T13

Assessment of the status of the development of the standards for the Terrestrial Essential Climate Variables

GTOS

Essential Climate Variables

GTOS 68

# FIRE

*Fire Disturbance*

WMO UNESCO UNEP ICSU FAO

T13

Assessment of the status
of the development of the standards for the
Terrestrial Essential Climate Variables

# FIRE

*Fire Disturbance*

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# List of Acronyms

| | |
|---|---|
| ABI | Advanced Baseline Imager |
| AIRS | Atmospheric Infrared Sounder |
| ASTER | Advanced Spaceborne Thermal Emission and Reflection Radiometer |
| (A)ATSR | (Advanced) Along Track Scanning Radiometer |
| AVHRR | Advanced Very High Resolution Radiometer |
| AWiFS | Advanced Wide Field Sensor |
| BAE | Burned Area Estimation |
| BIRD | Bi-spectral Infrared Detection |
| CBERS | China-Brazil Earth Resources Satellite |
| CEOS | Committee on Earth Observation Satellites |
| CIMSS | Cooperative Institute for Meteorological Satellite Studies |
| COMS | Communication, Ocean and Meteorological Satellite |
| CrIS | Cross-track Infrared Sounder |
| DMC | Disaster Monitoring Constellation |
| DMSP-OLS | Defense Meteorological Satellite Program- Operational Linescan System |
| ECV | Essential Climate Variable |
| ESA | European Space Agency |
| ETM+ | Enhanced Thematic Mapper Plus |
| FAO | Food and Agriculture Organization of the United Nations |
| FCDR | Fundamental Climate Data Record |
| FRE | Fire Radiated Energy |
| FRP | Fire Radiated (Radiative) Power |
| FTA | Fire Thermal Anomaly |
| FY | Feng Yun – Wind and Clouds |
| GBS | Global Burnt Surface |
| GCOS | Global Climate Observing System |
| GEMI | Global Environment Monitoring Index |
| GFED | Global Fire Emissions Database |
| GFMC | Global Fire Monitoring Center |
| GHG | Greenhouse Gas |
| GMES | Global Monitoring Environment and Security |
| GMS | Geostationary Meteorological Satellite |
| GOES | Geostationary Operational Environmental Satellite |
| GOFC-GOLD | Global Observation of Forest and Land Cover Dynamics |
| GOMS | Geostationary Operational Meteorological Satellite |
| GPS | Global Positioning System |
| GTOS | Global Terrestrial Observing System |
| GVM | Global Vegetation Monitoring |
| IASI | Infrared Atmospheric Sounding Interferometer |

| | |
|---|---|
| **ICSU** | International Council for Science |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **IRS** | Indian Remote Sensing Satellite |
| **JAMI** | Japanese Advanced Meteorological Imager |
| **JRC** | Joint Research Center |
| **LDCM** | Landsat Data Continuity Mission |
| **LPV** | Land Product Validation |
| **MERIS** | Medium Resolution Imaging Spectrometer |
| **MODIS** | Moderate Resolution Imaging Spectroradiometer |
| **MOPITT** | Measurement Of Pollution In The Troposphere |
| **MTSAT** | Multi-functional Transport Satellite |
| **NDVI** | Normalized Difference Vegetation Index |
| **NESDIS** | National Environmental Satellite Data and Information System |
| **NOAA** | National Oceanic and Atmospheric Administration |
| **NPP** | NPOESS Preparatory Project |
| **NPOESS** | National Polar-orbiting Operational Satellite System |
| **MIR** | Mid Infrared spectral range |
| **NIR** | Near Infrared spectral range |
| **OCO** | Orbiting Carbon Observatory |
| **SAR** | Synthetic Aperture Radar |
| **SCIAMACHY** | SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY |
| **SEVIRI** | Spinning Enhanced Visible and Infrared Imager |
| **SLST** | Sea and Land Surface Temperature |
| **SVISSR** | Streched Visible and Infrared Spin Scan Radiometer |
| **SWIR** | Shortwave Infrared spectral range |
| **TES** | Troposhperic Emission Sperctometer |
| **TET** | Technologie-Erprobungs-Träger - Technology Experiment Carrier |
| **TIR** | Thermal Infrared spectral range |
| **TM** | Thematic Mapper |
| **TRMM VIRS** | Tropical Rainfall Measuring Mission Visible and Infrared Scanner |
| **UNEP** | United Nations Environment Programme |
| **UNESCO** | United Nations Educational, Scientific and Cultural Organization |
| **UNFCCC** | United Nations Framework Convention on Climate Change |
| **VGT** | (SPOT) VEGETATION |
| **VIIRS** | Visible Infrared Imager Radiometer Suite |
| **VIRR** | Visible and Infrared Radiometer |
| **VIRS** | Visible and Infrared Scanner |
| **VIS** | Visible spectral range |
| **WCCV** | Working Group on Calibration and Validation |
| **WFA** | World Fire ATLAS |
| **WMO** | World Meteorological Organization |

# Executive Summary

Fire is an important ecosystem disturbance with varying return frequencies, resulting in land cover alteration and change, and atmospheric emissions on multiple time scales. Fire is also an important land management practice and is an important natural abiotic agent in fire dependent ecosystems. Fires not only affect above-ground biomass but also surface and below-ground organic matter such as peat. Information on fire activity is used for global change research, estimating atmospheric emissions and developing periodic global and regional assessments. It is also used for fire and ecosystem management planning and operational purposes (fire use, preparedness and wildfire suppression) and development of informed policies.

The Fire Disturbance Essential Climate Variable includes Burned Area as the primary variable and two supplementary variables: Active Fire and Fire Radiated Power (or Fire Radiative Power - FRP). Burned Area is defined as the area affected by human-made or natural fire and is expressed in units of area such as hectare (ha) or square kilometre (km2). Active Fire is the location of burning at the time of the observation and is expressed in spatial coordinates or by an indicator of presence of absence of fire in a spatially explicit digital raster map, such as a satellite image. FRP is the rate of emitted radiative energy by the fire at the time of the observation and is expressed in units of power, such as Watts (W).

Fire activity is a global phenomenon characterized by strong spatial and temporal variability. Documentation of fire activity by aerial means (including manned or unmanned aircraft), such as GPS plotting, post-fire photography or high resolution radiometers, is done traditionally in some countries, notably in Russia and other countries of the former Soviet Union. However, declining fire management budgets result in incomplete and inconsistent coverage. Other countries that have limited fire activity, e.g. Central European countries, are using aerial patrols for early fire detection. Ground-based observations from fire lookout towers or by automated observing systems are also in place but usually concentrated on limited areas of high-value forests or nature reserves. Data from satellite remote sensing are the most suitable and useful means for large and global scale monitoring. Observing systems have been developed using sensors on board both polar orbiting and geostationary satellites.

The methodologies used to estimate burned areas using satellite data are based on the identification of the post-fire spectral signature by various algorithms of change detection and image classification. While no single consensus approach exists, the various techniques use multi-spectral information in the visible, shortwave-infrared and infrared bands and the multi-temporal information based on analysis of satellite images over an extended period of time.

Active fire detection is based on the detection of the thermal signature from flaming and smouldering and its distinction from the non-burning surfaces based on spectral and spatial contrasts. Most methods use the thermal signal around 4 μm, but visible bands are also used at night time from some low-light optimised sensors without a 4 μm channel. A major issue with this approach is the elimination of false alarms from non-fire hot and/or bright surfaces from daytime data and the low saturation level of some of the sensors used. The methodologies to derive FRP use physical-empirical approaches to derive rates of total emitted radiative energy from narrow-band, unsaturated radiance measurements.

Validation of satellite-derived data products with *in situ* measurements is limited. For proper validation of satellite-based products fire activity over the entire area of the satellite pixel needs to be mapped by independent means. Fire perimeter maps or high resolution airborne imagery are potentially useful reference data, but issues with limited sampling and data quality remain. Validation of the moderate and coarse resolution global products is most often performed by higher spatial resolution (e.g. 30m Landsat-class) satellite data. The standard protocol for burned area validation adopted by CEOS includes the use of pairs of such imagery to validate burning mapped between their acquisition dates. For active fire products simultaneous observations are required. The prototype approach has been developed for the single-platform Terra/ASTER/MODIS configuration, but there is a need to extend it to multi-platform techniques. The validation of FRP requires unsaturated radiance measurements from high resolution space- or airborne sensors. These are currently not routinely available, but emerging systems exist.

The currently available fire products only marginally meet the requirements defined by the GCOS Implementation Plan (GCOS, 2006). No global products at the specified 250m spatial resolution and daily observing cycle exist and product continuity and consistency between products derived from the various sensors remains unresolved (CEOS, 2006).

The currently defined variables under the Fire Disturbance ECV focus on the presence, extent and characteristics of fires. However, there are numerous interactions between fire and climate that prompt the characterization of pre-fire conditions and post-fire impacts. The linkages between the Fire Disturbance and other ECVs need to be further explored and additional fire variables, such as fire weather, fire danger and fire-related emissions need to be considered.

## Recommendations regarding standards and methods:

- Finalize and adopt emerging consensus methods and standards for the validation of medium and coarse resolution satellite-based fire products using higher resolution spatially explicit reference data from *in situ*, airborne and spaceborne observations;
- develop standards for the intercalibration of fire products from various sensors to enable the creation of a long-term fire disturbance data record;
- develop multi-sensor algorithms and multi-product suites for a more comprehensive characterization of fire activity;
- develop systematic fire products from active remote sensing data;
- develop ground and surface fire characterization methods, particularly for areas of peat;
- coordinate linkages between surface and atmospheric ECVs and data requirements to model global fire danger, fire emissions, and a global early warning system for wildland fire at various time scales; specifically, these ECVs are:
  - atmospheric ECVs: surface temperature, precipitation, wind speed, wind direction, water vapour, upper air cloudiness
  - terrestrial ECVs: aboveground biomass, burn efficiency, and snow cover (extent, duration, depth)
- establish linkages between fire-related surface and atmospheric impacts and corresponding ECVs.

## Other generic recommendations regarding the Fire Disturbance ECV:

- re-evaluate the GCOS requirements to be more specific and realistic for the products generated at various time scales and resolutions;
- generate and distribute individual fire products and maintain historical archives;
- ensure the transition of proven experimental products to the operational domain;
- ensure data continuity to the new generation sensors on future satellite series;
- improve the exchange of information and facilitate timely and systematic availability of data, products and validation data;
- improve the availability of in-situ fire data.

# 1. Background

The emissions of greenhouse gases (GHGs) and aerosols from fires are important climate forcing factors, contributing on average between 25-35% of total $CO_2$ net emissions to the atmosphere, as well as CO, methane and aerosols. Estimates of GHG emissions due to fire are therefore essential for realistic modelling of climate and its critical component, the global carbon cycle. Fires applied deliberately for land clearance (agriculture and ranching), or caused naturally (e.g. lightning strikes) or accidentally (e.g. human negligence) are also major factors in land-cover change, and hence affect fluxes of energy and water to the atmosphere. Fires are expected to become more severe under a warmer climate (depending on changes in precipitation as well as on extent and severity of droughts), giving a positive feedback. Observations suggest that this is occurring in the boreal zone, but long-term trends are hard to detect, because the area burnt in boreal forest is episodic; major burn years occur every 5-10 years, causing an order of magnitude more destruction than the mean rate of burn.

Spatially and temporally-resolved trace gas emissions from fires are the main target quantities. These can be inferred using both land-surface and atmospheric measurements, preferably in combination (the latter are dealt with in the atmospheric domain, e.g. in A.9[1]).

Burnt area, as derived from satellites, is considered as the primary variable that requires climate-standard continuity. It can be combined with information on available fuel load and burn efficiency (or fuel consumption) to estimate emissions of trace gases and aerosols. Burnt area can also include the combustion of surface and below-ground organic material such as peat. Measurements of burnt area can be used as a direct input (driver) to climate and carbon-cycle models, or, when long time series are available, to parameterize climate-driven models for burnt area. Satellite monitoring can also provide supplemental variables to support emission estimates based on burnt area. These are "global active fire maps" and "fire radiated power" data.

1 A.9 is the Atmospheric ECV related to Carbon Dioxide, Methane and other Greenhouse Gases

| **Variable** | **Definition** | **Unit** |
|---|---|---|
| Burned Area | Area affected by a human-made or natural fire | Square kilometer [km2] |
| **Supplementary Variables** | **Definition** | **Unit** |
| Active Fire | The area covered by vegetation that is currently being affected by a human-made or natural fire | Presence or absence of an active fire |
| Fire Radiated Power (FRP) | Rate of radiative energy emitted by an active fire, i.e. radiated power | Watts [W]; i.e. Joule per second [J/s] |

**Table 1 - Variables of the Fire Disturbance ECV**

# 2. Definition of variables and units

There are three variables within the Fire Disturbance ECV (Table 1).

## 2.1 Burned Area

Burned area, combined with other information (combustion efficiency and available fuel load) provides estimates of emissions of trace gases and aerosols. Measurements of burnt area can be used as a direct input (driver) to climate and carbon-cycle models, or, when long time series of data are available, to parameterize climate-driven models for burnt area (fire is dealt with in many climate and biospheric models using the latter approach). Fire induced emissions are a significant terrestrial source of GHGs, with large spatial and inter-annual variability.

## 2.2 Active fires

Detection of active fires provides indication of regional, diurnal, seasonal and inter-annual variability of fire frequency or shifts in geographical location and timing of fire events. Active fire information is also required by some algorithms used to generate burned area products. Detection of active fires can also serve as part of the validation process for burned area products.

## 2.3 Fire Radiated Power (FRP)

There is a strong empirical relation between FRP and rate of combustion, allowing $CO_2$ emission rates from a fire to be estimated from FRP observations. Multiple FRP observations can in principle provide estimation of the total $CO_2$ emitted during the fire through estimating time-integrated Fire Radiated Energy.

# 3. Satellite methods and standards

Satellite data obtained by remote sensing are the most suitable and useful means to monitor fire activity, a global phenomena characterized by a strong spatial and temporal variability. A list of major existing satellite systems providing measurements useful for the Fire Disturbance ECV is provided in Table 2. Table 3 lists several major satellite-derived fire products.

The raw data recorded by satellite instruments represent spectral radiances that can be converted into other geophysical parameters.

**Variable related to satellite data**: Spectral radiance. **Definition**: radiant energy per unit wavelength or wavenumber interval in a set of directions confined to a unit solid angle around a particular direction transferred across unit area of a surface projected onto this direction[2].

**Typical units**: WATTS PER STERADIAN PER SQUARE METER PER MICROMETER [$W \cdot sr^{-1} \cdot m^{-2} \cdot \mu m^{-1}$] or WATTS PER STERADIAN PER SQUARE METER PER INVERSE CENTIMETER [$W \cdot sr^{-1} \cdot m^{-2} \cdot (cm^{-1})^{-1}$]

Requirements for satellite instruments: VIS/NIR/SWIR/MIR/TIR moderate and coarse resolution multispectral imagery

MODIS, (A)ATSR and SPOT VGT are currently the only systems generating global systematic daily fire products. The MODIS Rapid Response System is also providing important advances in the web based distribution of global data within near real time of satellite acquisition. Future systems, such as NPP/NPOESS/VIIRS and sensors on GMES Sentinel Satellites should ensure continuity of fire mapping capabilities.

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2 Definition based on the online Glossary of Meteorology, American Meteorological Society

http://amsglossary.allenpress.com/glossary

| Geostationary | | |
|---|---|---|
| **Satellite / sensor** | **Resolution** | **Bands** |
| MSG-SEVIRI | 1 km – 3 km | VIS, SWIR, MIR, TIR |
| GOES | 1 km – 4 km | VIS, MIR, 2 TIR |
| FY-2C-SVISSR | 1.25 km – 5 km | VIS, MIR, TIR |
| INSAT-3D (2008)* | 1 km – 4 km | VIS, SWIR, MIR, TIR |
| GOMS Electro N2 MSU-G (2010)* | 1 km – 4 km | VIS, SWIR, MIR, TIR |
| COMS (2009)* | 1 km – 4 km | VIS, MIR, TIR |
| MTSAT-JAMI | 1 km – 4 km | VIR, MIR, TIR |
| GOES-R ABI (2015)* | 500 m - 2 km | VIS, NIR, SWIR, MIR, TIR |
| **Polar** | | |
| **Satellite / sensor** | **Resolution** | **Bands** |
| TRMM-VIRS | 2 km | VIS, NIR, SWIR and IR |
| NOAA/METOP-AVHRR | 1 km | VIS, NIR, SWIR, MIR, TIR |
| SPOT-VGT | 1 km | VIS, NIR, SWIR |
| ERS2-ATSR and ENVISAT-AATSR | 1 km | VIS,NIR,SWIR,MIR, TIR |
| FY-1 MVISR | 1 km | VIS, SWIR, MIR, TIR |
| FY-3 VIRR | 1 km | VIS, SWIR, MIR, TIR |
| DMSP-OLS | 2-3 km | VIS, IR |
| GMES Sentinel-SLST (2012)* | 500 m - 1 km | VIS, NIR, SWIR, MIR, TIR |
| TERRA/AQUA-MODIS | 250 m -1 km | VIS, NIR, SWIR, MIR, TIR |
| NPP/NPOESS VIIRS (2011)* | 375 m - 750 m | VIS, NIR, SWIR, MIR, IR |
| ENVISAT-MERIS | 300 m | VIS, NIR |
| BIRD satellite | 185 m and 370 m | NIR, MIR and TIR |
| TET satellite (2010)* | 42 m and 370 m | SW, NIR, MIR and TIR |
| Disaster Monitoring Constellation (DMCii) | 32 m | VIS and NIR |

*Future systems with approximate launch date.

**Table 2 - Major current and future satellite systems useful for the Fire Disturbance ECV**

| NAME | REFERENCE | SENSORS | COVERAGE | | COVERAGE | | DATA | STATUS |
|---|---|---|---|---|---|---|---|---|
| | | | spatial | temporal | spatial | temporal | | |
| **Burned Area Products** | | | | | | | | |
| Global Burnt Areas 2000-2007 (L3LRC) | www-tem.jrc.it/products_complete.htm | SPOT VGT | global | global | 1 km | 1 day | historical | finished |
| GBA 2000 | www-tem.jrc.it/products_complete.htm | SPOT VGT | global | global | 1 km | 1 month | historical | finished |
| GLOBSCAR | http://dup.esrin.esa.int/ionia | ERS2-ATSR2 | global | global | 1 km | 1 month | historical | finished |
| Modis Burned Area Product | http://modis-fire.umd.edu | Aqua/Terra –MODIS | global | global | 500 m | 1 day | historical | operational |
| Global Burnt Surface 1982-1999 | www-tem.jrc.it/products_complete.htm | NOAA-AVHRR | global | global | 8 km | 1 week | historical | finished |
| GLOB CARBON | http://dup.esrin.esa.it/projects/summaryp43.asp | ATSR2, AATSR, SPOT-VGT | global | global | 8 km | 1 month | historical | operational |

**Table 3 - Major satellite-derived burned area products**

| Active Fire Products | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| MODIS active fire | http://modis-fire.umd.edu/MOD14.asp | Aqua/Terra –MODIS | global | 2001-present | 1 km | 1 day | NRT +historical data | operational |
| World Fire Atlas (WFA-algo1/algo2) | http://dup.esrin.esa.int/ionia/wfa/ | ERS2-ATSR2, Envistat-AATSR | global | 1995-present | 1 km | 1 day | NRT | operational |
| EUMETSAT | www.eumetsat.int/Home/Main/Access_to_Data/Meteosat_Meteorological_Products/Product_List/index.htm#FIR | Meteosat-SEVIRI | Africa Europe | | 3km | 15 min | NRT | operational |
| Active Fire Monitoring (FIR) | http://earthobservatory.nasa.gov/Observatory/Datasets/fires.trmm.html | TRMM-VIRS | 40°N 40°S | 1998-present | 2 km | 1 day | historical data | operational |
| **Active Fire Products with FRP information** | | | | | | | | |
| GFED | www.geo.vu.nl/users/gwerf/GFED/index.html | MODIS ATSR VIRS | Global | 1997-2004 | 1° x 1° latitude/ | 1 mounth | historical data | finished |
| WF_ABBA* | http://cimss.ssec.wisc.edu/goes/burn/wfabba.html | GOES-E/W | N/S America | 1995-present | 4 km | 30 min | NRT | operational |
| MODIS FRP | http://modis-fire.umd.edu/MOD14.asp | MODIS | Global | 2001-present | 1 km | 1 day | NRT + historical data | operational |
| SEVIRI FRP | www.eumetsat.int/Home/Main/Access_to_Data/Meteosat_Meteorological_Products/Product_List/index.htm#FIR | Meteosat-SEVIRI | Africa Europe | | 3 km | 15 min | NRT+ limited historical data | pre-operational |

*Future systems with approximate launch date.

**Table 4 - Major satellite-derived active fire and FRP products**

## 3.1 Burned Area

### Methodologies

The spectral response of burned areas depends on ecosystem characteristics before fire occurrence (savannah, boreal forest, tropical forest etc.). Burned areas generally present changes in reflectivity due to various post-fire effects (removal of vegetation, exposure of bare soil, presence of char or ash, etc.). Increase of temperature due to decreasing evapo-transpiration, increasing absorption of solar radiation or the presence of remaining burning or smouldering in the pixel area, also often represents a detectable signal.

There is no consensus on a specific algorithm for burned area mapping. The reason for this is because it is very difficult for a single algorithm to detect burn scars in all vegetation types. The methodologies used to estimate burned areas using satellite data are based on satellite image classification using multi-spectral information in the visible, shortwave-infrared and infrared bands and the analysis of multi-temporal satellite imagery. Burned area maps are built using multi-spectral analysis of reflectance or various spectral indexes, such as GEMI (Global Environment Monitoring Index), NDVI (Normalized Difference Vegetation Index) and Normalized Burn Ratios. Some algorithms make corrections for the bi-directional (view direction) effects on satellite data.

### GCOS requirements (GCOS, 2006)

Target requirements:

- Accuracy: 5% (maximum error of omission and commission).
- Spatial and temporal resolution: 250m horizontal resolution, daily observing cycle.
- Stability: 5%.

Requirements for satellite instruments and satellite datasets:

- FCDR of moderate-resolution multispectral imagery, for example through:
  - Sustained moderate-resolution optical data of the MODIS/MERIS-class.
  - Reprocessing of the AVHRR archive held by NOAA (and NASA), with correction for known deficiencies in sensor calibration, and also for known directional/atmospheric problems.
- Calibration and data archiving needs:
  - Relative calibration of VIS, NIR and SWIR channels to within 2% over the full lifetime of each instrument. Either overlapping periods of operation or absolute calibration is needed to provide continuity from instrument to instrument. Orbital overpass time drifts should be minimized.

### Products

*Global Burnt Areas 2000-2007 (L3JRC product)*

A global inventory of burnt area has been generated for seven fire years defined as 1 April to March 31 (April 2000 to March 2007), at 1km spatial resolution and high temporal resolution (images providing almost total Earth coverage on a daily basis) from the SPOT VEGETATION Earth Observation system (see Tansey *et al.*, 2008). The product was derived from a single algorithm. It is known as the L3JRC product and is the result of a cooperation between the Joint Research Centre (JRC), the University of Leicester (UK), the Université Catholique de Louvain (B) and the Instituto de Investigação Cientifica Tropical (P).

*Global Burnt Area 2000 Project*

The Global Burnt Area – 2000 initiative (GBA2000) was launched by the Global Vegetation Monitoring (GVM) Unit of the Joint Research Centre (JRC), in partnership with other institutions, with the specific objectives of producing a global map of burned areas for the year 2000, using 1km satellite imagery provided by the SPOT-Vegetation system and deriving statistics of area burnt per type of vegetation cover (see Tansey *et al.*, 2004). Multiple algorithms were implemented in sub-regions across the globe. One of the algorithms was subsequently exploited to produce the L3JRC product.

*Global Burnt Surfaces 1982- 1999 (GBS 1982-99)*

The data for the Global Burnt Surfaces 1982-99 (GBS 1982-99) have been processed by the European Commission – DG Joint Research Centre – Institute for Environment and Sustainability – Global Vegetation Monitoring Unit.

This product, derived from the daily NOAA-AVHRR GAC 8km data set (1982-1999), allows characterizing fire activity in both northern and southern hemispheres on the basis of average seasonal cycle and inter-annual variability. Details can be found in Carmona-Moreno *et al.* (2005).

The burned surface detection algorithm implemented for obtaining burned surface maps uses weekly composites of the daily NOAA-AVHRR GAC 8km data. The algorithm is a global extension of the multi-temporal multi-threshold algorithm developed for Africa.

*The GLOBCARBON Project*

The GLOBCARBON Burnt Area Products (BAE) are monthly products representing the new burnt areas detected in the last month. These products are formed by combining the methods used in the GBA2000 project (JRC) and the GLOBSCAR[3] project (ESA; Simon *et al.*, 2004) and as such are derived from daily observations of the VGT-1, VGT-2, ATSR-2 and AATSR sensors.

3 The GLOBSCAR-project produces incremental global maps showing newly burnt surfaces. Every month a difference map is calculated, using daily ATSR images, initially for the year 2000.

*The GEOLAND Project*

The VGT specific part of GLOBCARBON (GBA2000 derived) is already used in the framework of the GEOLAND[4] project. Burnt area data for the years 1998-2007 have been produced. The data have been gridded to a range of raster grid sizes. The Geoland-2 project (commencing September 2008) will look to strengthen validation capabilities.

*The MODIS Burned Area Product (MOD45)*

The MODIS algorithm to map burned areas takes advantage of these spectral, temporal, and structural changes. The algorithm detects the approximate date of burning at 500 m by locating the occurrence of rapid changes in daily surface reflectance time series data. It is an improvement over previous methods through the use of a bidirectional reflectance model to deal with angular variations found in satellite data and the use of a statistical measure to detect change probability from a previously observed state (Roy *et al.* 2005b). The product is generated by South Dakota State University, University of Maryland and NASA.

## 3.2 Active Fires

### Methodologies

Active fire detection is based on the detection of the thermal signature from flaming and smouldering and its distinction from the non-burning surfaces based on spectral and spatial contrasts. Most methods use the thermal signal around 4 μm at day and night, but visible bands of certain sensors can also be used at night time (e.g. Kiran Chand *et al.*, 2006). Actively

4 GEOLAND is carried out in the context of GMES, a joint initiative of European Commission (EC) and European Space Agency (ESA), which aims to build up a European capacity for Global Monitoring of Environment and Security. GEOLAND-2 is funded under the EC Framework Programme 7.

burning fires are typically very much smaller in area than the spatial resolution of remote sensing imagers listed in Table 2, but the intense thermal emission from such hot targets in the MIR mean that they can be detected even if they cover only 0.1% or possibly 0.01% of a pixel (Roberts and Wooster, 2008). However, factors, such as clouds, sun glint, hot and bright surfaces, or sensor saturation can lead to false detections and need to be carefully accounted for in a detection algorithm.

Several algorithms have been implemented to detect active fires. They can be divided into the following categories: single fixed threshold; multiple thresholds; and contextual algorithms. The first two classify as active fire those pixels whose values are greater than predefined fixed thresholds. The contextual algorithms use variable thresholds and compare the pixel value to the values of surrounding pixels. Additional bands, such as a shortwave band to eliminate further false alarms are also used by all three categories of algorithms.

*Single fixed threshold*
These techniques (Langaas, 1992; Arino *et al.*, 2007) are based on the radiance measured in the MIR band (around 4 μm), in which black and grey bodies having temperatures between 800 and 1000 K, typical of forest fires, present a peak of emission. The algorithms detect a hot spot if Brightness Temperature > Temperature threshold. False alarms can be erroneously introduced using these algorithms during the day. The number of false alarms decreases at night-time, but other "hot spot" non-fire detections.

*Multiple thresholds*
These techniques (e.g. Kaufman *et al.*, 1990; Kennedy *et al.*, 1994) use multiple observations in MIR and in TIR bands and are based on the fact that considerably sub-pixel sized high temperature sources can produce a strong impact on a sensor's MIR signal at the pixel level, but have much less effect on the pixel's TIR signal (due to the fire's radiative emission peaking in the MIR).

*Contextual algorithms*
This fire detection process consists of two stages. First, pixels which may contain a fire are identified using a simple threshold which is low enough to ensure that all pixels which are fires are retained, but high enough to reject most pixels which are definitely not fires. The second stage is the confirmation of a potential fire pixel as a fire. This is achieved by comparing a potential fire pixel with its surrounding pixels through the use of statistical measures such as the mean and the standard deviation of the background temperature difference. For examples see: Prins and Menzel, 1994; Flasse and Ceccato, 1996; Justice *et al.*, 1996; Giglio *et al.*, 2003; Roberts and Wooster, 2008.

## GCOS requirements (GCOS, 2006)

*Target requirements:*
- Accuracy: 5% (maximum error of omission and commission).
- Spatial and temporal resolution: 250m horizontal resolution, daily observing cycle.
- Stability: n.a. in the context of a supplementary variable.

*Requirements for satellite instruments and satellite datasets:*
A data record of appropriate moderate-resolution multispectral imagery, for example through sustained moderate-resolution radiometer data from the ATSR-2/MODIS-class instruments.

*Calibration and data archiving needs:*
- Absolute instrument calibration for the entire dynamic range of the sensors is important; vicarious calibration to within 1-2% accuracy satisfactory.

- Past experience with post-launch calibration drift causes significant problems, as many fire detection algorithms rely on fixed thresholds and artifacts from the diurnal cycle of fire activity also arise.
- Existing archives (e.g., by ESA, NASA) must be maintained.

## Products

*ESA ATSR-WFA:*

The hot spot detection was obtained using fixed-threshold algorithms on the brightness temperature measured by a 3.7 μm channel. In order to minimize the number of false alarms the hot spot detection is performed only for night-time observations since the sensor saturates at a relatively low MIR brightness temperature (312 K). The related pixel resolution is 1 km. The algorithms have limitations due to cloud presence, atmospheric effects, bidirectionality of emissivity and the fact that at northerly latitudes the assumption of nighttime conditions may not always be valid. Fire temperature and extent are not taken into account in the processing.

ESA has been detecting and recording night time hot spot events since 1995 (Arino *et al.*, 2007). Data have been generated using ATSR equipment, on board of ERS-2 platform (since 1995), and AATSR on board of ENVISAT (since 2002).

A reprocessing of the ATSR WFA has been started using two new algorithms based on 1.6 μm and a background adaptive thresholding (Casadio and Arino, 2008). This will allow the time series to use the ATSR-1 on board ERS-1 and extend the series back to 1991.

*NOAA AVHRR FIMMA Product*

The FIMMA product is an automated system to detect fires from AVHRR data from the NOAA polar-orbiting satellites at NOAA/NESDIS. The related pixel resolution is 1 km. It is based on the contextual algorithm by Giglio *et al.* (1999), which considers the characteristics of surrounding pixels before deciding if a hot pixel is likely to be a real fire.

*NASA/UMd MODIS and VIRS TRMM*

The fire detection is performed using a contextual algorithm (Giglio *et al.*, 2003) that exploits the strong emission of mid-infrared radiation from fires. Before proceeding with the hot spot detection, cloud and water pixels are identified using cloud and water masks and obvious non-fire pixels are eliminated.
For those pixels that remain, potential fires are located using contextual algorithm and threshold test. The last steps are applied to reduce false alarms due to sun glint, desert boundaries, and errors in the water mask. Long-term global data records have been generated using MODIS and VIRS.

*Wildfire ABBA Fire Product*

The geostationary Wildfire Automated Biomass Burning Algorithm (WF_ABBA) is a dynamic multi-spectral thresholding contextual algorithm adapted from the original GOES ABBA contextual algorithm (Prins and Menzel, 1994). It utilizes the visible (when available) and the 3.9 and 11.2 μm bands to locate fires and characterize sub-pixel fire characteristics. The algorithm incorporates statistical techniques to automatically identify hot spot pixels in the ABI imagery. The 12 μm band is used along with the other bands to help identify opaque clouds. Once the GOES-R ABI WF_ABBA locates a hot spot pixel, it incorporates ancillary data in the process of screening for false alarms and correcting for water vapor attenuation, surface emissivity, solar reflectivity, and semi-transparent clouds. A rudimentary correction is also included to correct for diffraction. Various land, desert, and coastal masks are used to screen out non-fire regions and highly reflective regions and to assist in eliminating false alarms. Model output of total column precipitable water is utilized to correct for water vapor attenuation. Numerical techniques are used to determine instantaneous estimates of subpixel fire size and average temperature using a modified Dozier (1981) technique. High temporal resolution data is used to filter out false alarms. FRP estimates are derived using the radiance method (Wooster *et al.*, 2005).

The latest version of the WF_ABBA fire algorithm (version 6.5.005) provides fire/metadata mask files that include information regarding processing region, fire locations, opaque cloud coverage, block-out zones due to solar reflectance, extreme view angles, saturation, biome type, and various processing error codes. The code also produces a temporally filtered and non-filtered ASCII file that contains the following information for each detected fire pixel: longitude (deg), latitude (deg), satellite zenith angle (deg), pixel size (km2), 3.9 µm observed brightness temperature (K), 11 µm observed brightness temperature (K), instantaneous estimates of sub-pixel fire size (km2) and temperature (K), fire radiative power (MW), ecosystem type, and fire flag.

Currently the GOES WF_ABBA generates half-hourly fire data for the Western Hemisphere. The geostationary NOAA weather satellite GOES-12 provides coverage for most of North and South America while GOES-11 covers most of North America only. The WF_ABBA has been adapted to Met-8/-9 SEVIRI and MTSAT-1R and will become operational at NOAA/NESDIS by the first quarter of 2009 (www.ssd.noaa.gov/PS/FIRE/hms.html). Future plans include adapting the code to INSAT-3D, COMS, and GOMS Electro N2 MSU-G as part of a global geostationary fire monitoring system (Prins *et al.*, 2001).

## 3.3 Fire Radiated Power (FRP)

### Methodologies

The Fire Radiated Power product provides information on the measured rate of radiant energy output of detected fires. According to theory, which is at a research and development stage, the FRP is proportional to the MIR difference between the observed fire pixel radiance and the "background" radiance, i.e. the radiance that would have been observed at the same location in the absence of fire. It has been demonstrated in small-scale experimental fires that the amount of radiant energy released per unit time (the FRP) is related to the rate at which fuel is being consumed. Therefore, measuring this FRP and integrating it over the lifetime of the fire provides an estimate of the total Fire Radiated Energy (FRE), which for wildfires should be proportional to the total mass of fuel biomass combusted. In addition, there has been good progress in establishing direct relationships between FRP/FRE and rates/totals of trace gases and aerosol production, both at the laboratory scale (e.g. Freeborn *et al.*, 2008) and from satellite observations (Ichoku *et al.*, 2005).

Current methods to obtain fuel combustion estimates are based largely on burned area mapping approaches, using fuel density and combustion completeness variables. Uncertainties on this method could be due to burned area estimation, to fuel load estimation and to uncertainties in combustion completeness (which can vary greatly with land-cover/climate/timing-of-fire). The FRP approach provides a geophysical variable potentially more directly related to the amount of combusted biomass, and to the rate at which the fire is releasing $CO_2$ and other carbon containing trace gases and aerosols.

For most regions and times, there exist many more small/weakly burning fires than larger/very intense fires. For applications requiring total fire fuel consumption/carbon emission it is therefore important to attempt to detect the numerous smaller fire events that by definition have a relatively weaker signal. The most effective way of doing this is to use a higher spatial resolution instrument, but with the proviso that limited fire durations mean that frequent views are also a necessity.

## GCOS requirements (GCOS, 2006)

*Target requirements:*

- Accuracy: 5%.
- Spatial and temporal resolution: 1km horizontal resolution, daily observing cycle.
- Stability: n.a. in the context of a supplementary variable.

*Requirements for satellite instruments and satellite datasets:*

A data record of appropriate multispectral imagery, for example through:

- SEVIRI-class instruments, to be extended to the full set of geostationary meteorological satellites.
- MODIS-class observations, to be extended post-Aqua and Terra through VIIRS.
- Future BIRD-type instruments, required for high spatial resolution acquisition with reduced spatial coverage, to allow the more frequent but lower spatial resolution datasets to be adjusted for missing smaller and weaker fires.

*Calibration and data archiving needs:*

- Absolute calibration is important across the entire dynamic range of the sensor.
- High sensor saturation is needed, in both the mid-infrared and the thermal infrared spectral bands.
- Preferably the mid-infrared channel will be narrow band, avoiding the effects of $CO_2$ and water vapour (following design of MODIS 3.9 µm narrowband channel).
- MODIS FRP archive to be extended into the future through follow-on instruments.
- Geostationary satellite operators need to commence archiving of FRP products.

## Products

*MODIS FRP*

FRP is part of the standard suite of MODIS active fire products. It is estimated by an empirical relationship between the 4 µm brightness temperature of the fire pixel and the mean 4µm brightness temperature of the non-fire background (Kaufman *et al.*, 1998). Gridded monthly mean values of FRP have been included in the analysis of global fire dynamics from MODIS (Giglio *et al.*, 2006).

*SEVIRI FRP*

The FRP retrieval is carried out using the MIR radiance method, which assumes that FRP is proportional to the difference between the observed fire pixel radiance in the SEVIRI middle infrared (MIR, 3.9 µm) channel and the "background" radiance that would have been observed at the same location in the absence of fire (Wooster *et al.*, 2005). This background radiance is at present derived from the set of fire-free and cloud-free pixels surrounding each fire pixel. The FRP product is derived every 15 minutes at the native SEVIRI pixel resolution.

The disseminated product is available in near-real time via the GEONETCast satellite communication link or via FTP and includes for each processed pixel: the FRP (in MW), the corresponding uncertainty in the FRP retrieval based on the variability of the background radiance estimation, a confidence measure (representing the level of confidence that the observation is indeed a "true" fire), together with other ancillary information. The FRP product will also be available at a reduced spatial and temporal resolution, e.g. hourly at 5 x 5 degrees, with statistical adjustments made for non-detected small fires and cloud cover.

*Global Geostationary WF_ABBA FRP*

The global geostationary WF_ABBA fire product for

GOES, Met-8/-9 SEVIRI, and MTSAT-1R will provide FRP (MW) for each non-saturated and non-cloudy high confidence fire pixel identified in global geostationary satellite imagery. FRP will be computed using the radiance method (Wooster *et al.*, 2005).

*SLST FRP*

The ESA Sentinel SLST instrument product suite is planned to include an active fire detection and FRP product at 1 km spatial resolution. A contextual algorithm will be used to detect fire pixels, and the MIR radiance method used to determine their FRP.

## 3.4 Validation of satellite fire products

There are several fire products generated from remote sensing data using different methodologies and algorithms. The international scientific community agrees on the need of standard validation protocols for fire products.

The Land Product Validation (LPV), one of the six subgroups of the Working Group on Calibration and Validation (WGCV) of the Committee on Earth Observing Satellites (CEOS), works on the standardization of the validation process for global land products. A general consensus now exists within the CEOS community to identify three stages of validation for satellite products. The guidelines for the CEOS Hierarchy of Validation are:

**Stage 1**: Product accuracy has been estimated using a small number of independent measurements obtained from selected locations and time periods and ground-truth/field program effort.

**Stage 2**: Product accuracy has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts.

**Stage 3**: Product accuracy has been assessed, and the uncertainties in the product well-established via independent measurements made in a systematic and statistically robust way that represents global conditions.

The need of the establishment of a network of sites for a long term validation of fire products has been recognized by the CEOS/WGCV/LPV Subgroup (Rasmussen *et al.*, 2001). The selection criteria for the validation sites take into account:

- biomass characteristics: the most affected, contributing most to emission and/or representing the largest source of sinks
- types, size and distribution of fires
- land use: areas dominated by different land-use should be included
- availability of data: sites that have historical and current data sets available and were active fire remote sensing groups are concentrating efforts should be included (note that this is only for burned area validation).

Validation of satellite-based products with *in situ* measurements is limited, especially in developing countries. For proper validation of satellite-based products fire activity over the entire area of the satellite pixel needs to be mapped by independent means. Fire perimeter maps or high resolution airborne imagery are potentially useful reference data, but issues with limited sampling and data quality remain. Validation of the moderate and coarse resolution global products is most often performed by higher spatial resolution (e.g. 30m resolution Landsat-class) satellite data. The protocol recommended by CEOS includes the use of Landsat-class (i.e. 30m) satellite imagery as reference for the validation of moderate and coarse resolution products. The standard for burned area adapted by CEOS includes the use of pairs of Landsat-class imagery to validate burning mapped between their acquisition dates (Roy *et al.*, 2005a). For active fire products simultaneous observations are required. The prototype for this approach was developed using

Terra/ASTER imagery to validate the Terra/MODIS active fire product, taking advantage of the single-platform sensor configuration (Morisette *et al.*, 2005; Csiszar *et al.*, 2006). However, there is a need to extend this approach to multi-platform techniques. Cross calibration of FRP products between geostationary and polar orbiting systems has commenced (e.g. Roberts and Wooster, 2008) but the full validation of the FRP approach requires unsaturated radiance measurements from high resolution space- or airborne sensors. These are currently not routinely available, but emerging systems exist and opportunistic experiments have been commenced with airborne thermal imaging systems underflying polar orbiting satellites.

# 4. *In situ* measurement methods and standards

The availability of *in situ* measurements of active fire and area burned is limited to certain regions and is lacking especially in developing countries. Therefore there is currently no standard, global *in situ* measurement/reporting system. National reporting is extremely variable and wholly inadequate to provide a consistent regional or global assessment. Documentation of fire activity by aerial means (including manned or unmanned aircraft), such as GPS plotting, post-fire photography or high resolution radiometers, is done only by countries with significant fire management budgets or limited fire activity. Ground-based observations from fire lookout towers or by emerging automated observing systems also provide incomplete and inconsistent coverage.

Collection of *in situ* measurements related to fire is under the responsibility of the national forest agencies or other agencies (fire services, emergency services), which may collect data on their own or compile data from sub-national levels. The

| Moderate resolution sensors | | |
|---|---|---|
| **Satellite / sensor** | **Resolution** | **Bands** |
| IRS-P6 AWiFS | 56 m | VIS, NIR |
| Landsat-TM, ETM+ | 30m | VIS, NIR, SWIR, TIR |
| LDCM (2012)* | 30 m | VIS, NIR, SWIR |
| SPOT-HRV | 20m | VIS, NIR, SWIR |
| Terra-ASTER | 15 m – 90 m | VIS, NIR, SWIR, TIR |
| CBERS | 20 m – 80 m | VIS, NIR, SWIR, TIR |

*Future system with approximate launch date.

**Table 5 - Major current and future satellite systems useful for the validation of Fire Disturbance ECV products.**

national fire monitoring policies vary depending on existing regulations on fire management, on land conformation, land accessibility, the extent of cultural use of fire, and the financial means of the country. An example of airborne data collection is Russia's Avialesookhrana (National Aerial Fire Protection Branch of the Federal Forest Service of Russia), which provides systematic airborne fire monitoring over a certain part of the country's territory (remote areas are monitored by satellites only) (Goldammer, 2006a). *In situ* measurements are limited to small areas and are used mainly for validation of remote sensing data.

Burned Area: Fire perimeters are measured after fire occurrence. GPS measures are usually collected along the borders of burnt areas by helicopter and used to visualize the fire perimeter with a GIS system and validate satellite-based burned area products. Inconsistent coverage and unmapped unburned areas within the fire perimeter limit the usefulness of these datasets. In distant remote areas, fixed-wing aircraft may be used (rather than helicopter due to higher cost, ferrying distance and available range) to plot fire boundaries by hand on maps. In many cases, remote fires are seldom mapped by *in situ* methods; they are mapped using satellite imagery or not mapped at all.

Active Fire: Fire detection and monitoring is performed using manned or automated observation towers or aircraft. Often only location and an estimate of the total area burning are reported without spatially explicit information.

Fire Radiated Power: This kind of data is rarely collected using *in situ* measurements, as it is still a product under research and overhead observations of a fire are necessary for its assessment. Collection is usually performed in small areas by means of IR radiometers mounted on manned aircraft or unmanned aerial systems (UAS).

# 5. Additional data needs

The standard method for estimating wildland fire carbon emissions is to calculate the product of area burned, carbon density (or fuel load), and burn efficiency (Seiler and Crutzen, 1980). There are numerous examples of standard burn efficiency factors have been published for different global biomes. However, carbon emissions can range by a factor of 10 within a single biome (e.g., boreal forest) due to differences in fuel dryness. There will also be different emission factors for soil and vegetation components. One method to significantly improve wildland fire GHG emission estimates is to combine area burned data with fire behaviour-based emission models (rather than using standard burn efficiency factors). In these models, emissions are calculated as a proportion of fuel consumed. The greatest emissions come from fires that burn large areas over long time-periods (sometimes months). Fuel consumption (and emissions) on large fires can be modeled with greater accuracy by 1) using a fuels data base to spatially model pre-fire fuel loads and fuel type, and 2) using fire weather data to temporally model changing burning conditions as the fire spreads across the landscape. Daily fire initiation and spread can be mapped with good accuracy using active fire products. Fuel and weather data are also needed for fire initiation and spread modeling.

## 5.1 Fuels data

The required fuels database has two components: fuel type data, and fuel load data. Fuels databases are scarce. However, there is good opportunity to develop new global- or regional-level fuel type databases by converting existing satellite-derived landcover data. This will result in very broad-based fuel categories, but it will provide a universal fuels classification structure with which to make large-scale emissions estimates that are driven by a bottom-up (i.e. fuel consumption) process. This database should also be relatively easy to update. There are several ways to develop a fuel load database, including the use of growth and yield models, using a distribution of known fuel loads based on age-class structure of the region, or using remotely-sensed products. A coordinated effort linking remotely sensed fuel load to the Terrestrial ECV 'Aboveground Biomass' identified in the GCOS Implementation Plan (WMO 2004) should be actively pursued.

In addition to the fuels database, a closely related fire behavior-based fuel consumption model needs to be developed with separate algorithms for each fuel category in the classification. In some global regions, this is a simple task because the fuels are very simple (e.g. grasslands and savannah of Africa), or because robust fuel consumption models (or at least a large amount of data) already exist (e.g. North America and Australia). In other regions, models would have to be developed, likely using a combination of existing data from similar fuel types in other global regions, and expert opinion. Global fuel consumption models should be developed in parallel with Terrestrial ECV "Burn Efficiency" as identified in the GCOS Implementation Plan (WMO 2004).

Another important fuel aspect to spatially modeling fire danger and fire behavior is proper mapping of 1) grass greenness or curing, and 2) leaf-out and leaf-fall of deciduous, broadleaf tree species. These represent cyclical, annual processes that can best be monitored by remote sensing. The most common approach is to combine spectral measurements into indices that capture the variability of the spectral signal as a function of biomass amount or condition. NDVI from AVHRR provides the longest times series available (Goward *et al.*, 1991), but the suboptimal spectral sampling leads to limitations of its use. Improved spectral sampling of recent imagers or hyperspectral sensors have allowed for the development of indices that are more suitable for vegetation characterization, such as the Normalized Difference Water Index (Gao *et al.*, 1996) or the Visible Atmospherically Resistant Index (Gitelson *et al.*, 2002).

## 5.2 Fire weather and fire danger

Fuel dryness is dependent on past and present fire weather conditions, and fire behaviour (e.g. fuel consumption, fire rate of spread, fire intensity) is a reflection of fuel (dryness, load, type) and weather (i.e. wind) conditions. For these reasons, fire weather (or the weather parameters that affect wildland fire) is a primary driver of fuel consumption models. Ground-based weather data is collected continuously in many countries around the world and used to calculate fire danger[5]. Fire danger calculations are usually done within the framework of an existing 'fire danger rating system'.

There are numerous fire danger rating systems (some are referred to as fire danger indices) in practice around the world, but the 3 primary systems are: the Canadian Forest Fire Danger Rating System (CFFDRS), which includes the Canadian Forest Fire Weather Index (FWI) System (a subsystem of the CFFDRS); the National Fire Danger Rating System (NFDRS) of the USA; and the McArthur Forest and Grassland Fire Danger Meters of Australia. The type and amount of fire weather data collected to calculate fire danger is dependent on the fire danger rating system used; the NFDRS has more weather input requirements than the Canadian and Australian systems. Presently, fire weather is collected daily and used to calculate fire danger in countries representing less than half of the vegetated biomes of the world. However, this is a procedure that could be done globally using the existing WMO network of weather stations.

5 Fire danger is a general term used to express an assessment of the fire environment including ease of ignition, rate of fire spread, difficulty of control, and fire impact.

### Global Early Warning System for Wildland Fire

Fire danger rating systems typically use early afternoon weather data (1200-1500 LST) to provide information of peak daily fire danger conditions that occur mid to late afternoon (1500-1800 LST). For fire management planning purposes, including the hiring of aircraft and mobilization of suppression crews, some fire agencies use forecasted weather data to provide an additional 1-3 days advanced warning of fire danger. A 2-week product is available in the US. Longer-term (monthly or seasonal) predictions of fire danger trends are also available in some countries, but these do not provide detailed fire danger information that is required for daily operational decision-making.

Under the current global fire environment of increasing fire activity, and the increasing social, economic and environmental costs of wildland fire disaster, there is a general movement within the international fire community towards greater integration and resource-sharing (Goldammer, 2006b; Carle, 2007). Fire managers understand that the implementation of resource-sharing agreements and the physical transfer of suppression resources are time-consuming and require advanced notice of future burning conditions. As well, early warning of extreme fire danger allows fire managers time to put into effect fire prevention and early detection activities in critical areas. Often these activities can mitigate or prevent disaster fires, or megafires, from occurring. To effectively implement national prevention, detection and suppression programs, and to facilitate international mobilization of suppression resources, the international fire community requires a fire danger forecast of about 1.5 weeks.

As a result, a Global Early Warning System for Wildland Fire has been proposed (de Groot *et al.*, 2006). The system is based on existing science and technology, and integrates ground-based weather data, remotely-sensed fire and fuels data, and predictive weather models for ensemble forecasts of future fire weather. A global early warning system would provide:

- an operational fire danger rating system for the many countries that do not have the financial or institutional capacity to develop a national system,
- a common system to globally evaluate fire danger, which can be used as the foundation to build international fire agreements,
- global fire danger data, which can be combined with fuels data to provide global GHG emission estimates.

A demonstration of products for a potential prototype system for sub-Saharan Africa was completed in 2007. Pursuit of a fully-funded operational system continues. Currently the UK funded FireMAFS project is also examining the possibility of seasonal fire forecasting, based on ensemble seasonal weather forecasting.

### Fire Weather Data Requirements

All of the fire weather data required to drive fire danger and early warning models are currently being collected by the WMO network. Additionally, all of these data have been identified within the Atmospheric Surface and Terrestrial ECVs of the GCOS Implementation Plan. Following is a summary list of the ECV standards required for the 3 longest-existing fire danger rating and early warning systems (Table 6).

## 5.3 Fire initiation and spread modeling

People are the major source of all global wildland fire, which is reflected by >80% of wildland fire occurring in tropical grasslands and savannas where fire is used to manage vegetation for various purposes (Goldammer 1990, FAO 2007). As well, the exponential increase of tropical forest fires in recent decades is due to the use

| Domain | ECV | Fire Danger Rating System | | |
|---|---|---|---|---|
| | | CFFDRS | NFDRS | McArthur models (grass and Eucalypt forest) |
| Atmospheric | Temperature | 1200 LST * | 1400 LST *<br>Daily max<br>Daily min | 1500 LST ** |
| | Precipitation | 24-hr total 1200 LST | Precipitation type<br>24-hr total<br>and duration<br>1400 LST | 24-hr total<br>0900 LST<br>Days since rain |
| | Wind speed | 1200 LST<br>@ 10 m | 1400 LST<br>@ 6.1 m | 1500 LST<br>10 m |
| | Wind direction | 1200 LST *** | 1400 LST *** | 1500 LST *** |
| | Water vapour | RH %<br>1200 LST | RH %<br>1400 LST<br>Daily max<br>Daily min | RH% ****<br>1500 LST |
| | Upper air-cloud properties | NA | Cloudiness | NA |
| Terrestrial | Snow cover extent | Snow-free date and snow depth used in spring to calibrate indices | Snow-free date used in spring to initiate system startup | NA |
| | Snow cover duration | | | |
| | Snow depth | | NA | |

* CFFDRS and NFDRS use 1200 LST or 1400 LST weather data to calculate fire danger for the peak daily burning period at mid-afternoon.

** McArthur models calculate real-time fire danger; data is usually collected at 1500 LST to calculate fire danger during the peak daily burning period at mid-afternoon.

*** Not required to calculate fire danger, but operationally valuable for predicting and mapping fire spread

**** Must correspond to time of temperature data collection.

**Table 6 - Summary of ECV standards required for a global early warning system, including global fire danger and emissions modeling.**

of fire for deforestation and agricultural expansion (Moulliot and Field 2005). In terms of natural (or non-human-caused) fires, lightning is the major ignition, although there are a small number of other natural sources (e.g. volcanoes, underground burning coal). There are numerous existing wildland fire initiation models, and ongoing research is continually producing new ones. For these models to properly simulate 'fire initiation' (i.e. an ignition that is self-sustaining and able to spread), models need to simulate the moisture content of fine (< 1 cm diameter) fuels, which is the vegetation component that supports fire ignition and spread.

Fine fuels are represented by dead organic debris (fallen leaves, needles, cured grasses and forbs) and flammable live vegetation (foliage, bark, small branches). Live fuel moisture content is largely dependent on seasonal plant growth processes and long-term weather conditions (i.e. drought). Therefore, a continuous historical record of recent daily precipitation and temperature data is usually sufficient for modeling purposes (previous 12 months of data, but longer if there is an extended drought period). Modeling dead fine fuel moisture content is much more data intensive and short-term because those fuels exchange moisture (gains and losses) very quickly with the surrounding atmosphere. Therefore, hourly data of temperature, relative humidity, and wind speed are critical. In some models, precipitation amount and/or precipitation duration are important variables, and their time of occurrence can be important for daily modeling, so an hourly record is required. Fire initiation models are primarily developed to assist fire management agencies to plan daily fire prevention and detection activities, so weather data is usually required as close to real-time as possible. During dry periods of high fire danger conditions, forecasted temperature, relative humidity, and wind data are often used to provide early warning.

In general, human-caused fire models rely heavily on the simulation of fine fuel moisture content, often predicting daily fire occurrence based on historical relationships between fire occurrence and fine fuel moisture content. Historical fire records are often difficult to acquire for most countries, but at a regional or global scale, hot spot data is extremely valuable to calibrate human-caused fire initiation models (e.g. de Groot *et al.* 2005). Because fire is constantly used to manage fine fuel-dominated ecosystems in the tropics, there is very strong relationship between hot spots and fine fuel dryness in that global region.

Lightning fire initiation models differ from human-caused models because those fires generally start as a smouldering fire in organic soil, which ignite the fine surface fuels. Lightning is often accompanied by precipitation, which wets the surface fine fuels. As a result, lightning fires often occur several days after lightning occurrence, when the surface fine fuels dry out. As a result, lighting initiation models need to simulate the moisture content of shallow organic soil, as well as the fine surface fuels. Organic soil moisture content changes occur more slowly than fine fuels, so modeling the former can be done using daily temperature (max, min), precipitation (amount), and relative humidity (max, min) data.

Wildland fires are spread by wind through the fine fuel component of the fuel (vegetation) complex. Therefore, fire spread models are dependent on wind data (preferably hourly) and weather data used to simulate fine fuel moisture content. Fire spread models are developed to assist fire agencies in planning pre-suppression mobilization for new fire starts, and suppression strategies at on-going fires. To accomplish this, forecast weather data is often used for early warning.

## 5.4 Verification of fire-related emissions from atmospheric sensors

Verification of trace gas emissions (flux units - mass per unit area per time) from fires is a hard problem because most measurements of trace gases from the ground or satellite are in concentration units, often column amounts. Therefore, emissions must be converted into concentration units or trace gas concentrations and must be inverted to obtain emissions to make comparisons. Either of these two approaches will require knowledge of atmospheric transport. For example, Reid *et al.*, GRL, 2004 assimilated GOES satellite derived fire emissions for 2001 and 2002 into their global aerosol model and compared model predicted aerosol optical depth to satellite (MODIS) and ground-based (AERONET) measurements to verify the accuracy of GOES emissions. In the absence of direct *in situ* flux measurements during the fire events, these sort of indirect methods are the only way to verify emissions. To avoid the complicated chemical loss and production mechanisms of short-lived trace gases and aerosols, long-lived trace gases such as carbon dioxide, carbon monoxide, and methane must be considered. Routine measurements of one or all of these trace gases are currently available from satellite sensors such as Envisat/SCIAMACHY, Aqua/AIRS, Aura/TES, Terra/MOPITT, and MetOP-1/IASI. Spatial and temporal resolution of these satellite measurements are not at the scale comparable to emissions but is not critical when a model with spatial scale comparable to satellite measurements is used to disperse the emissions into gridded concentrations. Current satellite measurements of trace gases will likely continue in the NPP/NPOESS era with CrIS, as well as with targeted future missions such as Orbiting Carbon Observatory (OCO).

# 6. End Users and Products

The only existing product aiming to quantify fire emissions on a global scale is the Global Fire Emissions Database (GFED) Project (1997 – now). Over the last 5 years, emissions estimates have been refined using the burned area approach. Monthly data is available for the community to download and use. Burned area estimates are derived from a combination of active fires depicted by MODIS (2001 onwards), TRMM-VIRS and ATSR (for the pre-2001 period) and burned area (MODIS) for selected regions.

The recently generated MODIS burned area product (Roy, 2005b) over southern Africa for the month of September 2000 was used to calculate spatially-explicit regional biomass burning emissions from grassland and woodland fires for a number of trace gases and particulates at 1 km spatial resolution. A dynamic regional fuel load model (Hely *et al.*, 2003) developed for southern Africa in support of SAFARI 2000 fire emissions modeling is used to compute spatially explicit southern Africa fuel load data. Regional grassland and woodland emissions are estimated using ecosystem-specific emission factor algorithms for carbon dioxide (CO2), carbon monoxide (CO), methane (CH4), non-methane hydrocarbons (NMHC) and particulate matter with diameter less than 2.5 µm (PM2.5) for southern African savanna fires (Korontzi *et al.*, 2003). A bottom-up methodology to calculate carbon emissions for savanna burning in northern Australia has recently been published (Russell-Smith *et al.*, 2008). This procedure incorporates detailed fire history, vegetation structure, and fuels mapping data from satellite imagery; field-based assessment of fuel load, burning efficiency, N:C composition; and use of regionally derived emissions factors.

At a national scale, Canada has developed an operational method to estimate annual carbon emission from wildland fires for international reporting (de Groot *et al.*, 2007). Area burned and daily fire spread estimates are derived from satellite products. Spatially and temporally explicit indices of burning conditions for each fire are calculated using fire weather data. Fuel consumption for different live biomass and dead organic matter pools in each burned cell is calculated according to fuel type, fuel load, burning conditions, and resulting fire behavior. Carbon emissions are calculated from fuel consumption. The data are summarized in the form of disturbance matrices and provides spatially explicit estimates of area burned for national reporting. The fire data are integrated at the national scale with data on forest management and other disturbances.

*In the EU funded project SIBERIA-II a remotely sensed burned area map from 1992-2003 (Balzter et al., 2005; George et al. 2006) was used by the International Institute for Applied Systems Analysis in Vienna to produce the first full carbon account for a region of about 3 million km2 in Siberia (Nilsson et al., 2007). The burned area map was imported into a GIS that was linked to a landscape-based model of the carbon cycle using a multitude of environmental data layers. Fire scar areas were used to quantify carbon emissions during the fire. The age of fire scars was used to determine the post-disturbance carbon flux.*

There are very few examples of emission estimates as a result of ground fires, yet their potential impact could be significant. Page *et al.* (2002) estimated that between 0.19–0.23 gigatonnes (Gt) of carbon were released to the atmosphere through peat combustion, with a further 0.05 Gt released from burning of the overlying vegetation during the fires in southern Borneo in 1997. These fires can often burn for many months during the dry season. A spatial database of the location and characteristics of regions of tropical peat swamp forest is available[6].

Carbon emissions data from vegetation fires, however, should be used cautiously. The majority of vegetation fires globally are recurrent events taking place in return intervals ranging from several months (several fires per season affecting the same area in some ecosystems such as tropical and subtropical deciduous forests), years (e.g. savanna and steppe / grassland fires burning in intervals of one to several years), decades and centuries (e.g. in some temperate and boreal forests). As many of these ecosystems are adapted to short- to long-term interval fires, the amount of carbon emitted by fire is sequestered by vegetation re-growth if no other factors are involved that would contribute in ecosystem degradation and thus in the reduction of carbon sequestration potential. Thus, models aimed at producing data on the contribution of vegetation fires to the human-induced Greenhouse Effect should carefully distinguish between the prompt and the net release of carbon to the atmosphere – an approach that must involve ecosystem recovery potential and the various pathways of post-fire carbon fluxes (e.g. Goldammer *et al.*, 2005).

In this context it is necessary to develop *in situ* observation methodologies that consider short- to long-term effects of fire on ecosystem functioning and carbon balances. The development of a Global Wildland Fire Assessment based on the potentials of Earth Observation on the one side, and the needs

6 This information has been collected through the EC FP6 funded project CARBOPEAT:

http://www.carbopeat.org

of careful validation of fire effects on the ground is therefore imperative in order to assess the long-term effects of fire on carbon fluxes.[7]

# 7. Conclusions

There are several fire observing systems currently in use around the world. Consistent global and large-scale fire monitoring is possible only by means of satellite systems, which can potentially be complemented by *in situ* and airborne observations in areas of systematic monitoring. There is a need to document all systems and to understand their reliability, the relationship between the various methods and their applicability to various fire and management regimes. International coordination is carried out by the Global Fire Monitoring Center (GFMC) and the Fire Mapping and Monitoring theme of the GOFC-GOLD, a Technical Panel of GTOS.

The currently available fire products only marginally meet the requirements defined by the GCOS Implementation Plan (GCOS, 2006). No global products at the specified 250m spatial resolution and daily observing cycle exist and product continuity and consistency between the various systems remains unresolved (see also CEOS, 2006). The GCOS requirements need to be re-evaluated and be more specific and realistic for the products generated at various time scales and resolutions. For example, all active fire products contributing to the Fire Disturbance ECV should include cloud masks to provide information on missing detections due to cloud obscuration. The potential from alternative and emerging observing systems, such as active remote sensing (i.e. SAR) also need to be explored.

The Space Agencies are expected to continue to generate, archive and distribute individual satellite-based fire products and to maintain historical archives. The various fire products also need to be systematically validated. The quality, coverage and observing standards of *in situ* observations currently do not allow for systematic validation and current standards recommended by CEOS are based on the use of high resolution remote sensing data.

Understanding of the fire mapping capabilities, detection limits and overall accuracy of the various products will facilitate their inter-calibration and the creation of the multi-sensor, multi-product fire disturbance data record. Additionally, the combination of multiple satellite products that provide more comprehensive information on various fire characteristics and the development of multi-sensor algorithms would lead to the optimization of the existing remote sensing systems.

The transition of experimental products to the operational domain needs to be facilitated and data continuity to the new generation sensors on future operational environmental satellite series needs to be ensured. Improved exchange of information and timely and systematic availability of data is critical for global fire monitoring. An integrated data system or single international centralized data centre could manage data and provide easy identification of data holders. The GCOS and GTOS Science Panels will continue to facilitate this process.

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7 First proposal for the development of a globally standardized fire inventory system (1996): http://www.fire.uni-freiburg.de/iffn/org/ecefao/ece_3.htm

A draft version of the 2004 Global Wildland Fire Assessment is available at:
http://www.fire.uni-freiburg.de/inventory/assessment.htm
and:
http://www.fire.uni-freiburg.de/inventory/assessment/GFMC-Fire-Report-Format-Countries-13-December-2005-ENG.doc

# 8. Recommendations

### Recommendations regarding standards and methods

- finalize and adopt emerging consensus methods and standards for the validation of medium and coarse resolution satellite-based fire products using higher resolution spatially explicit reference data from *in situ*, airborne and spaceborne observations;
- develop standards for the intercalibration of fire products from various sensors to enable the creation of a long-term fire disturbance data record;
- develop multi-sensor algorithms and multi-product suites for a more comprehensive characterization of fire activity;
- develop systematic fire products from active remote sensing data;
- develop ground and surface fire characterization methods, particularly for areas of peat;
- coordinate linkages between surface and atmospheric ECVs and data requirements to model global fire danger, fire emissions, and a global early warning system for wildland fire at various time scales; specifically, these ECVs are:
    - atmospheric ECVs: surface temperature, precipitation, wind speed, wind direction, water vapour, upper air cloudiness
    - terrestrial ECVs: aboveground biomass, burn efficiency, and snow cover (extent, duration, depth)
- establish linkages between fire-related surface and atmospheric impacts and corresponding ECVs.

### Other generic recommendations regarding the Fire Disturbance ECV

- re-evaluate the GCOS requirements to be more specific and realistic for the products generated at various time scales and resolutions;
- generate and distribute individual fire products and maintain historical archives;
- ensure the transition of proven experimental products to the operational domain;
- ensure data continuity to the new generation sensors on future satellite series;
- improve the exchange of information and facilitate timely and systematic availability of data, products and validation data;
- improve the availability of in-situ fire data.

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# Web links

Global Fire Monitoring Center (visit this website for further fire-related links)
www.fire.uni-freiburg.de/

GOFC-GOLD Fire (visit this website for further fire-related links)
http://gofc-fire.umd.edu/

MODIS Fire
http://modis-fire.umd.edu

MODIS Land Validation
http://landval.gsfc.nasa.gov/

ESO Ionia Server
http://dup.esrin.esa.it/ionia/index.asp

CEOS
www.ceos.org/

EUMETSAT
www.eumetsat.int/Home/index.htm

GFED2
http://ess1.ess.uci.edu/~jranders/data/GFED2/readme.pdf

US Forest Service Fire, Fuel and Smoke Science Program
www.firelab.org/

JRC Terrestrial Ecosystem Monitoring
www-tem.jrc.it/

WF_ABBA
http://cimss.ssec.wisc.edu/goes/burn/wfabba.html

NOAA/NESDIS Hazards Mapping System
www.ssd.noaa.gov/PS/FIRE/hms.html

University of Maryland / NASA Fire Information for Resource Management System
http://maps.geog.umd.edu/firms/

GMES-Geoland
www.gmes-geoland.info

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