

HALO / GEMS PROJECTS
MEMORANDUM



To: GEMS Management Board
 Copy: HR
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1 Introduction

Fires from agricultural practices and land clearing, forest fires due to arson and natural fires ignited by lightning flashes play an important role in the Earth system. Besides their role in the carbon cycle, where they can be a limiting factor for carbon assimilation in the terrestrial biosphere, or lead to enhanced biodiversity in some forest and savanna ecosystems, fires also constitute a very large source of aerosols and air pollutants, thereby affecting regional air quality, weather, and climate. Long-range transport events of smoke plumes and associated air pollutants can also impact air quality on a hemispheric or global scale, and emissions from fires are among the most important contributors to the global budget of various trace gases and aerosols (Figure 1).

Fires occur in almost all ecosystems on earth, and their frequency, size, and severity depends largely on climate and weather conditions. Prolonged draught, for example, can on the one hand increase the likelihood for fire occurrence (for example in tropical in temperate forests), but it can also lead to fewer and more dispersed fires (as it is the case for some semi-arid savanna regions). It is commonly assumed that the majority of present fires is of anthropogenic origin. Humans also affect fire occurrence and severity in other ways, for example through forest management practises (e.g. the US, where fire prevention led to unprecedented accumulation of biomass litter which could then burn much more severely), or through peat draining (as in Indonesia, where tropical swamps have been converted to rice fields with severe consequences for fire susceptibility). Yet, natural fires also play an important role, because they often occur in remote regions where fire control is difficult or impossible, so that very large areas can be burned during a single event.

Accurate estimates of trace gas and aerosol emissions from fires including their detailed spatial and temporal distribution are needed in atmospheric composition monitoring for a number of reasons:

1. Regional scale air quality can be dominated by fire smoke, i.e. emitted gases and aerosols. Thus, there is

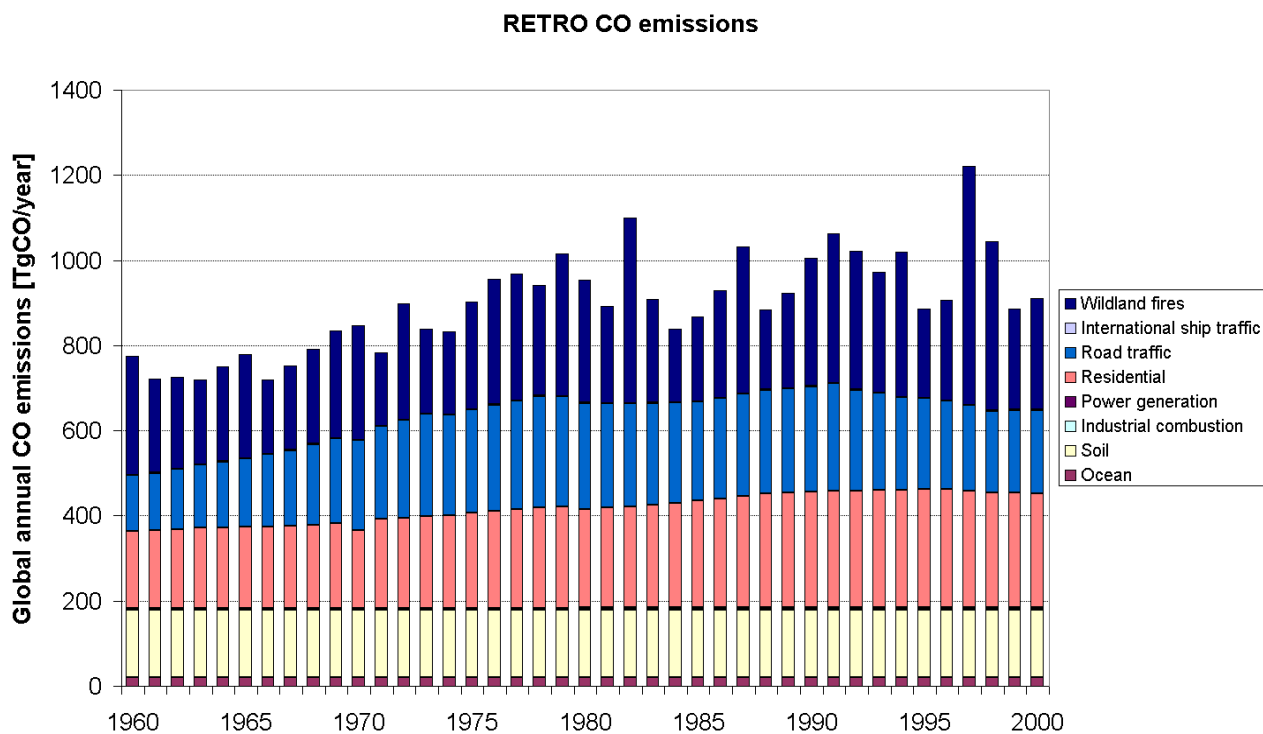


Figure 1: CO global annual emissions from the RETRO database. www.retro.enes.org

a need to establish an operational system which could provide timely forecasts of plume transport so that the population can be warned. (Figure 2)

2. Smoke plumes absorb radiation and can thus influence the local- and regional-scale weather. The inclusion of fire smoke into numerical weather prediction systems could therefore lead to a significant improvement of weather forecasts.
3. Long-range transported smoke plumes influence background levels of air pollutants and may thus impede pollution control measures in regions far away from the source region. [NO_x, e.g. Spichtinger et al., 2001] [ozone: e.g. Stohl et al., 2001, Andreae et al., 2001] [aerosol: e.g. Forster et al., 2001] [CO: e.g. Andreae et al., 2001]
4. Fire emissions contribute significantly to the global budgets of several air pollutants and greenhouse gases and must therefore be taken into account when emission control regulations are negotiated (i.e. Kyoto, CLRTAP, etc.).
5. Emission estimates from fires provide a priori information on the tropospheric profiles and the aerosol types that are needed for accurate retrievals of the tropospheric composition from satellite-based observations. (Figure 2)

Current estimates of trace gas and aerosol emissions from fires are highly uncertain (e.g. IPCC, 2001), and this is related to a number of factors, among which the determination of the actual burned area plays an important role. [see for example the discussion in Schultz et al., 2006] Recently, a number of different satellite data products have become available, which provide information on various fire properties and can in principle be used to constrain the location, timing, and magnitude of fire emissions. However, there are still several inconsistencies

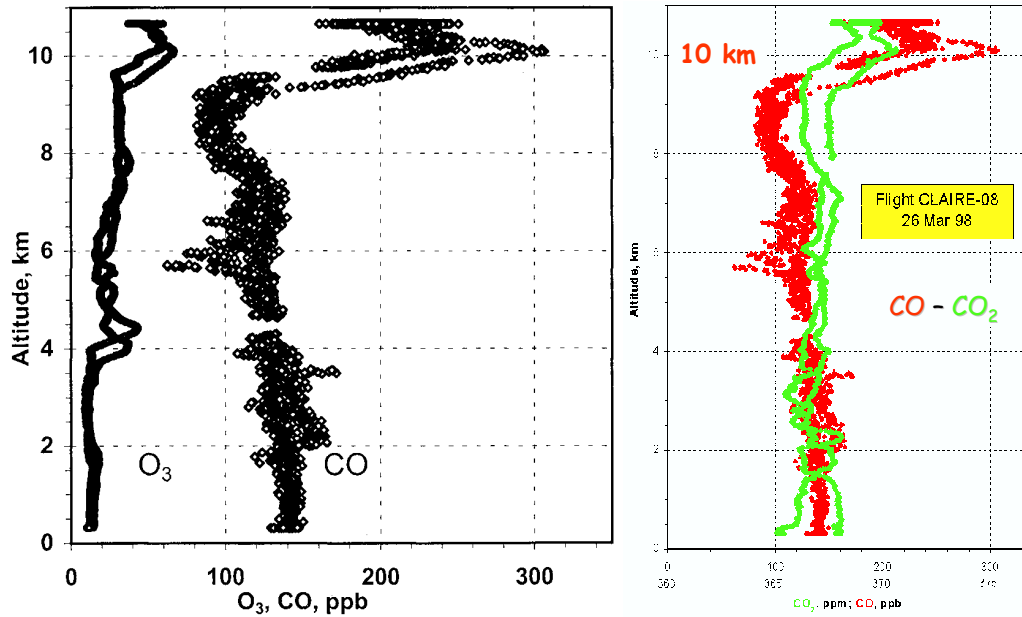


Figure 2: Aged biomass burning pollution at high altitude. [Andreae et al., 2001]

between different satellite data products, which are related to the sensor resolution, the observation frequency and overpass time, spectral and saturation properties of the sensors, and algorithm problems. [e.g. Boschetti et al., 2004] Besides a strong need to improve the quantification of fire emissions in retrospect, there is also a demand for setting up a high-quality near-realtime fire observing system in order to enable the inclusion of fire emissions into operational environmental prediction systems such as GEMS.

In order to be of use for a global modelling system, observational fire data must be homogenized, screened for errors, and converted into emission estimates, which requires additional EO data on the land surface (vegetation cover, soil moisture, temperature, etc.). This can best be accomplished in a data assimilation approach, where observations are combined with modelling tools as is presently done for many physical properties related to weather forecasting. In this document we present a strategy for the development of such a "Global Fire Assimilation System" (GFAS) in support of the GEMS project. Details of this system will have to be specified at a later stage when financial support of this project has been secured and the project partners (from both the EO side and the modelling side) have been identified. At the GEMS kickoff meeting in Hamburg (July 2005), fire emissions were identified as one of the major crosscutting issues between the four GEMS sub projects greenhouse gases (GHG), global reactive gases (GRG), aerosols (AER), and regional air quality (RAQ). Strong links also exist with other integrated projects concerning the land surface (e.g. *geoland*, <www.gmes-geoland.info>), and it will be important to ensure good communication and collaboration with expert teams working on the development of fire retrieval products, and with space agencies for ensuring data delivery and the long-term continuity of fire observations from space.

In the next sections we give a brief overview over the GEMS project and specify the requirements for fire emissions and fire EO data arising from the GEMS needs and specifically the requirements of each of the GEMS subprojects (GHG, GRG, AER, and RAQ). Next, we survey existing EO fire products and emission models and examine their suitability for an operational near-realtime assimilation system considering also the issues of data availability and long-term continuation of data products. Other fire products, which might be valuable to improve the quality of the emissions estimates, are given only brief consideration in this document. Their inclusion and optimal use will have to be discussed at a later stage. Sections 6.2–6.6 outline the technical layout

of the global fire assimilation system and sketch a tentative work plan. The proposed strategy will progressively meet the GEMS needs and has been designed to interfere only minimally with other developments in the GEMS system. The final section gives some general conclusions and recommendations.

2 GEMS Requirements

The Global Monitoring of Environment and Security (GMES, <www.gmes.info>) initiative was launched in May 1998 in Baveno and adopted by the ESA and EU councils in June and November 2001, respectively. GMES aims at "designing and establishing by 2008 a European capacity for the provision and use of operational services for Global Monitoring of Environment and Security". More specifically, GMES has to support several EU objectives and policies, among which "Europe's environmental commitments, within EU territory and globally, by contributing to the formulation, implementation and verification of the Community environmental policies, national regulations and international conventions" ranks on a top position.

The EU framework programme 6 integrated project Global and regional Earth-system (Atmosphere) Monitoring using Satellite and in-situ data (GEMS, <www.ecmwf.int/research/EU_projects/GEMS>) constitutes a major component towards realizing the GMES objectives as far as they concern the monitoring and prediction of the atmosphere component in the earth system. GEMS involves scientists from more than 30 European research institutions and is co-ordinated by the European Centre for Medium-Range Weather Forecasts (ECMWF). The main objective of GEMS is to build and test an operational environmental prediction system for greenhouse gases, reactive gases, aerosols, and regional air quality. The global system shall be closely linked to the existing numerical weather forecasting and data assimilation system at ECMWF, the Integrated Forecast System (IFS). The regional systems will be operated by local institutions. The GEMS system will thus monitor and predict the daily atmospheric trace gas and aerosol abundances and it will be used to reanalyse specific periods in the past in order to assess atmospheric chemical composition and greenhouse gas trends. The main focus of the project work lies on the technical integration of the different earth system model components and on the assimilation of trace gas and aerosol observations into an atmospheric model. Emission sources (surface fluxes) of these compounds provide essential boundary conditions.

Due to their high variability and overall importance for determining the atmospheric concentrations of several air pollutants, greenhouse gases, and aerosols, emissions from open fires (in particular wildland fires) are of particular concern for the GEMS project. Wildland fire emissions were identified as one of the major cross-cutting issues involving the four subprojects aerosols (AER), greenhouse gases (GHG), global reactive gases (GRG), and regional air quality (RAQ) [Hollingsworth, 2005]. This section attempts to summarize the requirements for a GEMS fire emissions module from the perspective of all four subprojects and establishes a timeline for when certain aspects of this module need to become available.

The AER, GHG, and GRG subprojects of GEMS deal with the emissions of different constituents, possibly from the same sources. The RAQ subproject deals with emissions of the same substances as AER and GRG but with a better spatial resolution. A unified approach on fire emission treatment across the subprojects is desirable in order to increase the consistency of the overall GEMS system and to benefit from each others expertise and work.

2.1 General requirements applicable to all GEMS subprojects

For the purpose of defining the requirements for estimating fire emissions, three project phases of GEMS can be identified. Additional development will be needed during the operational phase after 2008:

phase 1: During the second year (04/2006–03/2007) each of the GEMS subprojects will run separate test reanalyses for the year 2003 [Hollingsworth, 2004]. The main purpose of this exercise is to test the data assimilation systems within the individual subprojects before integration into the production system. In order to allow for a meaningful and consistent (across subprojects) evaluation of these simulations, realistic fire emission data needs to be available, which should at least broadly reflect the major fire events during the year 2003. Such a data set based on MODIS and MOPITT observations has been made available to GEMS by Gabrielle Petron at NOAA, cf. section 6.3.

phase 2: During months 30–42 (09/2007–08/2008) the production system will be used to perform an extended reanalysis. This is one of the main GEMS deliverables. A consistent and time-resolved fire emission product including at least the monthly and inter-annual variability of fires should be used in order to allow for a meaningful comparison to observational data. Near-realtime access to spaceborne fire observations is not necessary in this phase. The initial focus should be placed on fires in the midlatitudes and in the boreal zone, because these have a very strong impact on the variability of the atmospheric composition and they are directly related to core GEMS objectives (for example providing data in support of the CLRTAP convention). The exact reanalysis period will likely encompass the years 2000 through 2007, and a consistent set of fire emissions for this period is thus highly desirable. This data set (which could be produced externally) shall then serve as a benchmark for the GEMS Global Fire Assimilation System (GFAS), of which a prototype should be available by month 30 (09/2007).

phase 3: At the end of the GEMS project (09/2008–03/2009) the production system will be transformed into an operational system for NRT analysis and forecasts. At this point, the GFAS model must be sufficiently mature and the near-realtime data delivery of fire observations must be ensured. GFAS will need development of fallback strategies in case of data delivery failures and of diagnostics to identify anomalous situations which could either point towards data problems or merit special attention in the forecasts (e.g. trigger specific plume predictions as described in subsection GEMS GRG requirements below). As GFAS will be a new development, the potential for erroneous predictions will be quite large at the beginning, and the system will therefore initially require intensive manual supervision. This must be accounted for in the allocation of project resources. (See section 6.5)

phase 4 (post-2008): When the GEMS environmental prediction system will go into operation, the emphasis of GFAS work will be on increasing its robustness (so that it can eventually be run without or with only little manual supervision), and on improving its accuracy. For example, due to the requirement of NRT data availability, the first version of GFAS will likely be based on the observation of "hot spots". However, hot spots are often ill-suited to derive quantitative estimates of fire emissions. [Boschetti et al., 2004, S. et al., 2003] In order to obtain more reliable emission estimates, further developments of the fire assimilation system should be directed towards the use of other information, such as surface albedo changes (burned area retrievals), fire radiative energy, and burning area retrievals, cf. sections 3.2, 3.4, and 3.3, respectively. The observation frequency will need to be increased substantially by inclusion of products from geostationary satellites. Further refinements of the system must include a link to changes in land surface parameters (i.e. monitoring of fuel loads, droughts or flooding, land-use change) and a reparameterisation of emission factors based on individual fire properties (i.e. the ratio of flaming to smoldering combustion). Finally, the system will need to be adapted and extended to include observations from new satellite sensors (for example the replacement of MODIS by the VIIRS sensors on NPP in 2007 or 2008).

The modelling systems in the different GEMS sub projects and the final GEMS system will require information on the following fire parameters:

- location

- ignition time and duration
- amount $M(X)$ of emission for each substance X , i.e. aerosol and trace gases
- vertical distribution of the injection of different trace compounds (could be different for soluble and non-soluble species)

The vertical distribution of the injection is of particular importance for the assimilation of the space-borne observation of the atmospheric composition as most of these observations cannot distinguish different tropospheric profile shapes.

Currently, fire emissions are typically read from file as gridded monthly mean data. During phase 1 (and possibly 2), this should not be changed in order to avoid additional complications in the coupling between the different sub systems. Furthermore, the prototype data from the phase 2 and phase 3 fire assimilation module must be evaluated, and this should include a comparison to the gridded emission data used previously. Before phase 2, a common interface to the fire assimilation module needs to be defined, which will then have to be implemented into the different GEMS components. In order to preserve as much of the temporal and spatial information available, this interface might be designed as a continuous data stream with information on individual fires (order 10,000 per month) rather than as gridded fields. However, this strategy may have to be revisited. Additionally, a tool must be developed to generate gridded fields from, e.g., the continuous data stream so that the fire emissions can be visualised and evaluated.

2.2 GEMS GHG requirements

Vegetation fires are a source of atmospheric carbon in the short-term. The carbon is drawn from the land surface carbon pools of leaves, litter, wood, and fine roots. However, regrowth of the vegetation in the years after the fire re-fills these surface carbon pools and constitutes a sink for atmospheric CO₂. Thus vegetation fires are considered a major reason for the short-term and inter-annual variability of the surface carbon flux.

The GEMS GHG subproject places a strong emphasis on accurate estimates of the carbon release and fire-related ecosystem changes. QUESTION: can we quantify this? What error margin is tolerable here (and for which quantities)?

Consistent multi-year time series of fire emissions are needed.

Wildfires are believed to have a great impact on the carbon cycle by releasing tons of carbon out of storage in a short time and by causing strong disturbances to vegetation. Recent studies recognise their key contribution to the large observed inter-annual variations in carbon emissions. [Schimel and Baker, 2002, Langenfelds et al., 2002, Rödenbeck et al., 2003, Zeng et al., 2005] Fire is also a very important factor influencing ecosystem succession and land use. For all these reasons, world-wide information about biomass burning is necessary to calculate the net carbon budget.

Biomass burning emissions has generally not been explicitly accounted for in CO₂ inversions of sources and sinks. This omission could be justified as long as the surface measurements used for the inversion were sparse and remotely located from major sources. Air mixing reduces the effect of biomass burning on measured CO₂ concentrations and therefore represents a limiting factor to biases in the inversion scheme. The use of satellite global observations for CO₂ inversions requires the description of fire emissions.

CO₂ is mainly released during the flaming stage when the burning is hot and fast. This stage is likely to happen during the day while smoldering can continue to the night releasing products of incomplete combustion like carbon monoxide, methane and other hydrocarbons. Several observations per day are then required to estimate

carbon emissions by fires. Beside the biomass burning timing and their spatial distribution, information about fire intensity is required to calculate the injection height. This intensity depends on fuel type and is function of the fire rate spread and the amount of fuel consumed. Its estimation is subject to uncertainties attached to each of these parameters.

Taking into account biomass burning as a source of CO₂ requires quantifying the emissions but also to assess the uncertainty in the resulting estimates. Little attention has been paid to the second requirement and different products are released without attached uncertainty. It is also important to have geographically varying uncertainties depicting for example our better knowledge about emissions in one region than another.

2.3 GEMS GRG requirements

Fire emissions constitute a major term of the global budget of trace gases like CO and NO_x, and they can have a significant effect on tropospheric ozone concentrations, particularly in tropical latitudes. Trace gas predictions without realistic boundary conditions from fire emissions would be of very low accuracy and would be difficult to validate with independent trace gas observations. In several regions (i.e. North America, East Asia, Middle East, Africa, South America, and Australia), air pollutants from fires mix with those from fossil fuel combustion and other anthropogenic activities, and this can facilitate the violation of air quality thresholds. Long-range transported pollution plumes often contain a significant contribution from wildland fires [Forster et al., 2001], and an accurate assessment of fire emissions is therefore required to aid verification of the CLRTAP protocol.

As a prototype user service of GEMS GRG one can imagine a fire plume monitoring system, which would forecast the spread and transport of pollution plumes from major fire events on the regional to global scale and could be used as input for regional-scale air quality forecasts around the world or directly assist aviation warning centers for example.¹

The GEMS GRG subproject has therefore requirements for a near-realtime fire emission product with global coverage and reasonable accuracy (30 %) in order to assist in the data assimilation of trace gas concentrations and attribute pollution plumes in the operational forecasts to the right causes. As the diurnal variability of fires is also rather large, several observations per day are needed and should be interpolated in the fire assimilation system. Once a fire has been detected, one will need to predict its further evolution based on empirical time functions and diurnal cycles.

Ideally, the fire information from EO satellites will include some direct measure of emissions and fire intensity. Otherwise, quantitative relationships between hot spot occurrence and fire emissions and fire intensity will have to be established [e.g. Giglio et al., 2005]. Fire intensity is a required parameter for estimating the injection height distribution of fire emissions. Data on individual fires will need to be available 1–14 hours after the fact in order to include them in a full tracer prediction of the next 1–10 days. For an early warning system, the one-tracer fire model could be run with archived meteorological forecasts and provide a first assessment within a few hours after data delivery. The early warning system might also be embedded in the RAQ activities.

Aside from these near-realtime requirements, the monitoring of emission trends and the CLRTAP protocol also necessitates the production of a fire product with improved accuracy for reanalysis simulations (for example by including additional data from other sensors with more refined spatial or spectral resolution). Such a product could be produced externally with a few months lag time, but it should use a methodology consistent with the near-realtime fire assimilation system. Furthermore, the long-term stability and consistency of the product as

¹Technically, it would require the addition of one extra tracer (for example with properties like CO), which would be emitted exclusively by (large) fires, transported, and decomposed with a simple parameterisation (using a fixed lifetime or a prescribed OH field). Alternatively, one could implement a prototype aerosol tracer (as in the NAAQS, see below) — however, this requires the parameterisation of more complex loss processes.

well as its availability for ECMWF must be ensured.

2.4 GEMS AER requirements

Fires represent an important sources of aerosols in particular but not only in Tropical regions. Generally, the GEMS AER requirements are very similar to those of GEMS GRG. One additional motivation for accurate fire emission monitoring (even in near-realtime) arises from the insensitivity of aerosol observations by satellites to the aerosol type. Therefore it is important to constrain the model emissions from observations of fires.

GEMS AER also requires an accurate source attribution including a reliable estimate of injection heights. Methods for deriving the vertical distribution of aerosols from satellite-based passive observations are currently being investigated [e.g. Pierangelo et al., 2004]. However it is unlikely that passive radiometry can provide much information on biomass burning plume height on an operational basis. Active instruments (such as CALIOPE on CALIPSO) will provide aerosol profiles but will be operated on a research basis rather than an operational basis. GEMS AER should therefore not expect to rely on satellite observations to constrain injection heights of fire emissions.

2.5 GEMS RAQ requirements

The GEMS RAQ requirements are also quite similar to the near-realtime requirements of GEMS GRG and GEMS-AER. However, the demands on resolving the diurnal cycle of fires and the spatial accuracy of the source attributions are even more stringent than for the global model components due to the finer resolution of the RAQ models. On the other hand, GEMS RAQ does not necessarily require global coverage of fire observations and could therefore make use of different sensors such as SEVIRI on Meteosat MSG-II.

GEMS RAQ people to provide further input.

3 Available Fire Observations

Fires are observed by a heterogeneous global observation system either directly as “hot spots” identified by the thermal emission of the fire or indirectly as “burnt area” diagnosed after the burning event for example through albedo changes. Recently, new algorithms have been developed to directly measure the fire radiative energy, which should be directly proportional to emission fluxes. All of these methods have their strengths and weaknesses, and the few intercomparisons done until now indicate severe inconsistencies between the different methods and also between different retrieval products using the same approach [Boschetti et al., 2004].

A comprehensive overview of available fire observations is given in Flemming [2005]. The key properties of the relevant observations are highlighted here. The burning area and fire radiative power products can be considered hot spot products. They are nevertheless treated separately in this study in order emphasise their special capabilities for a quantitative analysis.

Figure 3 shows the spectral signature of fire. It is particularly pronounced near 4μ wavelength and virtually all direct observations of fire rely on this spectral region, possibly combined with other wavelengths. A quantitative analysis of direct fire observations requires that the observations do not saturate in this channel. Modern instruments designs achieve the required large dynamic range with a number of special design feature, e.g. MODIS contains two channels with the same spatial footprint and spectral band but different radiometric responses [Wooster et al., 2003].

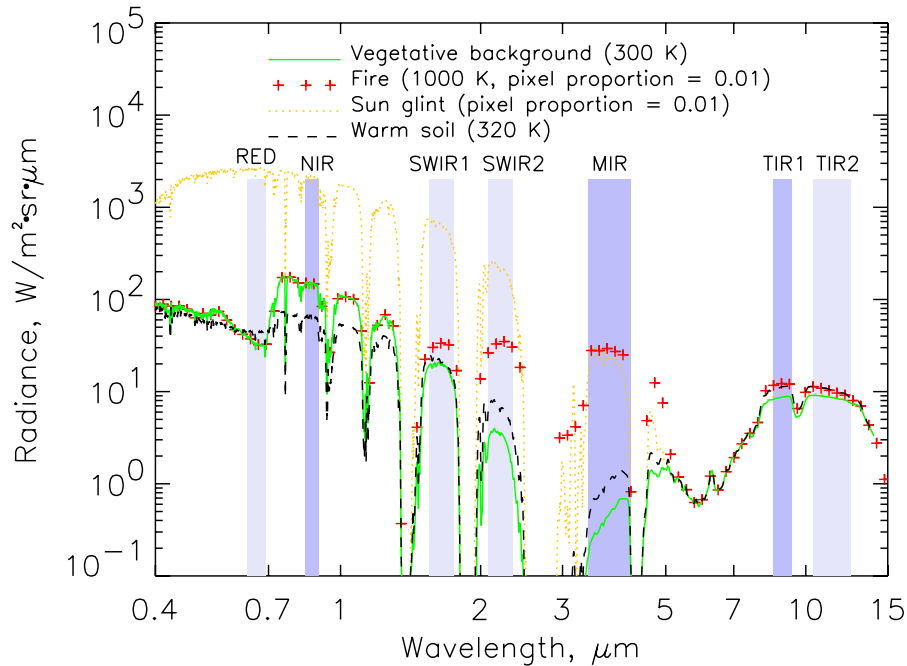


Figure 3: Simulated top-of-atmosphere spectral radiance of a 1000 K subpixel-sized fire in comparison to that of the vegetated background, sun glints from water surfaces, and homogeneous warm soils; the darkblue- shaded NIR, MIR and TIR1 spectral ranges correspond to the BIRD spectral bands, while the lightblue- shaded RED, SWIR1, SWIR2 and TIR2 spectral ranges correspond to the ETM+ spectral bands. The fire reflectance / emissivity is assumed to be that of burned vegetation in the VNIR and SWIR and of a blackbody in the MIR and TIR. Daytime observations under a 30 deg solar zenith angle are assumed, with mid-latitude summer atmosphere and a rural aerosol (23 km visibility) to account for the effects of the atmosphere. Reproduced from Zhukov et al. [2005].

3.1 Hot Spot Products from LEO Satellites

Hot spot, a.k.a. active fire, fire pixel, and fire count, products identify the thermal emission by fires. They can be available in NRT. Thus they can be used for analysis and forecasting. They yield the time and location of fires, but it is difficult to infer the burnt area, thus the amount of burnt material, thus the emissions, and this will have to be done on a regional level (e.g. using eco regions). A paper by Giglio et al. addressing this issue related to MODIS data is currently under review.

Examples of hot spot products are the World Fire Atlas (WFA) derived from the ATSR instruments, the World Fire Web (WFW) from AVHRR, the fire counts from TRMM-VIRS, and active fires from MODIS. No global product is operationally available in NRT. However, the MODIS Rapid Response System <rapidfire.sci.gsfc.nasa.gov> is producing a limited MODIS fire product in NRT and ECMWF is receiving a motion vector product from MODIS in NRT from the University of Wisconsin. Therefore, the NRT production of a hot spot product from MODIS seems technically feasible. VIIRS aboard NPP may provide continuity of the product beyond the lifetime of MODIS. <www.ipo.noaa.gov/Projects/npp.html>

For operational use, negotiations with the data providers must take place in order to assure data availability and to decide whether GEMS will obtain already processed fire products or whether the hot spot retrieval will be implemented at ECMWF.

Figure 4 demonstrates a general limitation of observations with global coverage, e.g. MODIS: The satellite is generally in a sun-synchronous polar Low Earth Orbit (LEO). Thus the diurnal cycle is sampled only very

sparsely. In order to cover the fire activity throughout the day, assumptions on the diurnal cycle have to be made. These vary with the observed region and introduce errors in the emission estimate. Geostationary (GEO) satellites cover the diurnal cycle at the expense of limited geographical coverage and generally larger pixels sizes, cf. sections 3.3–3.4.

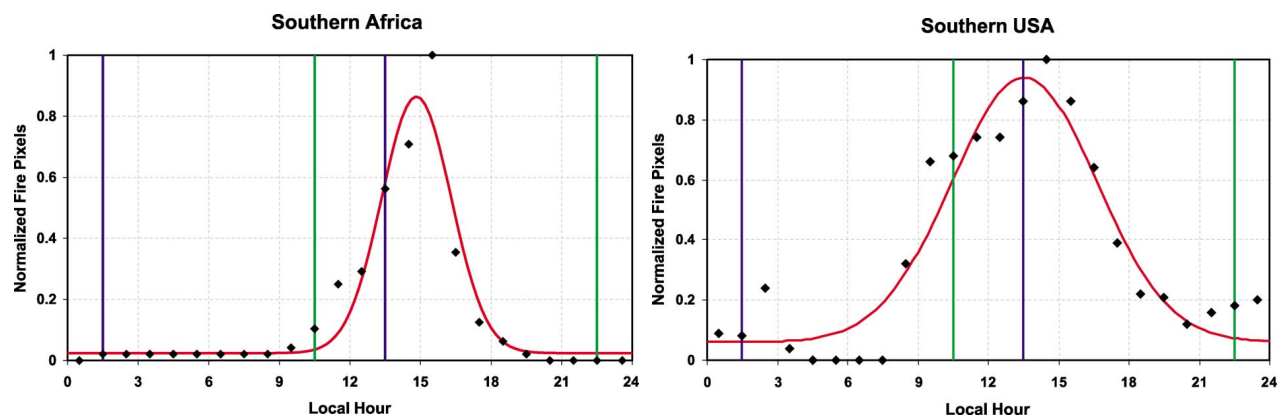


Figure 4: MODIS overpass times and diurnal cycles of fire activity for Southern Africa and Southern USA: observations by TRMM (black diamonds) and Gaussian fit (red line). [Justice et al., 2002]

Information on hot spot products

ERS-2/ATSR-2 World Fire Atlas (ESA)

- shark1.esrin.esa.it/ionia/FIRE/AF/ATSR
- "Based on ATSR night-time data in order to reduce false alarms"
- 1995 to 2002: ATSR-2 night-time data (level 1B product).
- "2003 to Present: AATSR night-time data (level 1B product).

AVHRR World Fire Web (EU/JRC)

- natural-hazards.jrc.it/fires/detection/wfw/help/overview.html
- The fire map is a latitude-longitude raster, where each raster cell contains the number of fires detected within that cell over a period of time. The cell size is typically 0.5x0.5 deg and the time period is typically 1 day or 10 days.

MODIS Global Fire Rapid Response System (NASA)

- modis-fire.umd.edu/products.asp
- 250 m product, daily update, North America emphasis
- 1 km global product composite 8 day fire product (MOD14A2)
- Several near real-time product on temperature anomalies

TRMM-VIRS fire counts

- daac.gsfc.nasa.gov/CAMPAIGN_DOCS/hydrology/TRMM_VIRS_Fire.shtml
- earthobservatory.nasa.gov/Observatory/Datasets/fires.trmm.html

- Tropical and Sub-tropical zones (+/- 40 deg from the equator) for 1998–2002, with possible extension to mid 2004
- Derived from Tropical Rainfall Measuring Mission (TRMM) Visible and Infrared Scanner (VIRS) measurements
- Number of 4.4 km² pixels in each half-degree grid cell

3.2 Burnt Area Products from LEO Satellites

Burnt area, a.k.a. Fire Affected Area (FAA), burnt pixel, and burnt scar, products pick up spectral characteristics of burnt area or its characteristically flat Bi-directional Reflectance Distribution Function (BRDF), or analyse time series of the spectral characteristics. They are typically not available in NRT. Therefore, they can be used in re-analysis mode only. The products yield the location of the fires very accurately and enable state-of-the-art emission amount estimates. However, the exact time of the fire is not known.

Important monthly burnt area products are GLOBSCAR from the ATSR instruments [Simon et al., 2004], Global Burnt Area 2000 (GBA2000) from SPOT-VEGETATION [Tansey et al., 2004], and burnt area from MODIS (under development by David Roy et al. and Giglio et al.). Uncertainties in the products are large, e.g. Boschetti et al. [2004] show that GLOBSCAR and GBA2000 differ by a factor of up to two. None of the products is available in NRT, however it is conceivable that one day albedo changes etc. could be assimilated NRT as well. The monthly MODIS product will become available operationally during 2006. It also contains the approximate day of the fire.

In the future, further burnt area products are expected from the *geoland*-CSP and GLOBCARBON projects.

Information on burnt area products

GLOBSCAR (ESA)

- shark1.esrin.esa.it/ionia/FIRE/BS/ATSR
- global monthly data for 2000 in 1 km resolution
- ATSR based burnt area product for 2000 (500 km swath)
- GLOBACARBON also provides burnt vegetation data (2000–2003)

Global Burnt Area 2000 — GBA2000 (ECE/JRC)

- www-gvm.jrc.it/fire/gba2000/index.htm
- global monthly data for 2000 in 1 km resolution
- Mapping, from SPOT-VEGETATION S1 (2000 km swath) imagery
- used for *geoland*CSP
- algorithms at regional scales by a network of partner

GLOBCARBON burnt area product (partially existing)

- global monthly maps of burnt areas for the period 1998–2007 in 10 km, 0.25 deg and 0.5 deg resolution
- based on the experience of both GLOBSCAR and GBA-2000

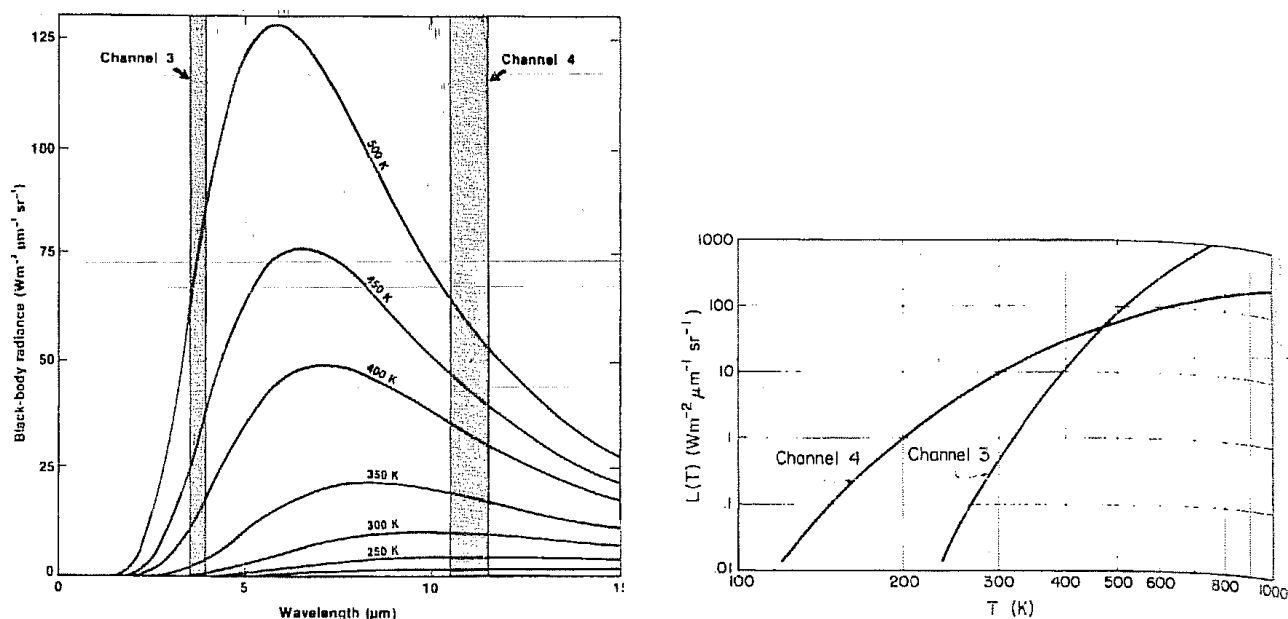


Figure 5: Planck radiances for several temperatures and sensitivities of NOAA-6 AVHRR channels 3 and 4 to surface temperature. [Matson and Dozier, 1981]

- used sensors for burn scar detection: ATSR-2, AATSR, and VEGETATION
- MERIS is used to add confidence to the preliminary results.

geoland-CSP burnt area product

- geoland-csp.mediasfrance.org/Produits/Vegetation/BurntAreas
- daily monthly maps for 2000–2003 for Africa and boreal Asia based on VEGETATION

3.3 Burning Area from GEO Satellites

Dozier [1981] and Matson and Dozier [1981] showed that “use of the 3.8μ and 11μ thermal infrared channels on board the [...] NOAA-6 environmental satellite provides the capability to detect sub-resolution scale high-temperature sources, and to estimate both the temperature and size of such sources.” The algorithm is today known as Dozier or bi-spectral method. It exploits the different sensitivities of the channels to thermal emission, see Figure 5. In particular, the 3.8μ radiance exhibits a very strong sensitivity to very high temperature sources.

A sensitivity analysis indicates that under realistic conditions the random errors in fire temperature and area retrieved using Dozier’s method are ± 100 K and $\pm 50\%$ at one standard deviation, respectively, for fires occupying a pixel fraction greater than 0.005. [Giglio and Kendall, 2001]

The WF_ABBA algorithm [Prins et al., 2001a] builds on the algorithm by Dozier [1981] to retrieve wildfire size and temperature products from the GOES-8 geostationary meteorological satellite operationally in NRT. The product is used by the FLAMBE system and INPE/CPTEC for their operational NRT forecasts of atmospheric aerosol and carbon monoxide over North and South America, see section 4.3. The particular advantages are:

- burning area in NRT
- high observation frequency, thus more cloud-free observations

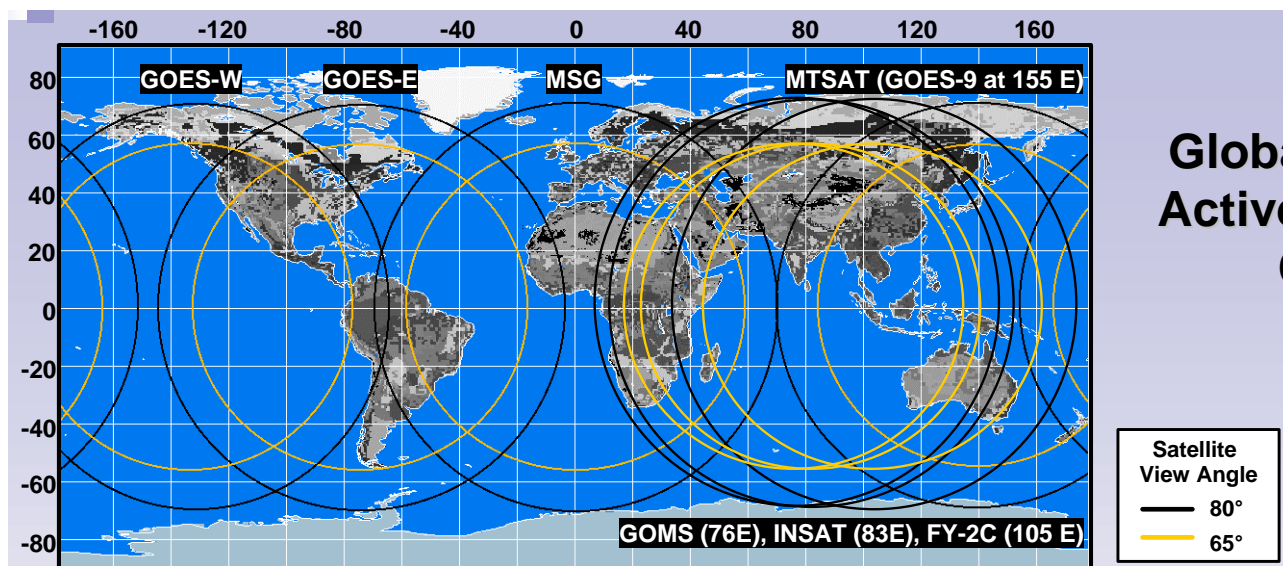


Figure 6: Future Global Geostationary Meteorological Satellite System. [Prins et al., 2005]

- fire temperature estimate

However, the geographical coverage is limited by decreasing sensitivity towards higher latitudes. Another drawback is the saturation limit of the 3.8μ channel (M. Wooster, personal communication, 2005).

Current efforts within the GOLD/GOFC-Fire program aim at implementing a global NRT operational geostationary fire monitoring network using GOES, MSG, and MTSAT data. [Prins et al., 2004] Figure 6 gives an overview of the geographical coverage of geostationary satellites. Figure 7 shows the minimum detectable fire sizes for the satellites. A recent assessment [Prins et al., 2005] shows that:

- “A global geostationary fire monitoring network is technically feasible, but that it must be supported by the operational agencies [...].”
- “Geostationary systems can provide valuable diurnal information that is complementary to fire products produced by higher resolution polar orbiting instruments.”

The Global Observations of Forest and Land Cover Dynamics (GOFC/GOLD) is a panel of GTOS and its overall objective is to improve the quality and availability of observations of forests at regional and global scales and to produce useful, timely and validated information products from these data for a wide variety of users, see <www.fao.org/gtos/gofc-gold>.

Information on burning area products

GOES Automated Biomass Burning Algorithm — ABBA/WF-ABBA (University of Wisconsin, NOAA)

- <cimss.ssec.wisc.edu/goes/burn/detection.html>
- The GOES-8 ABBA fire product includes: fire location (lat./lon.), estimates of fire size and temperature, 3.9 and 10.7μ observed brightness temperatures, background brightness temperatures, albedo statistics, ecosystem type, and a flag for non-processed fire pixels to indicate the reason for not processing.

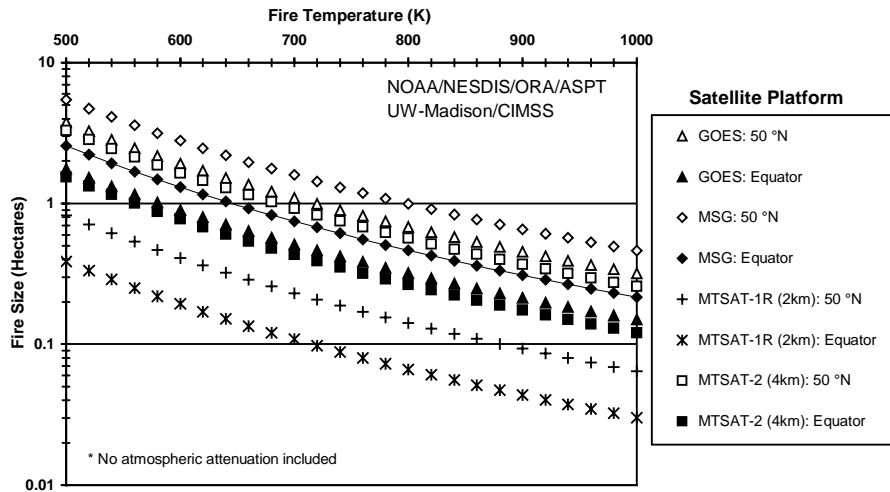


Figure 7: Estimates of Minimum Detectable Fire Size at Various Fire Temperatures. [Prins et al., 2001b]

- The Wild Fire-ABBA (WF-ABBA) imagery is generated blending data from the GOES 10 and 12 satellites and a land cover map derived from 1-km AVHRR. Plans exist to provide a global products based on the geostationary satellite network.

3.4 Fire Radiative Power from LEO and GEO Satellites

The fire radiative power (FRP) emitted over all wavelengths is an estimate for the chemical energy per unit time [W] released by a fire. Integration over time yields the fire radiative energy (FRE) [J], which has been shown to be approximately proportional to the amount of burnt biomass, cf. Figure 9. Thus errors due to the uncertainties in the knowledge of available fuel load and combustion factors can be avoided.

The operational MODIS product MOD14 contains the FRE calculated with an algorithm introduced by Kaufman et al. [1996] [Justice et al., 2002]. It has recently been used to derive smoke emission rates from fires for the monitoring of smoke emission with the help of FRP observations [Ichoku and Kaufman, 2005].

Another algorithm for the calculation of the fire radiative power (FRP) from satellite observations has been tested successfully by Wooster et al. [2003] using observations by the MODIS and BIRD satellite instruments. Future studies aim at establishing an operational FRP product using the geostationary SEVIRI observations. The algorithm is based on the fact that emitted radiation near 4μ wavelength is approximately proportional to the FRP, i.e. proportional to T^4 , for the relevant temperature range of 600–1500 K. The proportionality is valid with 30% accuracy. However, calibration of FRP retrievals with field measurements indicate that this quantity is indeed linearly related to the amount of biomass consumed in the fire, so that FRP has the potential to be used for a direct estimate of fire emissions.

The FRP products are very promising for the monitoring of wildfire emissions for GEMS as they

- bypass available fuel load and combustion factors and their associated large errors and
- first steps are being taken toward a global observation system comprising both GEO satellites with high observation frequencies covering low and middle latitudes, cf. Figure 6, and LEO satellites with frequent polar coverage.

Nevertheless, the FRE product have not yet been tested sufficiently for operational usage.

4 Existing Models of Fire Emissions

To obtain biomass burning emission data for the CTM-modelling three major problems have to be tackled. [Lioussé et al., 2004] All of them contribute to the large uncertainty of current biomass emission data

- Identifying location and duration of fire (see section 3)
- Estimating amount and biome type of the burnt biomass (available fuel load)
- Choosing the right specific species emission factors and injection height for the detected fire

The observation of fires and burnt areas by satellite instruments has been discussed in the previous section 3.

The available fuel load can be inferred from climatological vegetation maps, remote sensing of the vegetation status or from global vegetation modelling. Data assimilation of remotely sensed vegetation indices such as NDVI in vegetation models could account for the influence of the meteorological conditions on vegetation and consider satellite observed land cover change. However, estimates of available fuel load from NDVI or remotely sensed maps always need field data for validation. [Barbosa et al., 1999] Even after validation they are associated with large uncertainties. Satellite fire products such as Fire Radiative Power (see section 3.4) already include information on the burnt biomass.

Determination of emission factors is based on concentration measurements in fire plumes and is complemented by laboratory experiments and fire modelling. The BIBEX-programme diotima.mpch-mainz.mpg.de/bibex is part of GWAC and IGBP activities and started in the early 90ies. It coordinated several major field campaigns in different ecosystems of the world. The uncertainty in the emissions factor is also linked to the uncertainty in the information on the type of the burnt vegetation. Andreae and Merlet [2001] compiled a summary of emission factor data from the various field campaigns, which is typically used in emission modelling. As an example, figure 8 shows the CO emission factors for different kinds of fires.

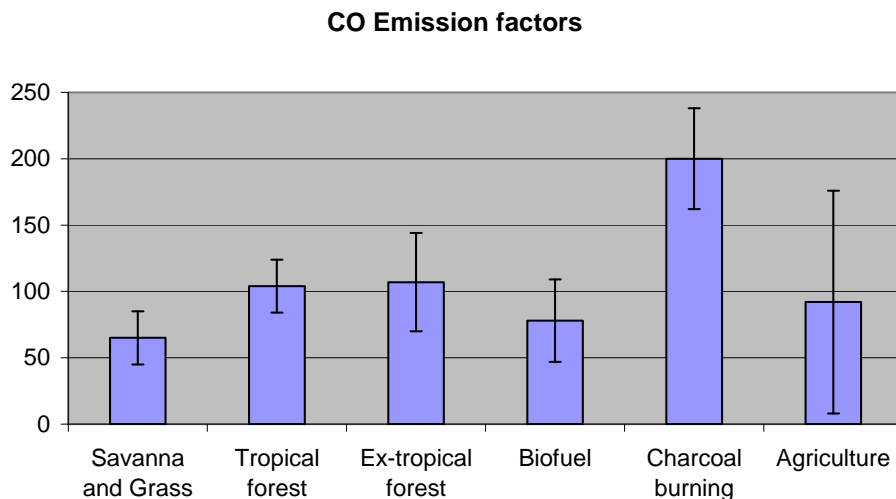


Figure 8: Emission factors for CO in gram species per kilogram dry matter burnt and associated errors. [Andreae and Merlet, 2001]

4.1 Climatological Fire Emission Inventories

Many CTMs are still based on climatological inventories such as Hao et al. [1994] or variants of these (e.g. the biomass inventory in EDGAR-3). These inventories do not reflect the inter-annual variability. The Hao et al. [1994] data set is provided for Africa, tropical Asia and Central and South America in monthly values in a 5×5 deg resolution eosweb.larc.nasa.gov/GUIDE/dataset_documents/bio_burn_5x5_hao_dataset.html

The inventories are climatologies of the emission data, which do not cover the temporal variability of the wild-fires. Hence, dynamic emission modelling would be required in order to describe the daily, annual and inter-annual variability. The development of these emission models often starts with the inventories, and consequently more and more temporal and spatial variability is introduced by utilising available satellite observation.

4.2 Formulation of Dynamic Fire Emission

Due to the operational constraint of producing global datasets covering several years and because of relatively limited observations available, GEMS has to restrict itself to model the fire emission with a relatively simple parameterisation. More sophisticated models [e.g. Trentmann et al., 2002] may be used for validation purposes and could be included into the system in the post-2008 phase.

Several fire emission models for the fast calculation of the emitted amounts $M(X)$ of species X in a time period have been published, see section 4.3. All basically calculate the amount of emission from similar quantities, for example Hoelzemann et al. [2004] propose:

$$M(X) = \sum_{i=1}^m \sum_{k=1}^n \left(Ef_k(X) \times A_{i,k} \times \beta_k \times AFL_k \right) \quad (1)$$

with the indices k and i distinguishing the ecosystems and time steps within the analysed period, respectively, and

- burnt area $A_{i,k}$
- burning efficiency β_k
- available fuel load AFL_k
- emission factors $Ef_k(X)$

The variation of the burnt area within ecosystems k and time steps i is being observed by satellites. Typical values of the latter three quantities are ascribed to different ecosystems. Their temporal variation is mostly neglected because of lack of time-resolved information. In Hoelzemann et al. [2004] the AFL is calculated with a dynamic vegetation model (LPJ) at 0.5×0.5 deg resolution. More accurate AFLs could potentially be obtained by assigning specific AFL values to high-resolution land cover maps (e.g. GLC 2000) and adding variability from NRT observations of greenness. A widely used collection of emission factors has been published by Andreae and Merlet [2001], and updates of these data are available to the authors.

Figure 9 represents the main data products involved in the observation and modelling of fire emissions. Eq. (1) is represented by the arrows connecting the burnt mass with the burnt area and the emission X on the centre line of the figure.

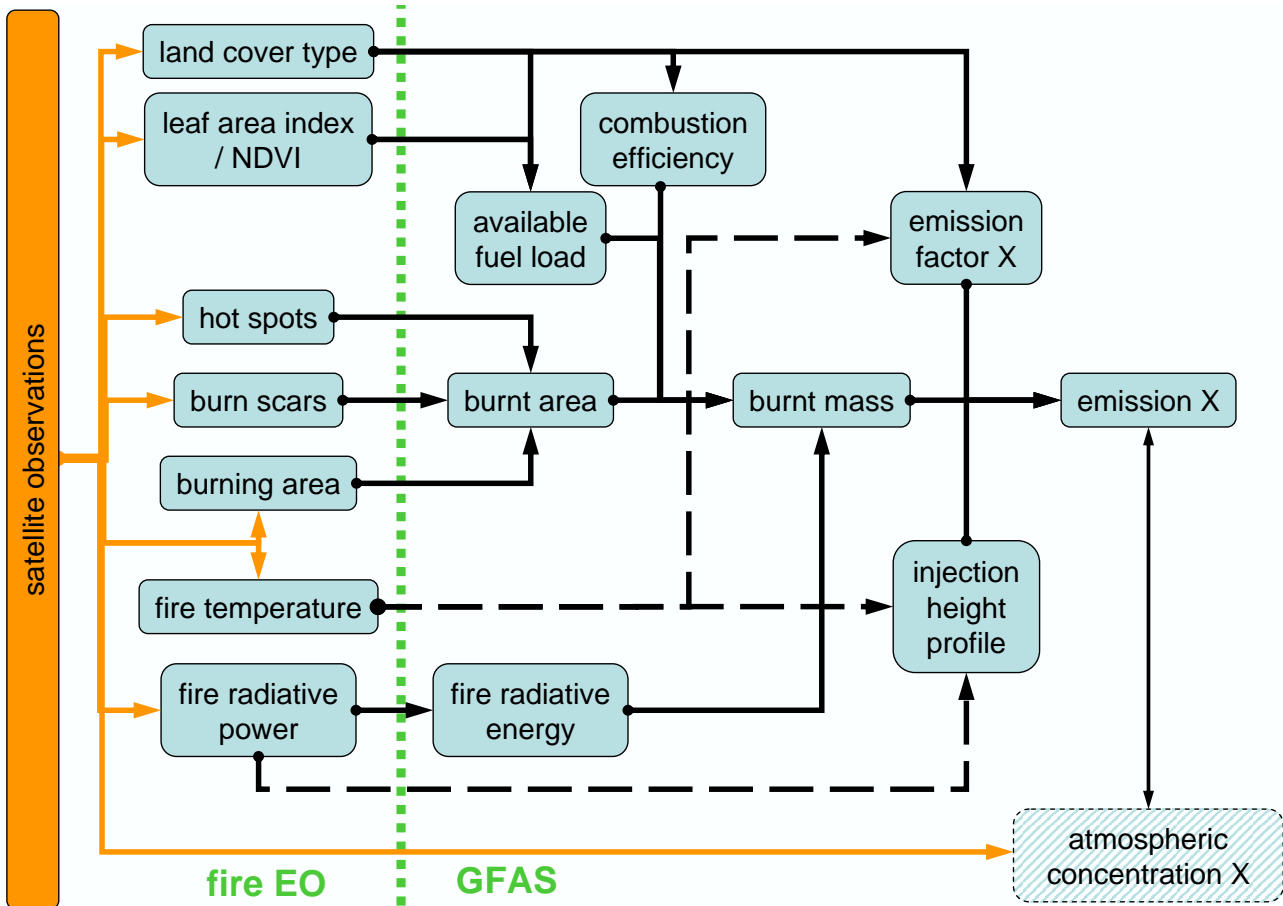


Figure 9: Fire-related data products and their connections.

4.3 Existing Dynamic Fire Emission Models

Four global or continental fire emission models are listed in Table 1. The GWEM model [Hoelzemann et al., 2004] has the advantage that it models emissions of all species that are relevant in GEMS. Additionally, it has been developed by the GEMS partner MPI-MET. The model uses the monthly burnt area product that has been derived from ATSR-2 observations in the GLOBSCAR project. A newer version of GWEM has also been run with the GBA 2000 data set derived from AVHRR data. Accordingly, it can currently not resolve shorter timescales. Land cover maps derived from AVHRR and MODIS together with the Lund-Potsdam-Jena-Dynamic-Global-Vegetation-Model (LPJ-DGVM) are used to calculate the AFL and the appropriate emission factors following Andreae and Merlet [2001].

The Global Fire Emissions Database (GFED) described by van der Werf et al. [2003], van der Werf et al. [2004], and Giglio et al. [2005] converts hot spot observations by VIRS aboard TRMM to a burnt area estimate using a scaling that depends on the tree cover. They have modified the Carnegie-Ames-Stanford-Approach (CASA) dynamic vegetation model to simulate the impact of wildfires for the calculation of AFL. The land cover map is derived from TRMM and SeaWiFS. Results are presented for the seasonal time scale only even though the approach would allow for shorter time scales. The amount of emitted carbon is reported. A dataset consisting of 1 x 1 deg gridded monthly Carbon, CO₂, CO, and CH₄ data is available for the time period 1997–2002. The newer versions of the model are based on the hot spot observations by MODIS and ATSR. Emissions of individual compounds are produced by multiplication with the corresponding emission factors.

Table 1: Published Fire Emission Models

	GWEM	GFED	FLAMBE	INPE/CPTEC
	Hoelzemann et al. [2004]	van der Werf et al. [2003]	Reid et al. [2004]	Freitas et al. [2005]
species	AER, GHG, GRG	carbon	AER	PM2.5, CO
timescale	months–years	months–years	hours–days	hours
operational	no	no	yes	yes
product type	burnt area	hot spots	burning area	burning area
observation- platform	ATSR-2 / AVHRR	TRMM-VIRS / MODIS / ATSR	GOES-8	GOES-8
product- name	GLOBSCAR/GBA2000 Simon et al. [2004] / Grégoire et al. [2003]	— Giglio et al. [2003]/ Justice et al. [2002]	WF_ABBA Prins et al. [2001a]	WF_ABBA Prins et al. [2001a]
land cover	AVHRR (IGBP), MODIS	TRMM, SeaWiFS	AVHRR	AVHRR (IGBP 2.0) [Belward, 1996]
vegetation- model	LPJ-DGVM Sitch et al. [2003]	CASA, modified Potter et al. [1993]	—	—

However, no daily product is available [G. van der Werf, presentation and pers. comm. at IGBP-QUEST Fire Workshop 2005]. See also <www.gps.caltech.edu/~jimr/randerson.html> and <www.env.duke.edu/faculty/prasad/research/biomassburning/biomassburning.htm>.

The FLAMBE project of the Naval Research Laboratory, Monterey, and partners is delivering NRT aerosol forecasts based on burning fire data from GOES, see <www.nrlmry.navy.mil/flambe/index.html>. The system focuses on the forecasting of extreme aerosol events. It uses the geostationary operational meteorological GOES observation in the $3.9\mu m$ and $10.7\mu m$ bands to calculate the burning sub-pixel area from the observed hot spots with the WF_ABBA algorithm, see section 3.3. The land cover from AVHRR is used and no dynamic vegetation model is needed since no seasonal or inter-annual phenomena are targeted, and little value is placed on accurate quantitative predictions.

The operational system at INPE/CPTEC in Brazil is delivering NRT aerosol and CO forecasts based on the burning fire data derived with the WF_ABBA algorithm from GOES, see <www.cptec.inpe.br/meio_ambiente>. The analysis and forecast windows extend of 24 hours each [Freitas et al., 2005]. The INPE/CPTEC system and FLAMBE seem to be the only operational NRT systems that link remote sensing of fires, emission product generation, and an atmospheric transport model as GEMS will do in the future.

Further experiences with the use of satellite data for fire emissions modelling are documented in the literature. For example Heald et al. [2003] used hot spot data over Southeast Asia in order to prescribe fire emissions for the TRACE-P campaign (special issue JGR, 2002/3). A detailed overview about the state-of-the-art emission estimates in different world regions can be found in Schultz et al. [2006].

4.4 Plume Models and the Issue of Injection Heights

Due to the heat release in the combustion process, large fires create their own buoyancy and may therefore develop smoke plumes with very large vertical extent (remnants from some tropical fires have been observed at 15 km altitude [Folkins et al., 1997]), and smoke plumes of Canadian stand-replacing forest fires can extend to

similar altitudes (see for example www.cpi.com/remensing/midatm/smoke.html).

In contrast to most other emissions (except air-planes), fires inject their emissions into various atmospheric heights throughout the troposphere and occasionally even lower stratosphere. The injection height is related to the flaming intensity and can be estimated with simple parameterisations or calculated with so-called plume models. Determining the correct injection height is a major source of error (Figures 10). For example, the aerosol optical thickness, which is observed by satellite, is vertically integrated. Therefore, the vertical distribution of aerosols is not observed. Instead, it must be modelled using the meteorology and injection heights.

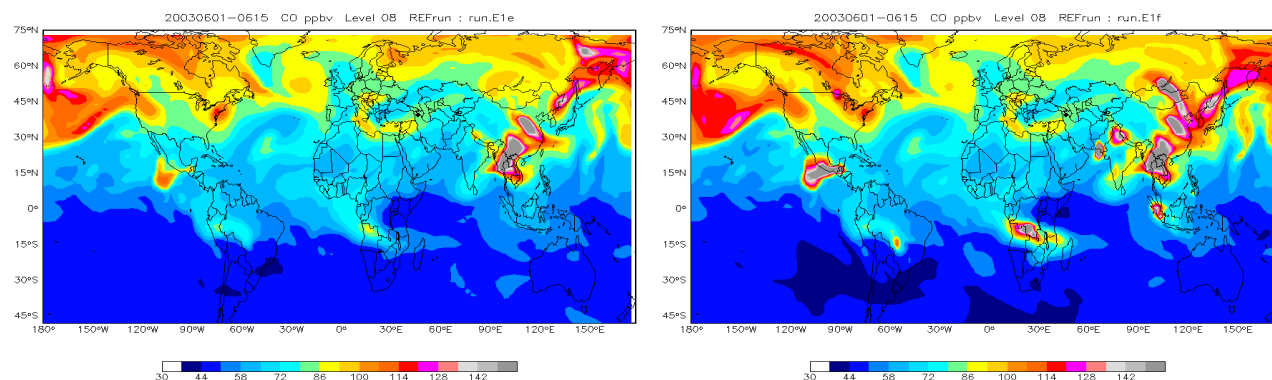


Figure 10: CO concentrations at 500 hPa modelled with the GEOS-Chem model and different fire injections height profiles with maximal injections heights at 3.5 km (left) and 6.5 km (right). [Courtesy of Sylvia Generoso, EPFL Lausanne]

In general, plume models require individual fire characteristics and the meteorological conditions as input. The plume model BUOYANT [Nikmo et al., 1999, Martin et al., 1997] has been developed by the GEMS partner FMI for emergency scenarios like a factory fire. It is a computationally cheap parameterisation and therefore suitable for operational calculations. However, its applicability to global wildfire modelling still needs to be proven.

5 Some Interactions with other Modelling and Monitoring Activities

5.1 Feedback in Carbon Cycle Modelling

The GEMS system will be able to link to the interactive vegetation model C-TESSSEL, which is being developed as part of *geoland-ONC*. The model focuses on the biomass in leaves and is being nudged to the observed leaf area index (LAI). Thus CO₂ and H₂O fluxes due to photosynthesis, plant respiration, and evaporation are modelled and the CO₂ uptake during the initial phase following a fire may be captured adequately. However, total carbon build-up is not modelled as this would require additional treatment of the carbon pools of wood, roots, and litter.

Many dynamic vegetation models that are currently being used in NWP suffer from inherent drifts. To correct for the drift, they are nudged to climatological values. Since soil respiration is poorly known, additional calibration is needed. For example, in many global vegetation models it is represented by assuming vanishing annual CO₂ flux of the combined vegetation-soil system. Thus inter-annual variability cannot be described with many of the available models.

In contrast, current “carbon cycle data assimilation systems” (CCDAS) are in fact variational parameter-tuning exercises on the soil-carbon models so they can simulate inter-annual variability in soil carbon emissions /

uptake, see, e.g., <camels.metoffice.com> and Rayner et al. [2005]. Other models that describe the inter-annual variability have been used by Thonicke et al. [2001], van der Werf et al. [2003], Krinner et al. [2005]. The possibility to incorporate the ORCHIDEE model, which is currently being used in *geoland*, in GEMS is currently being investigated. [Hollingsworth, 2005]

It remains to be seen what information can be obtained from dynamic vegetation modelling in terms of estimating fire emissions. This information will be limited due to the limited resolution of the models. Alternatives for estimating fuel load and fuel moisture content based on satellite retrievals should be explored.

5.2 Interaction with *geoland*

The monitoring of land surface properties is the goal of *geoland* in general.

The available fuel load (AFL) is currently not a product of *geoland*. Since the uncertainty on AFL is a major source of uncertainty for the modelling of wildfire emissions, it would be very desirable if a possible successor to *geoland* would include a dynamic AFL product or at least some parameter from which the AFL variability can be deduced. The observatories ONC “Natural Carbon Fluxes” and OLF “Global Landcover and Forest Change” are candidates for an extension to produce AFL.

Likewise, a dynamic land cover map may be produced by a future successor of *geoland* for improved assignment of ecosystems.

A burnt area product is incorporated in *geoland*-CSP. It is expected to use the GBA2000 algorithm for SPOT-VEGETATION data. [Lacaze, 2005] A hot spot product is planned for the future. These products might replace the MODIS products if they are produced operationally in the future. However, there are some strong concerns about the quality of the GLOBCARBON product which is identical to the *geoland* product.

On the other hand, *geoland* partners have expressed interest to use the GEMS fire emissions as input for their future projects. [J.-C. Calvet, pers. comm.]

5.3 Strategic implications of the use of burnt area/hot spot LEO/GEO Data

Possible strategies for assimilating the different fire observations in GEMS are summarised in Table 2.

Table 2: Possible Use of Fire Observations in GEMS

observation	information on emission	analysis/forecast	reanalysis	inversion
hot spots	time, location	yes	yes (combine obs.)	yes
burnt area	amount	no	yes	no, to be derived
burning area	time, loc., amount	yes	yes	yes (t., l.) / no (amount)
fire radiative power	time, loc., amount	yes	yes	yes (t., l.) / no (amount) (bottom-up vs. top-down)
atmosphere		Yes	yes	YES

Hot spots identify when and where emissions are drastically increased as compared to averaged inventories, but it is relatively uncertain how large the increase is. Therefore, a sensible means of using fire count products in the analysis may well be to increase the model accuracy estimate, J_b , at the given time and location. This would automatically give the subsequent observations of the atmospheric composition a relatively large weight. (requiring sufficient observations and also suggested by H. Eskes at GEMS kick-off [Hollingsworth, 2005]) It would conform to the general top-down approach of GEMS and facilitate future estimates of the fire emissions from the satellite observations by employing variational inversion. The product can thus be useful for reanalysis, NRT analysis/forecast, and variational inversion for surface fluxes.

Burnt area products identify how much has been emitted where, but it is uncertain exactly when. In Northern mid-latitudes and boreal zones the majority of fires is characterised as individual large scale events. In this situation, combining the burnt area product with the time of the fire derived from a fire count product, a relatively good estimate for the emission by the fire can be obtained from a fire model. However, this method will not work in many tropical regions where fires are more like a stochastic sub-grid-scale process. The approach would rely heavily on the fire modelling and give the observation of atmospheric composition less weight than the approach outlined above for fire counts. It would relax the requirements for atmospheric composition observations. It would be more of a bottom-up approach focusing on the best possible description of the atmosphere. (instead of subsequent estimation of surface fluxes) Therefore, the products are useful primarily for performing re-analyses.

The burning area product promises to identify when where how much is being emitted. The observation are more frequent since the instruments are flying aboard GEO satellites as opposed to the LEO satellite products discussed above. However, coverage does not extend to higher latitudes.

In one of the WPs of GEMS-GHG the top-down approach of observing the atmospheric composition and inferring the surface fluxes from the composition is followed. Such an inversion is explicitly anticipated in the last stages of the GHG subproject. It will not use direct observations of the amount of the emission from the surface but rely on the atmospheric observations to derive them, cf. last column of Table 2. The derived information on the emission might possibly be used further to determine burnt areas or emission factors or other parameters that describe the emission mechanisms in similar way as employed in the CAMELS project <camels.metoffice.com>. Information on the location and time of burning events might be used to constrain the inversion. Thus burnt/burning area observations would not needed for this part of GEMS.

6 Elements of an Overall Strategy for Handling Wildfire Emissions in GEMS

As outlined in Section 2, GEMS will have three production phases with increasingly stringent requirements on the fire emission products, plus the subsequent operational phase. The developments for each of the phases must provide the start point for the next to ensure continuously improving quality of the system.

6.1 Review of the Baseline Proposal as Described in the DoW

The modelling of emissions from wildfires is explicitly targeted in

- WP_AER_2, Task 2.2.: Assimilation of Wildfires
- WP_PRO_7: Build consolidated pre-operational system; with revised science modules and implement real-time Fire assimilation scheme

- WP_GRG_2, Task 2.13: Implementation of a global wildfire emission model (GWEM) on the ECMWF computer

It is planned to modify the emission model GWEM, see section 4.3, for determining the emitted amounts from hot spot observations based on LEO satellites. Further modifications may be necessary in order to make the code more efficient (and possibly parallel) and the use of AFL fields from LPJ shall be reviewed. The model BUOYANT [Nikmo et al., 1999, Martin et al., 1997] shall be adapted for the calculation of the injection heights. Since the latter model has not been developed with wildfire applications in mind the challenge seems to be the modelling of extended, intense wildfires with plumes rising through the entire troposphere.

Wildfire emission products from MODIS and, possibly, ATSR and VEGETATION will be assimilated in GEMS, cf. section 3.

Since MPI-MET is a partner involved in the wildfire emission modelling in the AER and GRG subprojects a good coordination between these subprojects is ensured. In the next 18 months plan for GEMS, a task group across all sub projects should be set up in order to ensure consistency between GRG, AER, GHG and RAQ.

Coordination with *geoland*, which is also anticipated in the DoW, is the task of HALO. The exact GEMS requirements are currently being formulated and coordinated with the HALO partners. (This document is contributing to this task).

6.2 Proposal of Global Fire Assimilation System (GFAS)

The modelling of wildfire emission from satellite observations is rapidly evolving area of research and it is expected that during the operational phase of the GEMS system better solutions will be available than today. In order to protect most of the GEMS system from repeated updating we propose to establish a global fire assimilation system (GFAS) that evolves with the observational capabilities and product algorithm development. The GFAS would deliver the fire emissions of the various relevant constituents to all the GEMS sub-projects. Since the time and the injection height profile need to be resolved, the GFAS would produce a 4-dimensional fire emission field for each species. Its input would evolve with time, from climatologies to satellite products to satellite radiances. Additionally, the meteorological fields would be need as input for the calculation of the injection height profiles.

The GFAS interfaces are shown graphically in Figure 11. The data stream taken into account within the GFAS are outlined in Figure 9. Such a complex GFAS can be realised only partially in the time frame and source allocation of the GEMS project.

6.3 Proposal to meet the phase 1 needs

For the initial reanalysis simulations, the fire emissions will be provided as gridded monthly mean files. Such data are available from the RETRO project for the time period 1960–2000, and from AEROCOM for 1996–2001. A data set of 2003 fire emissions based on MODIS and MOPITT observations has been compiled by NCAR [Claire Granier, pers. comm.] and can be made available to GEMS with short notice. If not all required species are included in this data set, others can be derived from simple scaling approaches using the emission factors from Andreae and Merlet [2001].

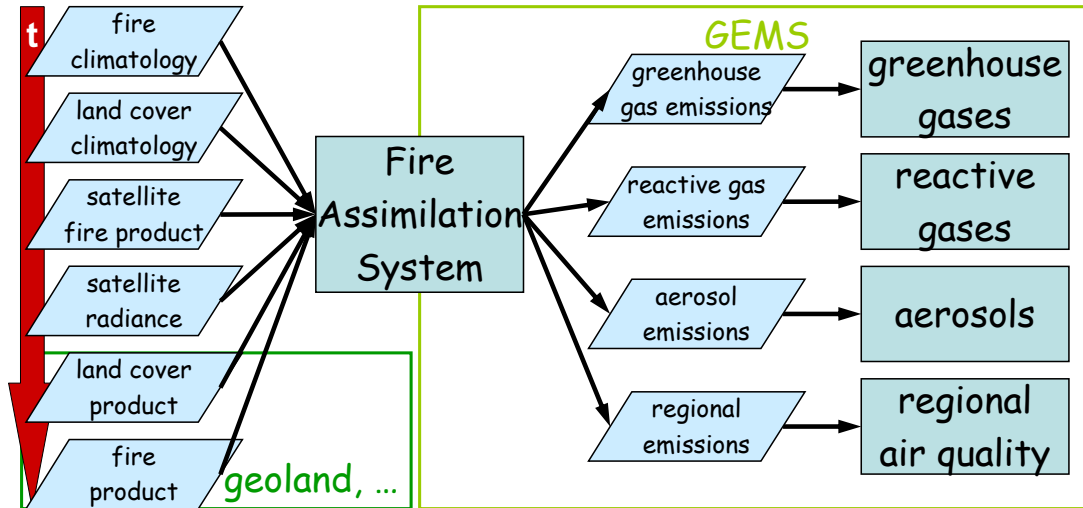


Figure 11: Global Fire Assimilation System.

6.4 Proposal to meet the phase 2 needs

We propose to implement a software module based on GWEM that can provide fire emissions to all GEMS subprojects. The initial focus shall be on mid-latitude and boreal forest fires. Different satellite data products shall be tested starting with the MODIS products. The GWEM parameterisations will be reviewed and adapted to these data sets. Emissions shall be provided primarily as a continuous data stream describing major properties of individual fires as this format allows for maximum flexibility. However, a tool shall be developed to sample these data into gridded files of varying grids and resolution. The GEMS models shall continue to use gridded files during this phase, but first tests shall be made to use the continuous data stream directly. This requires the development of a common interface that can be used by all GEMS models so that adaptive work in the four subprojects can be minimised.

At the end of phase 2 or the beginning of phase 3, the approach shall be extended to cover tropical fire regimes as well. This work must be performed in parallel to the adaptation of the system to NRT data described below.

6.5 Proposal to meet the phase 3 needs

The **analysis and forecasting** mode of GEMS requires observations to be available in NRT. Therefore, burnt area products cannot be used for analysis and forecast, cf. column “analysis/forecast” of Table 2. The bottom-up modelling of fire emissions from hot spot or burning area observations will complement the atmospheric

observations with crucial information, e.g. on the vertical distribution of emissions and types of aerosols.

The fire emission module implemented in phase 2 shall be adapted for NRT operations. Firstly, the list of used products would be limited to those available in NRT. Secondly, the list may be extended by implementing established fire product algorithms for application in NRT. Thirdly, the list might be extended by taking the burning area product from GEO satellites into account. Finally, provisions must be taken to ensure reasonable emission fluxes are provided even in the case of acute data failures or delayed data delivery.

6.6 Proposal to meet the phase 4 needs

After successful testing of GFAS for operational purposes, further work will be needed to improve the robustness and accuracy of this tool. New EO data sets with better time resolution or improved accuracy (but perhaps limited temporal coverage) will be explored and included into the system where feasible. A particularly attractive option would be the establishment of a network of geostationary sensors with global coverage and frequent observations, which should then be augmented by a few LEO satellites to cover the polar regions and to provide better accuracy and cross-calibration between the GEO sensors. The initial emphasis on hot spot observations will shift towards burning area or FRP data products, and user services will be developed which may directly benefit from the GFAS system.

The burning area observations from GEO satellites may also offer a tested and versatile fire characterisation due to their NRT information on the burning area and their high observation frequency. They may form the backbone of fire observations in the operational phase of GEMS beyond 2009.

Even though the GEO observations have proven useful on a continental scale the global coverage targeted by GEMS would require the current initiative to establish a global GEO fire observation system by implementing operational versions of the burning area or/and FRP algorithms for GOES, MSG, and MTSAT to succeed. Furthermore, a polar orbit instrument would be required to achieve true global coverage and improved accuracy, in particular for high-latitude regions.

The proposed common GEMS fire emission software module would complement a geostationary fire observation system with its initial focus on LEO satellite products. It could therefore relative easily be extended to incorporate products from a future global GEO fire observation system for the benefit of AER, GRG, and GHG species monitoring.

7 Conclusions

1. Wildfires are a major source of emissions and of the variability of tropospheric trace compound concentrations. Therefore, fire observations must be assimilated in the GEMS system.
2. The currently available fire emission products do not meet all requirements of GEMS. However, the state of the art is developing rapidly.
3. A global fire assimilation system (GFAS) producing 4-d fire emission fields for all four GEMS sub-projects seems best suited to exploit the anticipated scientific developments.
4. The requirement of consistency across the GEMS subprojects also suggests that the fire emission modelling shall be linked to the individual GEMS components via a common interface, i.e. the global fire assimilation system.

5. The GEMS test reanalysis of 2003 should use an established monthly fire emission inventory, i.e. RETRO and AEROCOM-B. It may be adapted to the specific situation of 2003, e.g. with inversions produced by G. Petron (NOAA) from MOPITT CO observations.
6. The extended GEMS reanalysis of 2000-2007 should be produced using fire emissions derived from the existing global hot spot and burnt area observations and existing land cover inventories. It may access existing gridded products like GLOBCARBON.
7. The MODIS hot spot product is currently the only globally available operational NRT fire product. It is therefore a sensible choice for the first operational real-time analysis and forecasting system of GEMS.
8. The burning area observations by geostationary satellites have proven useful and may form the backbone of a future global fire assimilation system for GEMS, due to their information on the burning area and their high observation frequency. However, a GEO observing system with global coverage supported by additional LEO observations will be needed in order to achieve global coverage and better accuracy.
9. The fire radiative power product seems most promising for fire emission monitoring in the long term, because its output is directly related to the emission flux. Again, a global observation system with operational products from GEO and LEO satellites would have to be established.
10. GEMS has a strong interest in the development of consistent global burning area observations and/or fire radiative power products from meteorological GEO satellites and polar orbiting instruments like MODIS. Related activities of GTOS GOF-C-GOLD and IGBP should be encouraged and supported.
11. Meetings of partners from the GEMS subprojects dealing with wildfire emissions should be arranged (the topic will be discussed during the GEMS Assembly on 7-10 Feb in Reading). A task group across all GEMS sub projects shall be formed in order to monitor progress in the development of the global fire assimilation system.
12. Two systems for the real-time analysis and forecasting of atmospheric pollution due to the emission by fires are operating at present at NRL and INPE/CPTEC. They have limited geographical coverage and consider only aerosols and CO.
13. Experts from GOF-C-GOLD, NRL, INPE/CPTEC and other remote sensing data centres should be invited to participate in the above mentioned meetings. This would help to gain know-how from the existing operational models and to link the GEMS activities with the activities in GTOS related to the development of a global fire observation system.
14. For operational use, negotiations with the data providers must take place in order to assure data availability and to decide whether GEMS will obtain already processed fire products (e.g. MODIS hot spots) or whether the fire product retrieval from observed radiances will be implemented at ECMWF. Different strategies might be needed for different products.
15. HALO needs to stress the importance of an available fuel load (AFL) product by *geoland*. The strengths and weaknesses of using dynamic vegetation models versus satellite data products for estimating AFL need to be assessed.
16. The different assimilation modes analysis/forecast, reanalysis, and inversion in GEMS have different requirements on the fire observations in terms of data delay, coverage, and accuracy.
17. Fire modelling requires a regionalised approach, because fire regimes and fire properties differ strongly between eco regions and even on finer scales. In particular, a methodological distinction is necessary

between mid-latitude and boreal fires (which can be characterised as individual fire events) and tropical fires (which require a more statistical approach).

18. The GWEM model has been selected as a basis for a first development of the GEMS global fire assimilation system as it already contains several modules suitable for the processing of satellite fire data sets and other necessary information.
19. Additional funding, extending into the operational phase of the GEMS system, is needed to establish a consistent global fire assimilation system and keep track of the anticipated scientific development over the next years.

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