily target at studying the impact of fires on the atmosphere. It was discussed, for example, how the outcomes of U.S. fire field campaigns can serve to verify and enhance satellite products. It was suggested that the U.S. filed campaigns should link the smoke plume properties to fire characteristics like temperature and FRP to make the results applicable to large-scale satellite observation analyses for smoke forecasting.

The requirements specified for burned area products differ substantially between these programmes and over time. Differences also arise from the differing definitions of the terms accuracy and stability, as these are not understood in the same manner. Nevertheless, a set of target characteristics can be extracted from the more recent specifications.

The global burned area data should have or be:

- Length of time series:
  - long-term, but at least 10 - 20 years. These time series can be generated from various sensors but temporal consistency should be assured.
- Temporal resolution:
  - daily data with original spatial resolution of the sensor
  - daily or monthly temporal resolution in the aggregated gridded product on global scale.
- Spatial resolution:
  - Pixel product with sensor resolution of 250 m
  - Gridded product with 0.5 and 0.1 degree spatial resolution on global scale; grid resolutions of 0.05 degree (~5 km) are also requested, although it is unclear if this refers to global products.
- Global accuracy (expressed as error of commission and omission with respect to the reference validation data): acceptable below 15%.
- Temporal stability: within 15%. It is unclear, however, to what measure of temporal stability this estimate is referring to.
- Products should contain traceable uncertainty characterization and quality flags (e.g. for missing detections due to clouds).
- Auxiliary data layers containing information on the vegetation cover burned, fuel consumption and fire size distribution.
- Products should be validated following internationally agreed validation protocols.
- Ancillary products providing a spatiotemporal characterisation of the small fires missed by the product.
- Easy and public access to the data products.
- The products should be provided with sufficient and comprehensible documentation and a user guide to aid that the products are easy to be used in a correct manner by users in various applications.

These general recommendations are not linked to existing capabilities (or those available in the near future from planned satellites). Some programme reports (e.g. GCOS-154) point out that the proposed burned area requirements can only be met under certain conditions with existing observing system, but not in a systematic way. Principally, and as stressed in the response by ESA to GCOS (Bojinski and Fellous, 2013), it cannot be expected that all ECV products generated in the CCI are compliant with GCOS requirements, as they are target requirements.

5.2. Burned area product requirements identified from user surveys

The sections above provide a literature review of newly emerging priorities of international science programmes, recently released global fire data sets and peer-reviewed publications, which were analysed and summarised in terms of user requirements for satellite-derived burned area products.

This section analysis and summarises the feedback obtained from researchers, which participated in user requirement questionnaire surveys as well as feedback obtained from discussions with members of the Fire_cci team and of partner ECV projects. When deemed appropriate, the analysis is substantiated with related literature findings.

The surveys disclose several newly emerging and/or evolved user requirements. These changes are mainly driven by experiences gained from using the Fire_cci and other burned area products in model studies, by new research directions diversifying the application of burned area products, by technical and algorithmical advancements, and by recent releases of other fire or related satellite products.

5.2.1. User requirement questionnaire surveys

(a) Fire_cci Phase 1 user requirement questionnaire survey

In 2011, i.e. at the beginning of Fire_cci Phase 1, a user requirements survey by questionnaire was conducted. The survey contained questions about the actual and potential use of burned area data, the desired product characteristics, the expected product quality and means of data delivery. The Fire_cci phase 1 survey is described in detail in the Fire_cci Phase 1 User Requirement Document (URD, Schultz et al. (2011)) and in the peer-reviewed publication by Mouillot et al. (2014).

Of the in total 11 international organisations and projects plus more than 50 individuals were invited as targeted end users, 47 responses were received. The majority of answers were from researchers working in Europe, followed by people working in North and South America. Of the respondents, one third each belongs to the earth observation (EO). The other third belongs to the modelling community, which predominantly requires burned area information for the carbon cycle and dynamic vegetation modelling. The remainder of respondents mostly belongs to the data assimilation and atmospheric chemistry modelling community, and to researchers working with burned area information for fire hazard monitoring, the assessment of post-fire conditions and species migration and the production of land-cover maps. This geographical distribution and the distribution by research area largely mimics the origin of authors in the literature survey (see section 4.2), with the exception of a larger representation of European researchers.

The majority of fire products that the respondents were using were derived from MODIS, confirming the results from the bibliographical analysis (see section 4.2). In the modelling community, several users employed the gridded GFED burned area products (v2, van der Werf et al. (2006), and v3, van der Werf et al. (2010)). In the EO community preference was given to products resolving burned area information at the pixel level (e.g. MODIS MCD64 Giglio et al. (2009), MODIS MCD45 Roy et al. (2008)). Alternatively, the respondents developed their own retrieval products based on MODIS, SPOT/VEGETATION, NOAA/AVHRR or Landsat data.

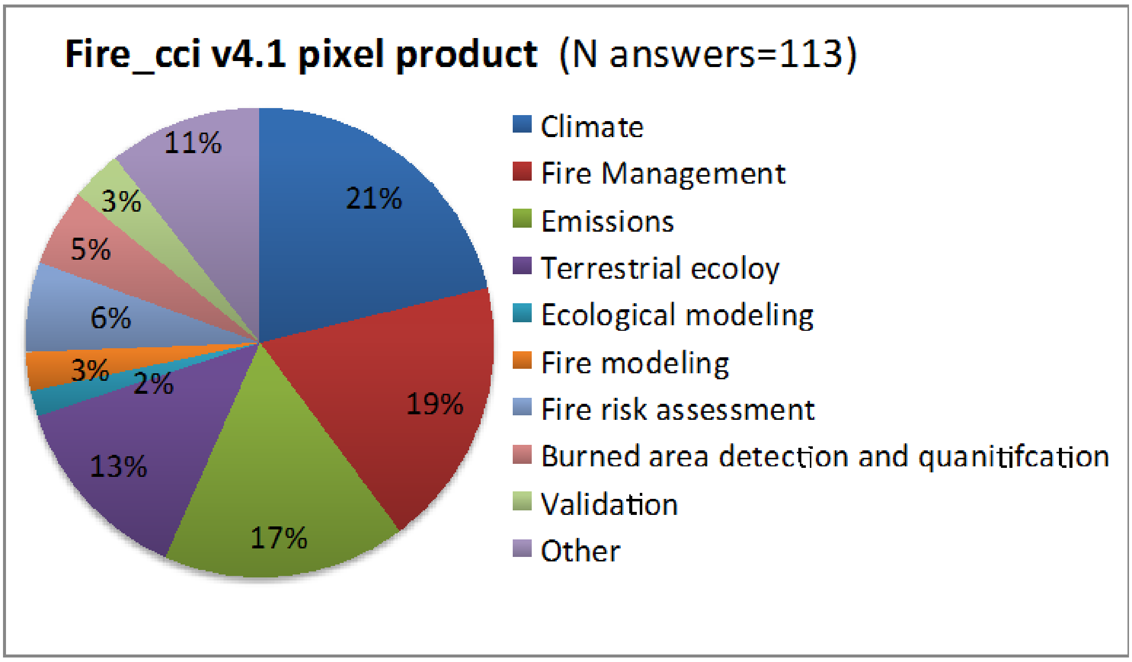
(b) Fire_cci Phase 2 user requirement questionnaire surveys

In the first semester of Fire_cci Phase 2, i.e. between September 2015 and March 2016, an update of the Fire_cci Phase 1 questionnaire was posted on the Fire_cci project webpage. The survey was advertised at several international conferences (e.g. GEIA and EGU). However, the response rate was very low. By November 2017, only two users submitted completed questionnaires. In addition, all Fire_cci project partners were asked to participate in a separate online questionnaire survey. There were in total eight participants that stated that they have used or intend to use burned area products. In summary, ten individual responses were analysed with respect to user requirements. All of these responses came from European users. Seven of the respondents require burned area information for numerical modelling purposes, here above all for atmospheric chemistry (-climate) modelling and then for biogeochemical or dynamic vegetation modelling. Most respondents state that they also require burned area information for statistical modelling of fire patterns and fire drivers, e.g. to identify empirical relations between burned area and individual fire drivers (vegetation, hydrology, land use). These empirical parameters can then be used to improve the representation of fires in numerical models.

A completely redeveloped user requirement online questionnaire was posted on the Fire_cci project in July 2016 (https://www.surveymonkey.com/r/RSV8PSF, last accessed November 30, 2017; see also Annex 3). Users visiting the Fire_cci project's website or trying to download Fire_cci products from there are asked to participate in this survey. Also other interested users were actively invited by announcements at conferences and workshops to fill in this questionnaire. Despite active promotion, there are, as of November 2017, only two questionnaires filled in properly. One of the respondents, a Swaziland governmental employee and an experienced user of MODIS burned area products, requires long-term (since 2000–present) pixel level burned area information for the Southern Africa region to analyse fire regimes in the light of forest and fire management planning. He expresses his need for detailed pixel-level characterisation of the uncertainty of detecting a fire in space and in time. In addition, a quality flag layer explicitly labelling water bodies and other unburnable pixels, cloud contaminations und otherwise unobservable pixels is considered helpful. Fire_cci pixel products would enhance in usefulness if they are provided as longer time-series (since 2000) and with higher spatial detail (resolution of 100 m). The other respondent, a university atmospheric chemistry-climate modelling scientist, from China, intends to use the full global Fire_cci v4.1 time series of both, pixel and grid levels product, to analyse the relationship between extreme temperatures and burned area. The product's characteristics are considered as sufficient for his applications, except that for the pixel product, he would want additional information on the temporal uncertainty in the detected day of burn and on sun glint contaminations. Finally, both respondents consider the Fire_cci product validation adequate for their application.

To be able to download the MERIS Fire_cci v4.1 product via the Fire_cci project's website (http://www.esa-fire-cci.org/), users have to provide information about their institution, the country they are coming from and whether they are interested in the pixel or the grid product and for what purpose. The results from this survey are given in Figure 5. The statistics indicate that climate-related research, fire management, emission estimation and terrestrial ecology are the dominant applications of both grid- and pixel-level burned area products. The statistics further indicate that there is a higher interest in pixel-level than grid-level burned area information and that climate research-related applications of pixel products relatively contribute a smaller share in the total number of different applications than in grid products. It has, however, to be noted that original results of the survey contained many duplicate or unevaluable entries that had to be manually cleansed. Since the cleansing has some subjective component, the statistics are only of reduced representativeness. It has to be further annotated that MERIS Fire_cci 4.1 products are also directly accessible from the Open Data Portal (http://cci.esa.int/data) or the CEDA database (http://catalogue.ceda.ac.uk) without the need of completing the download form of the Fire_cci website (although those additional sites encourage the users to do so). For this reason, the information provided on this section only includes the users who accessed the data through the Fire_cci website, and not those who used other accesses.

Participants of the Fire_cci user workshop in October 2017 (see workshop report in Annex 4) were asked to fill out a short questionnaire focussing on requirements regarding the product's uncertainty characterisation. The participants were also asked to provide free comments on what wishes they have for future products. The 10 responses obtained, most of which from Dynamic Global Vegetation Modellers, largely mirrors the participant's statements made at workshop. Except for fire patch analysis, the respondents have so far only used gridded global BA products. The grid product is used for DGVM model evaluation/benchmarking and for improving the model's process-based representation of fires. When asked for their uncertainty characterisation requirements in pixel-level burned area products, all respondents request burn probabilities provided for every pixel. None of the respondents is satisfied with only a simple binary (burn/unburned) layer. Only half of the respondent's request uncertainty information on the detected date of burn; the other half is satisfied with an estimate of the most likely date of burn. Eight out of ten respondents favoured a probabilistic aggregation (as presented in Appendix 4: section WS3) when asked how pixel level burn information should be transferred to a grid estimate. The other two respondents preferred a grid burned area estimate resulting from the sum of pixels classified as burned. When asked what uncertainty estimates they require for the grid-level burned area estimate, seven out of ten respondents stated the standard uncertainty (estimated standard deviation). Three of them additionally request an indication of biases. Two respondents request no grid-level uncertainty information. Finally, when asked for expected product developments, there is the request for merged, long-term burned area products, information on fire size distribution, combustion completeness, rate of spread and fire intensity (radiative power) and duration, and post-fire recovery.



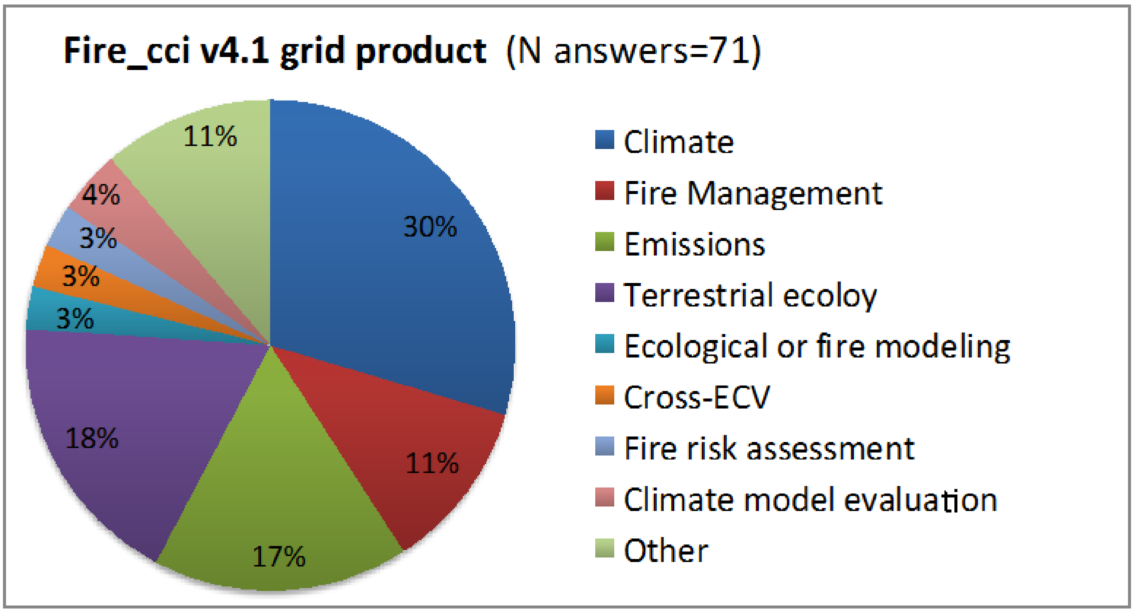


Figure 5: Statistics collected from users that downloaded the Fire_cci v4.1 burned area product from the Fire_cci project webpage between July 2016 and October 2017. The figures show the intended applications of the pixel (top) and the grid (bottom) product.

(c) QA4ECV survey

The EU FP7 funded QA4ECV (Quality Assurance for Essential Climate Variables) project aims at developing traceable quality assurance (QA) methods for ECVs, which are then applied to generate multi-decadal satellite-derived global ECV records[27]. The focus of the Q4ECV is on terrestrial and atmospheric ECVs. Within the QA4ECV project, a questionnaire survey was opened in 2014 at http://www.qa4ecv.eu/survey (last accessed September 20, 2016) and thousands of users of satellite-derived ECVs were invited in order to explore their specific usage of satellite data and their

[27] http://www.qa4ecv.eu/node/5 (last accessed September 4, 2016).

requirements for data quality information flags, traceability, uncertainty, and validation (Nightingale et al. 2015). The responses can be downloaded publically[28].

21 of all 176 QA4ECV survey respondents state that they apply satellite data for the detecting and analysis of vegetation fires. It is not clearly stated if active fire or burned area products are used. The following section incorporates an analysis of the answers given by this subgroup. One half of these respondents require satellite information for scientific application, the other half for governmental and commercial decision support purposes. Most of the respondents apply satellite data either to address questions relating specifically to fires (e.g. fire management) or to address broader land cover, agriculture and forestry related issues. One third specifically mention that they use fire satellite data for climate, carbon or biogeochemical modelling purposes.

5.2.2. Type of burned area data products and spatial coverage

The respondents of the Fire_cci phase 1 survey in 2011 gave the highest preference to both, pixel and patch-level products. These products allow for the identification and analysis of individual fires. Relatively well-resolved (i.e. 0.1 degree) gridded continental scale products were rated second in terms of usefulness. The latter can, for example, be used in landscape to regional-scale models. Global 0.1 or 0.5 degree gridded products with weekly temporal resolution were rated third. Such globally gridded products are particularly useful for applications in global models with their relatively coarse resolution (Figure 6). Global gridded products with lower spatial or temporal resolution were rated with the lowest ranks.

All respondents of the Fire_cci phase 2 survey - most of which were from the modelling community – require burned area data with global coverage and they clearly prefer global gridded products over pixel products. Some of them stated that they would prefer to have both, a gridded product complemented by a consistent pixel product. The availability of both product types allows for maximal flexibility in the choice of scales. For example, the pixel product can be used to perform statistical studies at fine spatial resolution, but at small scale to work out empirical relationships between observed burned area and other potential fire drivers. The derived parameters can then be used to implement process-oriented fire modules in vegetation models that prognostically predict global burned area. Modelled burned area can then be validated with gridded burned area observations that are consistent with the derived parameters used in the model.

The majority (86%) of the QA4ECV survey respondents stated that they require fire information at the pixel level for their analysis. While the spatial extent of their applications is mostly regional or biome-scale (76%), the respondents opt for global coverage of the data to have sufficient flexibility in changing the region of interest.

In summary, most users of burned area products request global coverage and both pixel and gridded product types.

[28] https://www.surveymonkey.com/sr.aspx?sm=mjv4zm9I5PAIPy8JqQJPGsBj3Ym5F5GjEr%2b24lA5%2bqg%3d (last accessed September 4, 2016).

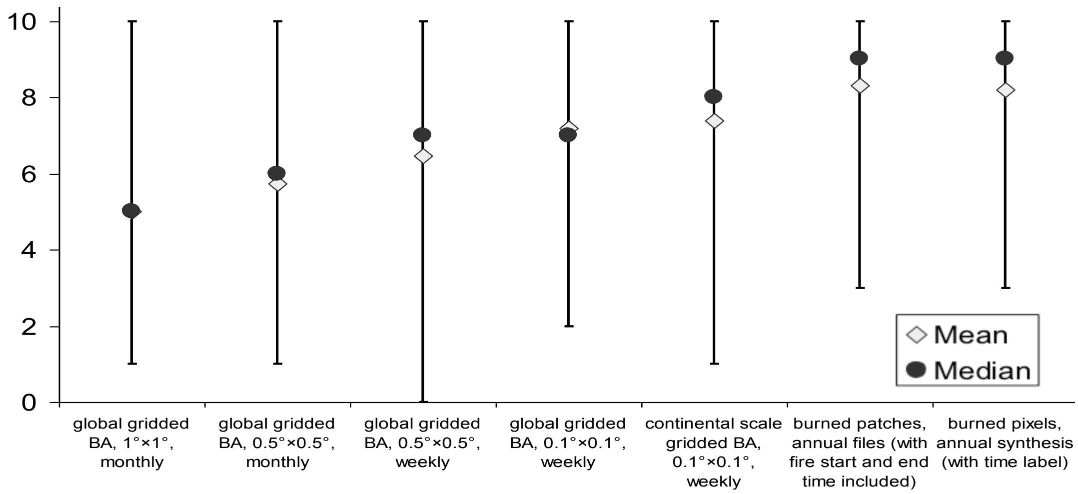


Figure 6: Requested product characteristics for burned area products explored from the Fire_cci phase 1 user survey (Schultz et al. 2011)[29].

5.2.3. Temporal coverage

A fundamental requirement to detect a significant climate trend for a climate variable is a sufficient length of the time series. The required length increases with decreasing accuracy of the satellite observations (Wielicki et al. 2013). For climate variables that are highly variable in time and space, such as burned area, it will take a particularly long time before a climate trend can be detected, even with a perfectly accurate climate data record. Wielicki et al. (2013) exemplifies for global surface air temperature that a climate record of 12 years is required to reach a trend uncertainty of 0.2K per decade at 95% confidence - even for a perfect observing system - because of the need to average out the noise in the climate system. 0.2K per decade is roughly the IPCC predicted global surface air temperature for the next few decades. Wielicki et al. (2013) further illustrates that to reach a 95% confidence level, which is half the expected temperature trend of 0.2K per decade, would require 20 years of perfect observations. For the non-perfect observations of current EO instruments, it would require even more than 35 years of records to detect trends. Similarly detailed statistics on the record length that is required to depict significant climate trend in global burned area have not yet been published.

CMUG (2015a) stated that due to the strong interannual variability of fire activity, the development and evaluation of process-based fire modules in vegetation models will require data products that cover a multiyear timespan (10-20 years). The user requirements with respect to the length of burned area records were not explored in the Fire_cci phase 1 user survey. In the first Fire_cci phase 2 questionnaire survey (section 5.2.1b) all respondents to the question about the required length stated “as long as possible” or “at least 15 years of records”. In agreement, most (71%) of the users of burned area products answering in the QA4ECV survey (section 5.2.1c) state that they would require the entire temporal range of data that is available.

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[29] Users were asked to assess usefulness of each product type on a scale from 0 (not useful) to 10 (maximum usefulness). Vertical lines denote the range of answers provided.

5.2.4. Spatial resolution of the grid product

The Fire_cci Phase 1 URD (Schultz et al. 2011) identified a global gridded burned area product with intermediate (0.5 degree, i.e. around 50 km) spatial resolution as the product type that meets most requirements of global and regional modellers. As a consequence, a global 0.5 degree gridded burned area product was produced and released by the end of Fire_cci Phase 1[30].

Since the Phase 1 URD in 2011, the demand for globally gridded burned area products with spatial resolution higher than 0.5 degree has increased. As a response, a global 0.25 degree gridded Fire_cci burned area product was released in the beginning of Fire_cci Phase 2[31].

The demand for gridded products with increased spatial resolution reflects several aspects of user requirements:

(a) Rapidly increasing spatial resolution of global or regional climate and atmospheric transport models

Citing from the IPCC AR5 (IPCC 2013): “Since the AR4[32], typical regional climate model resolution has increased from around 50 km to around 25 km”. While a typical model grid of complex dynamic vegetation models (DVMs) embedded in general circulation models is still 0.5 degree (~50 km) (Kantzas et al. 2015), there are many atmospheric modelling efforts that take advantage of higher resolution fire information as boundary condition. As specified in section 4.1.1, many regional to continental scale atmospheric model applications are nowadays performed with horizontal resolutions of 20 km and higher. There are an increasing number of studies where terrestrial model simulations with strong relevance to fires are performed at spatial resolutions higher than 0.5 degree. For example, the Terrestrial Model Intercomparison Project of the North American Carbon Programme performed simulations at 0.25 degree resolution over North America. This resolution was chosen to allow for improving the diagnosis and attribution of carbon exchange at scales relevant to carbon management and climate change predictions (Huntzinger et al. 2013).

(b) Compatibility with common satellite grid products which are already provided at 0.25 degree (or higher) spatial resolution

Several common global satellite products which are provided on a regular horizontal grid already have spatial resolutions of 0.25 degree and higher.

The objective of globally gridded data – so-called Climate Modelling Grid (CMG) products – is to provide products at consistent low resolution, both in terms of spatial and temporal scales, so that they are most suitable for global modelling. In practice, there is substantial variation in the spatial and temporal gridding conventions used among different CMG products. Global gridded satellite products provided at 0.25 degree spatial resolution are, for example:

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[30] Fire_cci Phase 1 global MERIS burned area products (version 3.1) publically released in October 2014 is still available at ftp://anon-ftp.ceda.ac.uk/neodc/esacci/fire/data/burned_area/grid/v3.1/ in the case of the grid product, and ftp://anon-ftp.ceda.ac.uk/neodc/esacci/fire/data/burned_area/pixel/v3.1/ for pixel product (last accessed September 20, 2017).

[31] Fire_cci Phase 2 global MERIS burned area products (version 4.1) released in July 2016 (see https://www.esa-fire-cci.org/content/new-version-firecci-burned-area-product-released, last accessed November 3, 2017).

[32] AR4 refers to the Fourth IPCC Assessment Report (IPCC 2007).

- MODIS Collection 6 CMG fire products (Giglio 2015, Giglio et al. 2016)[33]
- GFED4 burned area (Giglio et al. 2013) and GFED4s burned area and emissions[34]
- MODIS global albedo, BRDF and nadir BRDF-adjusted reflectance CMG products (Schaaf et al. 2002)
- MODIS land cover (MOD12CI[35]) and snow (MOD10_CG[36]) CMG products
- ESA CCI soil moisture (Dorigo et al. 2015)
- NCEP GFS Global Forecast Auxiliary Grids (Historical Archive)[37]
- TRMM precipitation (Huffmann et al. 2007)

There are several global gridded products provided at 0.1 degree spatial resolution, such as the CAMS GFASv1.2 fire emission product (Kaiser et al. 2012) or the CPM precipitation product, which is the TRMM successor (Yong et al. 2015).

There are also various global CMG products from MODIS provided at 0.05 deg (MCD10CM, MCD43C[1-4], MOD09CMG) (e.g. Gao et al. 2005; Liu et al. 2012; Claverie et al. 2013). By remote sensing researchers, these 0.05 deg CMG products are still is denominated as “coarse resolution” products, see e.g. Claverie et al. (2013).

The requirements of climate users for 0.25 degree and higher gridded EO data is also reflected in the questionnaire survey conducted among climate users, primarily reanalysis data users, in May/June 2015 by the Integrated Climate Data Center (ICDC). The ICDC has the mandate to provide easy-to-use, easy-to-access climate relevant EO data. When asked which spatial resolution they require for grid products, the majority of respondents stated as “as high as possible”. Among those detailing specific grid resolutions, more respondents stated that they would require 0.25 degree or higher resolved than coarser resolution data. As a result, most global gridded datasets, which have recently been added to the ICDC archive, have spatial resolutions of 0.25 to 0.05 degree.

With the increasing spatial resolution of common global CMG products, users of global burned area information increasingly request products that catch up with these resolutions. The availability of global CMG products with increased spatial resolution allows, for example, for more spatially explicit multiproduct analysis. It is principally easier for climate users to ingest different fire input data when they are on the same grid. One major benefit of the gridded MERIS Fire_cci product released in 2016 with 0.25 degree spatial resolution is, for example, the direct grid-by-grid comparability with GFED4. GFED (see section 0), the most widely used reference for benchmarking burned area by climate researchers, has increased spatial resolution from 0.5 to 0.25 degree when going from version 3 to version 4 in 2013.

(c) Consistency across CCI ECVs

ESA requests to foster cross-ECV consistency and combined ECV studies to maximize synergistic effects between the CCI consortium[38]. One on-going cross-ECV activity of the ESA CCI Climate Modelling User Group (CMUG) is to use gridded Fire_cci data in combination with the CCI soil moisture product to obtain an observational description

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[33] The MODIS CMG fire products provide gridded statistical summaries of fire pixel information.
[34] http://www.globalfiredata.org (last accessed September 20, 2017).
[35] http://webmap.ornl.gov/ogcdown/dataset.jsp?ds_id=10011 (last accessed September 20, 2017).
[36] http://www.icess.ucsb.edu/modis/SnowUsrGuide/usrguide_1dcmg.html (last accessed September 20, 2017).
[37] http://rda.ucar.edu/datasets/ds084.3/ (last accessed September 20, 2017).
[38] http://cci.esa.int/projects (last accessed September 20, 2017)

of the functional relationship between soil moisture and burned area (CMUG 2015b). Because of observational limitations, the spatial resolution of the CCI soil moisture product is provided at 0.25 degree (Dorigo et al. 2015). Provision of the Fire_cci grid products at the same grid strongly enhances cross-comparability and usability.

(d) Technological advancements

The drastic advancements in computer and software technologies of the last decade increasingly facilitate the handling of large data volumes of high-resolution products. Technically, all climate users can nowadays easily upscale high-resolution data to gridded products with lower resolutions. From this point of view, high-resolution products constitute no longer a major hindrance. However, certain variables such as those referring to the uncertainty quantification, require specialized interpolation methods and inappropriate use may lead to misleading results in the regridded product. In addition, the decreased manageability of the large data volumes of relatively high-resolution global products may constitute a non-negligible drawback for users.

5.2.5. Temporal resolution of the grid product

Atmospheric chemistry modelling studies focussing on individual fire events have highlighted that a high temporal resolution of the input emission data is important to realistically capture the temporal and spatial dynamics of the smoke plumes (e.g. Mu et al. 2011, Roberts et al. 2015). These applications would require daily to hourly temporal resolutions.

When opting between monthly or weekly temporal resolution of the grid product, the participants of the Fire_cci Phase 1 user requirement survey (Schultz et al. 2011) gave preference to weekly data (Figure 6). When users provided answers about the required temporal resolution of gridded burned area product in the Fire_cci Phase 2 user survey, most opted for daily resolution. In agreement, most users interviewed for the CMUG Requirements Baseline document (CMUG 2015a), responded that they would require daily to 3-daily temporal resolution for climate trend monitoring applications. For the prescription of model boundary conditions, up to 3-hourly temporal resolutions would be required.

These preferences, however, are given under the presumption that the sensors do not limit meaningful estimates at the requested temporal resolutions. For a more realistic judgement, users would require information about the highest reasonable resolution of globally gridded products that can be achieved from the different existing global observing systems. Such information could be obtained from statistics of the spatiotemporal sampling of the underlying satellite constellation (Zhang et al. 2006). Because of the relatively low temporal coverage of the MERIS sensor, a bi-weekly temporal resolution was considered as most reasonable for the global gridded MERIS Fire_cci product released in 2014 and 2016 (see section 3.1.5).

To address the increasing user's needs for daily to hourly temporal resolutions, GFED3 and GFED4s, for example, provide complementary files containing gridded scalars that allow calculating daily and 3-hourly burned area and emissions from the monthly grid products. The approach used to derive these scalars relies on MODIS and GOES active fire information and is described in Mu et al. (2011).

5.2.6. Accuracy requirements

In the Fire_cci Phase 1 survey in 2011, users were asked to estimate their required product accuracy in terms of burned area (in %), completeness (omission errors in %), false attributions (commission errors in %), geolocation accuracy (in m), temporal accuracy (in days) and temporal stability (in % per annum). Users were asked to provide different estimates for goal, intermediate and threshold product accuracies. The latter was defined as threshold beyond which the product becomes useless for their applications (

Table 5).

It was, however, not clearly specified to what regional or temporal scale the estimates should refer to[39]. It is therefore unclear if the users provided best guesses with respect to global or regional burned area products. It is also unclear if these guesses refer to short-term or long-term averages of burned area products.

Furthermore, it is unclear how users understood individual accuracy metrics. From the ambivalent answers obtained on the required product accuracies, for example, it was clear that some users rather quantified the accuracy margins while others some kind of error rates (e.g. 1 – accuracy). To use the results, the answers were roughly harmonised into a guess for a "threshold error" (labelled as "overall" in

Table 5). Yet, it remains unclear if product accuracy is understood as overall accuracy (quantifying the burned/unburned classification errors via comparison with ground truth information in a confusion matrix) (see e.g. Padilla et al. 2015) or as accuracy metrics that are more commonly used in climate research, such as root mean square error (RSME) or mean absolute error (MAE) (Warner 2011) or else as kappa coefficient of agreement (Olofsson et al. 2014, Mohler and Goodin 2012, Bastarrika et al. 2011). There is an even wider range of possible interpretations for temporal stability requirements as, in excess of thereof, it is unclear if temporal stability refers to the temporal (random) variability or to a systematic trend throughout time (Padilla et al. 2014b, Chuvieco 2016). The estimates provided by the users have therefore to be interpreted with reserve.

On average, the respondents of the Fire_cci phase 1 survey require an overall error of less than 5% in the goal requirement. 15% is stated as intermediate and 25% as threshold error requirement (

Table 5). The users requested, on average, slightly more stringent requirements applied to commission errors (goal = 4 %, intermediate = 11 %, threshold = 17 %) than to omission errors (goal = 4 %, intermediate = 13 %, threshold = 19 %). Several users noted that a certain omission and commission error was acceptable as long as both errors were well balanced. With one exception, respondents of the Fire_cci phase 2 survey only provided the qualitative statement when asked for the required accuracy, namely that they would require improved product accuracies in either product type to what is currently available. One respondent quantified required accuracy as an error of 25 %. Also in this questionnaire, it was unclear to what definition of accuracy and to what spatial or temporal integrals of the products the users were referring to.

The answers of the respondents of the Fire_cci Phase 1 survey with respect to positional accuracy varied largely and were rather ambiguous (

[39] See also design of the questionnaire in Annex 1 of Mouillot et al. (2014).

Table 5). Estimates for the reasonable geolocation error, for example, ranged between 5 m and 50 km; the mean value is 2 km. Generally, the exact location of a fire should principally be of lesser importance for earth system modelling (including atmospheric chemistry, carbon cycle and dynamic vegetation modelling). When the severity of individual burns has to be assessed or when satellite data are being used in real-time to guide firefighting measures, high spatial accuracy is required. Positional accuracy also gains importance for spatially resolved statistical analysis of fire drivers at regional scales, such as investigations between fire occurrence and orography.

Table 5: Accuracy requirements for future burned area products based on the Fire_cci Phase 1 questionnaire survey. "Overall" refers to the product accuracy: burned area (in %).

Product error		Overall (%)	Omission (%)	Commission (%)	Geolocation (km)	Timing (days)
Goal	**Mean**	5	5	4	1	2
	Range	0-20	0-10	0-20	0-20	0-20
Intermediate	**Mean**	15	12	10	2	10
	Range	5-30	0-40	0-30	0.005-50	1-150
Threshold	**Mean**	25	20	17	5	15
	Range	10-50	0-50		0.008-10	2-200

The required temporal accuracy of the date of burn detection explored in the Fire_cci Phase 1 survey ranges from 1 to 9 days (goal to threshold error). The reasonable error is given as 6 days. For comparison, the accuracy of the day of detection in the Collection 5 MCD45 product calculated as the median time difference in reporting between the date of burn reported in the MCD45 product and the active fire product detections is one day[40]. These results refer to a global assessment over 6 years.

With respect to the temporal stability, the respondents of the Fire_cci Phase 1 survey stated that less than 15% variability in the data products would be required in order to make reasonably accurate assessments of actual fire variability.

5.2.7. Uncertainty characterisation

Povey and Grainger (2015) state that "Confidence in satellite data is communicated to users through uncertainty estimates and quality assurance statements [...]. Uncertainties in retrievals of burned area from satellite imagery are related to a variety of errors such as instrument noise, systematic effects, and, in aggregated products, sampling effects. Uncertainty in satellite burned area retrievals is characterised by estimating the distribution of errors and hence requires a good understanding of the errors sources. Error propagation is one method to quantify uncertainty and targets at quantifying how an error in the fundamental satellite measurement (e.g. noise in reflectances) changes the retrieved burned area (Merchant and Embury 2014) Or, in other words, error propagation quantifies the uncertainty in a measurement due to (a) well-understood perturbations in a measurement and in auxiliary data – known, quantified "unknowns", and (b) the propagation of these errors to the final product. [...] (Povey and Grainger 2015).

[40] http://landval.gsfc.nasa.gov/ProductStatus.php?ProductID=MOD45 (last accessed September 20, 2017).

The provision of uncertainty information associated with climate data records is an integral part of all CCI ECVs (Hollmann et al. 2013). Nevertheless, the provision of fully uncertainty-characterised products is still in a fledgling stage. Sufficient information on the uncertainties associated with long-term ECV datasets is a critical requirement for evaluating predictions of climate change and for building the next generation of climate models (McConnel and Weidmann, 2009). Povey and Grainger (2015) comment that a quality assurance layer shall complement the uncertainty layer. They emphasize that it is not only important to quote the uncertainty on any measurement in any CDR, but that it is evenly important to validate the provided best estimate of the measurement *and* the corresponding estimation of measurement uncertainty.

The need for an adequate uncertainty characterization associated with the Fire_cci burned area estimates has been stressed as outcome of the Phase 1 user assessment (Schultz et al. 2011) and has been reiterated by Fire_cci product users and the Fire_cci team during Phase 2. However, only 4 out of the 27 respondents and none out of the 10 respondents that answered to the Fire_cci questionnaire surveys in Phase 1 and Phase 2, respectively, stated to have used uncertainty information contained in burned area products. Also none of the participants of the 2017 Fire_cci user workshop, which mostly populated from the DGVM community, have used the uncertainty layer contained in burned area products. In contrast, QA4ECV survey respondents stated that they widely used the uncertainty values contained in a satellite product or of separately provided statements of a variable’s, uncertainty. These users clearly request uncertainty information at the pixel level. As usages of uncertainty information, they quote thresholding, weighting, data aggregation, extracting 'good enough' quality data points, statistical testing, data assimilation, uncertainty bounds for ground data comparisons.

From discussions within the Fire_cci team, the request emerged to explore in more detail what uncertainty characterisation and quantification users require. There are different approaches (Bayesian error propagation, ensemble techniques, uncertainty components) and measures of uncertainty (e.g. standard error of the mean, standard deviation), and users would require a comprehensible description of each of those to better judge what would be most beneficial for their applications. The appropriate choice of the measure used to estimate the uncertainty is crucial as wrong choices could lead to spurious results (IPCC 2000).

The most common quantitative measure to present uncertainty information in satellite climate data records (CDRs) is a variable's best estimate together with its “standard uncertainty” (Merchant et al. 2014, 2017[41]). In the Guide to the Expression of Uncertainty in Measurement (GUM), published by ISO, defines standard uncertainty as the uncertainty expressed as a standard deviation. In agreement, the EU H2000 funded FIDUCEO (Fidelity and uncertainty in climate data records from Earth Observations[42]) defines that "Standard uncertainty describes the standard deviation of the probability distribution describing the spread of possible values".

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[41] For ESA CCI products, see Merchant et al. 2017. Example for other products, e.g., is the global satellite-derived product of daily surface air temperature derived within the EUSTACHE project (https://www.eustaceproject.eu/) (Merchant et al. 2015). It contains error-propagated uncertainty quantifications expressed as standard deviation. Also, the uncertainty estimates for the FAPAR operational products derived from MERIS are given as standard deviations (Gobron et al. 2008).

[42] http://www.fiduceo.eu/content/standard-uncertainty (last accessed December 1, 2017).

Within the EU FP7 funded QA4ECV (Quality Assurance for Essential Climate Variables) project, a survey about uncertainty was circulated among data producers of atmospheric ECVs, asking for used terminology, components taken into account, and the calculation method. The respondents stated that, in practice, they consider uncertainty propagation on the satellite signal, but not always on auxiliary data while uncertainty due to method approximation is often not included. As a quantitative measure, always the 'standard uncertainty' (standard deviation) is calculated (Compernolle et al. 2016). Also in the 2017 GCOS user requirement survey, users are asked to specify threshold requirements for the uncertainty of ECV products in terms of standard deviation (see Section 5.3).

Merchant et al. (2017) show that most projects in the CCI programme adopted standard uncertainty as the provided uncertainty information, which is a convergence that arose after sustained discussion across the programme and which is in line with metrological guidance. As stated by Merchant et al. (2017) standard uncertainty is a highly informative measure when the error distribution is close to Gaussian; they recommend that "as a baseline for good practice, total standard uncertainty should be quantified per datum in a CDR, meaning that uncertainty estimates should clearly discriminate more and less certain data".

The CCI SST products, for example, contain an estimate of total uncertainty of the SST retrieval expressed as standard deviation. In addition, they contain layers quantifying the uncertainty components: uncorrelated uncertainty (due to effects that are random between locations), synoptically correlated uncertainty (due to effects that are correlated over scales of approx. 100 km and 1 day), large scale correlated uncertainty (due to effects that are highly correlated over large scales) and adjustment uncertainty (uncertainty component associated with adjusting SSTs to a standard depth and time)[43]. Also the ESA CCI Aerosol project implemented a detailed uncertainty characterisation, which comprises assessing different sources of error and their behaviour, an assessment of the sensitivities of the retrieval algorithm to each source of uncertainty, a description of all the different contributions to the total error budget of satellite data and the consideration of error propagation.

In January 2016, a Fire_cci telecon was held to discuss possibilities to improve on the uncertainty characterisation of the Fire_cci Phase 1 pixel product towards user requirements. It was stated that the “unknown” state contained in the Layer 1 (JD) of the product should be differentiated into pixels that are not processed (e.g. water bodies) and pixels for which insufficient observations are available for the algorithm to classify if there is burned areas or not. It was also stated that the pixel product should not only contain uncertainty information for the pixels classified as burned, but should also include information on the omission uncertainty, i.e. an uncertainty characterisation of pixels classified as unburned. It was also stressed that the Fire_cci pixel product should include a qualifier providing information on the accuracy of the estimated burn date. Both types of information are, for example required for correctly identifying burn patches. It was also proposed to enquire which scaling strategy to translate the pixel level uncertainty to a gridded estimate of the burned fraction is most useful to users. In the MERIS Fire_cci v3.1 and v4.1 products, the scaling of pixel-level information to a grid level burned area estimate relies on summing up the area of pixels that are

[43] http://www.esa-sst-cci.org/PUG/pdf/SST_CCI-PUG-UKMO-201-Issue_1-signed.pdf (last accessed November 26, 2017).

classified as burned. It was recommended that a simple, burn confidence-weighted scaling approach should be implemented to enhance consistency between pixel and grid level information. It was also stressed that the meaning of the grid and pixel level uncertainty information should be better described in the Product Specification Document (PSD) and Product User Guide (PUG).

The proposed scaling agrees with the requirements expressed by the participants of the 2017 Fire_cci user workshop. They clearly favoured grid burned area products that rely on such a probabilistic aggregation of pixel level uncertainties over 'traditional' grid estimation approaches. The latter relies on the summation of pixels classified as burned with a fixed burn probability threshold (see Annex 4).

In July 2016, a Fire_cci workshop was held dedicated at the uncertainty quantification of burned area algorithms (Gomez-Dans and Brennan 2016). During the workshop, different sources of uncertainty inherent in the Fire_cci MERIS burned area detection algorithm were identified and investigated. The final objective was to demonstrate to algorithm developers which techniques they will need to use in order to effectively report uncertainty in their products. Gomez-Dans and Brennan (2016) point out that uncertainty quantification of burned area products is crucial for the correct use of burned area information e.g. in global vegetation models through either parameter optimisation or data assimilation. In each of these cases, the burned area observations need to be weighted by the trust that can be attached to individual data points. Information from burned area products should obtain less weight in the parameter optimisation or data assimilation in regions for which the observational data that went into the product was very sparse than in regions for observations were plentiful and unambiguous. Gomez-Dans and Brennan (2016) also point out that the flagging of low confidence information in products is crucial to the gain in knowledge that can be drawn scientific applications that combine heterogeneous data inputs. For example, a strong belief in the timing information of fires, which, in reality, is highly doubtful, significantly lowers the scientific gain that can be drawn from impact studies that contrast bottom-up and to-down emissions from fires. As an outcome of the workshop, Gomez-Dans and Brennan (2016) suggested that the following simplified description of the uncertainty in the pixel product with respect to the timing of the detected burn is used: most likely day of burn (DoB), probability of a burn happening at the most likely DoB, and the earliest and latest possible DoB. The requirements expressed by the participants of the 2017 Fire_cci user workshop mostly agreed with these suggestions (see Annex 4).

Finally, the ESA CCI climate user modelling group (CMUG) (CMUG 2015a) stressed the need of using a consistent terminology for error characteristics across CCI projects and provides in the appendix of CMUG (2015a) a rather descriptive definition for the main error measures (accuracy, precision, stability, measurement error, bias, uncertainty, traceability and representativity). However, as a mathematically precise definition is still missing, misinterpretation and misuse of the individual error measures is likely.

5.2.8. Ancillary data layers: Quality assurance indicators

Respondents to the Phase 1 Fire_cci questionnaire survey requested quality information in the pixel product specifically flagging algorithm or sensor failure, the sensor type in merged products, contaminations by clouds, cloud or topographic shadows or smoke, or otherwise poorly or unobservable pixels. This request was reinforced by participants of the Fire_cci Phase 2 surveys and workshops.

Users participating in the QA4ECV survey (online at http://www.qa4ecv.eu/survey, last accessed 1 December 2017) stated that they used quality information, whenever it was contained in satellite products. The users made use of it for e.g. thresholding, error estimates for data assimilation, quantifying uncertainty bounds, masking/eliminating outliers, identification of contaminated spectral signatures. The users participating in the QA4ECV survey clearly state their interest for detailed data quality information at the pixel level.

Povey and Grainger (2015) explain that "Quality assurance (or flagging) is a qualitative judgement of the performance of a retrieval and the suitability of that technique for processing the data. This complements the uncertainty, whose calculation assumes that the forward model is appropriate to the observed circumstances."

5.2.9. Ancillary data layers: land cover

The Fire_cci Phase 1 user requirement survey (Schultz et al. 2011) disclosed a clear demand for ancillary data layers providing information on the vegetation type affected by fire. In compliance, the Fire_cci products contain separate layers specifying (a) the land cover class of the burned pixel (pixel product) and (b) the sum of burned area per land cover class and grid cell (grid product). As land cover map, the Globcover map for the year 2005 was used in the Fire_cci Phase 1 products (Arino et al. 2008a). For the released of the Fire_cci Phase 2 MERIS burned area products in 2015/2016, the land cover map was changed to the ESA CCI Land Cover (LC_cci) data.

In 2013, the ESA CCI Land Cover project released three new global land cover data sets, one for each of three epochs (1998–2002, 2003–2007 and 2008–2012) (Poulter et al. 2015a) using a the Globcover spectral classification approach (Arino et al. 2008a), but with major improvements (Radoux et al. 2014), and with implementations ensuring temporal consistency across epochs (Bontemps et al. 2012). The scientific exploitation report prepared by ESA CCI Climate Modelling Group (CMUG 2015c) recommended the use of the LC_cci data in Fire_cci burned area products. First of all, large-scale bottom-up estimates of terrestrial carbon fluxes, whether based on models or inventory, are highly dependent on the land cover map used (Quaife et al. 2008). Estimates of carbon fluxes and emissions of trace species and aerosols are similarly sensitive to the underlying land cover information (Wiedinmyer et al. 2011). Tsendbazar et al. (2016) showed that the overall accuracy of the Globcover map (61.3 ± 1.5%) is distinctly poorer than the overall accuracies of the LC_cci or MODIS maps (70.8 ± 1.4% and 71.4 ± 1.3% respectively). The GlobCover map quality varies strongly across regions (Defourny et al. 2012) and its thematic accuracy is particularly poor for the aggregated cropland and forest classes (Fritz et al. 2011). The CMUG scientific exploitation report (CMUG 2015c) furthermore states that the use of the LC_cci data as the land cover input, combined with the CCI Fire data, would allow for better localization of peat and deforestation fires.

Secondly, the use of the LC_cci data in the Fire_cci products constitutes one major step towards more consistency across CCI ECVs. Technical and scientific consistency between the different ECV datasets is one of the outstanding benefits of the ESA CCI project (Hollmann et al. 2013) and a substantial advancement towards user requirements. It not only strongly facilitates cross-ECV or multi-ECV studies, it also enhances the scientific gain.

5.2.10. Ancillary data layers: Fire size and patch ID information

Fire size distributions have been increasingly important to descriptions and explanations of ecosystem organization and structure in general (Moritz et al. 2011). Information on the fire size distribution is essential to characterise fire regimes (Loepfe et al. 2010, Yue et al. 2014a) and to understand and quantify the linkage between fire behaviour and climate patterns, vegetation type and anthropogenic disturbances (Hantson et al. 2015a). Mechanistic fire modelling in large-scale dynamic vegetation models would particularly benefit from spatially and temporally resolved fire size distribution information.

Fire size distribution data is also needed for model evaluation (Yue et al. 2014b): comparing observed and simulated fire regimes, i.e. the combined information on fire timing, size, numbers and intensity (Gill and Allan 2008), will help to reveal our current gaps in understanding the mechanisms that drive burned area: i.e. the rate of spread, fire patch length, daily active burning time, fire size, ignition frequency, and fireline intensity (Yue et al. 2014a). Finally, detailed, observation-based knowledge on the fire size distribution is a requirement to better predict spatial fire characteristics under changing social and climatic conditions (Hantson et al. 2015a, b).

Yet, Archibald et al. (2013) state that ground observation-based spatial information on fire spread and fire size distributions is very rare, and, like fire return time, available only at few locations at which detailed records of individual fire scars have been kept.

Over the past 5 years, several global or regional fire size distribution analysis have emerged that take advantage of newly developed pixel aggregation methods to compute burn patches from satellite burned area pixel products (Archibald and Roy 2009, Archibald et al. 2010, Balch et al. 2013, Hantson et al. 2015a,b, Chuvieco et al. 2016). Satellite-based burned pixel products are therefore gaining increasing importance in various climate science applications relating to fires. Pixel-level burned area products typically deliver pixel identification of burned dates. Neighbouring burned pixels with burned dates within a short temporal window are considered as belonging to the same fire or "fire patch". The flood fill method (Archibald and Roy 2009, Archibald et al. 2010, Hantson et al. 2015a) allows for an aggregation of pixels into burn patches. The setting of the threshold of the time windows for patch partitioning, however, is critical (Archibald and Roy 2009). An inadequate temporal window either leads to an artificial joining of adjacent fires into one burned patch or the inaccurate fragmentation of individual fires into several burn patches. Particularly in areas where individual fires can occur in close proximity, such as in the savannahs, the performance of the flood fill method is highly sensitive to the temporal threshold.

With the exception of the Fire_cci grid product, currently publically available global burned area products do not provide information on the patch number. Since the flood fill method is not a trivial task to develop for end users and since is time consuming when performed at the global level, the community would greatly benefit from ancillary layers – or a separate supplementary product - containing information on the size and morphology of individual fires. Users would also benefit from the development of product-specific flood-fill algorithm with time windows thresholds suitable for each biome. For the pixel level product, yearly patch IDs (to prevent from bi-weekly cutting of fire patches) should be delivered. From this patch ID information, relevant information on fire rate of spread, patch characteristics will be easily computed from the community. Finally, there should be a comprehensive documentation describing the patch discrimination and identification method and a justification for the selected time window thresholds.

In the grid level product, information on the number of patches should be delivered and, ideally, the parameters of a power-law function describing the fire size distribution (Hantson et al. 2015a). Specific care should, however, be considered regarding the overlap of large patches over neighbouring grid cells. Global scale studies use spatial resolutions close to 2 ° resolution (Hantson et al. 2015a,b) to minimize this issue; an increased resolution (0.25° or higher) will increase biases in large patch fragmentation. The location of fire start (earliest burned date) for each patch could be considered for each patch to attribute the grid cell it belongs to. On a bi-weekly basis, the largest patch size per grid cell would inform on the extreme events - a critical information for DGVM's fire spread calibration.

5.2.11. Data formats

In the Fire_cci phase 1 user survey in 2011, the users equally preferred the proposed data formats ArcGIS shape files, ASCII, HDF5, or NetCDF. Some user groups, however, indicated no interest in ArcGIS or ASCII files, while others disapprove of HDF5 or NetCDF data. Users participating in the Fire_cci Phase 2 survey stated that they are satisfied with the data formats of currently released Fire_cci burned area products, namely GeoTIFF for the pixel product and NetCDF for the grid product.

ESA predefined minimum requirements in terms of data types, formats, metadata and file names intended to be taken into account by all CCI projects (ESA Climate Office 2015). The objective is to ensure consistency between output products from the different CCI projects. The CCI Data Standards Requirements specify that output data should be produced in NetCDF-4 (classic) data format and should be compliant with the CF convention (CF-1.6). Nowadays, the climate and atmospheric science community increasingly also use HDF5 formats in addition to NetCDF-4 (e.g. Yang et al. 2005; Atkinson et al. 2013) while other communities prefer GeoTIFF, ArcGIS or ASCII.

5.2.12. Documentation and user support

The CMUG product assessment team (CMUG 2015d) stresses that the current Fire_cci products (v4.1) miss an accompanying guideline on how to understand and use the reported uncertainties and what the different advantages of using the uncertainty information are. Such a guideline would contribute to promote that uncertainty information contained in the products are widely used and thereby contribute to overcome the persisting reservation among of most users in using this information.

In agreement, most users participating in the QA4ECV survey stressed that they would value advice on how to use the uncertainty information in their specific application (e.g. forum in which to ask questions, share best practices etc.) and to have product-specific best practice guidelines for doing independent product validation (e.g. a set of documents describing the state-of-the-art, community agreed optimal method/s for undertaking a particular activity).

The ESA CCI sea surface temperature (SST) project, for example, held a 3-day user workshop on uncertainties in November 2014[44]. Via two-way discussion between SST data providers and users, common understanding was established of where uncertainties come from and of how to talk about them. It was further jointly analysed how well the uncertainty information that current SST products are providing addresses users´ needs. Finally, it was demonstrated how to practically use the uncertainty information

[44] See http://www.esa-sst-cci.org/PUG/workshop.htm (last accessed September 20, 2017).

contained in the ESA CCI SST datasets. Some of these practical examples, including the python code, are also incorporated into the most recently released SST CCI Product User Guide (Rayner et al. 2015). Similarly, the Ocean Colour (OC) CCI Product User Guide (PUG) provides formulas how to calculate the uncertainties when creating composites from the pixel products (Grant et al. 2015).

86% of the users participating in the QA4ECV survey stated that it is important for their application to know the nature of the entire processing chain of the dataset they are using. However, only 19% consider this information to be easily accessible. However, to better adapt methods from these projects to Fire_cci data, it should be considered that SST and OC are quantitative variables, while Burned Area is a categorical one.

5.2.13. Data access

In the Fire_cci phase 1 survey in 2011, most users preferred open access to the data via web download or FTP allowing for a systematic and fast download of large volumes of data. There was only moderate interest in internet-based mapping or web coverage services and on-demand access was generally not regarded as an attractive option.

The Fire_cci project allows for FTP-download of the global Fire_cci burned area products. To accommodate Fire_cci users with limited access to heavy computing facilities, the global Fire_cci pixel-based BA product is delivered in continental tiles, to reduce the size of the files and improve downloading time.

With respect to timeliness, the users responding to the QA4ECV survey (Section 5.2.1c) stated that they would require updated fire information data within 8-16 days (43% of the respondents), 1 day (29%), or monthly (24%).

5.2.14. Web-based data visualisation and extraction tools

To address the diversifying specific requirements of user communities in terms of resolution, region of interest or file formats, there is an increasing demand for web-based tools to visualise, analyse and extract the data. An example for such a tool is the Carbon Data Explorer, a web-based open-source application to manage, aggregate, visualize, and share any time-varying, spatially explicit scientific dataset (Endsley and Billmire 2015).

Users also increasingly ask for online tools or source codes (R, Matlab or Python) to process the pixel products into the specific resolution (temporal and spatial) that the users desire. The GFED website, for example, provides example code (Python and Matlab)[45] how to read the hdf5 GFED files, to regrid them and to compute emission estimates. Also the ESA CCI Land Cover project provides a user tool for sub-setting, re-projecting and re-sampling the LC_cci products in a way that is suitable to each climate model[46]. These tasks have been addressed by the CCI with the release of the CCI Toolbox (http://climatetoolbox.io/), which provides those capabilities for all the CCI projects. In addition, the CCI Open Data Portal (http://cci.esa.int/data) also provides a web-based data visualization tool for the different CCI products, including Fire_cci MERIS v4.1.

[45] http://www.falw.vu/~gwerf/GFED/GFED4/ancill/code/ (last accessed September 20, 2017).
[46] http://maps.elie.ucl.ac.be/CCI/viewer/download.php (last accessed September 20, 2017).

5.3. Ongoing survey of user requirements

The Fire_cci project has implemented a "rolling requirements review" (RRR) [47] user survey with the aim to get ongoing feedback from active product users on the use and usefulness of Fire_cci and other burned area products. Optimally, this allows to continuously explore newly emerging requirements that are then translated into specific recommendations for product developments. In addition to the on-going public Fire_cci user questionnaire survey accessible via the Fire_cci project webpage, product usage information is registered from users downloading Fire_cci products (see also Section 5.2.1).

Besides the Fire_cci project, ESA CCI Sea Ice project is currently the only partner of the ESA CCI projects that has implemented a similar RRR user survey [48]. The user requirements questionnaire surveys of other projects were typically closed after a few months of runtime. Uncertainty characterisation requirements in the ESA CCI questionnaires were and are typically explored in a general manner. Users are, for example, asked to rate the utility of the uncertainty estimates of a given ESA CCI product, to specify if and for what purpose the uncertainty estimates were used. Furthermore, they should rate the importance to have a full uncertainty characterisation for the chosen application. The usefulness of the answers, however, is questionable. As explored in Section 5.2.6, the respondents may have different understanding of what uncertainties and errors are and how they are estimated.

In principle, answers contained in unsupervised self-administered questionnaires have to be analysed with caution since it remains unclear if the questions are interpreted as intended. This is particularly relevant for inquiring data regarding uncertainty since no common understanding can be presumed among the interviewees. Because of this, a recent survey [49] assessing the uncertainty requirements of fundamental climate data record (FCDR) users was carried out through structured interviews [50]. Another, more substantiated approach to explore user requirements with respect to rather complex issues are dedicated user workshops. Such workshops have been held for several of the CCI ECV projects, e.g. for SST in 2014 (see Section 5.2.12) or for soil moisture in 2016 and 2017. The first Fire_cci user workshop took place in October 2017 and is summarised in Appendix 4.

By November 2017, Global Climate Observing System (GCOS) has issued a public questionnaire survey at https://www.research.net/r/ECVRequirements (last accessed November 30, 2017) which will be open until end of 2017. The survey aims at gathering comments on the ECV product requirements, which have been compiled from statements from the various user communities and which are recorded in GCOS (2016). The gathered comments will flow into a future revision of the ECV product requirements expected in 2021-2022. The questionnaire survey allows users to define their product specifications for threshold, intermediate and goal requirements [51] in terms of frequency of observation, spatial resolution, latency (time between observations and

[47] see also http://www.wmo.int/pages/prog/www/OSY/GOS-RRR.html (last accessed September 20, 2017).

[48] https://www.surveymonkey.com/r/PTN7P2T (last accessed September 20, 2017).

[49] Survey of the EU H2000 funded FIDUCEO (Fidelity and uncertainty in climate data records from Earth Observations) project.

[50] Holl, G., Merchant, C., Mittaz, J., Phipps, R. FIDUCEO User Requirements Report. Deliverable D1.1, December 2015. http://www.fiduceo.eu/content/user-requirements-report (last accessed September 20, 2017).

[51] For the definition of threshold, intermediate and goal requirements, please refer to Note 3 in Table 4.

data becoming available), geographic extent, temporal stability, measurement uncertainty (expressed as ± 2 standard deviations). In addition, free comments and justifications for the specified values are encouraged.

5.4. Common terminology

There is a need for a common terminology of individual terms used to describe data uncertainty and a common understanding of the principal approaches and limitations to classify and quantify data uncertainty. Climate modellers across all ECVs have stressed this need. For example, in the Ozone CCI ATBD (Rahpoe 2016), for example, it is stated that "[…] there exists a chaotic ambiguity in terminology: the term "accuracy" has at least two contradictory definitions, depending on which literature is consulted; the meaning of the term "systematic error" is understood differently, the term bias changes its meaning according to the context". It is further stated that "Terminology is a particular problem because most of the related literature, particularly that recommended in CCI -GUIDELINES (2010), namely the Beers (1957), Hughes and Hase (2010) and BIPM (2008[52]), but also CMUG-RBD (2010), refers to scalar quantities" and not to "vectors where error correlations are a major issue" (Rahpoe 2016). "Part of the problem arises because the usual terminology has been developed for laboratory measurements where the same value can be measured several times under constant conditions, which obviously is not possible for atmospheric measurements. Another problem with established terminology is that it does not distinguish between error estimates generated by propagation of primary uncertainties through the system and those generated statistically from a sample of measurements." (Rahpoe 2016).

The Ozone CCI ATBD devotes an entire chapter to establish a common terminology on error characterisation (Rahpoe 2016). In the document, it is suggested that the term "total error" of an instrument/retrieval characterizes the estimated total difference between the measured and the true value. It is advised against calling the expected total error as "accuracy" as widely done in literature. The Ozone CCI ATBD furthermore suggests reserving the term "uncertainty" for the errors that come from other than measurements quantities involved in the retrieval.

Accordingly, the GHG-CCI project refuses using the terms "accuracy" and "precision" in a manner not consistent with (de facto) standard definitions given, e.g., by the Joint Committee for Guides in Metrology (JCGM). For this purpose they use the term "Systematic error" instead of accuracy in their User Requirement documents (URD) (GHG-CCI 2014). In analogy to the definition of accuracy in the glossaries of the CMUG Requirement Baseline Documents (CMUG 2012 and CMUG 2015a), systematic error is defined as "Quantitative measure of the systematic (i.e., non-random) offset, or bias, between the measured value and the true value that constitutes the SI absolute standard."

[52] This cite refers to JCGM 100:2008.

6. Synthesis of burned area data requirements and recommendations

From the analysis of the literature, the user questionnaire and the discussions within Fire_cci team and members of the ESA CCI consortium, the following points may be stressed:

- The main user group of burned area products from the climate community are dynamic vegetation and carbon cycle modellers. Fires also play a very important role in atmospheric composition modelling, since fire emissions are a major atmospheric disturbance. Emissions estimations with biogeochemical models, such as GFED-CASA, depend on prescribed satellite observations of burned area.
- It will be impossible to meet the needs of all user groups with one specific burned area product given the high inter-disciplinarity of biomass burning research. As a consequence, there should be at least a gridded product and a pixel-level synthesis product.
- The demands on product accuracy vary widely, both within and among the different user communities. A clearer definition of the concepts and measures of uncertainty is required. This will foster the general use of error measures in various applications and enable the users to provide more robust estimates for goal, intermediate and threshold values of errors in the future.
- The Fire_cci project should emphasise proper uncertainty and error characterisation of the burned area products. In consultation with different user groups, the Fire_cci team should explore which measures of uncertainty (e.g. uncertainty expressed as standard deviation or minimum to maximum range of values) are most adequate for the different applications and should take this into consideration in the burned area product development.

6.1. Product type, temporal and spatial resolution and record length

The user requirement analysis has shown that there is a great demand for both, pixel-based and global climate model grid (CMG) products. Pixel products provide information at the native spatial resolution of the satellite sensor and are particularly useful for regional applications where the spatial level of detail is of relevance. Global CMG burned area products are primary requested by global modellers, particularly dynamic vegetation and carbon cycle modellers.

The spatial resolution of grid product requested by most users is between 0.1 and 0.25 degrees. For most DGVM applications, a spatial resolution of 0.5° is still adequate on the medium term. In the last decade, there has been clear trend towards the production of satellite CMG products with higher spatial resolution, and for the sake of compatibly, users wish the spatial resolution of the burned area products to keep pace with that of other satellite CMG products they use for their work.

Higher resolutions, such as 0.1 or even 0.05 degrees, will be particularly useful for future applications in regional models and analysis of fire patterns and fire impact in heterogeneous landscapes. The added value gained from an increased spatial resolution of the grid product, however, shall be weighed against possibly difficulties arising from increases in data volume. Since high performance computing systems and tested remapping routines are nowadays accessible to most users, they could relatively simply remap the pixel product to grid product with custom resolution. To facilitate this, easy-to-understand scripts that perform the remapping routines could be provided with the products.

The preferred temporal resolution of the grid product is daily or monthly. If data constraints only allow for monthly temporal resolutions, then supplementary gridded information on how to scale the time integrals to daily or hourly estimates is increasingly requested. One option could be to follow an approach similar to that of Mu et al. (2011), which is used in GFED3 and GFED4s. Here, complementary files containing gridded scalars that disaggregate the monthly products into daily and 3-hourly values are provided. In all scientific publications showing applications of the Fire_cci MERIS grid product (v3.1 or v4.1), the original biweekly resolution of the product is converted to monthly resolution (e.g. Forkel et al. 2016; Hantson et al. 2016; Chuvieco et al. 2016, Nogueira et al. 2017). Hence, it appears that the bi-weekly resolution of the Fire_cci MERIS grid products is rather a hindrance than a help for users. Firstly, it demands for additional processing to convert the biweekly data into monthly time series. Secondly, the conversion can introduce inaccuracies because layers with fuzzy spatial characteristics such as the biweekly fraction of the observed area cannot be converted to a monthly fraction of observed area. In agreement, none of the participants of the Fire_cci user workshop in October 2017 could see practical benefits from biweekly or weekly time resolutions (see Annex 4 Section WS6.WS6.11). For the pixel product, a layer containing the date of burn is the general request.

The requested length of the burned area time series is as long as possible, but at least 15 years. Temporal consistency of the time series is a key requirement in many climate applications. Time series of more than ~15 years can only be reconstructed by merging observations from multiple sensors. Much attention has therefore to be paid to the cross-sensor consistency in merged products.

6.2. Product accuracy

The majority of users explored during the Fire_cci phase 1 survey stated that they would be satisfied with an overall accuracy of the product of 85%, translating in overall error of below 15%. The goal overall accuracy was estimated with 5% error and the threshold value for the error was quantified with 25%. A largely similar range of error estimates for product accuracy is given in the Requirements Baseline Documents prepared by the Climate Modelling User Group (CMUG 2012, 2015a), which specifically focus on the needs of the climate modelling community and other expert users of climate data. For climate trend monitoring, the requested accuracy is specified with 10%, 20%, and 30%, respectively, for goal, intermediate and threshold values of the errors of the products. Respondents to the Fire_cci Phase 2 survey more generally stated that they would require product accuracies than are higher than those achieved in present burned area products.

As explained in section 5.2.6, it is neither exactly clear to what exact accuracy metric these statements are referring to and nor is it clear for what reference period or spatial domain the users were giving accuracy estimates.

Respondents to the Fire_cci phase 1 survey stated that the omission and commission errors should be well characterised and that omission and commission errors should be well balanced and limited to 15%. The goal value lays around 5% and the threshold value of the error at around 17%. Also here, it is unclear to what reference period or spatial domain these estimates are referring to.

Please note that according to GCOS-154 (2011), that an omission and commission errors threshold target of 15 % is the maximum accuracy achievable at 250 m resolution, provided that all improvements in image-acquisition strategies, classification algorithms and processing power are maxed out. Future product developments shall therefore work towards identifying and implementing improvements that are effective but at the same time feasible to minimize omission and commission errors. Moreover, the unavoidable omission and commission errors shall be characterised and quantified in detail. A clear description of the errors, detailing which fire types are commonly missed by the product seems to be a common requirement among users. There is a particular increasing demand for a detailed characterisation of small fires missed by most satellite sensors. Ancillary, regional-scale products from high resolution satellite observation are expected to detect small fires which are missed by the coarser resolution satellite products and are therefore increasingly requested.

Atmospheric chemistry modellers require high accuracies in the description of the date of burn. The pixel-based burned area product should therefore aim at the best possible timing information, optimally with timing errors less than 1-2 days.

6.3. Uncertainty characterisation

- The products shall have a full uncertainty characterisation. The approach and results of the uncertainty quantification shall be described in a related documentation.
- Users request information on the uncertainty in the date of burn detection. Future burned area product developments shall take into consideration the recommendations elaborated during the Fire_cci uncertainty characterisation workshop (Gomez-Danz and Brennan 2016). The recommendations comprise the provision of data layers in the pixel product which quantify the most likely day of burn (DoB), the probability of a burn happening at the most likely DoB, and the earliest and latest possible DoB. Following their recommendations, it shall also be taken into consideration that instead of a confidence level, a probability of burn is provided in future Fire_cci pixel products. In the MERIS Fire_cci v3.1 and v4.1 products, a confidence level is assigned to each burned pixel; however, no uncertainty is assigned to the pixels classified as unburned. This has been added in the MODIS Fire_cci v5.0.
- Users request grid burned area estimates that rely on probabilistic aggregation of pixel-level burn probabilities. The probabilistic aggregation yields a description of the distribution of burned area within the grid cell. If the distribution is assumed to be Gaussian, the probability density function (PDF) can fully be characterised with the mean (the most likely estimate of burned area for the grid) and the standard deviation. Users prefer the standard deviation over other quantitative measures of uncertainty (such as standard error or interquartile range). The standard deviation is the default measure of uncertainty within the ESA CCI projects and should therefore also be chosen as measure for the gridded burned area product.
- Users request the validation of the product's uncertainty layer. Hence, not only the most likely estimate of gridded burned area needs to be validated, but also the uncertainty of this estimate.

6.4. Data quality flagging

- Data quality information at the pixel level shall be provided comprising a specific flagging for cloud contamination/shadow, aerosol contamination, saturation, algorithm or sensor failure, etc.

- To guarantee traceability, users also request pixel-based information on the sensors used when merged multi-sensor products are provided.

6.5. Ancillary data layers

- Information on the vegetation cover that burned and classes of burn severity are the most important ancillary layers requested by the modelling community. To ensure cross-ECV consistency, the ESA CCI Land Cover product shall be used as the map source. Information on the size and morphology of individual fires and the number of individual fires and their size distribution are increasingly requested. This request shall be included in future product developments, but will require substantial method development to adequately identify burn patches in various biomes.
- Users increasingly request the complementary information, which characterises the detected fires in terms of fire energy (Boschetti and Roy 2009, Ellicott et al. 2009), fire temperature and fire size (Eckman et al. 2008) or the specific identification and quantification of crop residue burning (Punia et al. 2008). These requests should be considered carefully for algorithm development and output delivery to ensure a further extensive use of the burned area product.

6.6. Validation

- Validation shall be performed following internationally agreed validation protocols.
- The validation process shall be described in detail. The validation documentation shall provide explicit statements of the specific conditions that limit the accuracy of the products.
- Collecting and delivering high resolution burned areas on validation sites would be beneficial to the community for special aspects of product evaluation such as fire shape characteristics.

6.7. Data format and product dissemination

- Current users of the Fire_cci burned area products are generally satisfied with the data formats in which they are provided: **N**etCDF for the gridded product and GeoTIFF for the pixel products. However, to promote the use of Fire_cci products in communities, which are not familiar with these two standard formats since they are accustomed only to e.g. ArcGIS or ASCII, Fire_cci shall consider producing data in other formats in addition to the standardised products or shall provide links to data format conversion tools.
- Data dissemination of Fire_cci products shall be established in the specific tools developed by CCI: the Open Data Portal and the Toolbox.

6.8. Documentation and user support/feedback

- The documentation attached to Fire_cci burned area products shall include a product manual providing a detailed scientific description of the products, a list of all required inputs and needed ancillary data, and a description of the quality flags.
- Comprehensive and unambiguous explanations of the meaning and derivation of the uncertainty and accuracy measures used in the products shall be jointly elaborated within the Consortium and in consultation of major climate users. The agreed definitions shall be precisely described in a dedicated document.

- The documentation shall also include a detailed description of the product formats. The documentation shall describe all required inputs and needed ancillary data along with a description of the uncertainty associated to the product. The manual shall also contain a description of the strengths and limitations of the products and recommendations for their use.
- The Consortium shall provide users a practical guidance how to use the uncertainty information contained in the products. The guidance documents shall contain a set of sample calculations for various common product applications.
- All scientific results of the Fire_cci project development activities shall be properly documented either in scientific journals or in internal scientific progress reports.
- The Consortium shall organise regular workshops with the key end-user communities and shall establish and maintain direct contact with relevant users (e.g. EO, climate research and modelling communities) in order to assess the use and usefulness of the products being developed.

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Annex 1: Acronyms and abbreviations

AR	IPCC Assessment Report
ASCII	American Standard Code for Information Interchange
AATSR	Advanced Along-Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
ATSR	Along-Track Scanning Radiometer
BA	Burned Area
BAECV	Burned Area Essential Climate Variable
BC	Burn Classification
BIMP	Bureau of Weights and Measures
BP	Burned Probability
BRDF	Bidirectional Reflectance Distribution Function
BSQ	Band SeQuential image encoding
CAMS	Copernicus Atmosphere Monitoring Service
CASA	Carnegie-Ames-Stanford-Approach
CCI	Climate Change Initiative
CDR	Climate Data Record
CE	Commission Error
CEOS	Committee on Earth Observation Satellites
CMG	Climate Modelling Grid
CTM	Chemical Transport Model
CMIP6	Coupled Model Intercomparison Project Phase 6
CMUG	Climate Modelling User Group
CONUS	Conterminous United States
COP	Conference of the Parties
CORINE	Coordination of Information for the Environment
DAAC	Distributed Active Archive Center
DB	Direct Broadcast
DGVMs	Dynamic Global Vegetation Models
DoB	Day of Burn
DVM	Dynamic Vegetation Models
ECV	Essential Climate Variables
EFFIS	European Forest Fire Information System
ENVISAT	Environmental Satellite
EO	Earth Observation
EOSDIS	Earth Observation System Data and Information System
ERS	European Remote Sensing satellite
ESA	European Space Agency
ESDR	Earth Science Data Record
ETM+	Enhanced Thematic Mapper plus

EU	European Union
FAO	Food and Agriculture Organization
FAPAR	Fraction of Photosynthetically Active Radiation
FCDR	Fundamental Climate Data Record
FIDUCEO	Fidelity and uncertainty in climate data records from Earth Observation
FireMIP	Fire Model Intercomparison Project
FIRMS	Fire Information for Resource Management System
FP7	7th Framework Programme
FRP	Fire Radiative Power
FRS	Full Resolution full Swath
FTP	File Transfer Protocol
GBS	Global Burned Surfaces
GCM	General Circulation Model
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GFAS	Global Fire Assimilation System
GFED	Global Fire Emissions Database
GFIMS	Global Fire Information Management System
GHG	Greenhouse Gas
GIO-GL	Copernicus Global Land Service burned area product
GOES	Geostationary Operational Environmental Satellites
GTOS	Global Terrestrial Observing System
GUM	Guide to the expression of Uncertainty in Measurements
HDF	Hierarchical Data Format
HMS	Hazard Mapping System
IBBI	Interdisciplinary Biomass Burning Initiative
ICDC	Integrated Climate Data Center
ID	IDentity number
IGOS	Integrated Global Observing System
IPCC	Intergovernmental Panel on Climate Change
IRD	Institute de Recherche pour le Developpement
JCGM	Joint Committee for Guides in Metrology
JD	Julian Day
LC_cci	Land Cover CCI product
LSCE	Laboratoire des Sciences du Climat et de l'Environnement
MAE	Mean Absolute Error
MERIS	Medium Resolution Imaging Spectrometer
MIPs	Model Intercomparison Projects
MODIS	Moderate Resolution Imaging Spectroradiometer

MSI	MultiSpectral Imager
MTBS	Monitoring Trends in Burn Severity
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NetCDF	NETwork Common Data Format
NIR	Near InfraRed
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Pola-orbiting Operational Environmental Satellite System
NPP	National Polar-orbiting Partnership
NRT	Near Real Time
OA	Overall Accuracy
OC	Ocean Colour
OE	Omission Error
OMI	Ozone Monitoring Instrument
p_b	Probability of burn
PDF	Probability Density Function
PUG	Product User Guide
PSD	Product Specification Document
QA	Quality Assessment
QA4ECV	Quality Assurance for Essential Climate Variables
QA	Quality Indicator
RBD	Requirement Baseline Documents
RRR	Rolling requirements review
RSME	Root Mean Square Error
SDS	Science Data Set
SI	International System of units
SPOT	Satellite pour l'Observation de la Terre
SST	Sea Surface Temperature
t.b.d.	To be disclosed
TIFF	Tag Image File Format
TM	Thematic Mapper
TRMM	Tropical Rainfall Measuring Mission
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
URD	User Requirements Document
USGS	United States Geological Survey
VGT	Vegetation
VIRS	Visible and Infrared Scanner
VMB	Vegetation Model Benchmarking
WGCV	Working Group on Calibration and Validation

Annex 2: Definitions of accuracy, error, uncertainty measures

There is a crucial difference between error and uncertainty. There is, however, a long tradition in written and oral science of using these terms in an interchangeable manner (Tumeo 1994). Also the terms "uncertainty" and "validation" are used inconsistently (Povey and Graigner 2015). Also "accuracy assessment" may easily be confused with "uncertainty characterization" (Chuvieco 2016). When exploring user requirements, it is essential to ensure the different terms are understood and interpreted in a similar manner.

In metrology, i.e. the science of measurement, and in various product user communities the following definitions of error, uncertainty, accuracy and related terms are common:

=== Measurement error ===

According to International Vocabulary of Metrology published by the International Bureau of Weights and Measures (BIPM) (JCGM 2012), the **measurement error** [also referred to as error of measurement or error] is the "measured quantity value minus a reference quantity value"[53]. Similar definitions of error are also given in other references, except that the reference quantity value is referred to as "true value" (Bell 2001) or "correct value" (Tumeo 1994).

Chris Merchand from the ESA CCI SST project[54] stresses that the concept of error puts the question "How different is the measured value from the (unknown) true value of the measurand?" and inquires about the "wrongness" of the data.

=== Measurement uncertainty ===

According to JCGM (2012), the **measurement uncertainty** [also referred to as uncertainty of measurement or uncertainty] is a "non-negative parameter characterizing the dispersion of the quantity values being attributed to a measurand, based on the information used".

JCGM (2012) further specifies: "The objective of measurement in the Uncertainty Approach is not to determine a true value as closely as possible. Rather, it is assumed that the information from measurement only permits assignment of an interval of reasonable values to the measurand, based on the assumption that no mistakes have been made in performing the measurement. Additional relevant information may reduce the range of the interval of values that can reasonably[55] be attributed to the measurand.

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53 Appendix A of the 2015 CMUG Requirements Baseline Document (CMUG 2015a) and in Dowell et al. (2013) use definitions of the "measurement error" and "uncertainty" which are identical to JCGM 200: 2012.

54 http://cci.esa.int/sites/default/files/01_Merchant-Metrol-Uncertainty.pdf [last accessed September 20, 2017].

55 Vosk (2013) explains the term "reasonable" as follows: "Given a measured value, *y*, the question of what values can *reasonably* be attributed to a measurand involves two competing considerations. First, we want to exclude values that, although possible, are highly improbable. Second we need to include enough values so that there is a significant probability that the measurand's value is actually among those considered. The measurement's probability distribution provides a conceptually straightforward way of accomplishing this. Simply slice off the tails of the distribution while including enough of its middle so that the area of the remaining region represents a significant probability that the measurand's value lies within it". "From this, we can obtain a range of values reasonably attributable to a measurand, along with an associated probability that the value of the measurand lies within it. This defines the uncertainty of a measurement. Measurement uncertainty is the quantitative characterisation of the dispersion of values that, based on the universe of information concerning a measurement, are believed to be reasonably attributable to a measurand."

However, even the most refined measurement cannot reduce the interval to a single value because of the finite amount of detail in the definition of a measurand."

The definitional uncertainty, therefore, sets a minimum limit to any measurement uncertainty. The interval can be represented by one of its values, called a "measured quantity value"."

"For every measurement - even the most careful - there is always a margin of doubt. […]. **Uncertainty is a quantification of the doubt about the measurement result**." (Bell 2001), or - as defined by Tumeo (1994) - the "concept or condition of being in doubt about a value". Moffat (1988), in turn, specified that term "uncertainty" is used to refer to "**a possible value that an error may have**." Tumeo (1994) clarifies that **in "the definition of uncertainty, there is no judgment as to the "correctness" of a given value.** […]. While error implies that there is a single "correct" value that can be found, uncertainty involves doubt, perhaps even about the idea of "correctness" ". In principle, if errors are known, they can be corrected for. Any error whose value is not known is a source of uncertainty (Bell 2001).

Chris Merchand from the ESA CCI SST project[54] stresses that the concept of uncertainty puts the question "Given the measured value, what range of values is it reasonable to attribute to the measurand?" and inquiries about the "doubtfulness" of the data.

Uncertainty quantification in the process of remote sensing of climate data is, in the broadest sense, to "account for not only the uncertainty in individual parameters within the models that are used, but also to account for the uncertainty inherent in the actual models themselves, which are only approximate representations of physical processes." (McConnel and Weidmann, 2009).

Propagation of uncertainty is the effect that the uncertainties of the input quantities have on the uncertainty of a function that is based on them. The idea is that the uncertainty "propagates" from the input quantities to the output.

There are several mathematical approaches to propagate estimates of the input quantities and the uncertainties associated with the estimates through the measurement model to obtain estimates of the output quantities and the associated uncertainties.

The GUM uncertainty framework (JCGM 100, 2008), for example, ". . . provides a framework for assessing uncertainty . . . ", based on the law of propagation of uncertainty and the characterization of the output quantity by a Gaussian distribution or a scaled and shifted t-distribution (JCGM 101:2008). The Monte Carlo method is a practical alternative to this GUM framework (JCGM 101:2008). It encodes the available information in terms of probability density functions (PDFs) for the input quantities and operates with these PDFs in order to determine the PDF for the output quantity. This approach has particular advantages over the GUM approach when the PDF for the output quantity departs appreciably from a Gaussian distribution.

=== Accuracy ===

GCOS-143 (2010) states that accuracy is "measured by the bias or systematic error of the data, i.e. **the difference between the short-term average measured value of a variable and the true value**. The short-term average is the average of a sufficient number of successive measurements of the variable under identical conditions, such that the random error is negligible relative to the systematic error. The latter can be introduced by instrument biases or through the choice of remote sensing retrieval schemes".

Also the glossaries of the CMUG Requirement Baseline Documents (CMUG 2012 and CMUG 2015a) define **accuracy as "the measure of the non-random, systematic error, or bias,** that defines the offset between the measured value and the true value that constitutes the SI absolute standard."

However, Appendix A of the CMUG (2015a) defines accuracy as the "**closeness of the agreement between a measured or retrieved quantity value and a true quantity value of the measurand** (BIPM 2010)[56]. The concept 'measurement accuracy' is not a quantity and is not given a numerical quantity value. A measurement is said to be more accurate when it offers a smaller measurement error." The identical definition is also given in Hollmann et al. (2013).

GCOS-154 (2011) states that **accuracy** as used with respect to **ECV product requirements in GCOS-154 refer "not to measurements, but to products, i.e., physical values averaged over or sampled at the spatial and temporal resolutions cited for the product**. **Definitions and notes given in BIPM (2008[57]) and WMO (2008) for measurements are not fully appropriate for products […].** No general assumptions have been made on the statistical error distribution of products, given the diverse physical nature of the ECVs. Therefore, the requirements indicated for accuracy are not stated in terms of defined intervals of statistical significance (e.g. they are not stated in relation to the standard deviation from an expected value). Percentage values for accuracy and stability refer to a locally prevailing reference value. **Product requirements in terms of accuracy are indicative of acceptable overall levels for the uncertainties of product values.** Uncertainty can be influenced by factors such as spatial/temporal sampling, biases introduced by the retrieval method, biases introduced by interpolation methods, calibration errors, geo-location errors, and instrument noise. **It may be quantified by the root mean square (or other measure) of the estimated distribution of errors in product values over a spatial domain, a time interval or a set of similar synoptic situations**."

Merchand et al. (2015) stresses out that "GCOS requirements are currently inadequate for specifying the "accuracy" and "stability" of ECV products at intermediate spatio-temporal scales important for climate applications."

= Positional or absolute accuracy =

"Positional accuracy is defined as the accuracy of the position of features within a spatial reference system" (ISO 2013). Absolute accuracy is the "closeness of reported coordinate values to values accepted as or being true" (ISO 2016).

=== Precision ===

In their glossary, the CMUG Requirement Baseline Documents (RBD) (CMUG 2012 and CMUG 2015a) define precision as "the measure of reproducibility or repeatability of the measurement without reference to an international standard so that precision **is a measure of the random and not the systematic error.** Suitable averaging of the

[56] CMUG 2015a most likely refers to JCGM 200:2012 where "measurement accuracy" is defined as "closeness of agreement between a measured quantity value and a true quantity value of a measurand".

[57] This cite refers to JCGM 100:2008.

random error can improve the precision of the measurement but does not establish the systematic error of the observation."

In the Appendix A of the CMUG (2015a), precision is defined as "the closeness of agreement between measured or retrieved quantity values obtained by replicate measurements on the same or similar objects under specified conditions (BIPM, 2010) [58] . **Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation**, variance, or coefficient of variation under the specified conditions of measurement. "

=== Stability ===

In satellite remote sensing, stability of system outputs is understood as either "consistency of accuracy throughout time, measured either as (1) "temporal variation in accuracy" or as (2) "whether significant trends throughout time exist" (Chuvieco 2016).

GCOS-143 (2010b) defined stability as the "**extent to which accuracy remains constant with time.** Stability is measured by the maximum excursion of the short term average (e.g., daily, monthly, seasonal) measured value of a variable under identical conditions over the long term, e.g. a decade. The smaller the maximum excursion, the greater the stability of the dataset." Similar as for accuracy, stability as used with respect to ECV product requirements in GCOS-154 "**refer not to measurements, but to products**, i.e., physical values averaged over or sampled at the spatial and temporal resolutions cited for the product. Definitions and notes given in BIPM (2008[59]) and WMO (2008) for measurements are not fully appropriate for products […]. The glossaries of the CMUG Requirement Baseline Documents (CMUG 2012 and CMUG 2015a) state that "Stability is a term often invoked with respect to long-term records when no absolute standard is available to quantitatively establish the systematic error" and defines stability as "**the bias defining the time-dependent (or instrument-dependent) difference between the observed quantity and the true value**."

GCOS-154 (2011) states that "the user requirement for stability is in general a requirement on the **extent to which the error of a product remains constant over a long period, typically a decade or more**. The relevant component of error of a product for climate application is often the systematic component defined by the mean error over a period such as a month or year. Values quoted under the heading "stability" in this document refer to the **maximum acceptable change in systematic error per decade**, except for variables for which trends are usually expressed in terms of an annual rate of change, in which case the stability is expressed in terms of this rate of change. Stability of the random component may also be a requirement however, in particular for monitoring long-term changes in extremes."

In the Appendix A of the CMUG (2015a), it is stated that stability "may be thought of as **the extent to which the accuracy remains constant with time**. Over time periods of interest for climate, the relevant component of total uncertainty is expected to be its systematic component as measured over the averaging period. **Stability is therefore**

[58] CMUG 2015a most likely refers to JCGM 200:2012 where "precision" or "measurement precision" is defined as "closeness of agreement between indications or measured quantity values obtained by replicate measurements on the same or similar objects under specified conditions. NOTE 1 Measurement precision is usually expressed numerically by measures of imprecision, such as standard deviation, variance, or coefficient of variation under the specified conditions of measurement."

[59] This cite refers to JCGM 100:2008.

measured by the maximum excursion of the difference between a true value and the short-term average measured value of a variable under identical conditions over a decade. The smaller the maximum excursion, the greater the stability of the data set." The identical definition is also given in Hollmann et al. (2013).

Hollmann et al. (2013) points out "that accuracy and stability […] are two mandatory requirements for climate monitoring across all satellite missions. High accuracy of a measurement is needed to understand short scale climate phenomena and longer-term change processes. However, excellent accuracy is of secondary importance in the detection and quantification of long-term change in a climate variable. This can be determined as long as the dataset has the required error stability."

The estimates provided by users on the required stability could be referring to various interpretations of this term. In Figure 6, stability values of a hypothetical burned area product are calculated using different interpretations of the term stability. In the example, validation is performed with a 10-year time series of annual data by comparing product estimates with 800 km^2 of reference data. For each year, the overall accuracy (OA), omission and commission errors (OE and CE, respectively) and the relative bias (relB) are calculated following Padilla et al. (2014a). Kappa coefficient of agreement, another measure typically used to assess burned area product accuracy, was calculated following Congalton et al. (1983). Stability is calculated for two possible interpretations of long-term stability: (a) stability referring to the "maximum excursion" (largest annual error value within a decade) and (b) stability as the slope of the linear regression of annual errors calculated for a decade. Figure 7 illustrates that dependent on the interpretation of long-term stability and on the choice of the accuracy measures, stability for the same product and reference dataset may vary from 0.1% to 26% (referring to absolute values). Stability estimates are basically meaningless, unless it is not specifically defined to what exact interpretation and accuracy measure a given stability estimate is referring to.

	Reference			
Product	**Burned**	**Unburned**	**Σ Row**	OA=(a+d)/(a+b+c+d)
Burned	a	b	a + b	OE=(c)/(a+c)
Unburned	c	d	c + d	CE=(b)/(a+b)
Σ Col	a + c	b + d	a+b+c+d	relB=(b-c)/(a+c)

Year	a	b	c	d	CE	OE	(1-OA)	relB	(1-Kappa)
1	98	17	17	668	15%	15%	4%	0%	17%
2	110	21	19	650	16%	15%	5%	2%	18%
3	80	19	28	673	19%	26%	6%	-8%	26%
4	103	14	19	664	12%	16%	4%	-4%	16%
5	89	10	16	685	10%	15%	3%	-6%	15%
6	96	10	28	666	9%	23%	5%	-15%	19%
7	91	14	31	664	13%	25%	6%	-14%	23%
8	89	15	18	678	14%	17%	4%	-3%	18%
9	117	12	21	650	9%	15%	4%	-7%	15%
10	107	11	29	653	9%	21%	5%	-13%	19%
maximal excursion per decade per year					**19%**	**26%**	**6%**	**-15%**	**26%**
linear trend per decade (significant at 95% confidence)					**-7%**	**3%**	**-0.1%**	**-11%**	**-2%**

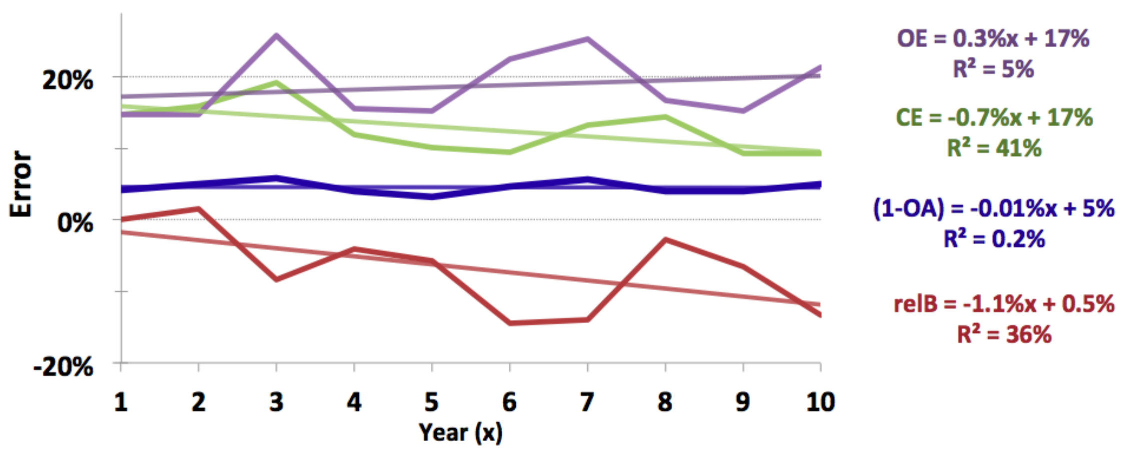

Figure 7: Stability measures of accuracy: Hypothetical example. Values in column a to c refer to areas in km^2. Further explanations, see text.

=== **Consistency** ===

According to CMUG (2014), consistency of a global satellite data ECV product may address several aspects:

• consistency in time (e.g. stability, uncertainty of bias)

• consistency with independent observations(e.g. in-situ or ground-based remote sensing)

• consistency with precursor datasets to understand the differences and assess if the CCI datasets are better representations of the atmospheric/surface state

• consistency compared to reanalysis fields

• consistency across ECVs

• ability to capture climate variability and small climate change signals(e.g. observed trends) for their use in Climate Monitoring and Attribution.

The fire_cci Product Validation Plan (Padilla et al. 2014a) states that "consistency can be defined as the temporal stability of accuracy over time. In other words, the term refers to whether the measured accuracy changes throughout time (year to year, for instance)."

== Quality indicator===:

According to Nightingale et al. (2015), a quality indicator is a "means of providing a user of data or derived products with sufficient information to assess its suitability for a particular application. This information should be based on a quantitative assessment of its traceability to an agreed reference or measurement standard (ideally SI), but can be presented as numeric or a text descriptor, providing the quantitative linkage is defined". In the Collection-6 MODIS Land Surface Temperature Products (Wan 2013), the quality indicator (QC) data layer provides additional information on algorithm results for each pixel. The QC information tells if algorithm results were nominal, abnormal, or if other defined conditions were encountered for a pixel. The QC information should be used to help determine the usefulness of the surface temperature data for a user's needs.

Annex 3: Fire_cci phase 2 online user requirement survey

Available online at https://www.surveymonkey.com/r/RSV8PSF since March 2016 (last accessed Nov. 30, 2017).

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

Survey objective

Welcome,

Thank you for your interest in the Fire_cci Burned Area (BA) product version 4.1. The dataset is generated by the Fire_cci project, which is part of the Climate Change Initiative (CCI) of the European Space Agency (ESA). The primary aim of the project is the generation of long time series of global BA maps in support of climate change modelling research.

Fire_cci BA version 4.1 was released in July 2016, superseding version 3.1 that was published in October 2014. The BA product relies on a newly developed algorithm that exploits spectral information from MERIS imagery in combination with thermal information from the MODIS active fires product (cf. Chuvieco et al. (2016)).

Fire_cci BA version 4.1 covers the period 2005-2011 and consists of a
(i) BA pixel product at full MERIS resolution (around 300 m) with date of detection, confidence level and land cover burned in GeoTIFF format.
(ii) grid product with 0.25 degree spatial and 15 days temporal resolution in NetCDF format including total BA, standard error, fraction of observed area, number of burned patches and BA by land cover type.

During the ongoing Fire_cci project, the BA time series will be extended in time to cover the period 2000 to 2017 by integrating the best combination of satellite sensors. Improvements in the uncertainty characterization and validation are also foreseen. In addition, a small fire database for Africa will be established based on Sentinel-2 MSI data.

For more information on the ESA Fire_cci project, please visit: http://www.esa-fire-cci.org/.

Your feedback is highly valuable for us to develop BA products that are best-suited for a wide range of users. Please help us shaping the Fire_cci products by filling the following 13 questions.

We are keen to receive ongoing feedback from you if you use the Fire_cci products.
For any question, please contact the Fire_cci project manager Dr. M. Lucrecia Pettinari.

Thank you for participating!
Best regards,

Your ESA Fire_cci Team

Refernces:

Chuvieco, E., Yue, C., Heil, A., Mouillot, F., Alonso-Canas, I., Padilla, M., Pereira, J., Oom, D., Tansey, K. (2016) A new global burned area product for climate assessment of fire impacts: the ESA Fire_cci project. Global Ecol. Biogeogr., 25: 619–629. doi:10.1111/geb.12440.

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

User identification

* 1. Please indicate what kind of institution you belong to.

- ☐ University/Research institute
- ☐ Governmental organization
- ☐ Non-governmental/Non-profit organization
- ☐ Commercial sector
- ☐ Other (please specify):

* 2. Please indicate the country in which you are working.

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

Burned area (BA) product use

3. For what general application(s) do you require burned area information?

- ☐ Atmospheric chemistry(-climate) modelling
- ☐ Biogeochemical modelling
- ☐ Dynamic vegetation modelling
- ☐ Statistical modelling of fire patterns and fire drivers
- ☐ Forest and fire management planning (e.g. fire prevention, early-response, post fire measures)
- ☐ Other (please specify):

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

Burned area (BA) product use

4. What satellite-derived burned area products have you used in the past?

- [ ] Fire_cci burned area products
- [ ] So far, none.
- [ ] Burned area products other than Fire_cci. Please specify:

5. Fire_cci pixel product: If you have used or intend to use this product, please provide some details on

the geographical region of interest (global or regional)

the time period of interest

the specific application and purpose

other (please specify):

6. Fire_cci grid product: If you have used or intend to use this product, please provide some details on

the geographical region of interest (global or regional)

the time period of interest

the specific application and purpose

other (please specify):

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

BA uncertainty characterisation

7. Fire_cci pixel product: What kind of uncertainty description do you need?

- [ ] Most likely day of burn (DoB).
- [ ] Probability of a burn happening at the most likely DoB.
- [ ] Temporal uncertainty of the DoB detection (earliest and latest possible DoB).
- [ ] So far, none.
- [ ] Other (please specify):

8. Fire_cci grid product: What kind of uncertainty description do you need?

- [ ] Uncertainty expressed as a standard error of the total BA estimated for each grid cell.
- [ ] Approximate description of the BA probability distribution function (PDF) (e.g. by percentiles).
- [ ] So far, none.
- [ ] Other (please specify):

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

Fire_cci quality indicators

9. Fire_cci pixel product: What quality flag do you need?

- [ ] Flags for unobservable or unburnable pixels are sufficient.
- [ ] Cloud contamination.
- [ ] Cloud shadow.
- [ ] Aerosol contamination.
- [ ] Algorithm failure.
- [ ] Sensor failure (drop out, striping).
- [ ] Sun glint.
- [ ] Water bodies.
- [ ] Snow/ice.
- [ ] Other (please specify):

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

Fire_cci product validation

10. Is the Fire_cci product validation adequate for your application? (1)

☐ Yes.

☐ No.

☐ If not, please specify why:

(1) Validation is "the process of assessing, by independent means, the quality of the data products derived from those system outputs" (http://ceos.org/ourwork/workinggroups/wgcv/). In the case of Fire_cci, the final product is assessed by comparison with reference data, which are derived from Landsat images, following CEOS Cal-Val guidelines (see Padilla et al., 2014, 2015).

References:
Padilla, M., Stehman, S.V., and Chuvieco, E. (2014) Validation of the 2008 MODIS-MCD45 global burned area product using stratified random sampling. Remote Sensing of Environment, 144, 187–196.
Padilla, M., Stehman, S.V., Hantson, S., Oliva, P., Alonso-Canas, I., Bradley, A., Tansey, K., Mota, B., Pereira, J.M., and Chuvieco, E. (2015) Comparing the accuracies of remote sensing global burned area products using stratified random sampling and estimation. Remote Sensing of Environment, 160, 114–121.

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

Your suggestions to improve Fire_cci products

11. Which changes in the Fire_cci products would enhance their usefulness?
Please specify if you are referring to the grid or the pixel product.
(italic: values of the current Fire_cci product)

Temporal frame *(2005-2011)*

Temporal resolution *(pixel: daily, grid: bi-weekly)*

Spatial detail *(pixel: 300x300m; grid: 0.25x0.25)*

Accuracy (1)

Stability (2)

Information layers

Data format *(pixel: tiff, grid: netcdf)*

Data access

Documentation

Other (please specify):

(1) BIPM (2012) defines measurement accuracy as the "closeness of the agreement between a measured quantity value and a true quantity value of a measurand". The GCOS (2011) target requirement for accuracy is 15% (error of omission and commission), compared to 30m observations).
(2) GCOS (2011) defines stability as the extent to which the accuracy of a product remains constant over time. The GCOS target requirement for stability is 15% (maximum acceptable change in systematic error per decade).

References:
BIPM, IEC, IFCC, ILAC, IUPAC, IUPAP, ISO, OIML (2012) The international vocabulary of metrology—basic and general concepts and associated terms (VIM), 3rd edn. JCGM 200:2012. BIPM Joint Committee for Guides in Metrology, Paris, France. [Available online at http://www.bipm.org/en/publications/guides/vim.html].
GCOS (2011) Systematic Observation Requirements for Satellite-Based Products for Climate. 2011 Update (GCOS-154). Supplemental details to the satellite-based component of the "Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC (2010 Update)",December 2011. [Available online at http://www.wmo.int/pages/prog/gcos/Publications/gcos-154.pdf].

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

Wish list

12. If you could influence future BA products, what characteristics would you request with priority?

ESA Fire_cci Phase 2 (2015-2018): Survey among Product Users

Open comments

13. Do you have any other comments, questions, or suggestions?

Thanks a lot!

Annex 4: Summary of the 2017 Fire_cci user workshop

(Report written by A. Heil, J.W. Kaiser, Max-Planck Institute for Chemistry, Germany)

Table of content

Workshop (WS) Summary

The Fire_cci User workshop was held on October 19, 2017 afternoon at IMK-IFU, Garmisch-Partenkirchen, Germany. Since the workshop was organised by MPIC in conjunction with the 4th FireMIP meeting, most workshop participants represented the Dynamic Global Vegetation Models (DGVM) community.

The main goals of the meeting were to (1) deepen the community's understanding of the Fire_cci products, (2) update their requirements on fire observation products and (3) improve a common understanding of uncertainty concepts and representations.

Angelika Heil had already presented the Fire_cci products during the FireMIP meeting and gave another, more in-depth, presentation at the workshop. Pierre Laurent complemented it with a presentation on fire patch morphology data derived from Fire_cci and other products. Jose Gómez-Danz and Johannes Kaiser presented new probabilistic concepts for uncertainty characterization of burnt area (BA) and fire radiative power (FRP) products, respectively.

The discussion sessions addressed the use of BA by the DGVM community, and their future requirements. FireMIP has a common benchmarking system that uses BA products to assess the fire components of DGVMs. It does currently not consider the uncertainty of the BA products explicitly, but would like to do so in the future. For the time being, the spread between different BA products is interpreted as uncertainty indicator when benchmarking model results. There was a **consensus on the need for taking uncertainties better into account**. Specific requests, in order of complexity, were:

1. As a short-term workaround: Compile and publish a **table with expert judgements** on which BA product is considered to be particularly reliable, resp. unreliable, in which time period in which continental-scale region.

2. Provide an easy-to-understand **reliability mask** in each BA product that indicates where the product may be unreliable, e.g. due to missing observational input or a high likelihood of signal confusion (e.g. mechanical soil preparation interpreted as burning).

3. Provide **burn detection probabilities for each pixel** in the BA pixel product and **spatio-temporally explicit BA uncertainty information in addition to the BA layer** in the BA grid product. As noted in Box 1, most users understood "uncertainty" to provide a description of the expected statistical properties of the BA measurements errors, i.e. the differences between the satellite-derived values and the "true values".

BOX 1: Measurement uncertainty or measurement error?

In the re-evaluation of the Fire_cci user workshop, it became evident that the participants did not have a common understanding of what measurement uncertainty means, of what an uncertainty layer in the grid product should contain and of how they would use and interpret this layer.

This confusion prevailed despite explanatory notes on the concept of uncertainty characterisation of satellite data with a Bayesian interpretation of probability (with error propagation from the input calibrated radiances through to the final product) following the requirements set by GCOS for quantifying uncertainties in ECVs (Hollmann et al. 2013). This concept is in line with, e.g. the approach of characterising uncertainty in the ESA CCI SST climate date records, described in Merchant et al. (2017).

In contrast, the participating users interpret the uncertainty layer in the gridded burned area product as quantitative information on the "measurement error". It is hence understood to contain a statistical description of the expected differences between the satellite-derived estimates for a variable and the corresponding true values on the ground. If a gridded burned area product contains an uncertainty layer associated to a "best estimate" burned area layer, and the uncertainty layer is defined as standard deviation, then the users expect that the "true" burned area lies in the interval best estimate burned area ± 1 standard deviation in 66% of the cases. "True" burned area refers to the burned area actually burned on the ground, e.g. as approximated by burned area references sites used for burned area product validation.

This confusion became evident only through a questionnaire survey conducted after the Fire_cci user workshop. In this survey, the participants were provided the two descriptive definitions without providing how the definitions are named, and were asked to state which of these definitions corresponds to their understanding of uncertainty. All respondents stated that the provided descriptive definition for the measurement error statistics corresponds to their understanding of the uncertainty layer. The provided descriptive definition for uncertainty as reasonably attributable distribution of values for measured BA, which has been derived using error propagation, was not compatible with their understanding of uncertainty. This implies that the participants, when requesting an uncertainty quantification layer in the gridded burned area product, actually requested an estimate for a quantitative "error characterisation" in a statistical sense. The Bayesian concept of uncertainty as described in Merchant et al. (2017) and a so-derived uncertainty layer did not meet directly meet the users' requirements. We expect it to be the main building block for calculating "uncertainty" values that conform to the user requirements. The user requirement also implies that the validation has to address both the BA and "uncertainty" values explicitly.

This illustrates how difficult it is to communicate uncertainties, and hence, to explore related user requirements. Intensive communication between product developers and product users to ensure that (a) product developers develop a well-founded understanding of what product characteristics users actually need and, Furthermore, the participants were highly interested in constraining the **effect of the fires on the vegetation** in more ways than just BA. FRP is a complementary constraint but it is difficult to compare directly to fire models. Instead, observational products containing information on the following fire properties would be very useful:

1. Fuel consumption
2. Combustion completeness
3. Rate of spread
4. Fire line intensity
5. Post-fire recovery

Such products would not necessarily required frequent global coverage; what is mostly needed is a **characterisation of the "typical" behaviour** in the various fire regions and seasons around the globe. It is expected that this characterisation will require

1. combined analysis/assimilation of BA and FRP observations, possibly/partly at reflectance level
2. evolution of BA products towards probabilistic "burn fraction" products.

The need for **unbiased long-term time series** of BA was reiterated. Avoiding any bias is paramount and compromises may rather be made concerning the coverage and product definition: **Regional** instead of global coverage would already provide a strong constraint on the fire models in changing climate conditions and some other indicator for fire activity than BA would also be used.

Finally, the participants expressed their interest in a BA product derived from **merged reflectances**. It is hoped that a "best stream" of reflectance data extracted from multiple sensors may enhance the opportunity of detecting burned areas and thus **improve burn patch identification**, which is an important but currently still poorly constrained parameter in DGVM benchmarking.

WS1. Introduction

The Fire_cci user workshop was took place on October 19th, 2017 from 1:30 to 6 pm pm at the IMK in Garmisch-Patenkirchen, Germany. The workshop immediately followed the end of the 4th FireMIP meeting, which was held at IMK from October 17th to 19th, 2017. The Fire Model Intercomparison Project (FireMIP) is an international initiative to compare and evaluate existing global fire models against benchmark data sets for present-day and historical conditions. The co-joined organization of the Fire_cci user workshop at a FireMIP meeting was an ideal opportunity to address this important user group of satellite burned area information.

In total, 17 persons participated in the workshop (WS Appendix B)

J. Kaiser welcomed all participants and outlined the scope of the workshop which covered three major aspects:

1) Inform users about the status quo of burned area (BA) product characteristics with focus on the uncertainty/error characterization.

2) Introduce to users advanced approaches to characterize BA uncertainty in BA products, which are primarily applied in climate applications.

3) Explore user requirements with respect to future BA products in an interactive discussion between producers and climate users of BA products. A particular focus was

set on the specific requirements regarding uncertainty characterization. Participants were challenged to think 10 years ahead.

J. Kaiser explained that there is a general ambiguity in the use of terms describing uncertainties. Following international metrological standards for discussing uncertainty in measurements (Merchand and Embury 2014, Merchand et al. 2017), we refer to uncertainty as a number quantifying the degree of "doubt" in a measured value while error means "mistake". The measurement error is the degree to which the measured value differs from truth. In practice the error is unknowable, except when the measured value can be compared with a reference value of negligible uncertainty, such as when satellite burned area data are validated with ground-truthed burn perimeters.

A print-out of the agenda was distributed, which, on the back side, contained a short questionnaire (see WS Appendix A). Participants were asked to fill it out at the end of the workshop. The answers to the questionnaire were principally identical to the participant's statements during the workshop (see WS Appendix C).

WS2. Specifications of current global burned area (BA) products (presentation by Angelika Heil, MPIC)

Angelika Heil provided a review of the product specifications of the global BA products Fire_cci, MCD45, MCD64 Collection 5/6 and GFED3/4/4s.

All pixel products (Fire_cci, MCD64 Collection 5/6, MCD45) have a date of burn layer, but only the MCD64 products provide explicit uncertainty quantification in the date of burn detection. MCD45 provides proxies for the temporal uncertainty of burn detection (e.g. as number of consecutive missing/cloudy days in the time series). All MODIS products explicitly flag pixels burned, unburned, water/snow or unobserved. The flags in Fire_cci do not allow for discrimination between unburned and unobserved.

None of the pixel products provide a fully propagated quantification of the burn probability. The Fire_cci pixel product provides a burn probability layer given as confidence level. However, the layer only gives some indications that a pixel classified as burned is "true burned". No indication is given for pixels classified as unburned. The confidence level scores are derived from scaling the number of burned pixels in a 9x9 moving window against Landsat reference burn perimeters. Pixels in the middle of large burn patches have highest confidence scores while isolated burn pixels the lowest. MCD45 contains a quality assessment (QA) layer, which provides scores qualitatively classifying the confidence of the detection and layers with flags detailing observational conditions such as cloud or smoke contaminations or high viewing angles. MCD64 contains a QA layer which labels burned pixels with shortened mapping period and which provides details whenever pixels were classified as unburned due to special circumstances. Only the Fire_cci pixel products contains a layer detailing the land cover burned.

Except for GFED4s, all gridded burned area products provide an uncertainty estimate in addition to the gridded burned area estimate. In Fire_cci, this uncertainty layer is called "standard_error" and in GFED3/4 "BurnedAreaUncertainty". Yet, the uncertainty layer is simply the product of burned area and a constant scalar c_b (in GFED, there are in total 5 region-dependent scalars). The scalars are derived from a few Landsat reference sites and represent the residuals when regressing the area of individual burn patches identified from the products against Landsat burn perimeters. In Fire_cci, the uncertainty layer is the gridded BA multiplied by c_b of 0.327. In GFED3/4, the uncertainty layer is the square root of the gridded burned area times c_b of 0.5, 2.8, 5.7,8.6, 31 km^2 (different values for the boreal regions, forested Africa and grassland Africa, USA, and all remaining regions). It is clear that none of the uncertainty layers capture the spatial-temporal variability of actual burned area.

WS3. Uncertainties in burned area (BA) products (presented by Jose Gómez-Dans, UCL/NCEO)

J. Gómez-Dans gave a presentation on uncertainty in burned area (BA) products from optical data, on how pixel-level uncertainty can be aggregated to climate model grid (CMG) products and on how BA uncertainty affects common climate applications.

BA from optical data is an indirect measurement and is based on the interpretation of the spectral reflectance signal. Burned area is usually detected as contrast between pre- and post-fire reflectance and relies on assumptions of what spectral changes a fire typically provokes. Different sensors and spectral bands have different spectral sensitivities to fire. Furthermore, spectral sensitivities vary by land cover type and also the impact of the fire affects detectability since different fire impacts on vegetation (e.g. surface vs. crown fires) cause different impacts on spectral reflectance. Then, if a pixel burned only partially – such as typical for pixels at the edge of a fire patch – there is less change in the reflectance. The opportunities of observation is another important factor influencing detectability and is largely driven by the sensor's orbit and scan width and by cloud cover. All these effects combine to make the decision on whether a pixel is burned or not prone to errors.

Uncertainty can be considered as a measure of the strength in the belief that a pixel has burned conditional on the observations (and any other assumptions, such as spectral effects of fire, etc.). Uncertainty can be phrased as a probability of burn, p_b, with

p_b ≈ 0: "little evidence of burning"

p_b ≈ 1: "strong evidence of burning".

J. Gómez-Dans provided some use cases of BA uncertainty in climate research applications. (a) In fire emission estimations, uncertainty in BA is directly mapped to emissions using the multiplicative Seiler and Crutzen (1980) approach. BA uncertainty in current BA CMG products is approximated by the information contained in the product's uncertainty layer. The layer simplistically quantifies the uncertainty of the estimation of burned area at the grid level and is obtained from validating the product's BA with few Landsat reference sites (see section WS2). To correctly quantify uncertainty in fire emission estimates, however, the actual spatio-temporal variability of BA uncertainty has to be taken into account. (b) Dynamic Global Vegetation Models (DGVM's) predict a diversity of ecosystem processes from vegetation dynamics, including disturbances such as fires, and the associated biogeochemical and hydrological cycles. BA is one of many inputs to DGVM fire model calibration. Bayesian calibration/data assimilation requires weights of evidence, which are derived from the uncertainties attributed to the input observations. Ignoring the uncertainty just in a single input data set may result in non-physical model states. DGVM fire model calibration therefore requires an probabilistic uncertainty characterization of the BA input, optimally in form of probability density functions (pdf's). Results from the BA product's error characterization, such as omission or commission errors, are not suitable for model calibration as they cannot be mapped to model outputs in a consistent manner. (c) Delineation of individual burn scars (or "burn patches") relies on the connectivity of fire signals across time and space. A correct delineation of individual fires requires pixel level information on the probability of burn in space and time, i.e. the burn detection probability for each pixel and the probability of a fire occurring on a given day. Fixed-threshold burned area products tend to underestimate burned area and result in the largest fires being split into a collection of small independent patches. This results in an underestimation of large fires, and an overestimation of small fires.

So far, none of the current satellite-derived BA products have implemented a fully propagated uncertainty quantification that results from the probabilistic characterization of the uncertainty on the input parameters (i.e. reflectances) and the propagation of the uncertainty through the burned area processing chain. As a result, meaningful, spatio-temporally resolved representations of propagated uncertainty (e.g. given as p_b describing the probability of burn as a function of time and space) are not yet provided in BA pixel products.

J. Gómez-Dans explained that the computation of meaningful pixel-level p_b values for Fire_cci products still requires more methodological developments and validation, but he expects that meaningful p_b could be established towards the end of the Fire_cci project. As an end product, a pixel product would then contain a p_b value for every pixel. To clarify, J. Gómez-Dans added that a pixel-level p_b layer is already being computed but only realistically captures the p_b variability. In other words, such a product is not a real probability, but a proxy to the real probability.

Burned area estimates in current state-of-the-art BA grid products are simplistically computed from the integrals of the area of all pixels that are classified as burned. To discriminate between burned and unburned, a fixed threshold is used.

The availability of meaningful pixel-level p_b information would allow for more advanced approaches to aggregate burn information from the pixel to the grid level. J. Gómez-Dans demonstrated a probabilistic aggregation approach using synthetic p_b data with unity pixel size: when p_b is assumed to be independent for each pixel, then the distribution of p_b over a CMG is given by a Poission Binomal distribution which can be approximated by a normal distribution (under some assumptions). The mode of the probability density function (PDF) is interpreted as the most likely estimate of BA for the CMG. The width of the curve around the mode (encoded in the standard deviation) describes the uncertainty of this estimate.

When comparing aggregation using the “sum of burned pixels” versus Poisson Binomial approach, the expected BA is vastly different. If p_b is properly reported, the Poisson Binomial approach broadly encodes the true burned area, whereas the sum of burned pixels will give very different results based on how the decision of a pixel being burned is arrived at. Additionally, summing the burned pixels does not provide an estimate of uncertainty.

For as long as meaningful, spatiotemporally explicit p_b information is unavailable, J. Gómez-Dans proposed the following workaround to address uncertainty in the gridded BA products. Product developers have more trust in pixels detected as burned than on p_b. However, *patterns* of p_b might be indicative of true uncertainty, although their actual value might not be correct, and may thus be used to approximate the Poisson Binomial distribution. One can proceed by scaling p_b so that the Poisson Binomial distribution mode is equal to the sum of burned pixels, and then calculate the standard deviation/variance of the Poisson Binomial distribution using the scaled p_b values.

WS4. Assessment of burned area (BA) products: Fire patch morphology (Pierre Laurent, LSCE)

P. Laurent presented the fire patch databases, which they have been developing from Fire_cci, MCD64, MCD45, and Sentinel-2 using the flood fill algorithm. When comparing fire patch morphological features at regional and global scales, Fire_cci and MCD64 show a decent, strongly region-dependent agreement. Fire patch morphology shows a good agreement when Sentinel-2 and Fire_cci are compared over agricultural areas in Africa. So far, uncertainties in the burn detection and date of burn are not taken into account in the compilation of the fire patch database. Also, there is no discrimination between unburned pixels and non-observed pixels. Future work will include uncertainties on burned pixels at the flood-fill level (removing pixels below a given burn detection probability threshold) and at the patch metrics extraction level.

WS5. Fire Radiative Power (FRP) uncertainty representation in the Global Fire Assimilation System (GFAS) (presented by J. Kaiser, MPIC)

J. Kaiser reported on recent developments to improve uncertainty information in the Global Fire Assimilation System (GFAS). Per-sensor uncertainty is calculated at the pixel level and propagated to a gridded FRP uncertainty estimate. Uncertainty is characterized as variance of the FRP signal and takes into account the instrument's signal-to-noise ratio and the viewing angle-dependent detection threshold. A quantitative uncertainty characterization combined with bias correction is essential for the data assimilation algorithm in GFAS to (a) merge information from different sensors, (b) fill observational gaps and (c) provide accuracy estimate for each pixel every hour. To combine FRP information from different sensors, GFAS performs an optimal interpolation based on gridded FRP and its gridded variance. J. Kaiser suggested that a similar approach could also be applied to merge BA information from different sensors.

WS6. User requirements: Question and answer session

WS6.1. Usage and potential benefits of uncertainty information contained in BA products

None of the participants so far have used the uncertainty layer contained in BA products. Indirectly, uncertainty of burned area products is addressed by using ensembles of different burned area products to force models and benchmark the performance of different fire models.

The ensemble's spread is interpreted as uncertainty of the burned area observations.

A brainstorming on potential applications and benefits of the BA product's uncertainty layer came to the following outcome:

The most obvious application of a BA uncertainty layer associated to the BA estimate is for emission estimation using the Seiler and Crutzen (1980) approach.

One participant mentioned that Poulter et al. (2015b) demonstrated that models show significant differences in the carbon cycle when forced with different burned area data. He then proposed that instead of forcing models with different burned area datasets to estimate the influence of forcing data uncertainty, the forcing data uncertainty influence could alternatively be estimated using the uncertainty information contained in the uncertainty layer of individual BA products.

All participants agreed that they require an uncertainty layer that is easy to understand and to use. For this, they require detailed advise how to best use and interpret the uncertainty information contained in the layer.

There was common sense that the future FireMIP benchmarking system should take into account uncertainties of the burned area observations. One option could be z-scores, which quantify how much a model result differs from observations given the uncertainty in observations.

WS6.2. Required characteristics of the uncertainty layer in future BA products

Referring to the elaborations by Jose Gómez-Dans on the quantification of uncertainty in BA from optical data and on methods to aggregate the pixel-level information to CMG BA products (section WS3), all participants were asked which approach they would prefer.

Pixel product

The participants clearly favoured pixel products, which provide burn probability for all pixels. A most likely DoB with temporal uncertainty is requested in addition. This information would be beneficial for many applications such as e.g. burn patch identification. In contrast to fixed threshold products, burn probability products would allow for more flexibility in choosing a burn threshold, which is most appropriate for a given application.

Gridded product

Most participants clearly favoured grid products that compute the estimated burned area from probabilistic aggregation of burn uncertainties. As an intermediate solution, a best guess fixed-threshold-based BA estimate combined with a realistic estimate of the variance, e.g. as standard deviation, would be beneficial.

The participants stated that the uncertainty quantification layer associated to the gridded BA product should take into account the ability to detect fires.

It was noted that the uncertainty information in the gridded BA product should be traceable back to the uncertainty information contained in the corresponding pixel product. Traceable back means that users could recalculate the gridded uncertainty layer from the pixel level product and hence could compute custom grid products (e.g. 0.1 degree resolution) if required.

As noted in Box 1, the participants most likely primarily interested in a measurement error characterisation layer attributed to the gridded BA estimate that that is derived from product validation with reference sites.

WS6.3. Requirements for explicit data flags

The participants agree that for most applications of grid products, it is important that areas are masked out and that partially observed grid cells are given a lower weight. It was therefore requested that unobserved grid cells are flagged as N/A and that a separate data layer is provided with information on the observed area fraction. There was also the request for information on the area fraction with water, snow, or ice in each grid cell. The users of grid products showed great interest in gap-filled BA products, but, at the same time, mentioned any gap-filling should be clearly flagged in a data source layer. It was agreed that the product's observational coverage should find consideration in future DGVM model benchmarking and empirical fire modelling.

Also in the pixel products, an explicit flagging of unobserved grid cells is considered indispensable. Helpful would be additional flags, which specify the presence of water bodies, ice and snow cover as well as potential contamination by clouds or aerosols. In the case of merged pixel data, a data source flag is required.

WS6.4. Request for BA product evaluation and "valuation"

Not only information on uncertainties in BA observations, but also information on – or indications of – systematic biases in BA products are of interest to end users. End users of BA products would highly benefit from complementary, product-specific information, on where there are regions or times with a high likelihood for systematic errors in the BA observations due to signal interferences with ploughing activities, build up areas or cloud shadows. They also request information on whether the problem tends to introduce over- or underestimations.

This information could, for example, be provided in form of a scientific report, which synthesizes the results from product validation and intercomparison efforts and from expert opinions on the accuracy of different burned area inventories at regional and seasonal scales.

WS6.5. Request for merged reflectance products

Participants expressed their interests in products that provide a best representation of burned area from combining burned area information from different sensors. A merged product, however, was considered most useful when merging is performed at production stage, i.e. by merging reflectance. A "best stream" of reflectance data filtered out from multiple sensors may enhance the opportunity of detecting burned areas. A BA product derived from merged reflectances was judged more viable than a product that was merged only at the end-product stage.

WS6.6. Request for fire patch products

The correct identification of individual fire scars (or "burn patches") would require (a) burn probability information for all pixels and (b) information on the temporal uncertainty. There was general agreement among the participants that burn patch identification would best be performed by the algorithm developers at the detection level. Also, it was commonly agreed that patch identification would benefit from merged reflectance. All users requested patch ID's in the pixel products.

WS6.7. Request for fuel consumption and combustion completeness products

Observational fuel consumption products are indispensable for various fire-related climate research applications. For example, fuel consumption is an indicator for the impact of fire on vegetation and hence determining tree mortality and post-fire recovery and fuel consumption observations are required to better constrain these processes in fire models. Fuel consumption information is also essential for fire emission calculations. As of today, spatio-temporally resolved fuel consumption products are unavailable. The participants therefore welcome any product development in this direction.

Also spatiotemporally resolved observational proxy products of fuel consumption would be very valuable. Since fuel consumption is traditionally calculated from the product of fuel loads and combustion completeness, observational products providing information on the spatial and temporal variability this quantity would already be very useful. For the longer term, the participants strongly promote the development of fuel consumption layers (or a proxy of it) to be either included into or complemented to the Fire_cci products.

WS6.8. Request for products indicating the dynamics of post-fire recovery

DGVM modellers expressed their interest in satellite-derived maps indicating the temporal evolution of post-fire recovery as ancillary layer to the BA time series. Currently, the dynamics of post-fire recovery cannot be constrained as related observations with sufficient temporal and spatial resolution not available. Satellite-derived products providing information on the time (e.g. in days) it takes to achieve 90% pre-fire greenness would therefore be viable. The product could also be used as a proxy for fire-induced tree mortality – another parameter that is insufficiently constrained in DGVM models.

WS6.9. Request for rate of spread products

Currently, global vegetation modellers are uncertain how to realistically parameterize the rate of spread in their fire models. Observation-based constraints, even if still associated with great uncertainties, would therefore greatly contribute to model improvements. There was a common agreement that the current fire model benchmarking system would greatly benefit from global maps of the rate of spread. It was suggested that high resolution burned area maps (e.g. from 10m Sentinel-2A images) or active fire maps (e.g. 375 m VIIRS images) with pixel-based date of burn information offer the potential for deriving maps of rate of spread. Any product development towards this direction is highly welcomed.

WS6.10. Request for fire frontline intensity products

Maps of fire frontline intensity could serve as an indicator for the fire-induced vegetation impact in DGVMs. Also here, modellers are still uncertain how to realistically parameterize this process. They emphasize that if fire frontline intensity cannot be derived at a global scale, they would also take great advantage from regional maps covering major fire regimes or even from "typical values" for different fire regimes.

WS6.11. Resolution requirements of BA products

All workshop participants agreed that in terms of spatial resolution of gridded BA time series, 0.25 degree will be adequate for their DGVM model applications in the decade to come. In terms of temporal resolution of the gridded product, monthly time series are still adequate for most applications. The next higher temporal resolution they would request is daily. None of the users could see practical benefits from biweekly or weekly time resolutions.

WS6.12. Long-term burned area time series

10 years is the minimum length of a BA time series that are useful for DGVM modellers. Any longer time series is urgently desired. Participants expressed their interest in BA time series that are extended by in time with AVHRR data. If longer BA time series cannot be established, any product which contains proxies of the long-term fire trend and interannual variability is beneficial.

Since the FireMIP participants have developed a strong focus on analysing extreme events and interannual variability in regional fire regimes, use of regional long-term burned area products would also be viable.

A long time-series derived from merging different satellite products is only of value if it is unbiased and complemented by an uncertainty layer.

WS6.13. A combined burned area (BA) and fire radiative power (FRP) assimilation system

The participants recognized that BA and FRP provide complementary observational constraints on fires, and expect that a consistent combination of both quantities will provide more accurate and comprehensive constraints for their applications than both of them separately. They thus recommend to start developing a prototype of a combined BA and FRP assimilation system. From the assimilation of burned area observation with FRP information, the participants expect a better representation of small fires. Assimilating FRP observation with BA information, in turn, would provide the basis for improving FRP-derived estimates of fuel consumption and emission fluxes.

WS6.14. Priority list of required product developments

Participants were asked to identify what product developments they would recommend for (a) the final phase of Fire_cci project (e.g. next 12 months) and (b) for any follow-on funding phase:

(a) Recommended developments for the final phase of the Fire_cci project

- → Rate of spread products from high-resolution burned area and/or active fire maps (section WS6.9).
- → Improved uncertainty characterization in BA products (see section WS6.2).
- → Merged reflectances (see section WS6.5) and derived BA products (see section WS6.6).
- → Product validation and error characterisation (see section WS6.4).

(b) Recommended developments for the follow-on funding phase

- → Fuel consumption time series (see section WS6.7).
- → Merged BA products to obtain the longest BA time series possible (see section WS6.12).
- → Satellite-derived maps of indicating evolution of post-fire recovery and of fire-induced tree mortality (see section WSWS6.8).
- → Maps of fire frontline intensity or other proxies of fire impact on vegetation (see section WSWS6.10)
- → A combined BA and FRP assimilation system (see section WSWS6.13).

WS Appendix A: Workshop agenda and questionnaire

Fire_cci User Workshop

19 October 2017

IMK-IFU, Garmisch-Partenkirchen (Germany)

Agenda

14:00 – 14:10: Welcome and introduction (A. Heil, J. Kaiser)

14:10 – 14:30: Review of currently available global burned area products (A. Heil)

- Burned area (BA) product specifications
- Uncertainty characterization
- Error characterization/Validation

14:30 – 15:00: Uncertainty in burned area (BA) products (J. Gomez-Dans)

- BA detection approaches (thermal and optical sensors)
- Sources of uncertainty in optical BA detection
- BA uncertainty quantification at the pixel level and aggregation approaches
- How does BA uncertainty affect usual "climate tasks"?

15:00 – 15:40: Discussion: User requirement w.r.t. BA uncertainty (all participants)

- Do you use or have you used uncertainty information from BA products?
  If so, for what application and with what benefit?
- Think 10 years ahead: In what future application BA uncertainty information could be beneficial?
- Is an uncertainty characterization (as presented by Jose) sufficient?
  If not, what other information would be more useful for you?

15:40 – 16:00: Coffee break

16:00 – 16:15: Use case: Fire patch morphology (P. Laurent)

- Method to derive global fire patch database
- Results and inter-comparison of patch characteristics from different BA products
- Can BA uncertainty information improve the quality of the fire patch database?

16:15 – 16:30: Recent developments to improve uncertainty information in GFAS (J. Kaiser).

16:30 – 17:15: Discussion: General user requirement

- Uncertainty/error characterization
- Observational coverage
- Spatial and temporal resolution
- Ancillary layers, flags

18:30 Fire_cci funded dinner @ Restaurant Rheinischer Hof

User requirements gathering...Please provide your name: _______________

1. What satellite-derived burned area products have you used in the past?
Please specify if pixel-level or CMG ("gridded") product.
For each product, please give some details on specific application.

2. BA pixel product: What kind of burn detection uncertainty description do you need?

☐Non. Binary burn/unburned layer.

☐Probability of a burn detection (Pb).

☐Other (please specify):

3. BA pixel product: What kind of temporal uncertainty description do you need?

☐Only most likely day of burn (DoB).

☐Temporal uncertainty of the DoB detection (earliest and latest possible DoB).

☐Probabilities of a burn happening at given days.

☐None.

☐Other (please specify):

4. BA grid product: What kind of BA estimate do you need?

☐Only mean BA estimate (sum of burned pixels).

☐Probabilistic aggregation (as presented by Jose)

☐Other (please specify):

5. BA grid product: What kind of BA uncertainty estimate do you need?

☐None.

☐Standard uncertainty

☐Other (please specify):

6. What other BA product characteristic would you like to see in future products?

WS Appendix B: List of workshop participants

Name	Institute	Position
Dr. Florent Mouillot	CEFE/CNRS, Montpellier, France	Senior scientist
Dr. Chao Wu	University of Exeter, Exeter, UK and Tsinghua University, Beijing, China	Senior scientist
Chantelle Burton	Met Office Hadley Centre, Exeter, UK	PhD Student
Lina Teckentrup	Max Planck Institute Meteorology, Hamburg, Germany	Master student
Dr. Gitta Lasslop	Max Planck Institute Meteorology, Hamburg, Germany	Senior scientist
Dr. Chao Yue	Université Paris-Saclay, Gif-sur-Yvette, France	Senior scientist
Dr. Matthias Forkel	TU Vienna, Austria	Senior scientist
Dr. Pierre Laurent	Université Paris-Saclay, Gif-sur-Yvette, France	Senior scientist
Dr. Matthey Forrest	Senckenberg Biodiversity and Climate Research Institute, Frankfurt/M., Germany	Senior scientist
Dr. Douglas Kelley	Centre for Ecology and Hydrology, Oxfordshire, UK	Senior scientist
Dr. Jose Gomez-Dans	University College London, London, UK	Senior scientist
Dr. Stijn Hantson	Karlsruhe Institute of Technology, Garmisch-Partenkirchen, Germany	Senior scientist
Dr. Stephen Plummer*	ESA Climate Office	ESA Technical Officer
Dr. Johannes Kaiser	Max Planck Institute Chemistry, Mainz, Germany	Senior scientist
Dr. Angelika Heil	Max Planck Institute Chemistry, Mainz, Germany	Senior scientist

* participation via skype.

WS Appendix C: Outcome of the questionnaire survey

Question 1: What satellite-derived burned area products have you used in the past? For each product, please give some details on specific application.

ID	Applications of BA products	BA products used
1	Evaluation of JSBACH-SPITFIRE, fire patch analysis, developing statistical process models for fires	CMG: MCD45, MCD64, Fire_cci, GFED4; pixel: Fire_cci, MCD45, MCD64, L3JRC
2	Optimisation of fire models, model evaluation	CMG
3	GFED4s: ORCHIDEE benchmarking; pixel products for fire patch analysis	CMG: GFED4s; pixel level: MERIS Fire_cci, MCD64, MCD45, Sentinel-2
4	Burnt area and fire emissions	CMG: GFED3/4/4s
5	DGVM model evaluation and improving their process-based representation of fires	CMG: GFED4/4s
6	Verifying fire model with burned area	CMG: GFED
7	Comparison with DGVM simulated burned area	CMG: GFED3/4/4s
8	DGVM benchmarking	CMG
9	DGVM model evaluation, data analysis, mostly using mean spatial patterns	CMG: GFED3/4/4s
10	Statistical analysis climate controls of burned area, constraining fuel comsumption by combining BA with FRP	CMG: MCD45, MCD64, Fire_cci, GFED4; pixel: Fire_cci, MCD45, MCD64

Questions 2&3: BA pixel product: What kind of burn detection uncertainty description and what temporal uncertainty description do you need?

ID	Detection uncertainty	Temporal uncertainty description (DoB is date of burn)
1	Burn probability	Burn probability at most likely DoB; no DoB detection uncertainty
2	Burn probability	Burn probability at most likely DoB; no DoB detection uncertainty
3	Binary product	Burn probability at most DoB; temporal uncertainty of DoB detection
4	Burn probability	Most likely DoB; no temporal uncertainty estimate
5	Burn probability	Most likely DoB; temporal uncertainty of DoB estimate
6	Burn probability	Burn probability at most likely DoB; no DoB detection uncertainty
7	Burn probability	Most likely DoB; temporal uncertainty of DoB estimate
8	Burn probability, uncertainty on merged products	Temporal uncertainty of the DOB detection
9	n.a.	n.a.
10	Burn probability	Most likely DoB; temporal uncertainty of DoB estimate

Questions 4&5: BA grid product: What kind of BA estimate and what uncertainty estimate do you need?

ID	BA aggregation	BA uncertainty estimate
1	Probabilistic aggregation	Standard uncertainty
2	Probabilistic aggregation	Standard deviation, RMSE
3	Probabilistic aggregation	None
4	Sum of burned pixels	None
5	Probabilistic aggregation	Standard uncertainty
6	Sum of burned pixels	Standard uncertainty
7	Probabilistic aggregation	Standard uncertainty
8	Probabilistic aggregation	Standard uncertainty, any indication of biases.
9	Sum of burned pixels	Standard uncertainty. Others: areas with high systematic uncertainty, due to ploughing, airports or other urban infrastructure, clouds etc. with indication whether the problem rather leads to over or underestimation.
10	Probabilistic aggregation	Standard uncertainty

Questions 6: What other BA product characteristic would you like to see in future products?

ID	Future BA product characteristics
1	Long-term BA time series
2	Combined BA product with RMSE; flags for %observed, water, snow, ice and sensor
3	-
4	Fire size, number of fires, fire duration
5	Combustion completeness, recovery time
6	Small fire database with uncertainty estimates
7	Fire size, number of fires, spread rate and intensity of fires (radiative power); long term time series (a consistent proxy would already be helpful)
8	Carbon consumption, recovery time
9	The developments with fire size, fire number and rate of spread are very interesting. For the aggregated burned area, the patchiness or continuity of the burned area could also be interesting, or how much of the area is still in a rather burned state, as compared to the area where the vegetation has already grown back.
10	Fuel consumption, flags for unobserved pixels/observational quality in grid products