23 The GOFC-GOLD Fire Mapping and Monitoring Theme: Assessment and Strategic Plans

Ivan A. Csiszar
NOAA/NESDIS Center for Satellite Applications and Research,
5200 Auth Road, Camp Springs, MD 20746, USA
Email: ivan.csiszar@noaa.gov

Christopher O. Justice
Department of Geography, University of Maryland, 2181 LeFrak Hall,
College Park, MD 20742, USA
Email: justice@hermes.geog.umd.edu

Johann G. Goldammer
Global Fire Monitoring Center, Max Planck Institute for Chemistry,
c/o Freiburg University, Georges-Koehler-Allee 75 D – 79110, Freiburg, Germany
Email: johann.goldammer@fire.uni-freiburg.de

Timothy Lynham
Natural Resources Canada, Canadian Forest Service Great Lakes Forestry Centre,
1219 Queen Street East, Sault Ste. Marie, ON P6A 2E5, Canada
Email: tim.lynham@nrcan.gc.ca

William J. de Groot
Natural Resources Canada, Canadian Forest Service Great Lakes Forestry Centre,
1219 Queen Street, East Sault Ste., Marie, ON P6A 2E5, Canada
Email: bill.degroot@NRCan.gc.ca

Elaine M. Prins
Cooperative Institute for Meteorological Satellite Studies, University of
Wisconsin-Madison, 1225W. Dayton St., Madison, WI 53706, USA
Email: elaine.prins@ssec.wisc.edu

Christopher D. Elvidge
NOAA National Geophysical Data Center, 325 Broadway, Boulder, CO 80303, USA
E-mail: Chris.Elvidge@noaa.gov

Dieter Oertel
Deutsches Zentrum für Luft- und Raumfahrt Optical Information Systems,
Rutherfordstrasse 2, Berlin D-12489, Germany
Email: Dieter.Oertel@dlr.de

J. J. Qu et al. (eds.), *Remote Sensing and Modeling Applications to Wildland Fires*

© Tsinghua University Press, Beijing and Springer-Verlag Berlin Heidelberg 2013

Eckehard Lorenz
Deutsches Zentrum für Luft- und Raumfahrt Optical Information Systems, Rutherfordstrasse 2, Berlin D-12489, Germany
Email: eckehard.lorenz@dlr.de

Thomas Bobbe
Remote Sensing Applications Center, USDA Forest Service, 2222 West 2300 South, Salt Lake City, UT 84119, USA
Email: tbobbe@fs.fed.us

Brad Quayle
Remote Sensing Applications Center, USDA Forest Service, 2222 West 2300 South, Salt Lake City, UT 84119, USA
Email: bquayle@fs.fed.us

Diane Davies
Department of Geography, University of Maryland, 2181 LeFrak Hall, College Park, MD 20742, USA
Email: ddavies@hermes.geog.umd.edu

David P. Roy
Geographic Information Science Center of Excellence, South Dakota State University, Wecota Hall, Box 506B Brookings, SD 57007, USA
Email: david.roy@sdstate.edu

Luigi Boschetti
Department of Geography, University of Maryland, 2181 LeFrak Hall, College Park, MD 20742, USA
Email: luigi.boschetti@hermes.geog.umd.edu

Stefania Korontzi
Department of Geography, University of Maryland, 2181 LeFrak Hall, College Park, MD 20742, USA
Email: stef@hermes.geog.umd.edu

Stephen Ambrose
NASA Headquarters, Washington, DC 20546, USA
Email: sambrose@nasa.gov

George Stephens
NOAA NESDIS, 511 Deerfield Ave., Silver Spring, MD 20910, USA
Email: George.stephens@verizon.net

Abstract The objectives of the fire mapping and monitoring theme of the global observation of forest and landcover dynamics (GOFC-GOLD) program are to refine and articulate the international requirements for fire related observations, to increase access to and make the best possible use of existing and future observing systems for fire management, policy decision-making and global change research and to ensure the provision of long-term, systematic satellite observations necessary for the production of the full suite of recommended fire products. The GOFC-GOLD Fire Implementation Team also fostered the development of regional networks of data providers and users to capture regional specific information needs and priorities. This chapter discusses specific goals of the program related to pre-fire evaluation, fire observations and post-fire assessment, and the implementation status of corresponding activities. Examples of contributory programs from US agencies are also presented.

Keywords Satellite fire monitoring; international collaboration; decision making support; global change

23.1 Introduction

The global observation of forest cover- global observation of landcover dynamics (GOFC-GOLD) was initiated in response to the committee on earth observation (CEOS) to develop a stronger linkage between the Space Agencies and the users of earth observation technologies (Townshend et al., 2004). The observation technologies were being developed and research and development undertaken to provide new and improved satellite products for monitoring the earth surface but the full potential of these technologies was not being realized. It was recognized that in some cases there was a mismatch between the information that was being provided and that which was really needed by those responsible for the operational monitoring and management of earth resources and those undertaking global change research. It was recognized that there was the need for a better understanding of the observational requirements from the user community. In other cases potential users were simply unaware of the available technologies and in many cases there were obstacles to accessing and utilizing the data.

GOFC-GOLD is currently a project of the global terrestrial observing system (GTOS), with a project office in Edmonton run by the Natural Resources Canada and the Canadian forest service (GOFC, 2007). The secretariat for GTOS is at the United Nations food and agriculture organization (FAO) in Rome (GTOS, 2005). A more detailed evolution of the GOFC-GOLD program can be found in Townshend et al., (2004).

The fire phase of GOFC-GOLD was initiated in 1998 at a kick-off meeting at the Joint Research Center, Ispra (Ahern et al., 2001). At that meeting it was evident that the satellite fire observations fell largely in the research domain and that the products are often of unknown accuracy. It was also recognized that there is often parallel development of methods and techniques amongst different groups and that there are a number of opportunities for efficiencies through information

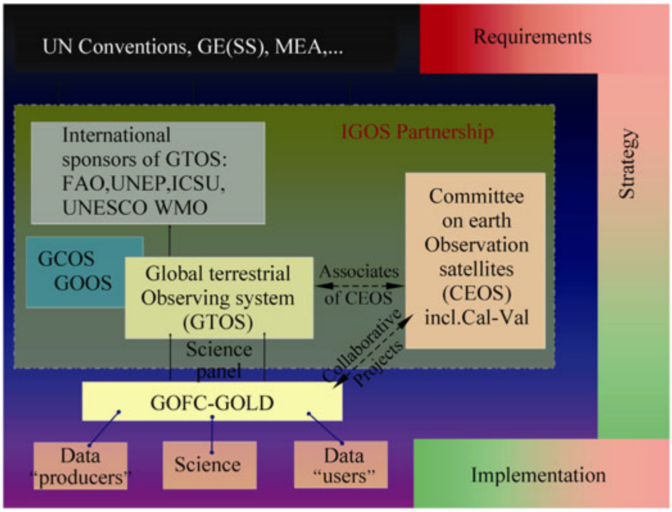

Figure 23.1 GOFC-GOLD within the overall structure of earth observation programs

and data exchange. It was recognized that for fire information users, the products must be reliable with sustained data provision and that there is a need to transition proven techniques in the research domain to the operational agencies. It was also recognized that there are often a number of institutional obstacles to such transition, most often related to funding responsibility. There is also a need for better integration of satellite, aircraft and ground based information. It was strongly recommended at the meeting that GOFC-GOLD Fire establish strategic partnerships with other national and international organizations building on existing programs, addressing other aspects of fire monitoring and management. In particular every effort should be made to also make available information to users beyond the international organizations at the regional to local level.

Since the 1998 kick-off meeting, GOFC-GOLD Fire has developed strategic partnerships with a number of organizations that share some of the program goals, for example with the U.N. Interagency strategy for disaster reduction (UNISDR) working group on wildland fire and its follow-up arrangements, the UNISDR global wildland fire network and the wildland fire advisory group, which is focusing on improving fire management capacity around the world. National fire reporting is inconsistent globally and is often of unknown accuracy. In many countries there is a scarcity of fire information and there is a need for better and timely information. To help coordinate and guide its fire program, GOFC-GOLD established a secretariat and a fire implementation team consisting of data providers and data users (GOFC FIRE, 2008). The aims of this team are to refine and articulate the international requirements for fire related observations, to increase access to and make the best possible use of existing and future observing systems for fire management, policy decision-making and global change research and ensure the provision of long-term, systematic satellite observations necessary for the production of the full suite of recommended fire products (Justice et al., 2003). The team is also involved in a number of global initiatives requiring international cooperation. Following the lead of the land cover component of GOFC-GOLD, the implementation team fostered the development of regional networks of data providers and users to capture regional specific information needs and priorities. Regional Fire Networks have been established in Southern Africa, Northern Eurasia, Southeast Asia and South America. The networks provide a forum for shared experience in fire observation and monitoring and opportunities for lateral transfer of technology. These networks complement and are coordinated with the regional fire management networks being developed by the UNISDR global wildland fire network. The implementation team set out the broad goals for the fire program and near term program objectives.

23.2 GOFC-GOLD Fire Goals and Current Implementation Status

23.2.1 To Increase User Awareness by Providing an Improved Understanding of the Utility of Satellite Fire Products for Resource Management and Policy Within the United Nations and at Regional, National and Local Levels

The challenge for nations and the international community is to develop informed policy and management capabilities that recognize both the beneficial and traditional roles of fire, while reducing the incidence and extent of uncontrolled burning and its adverse impacts. A major impediment for efficient wildland fire management and for strategic planning is the lack of reliable data and information on the occurrence and extent of wildland fires and their effects (Ahern et al., 2001). In most countries of the world there is also a lack of information on precursors of wildfires and fire use, such as weather-related information (wildland fire danger), ecosystem properties that influence fire behavior and fire severity (wildland fire hazard) and the probability of ignition (wildland fire risk). There is also a lack of internationally agreed standards for assessments, reporting and evaluation of the consequences of wildland fires. The development of a standardized wildland fire inventory system is urgently needed. However, even if an international consensus would be reached in future, it is evident that most countries do not have sufficient ground- or aircraft based systems for detection, monitoring and fire damage assessment. Thus, information generated by spaceborne instruments is essential to provide the information required.

The United nations recently have shown an increasing interest to develop informal partnerships, joint projects and formal agreements among governments and between government and non-governmental institutions that are essential to enable nations to develop sustainable fire management capabilities. In 2001 UNISDR provided a mechanism to facilitate a common policy dialogue at inter-agency and international levels. Starting in 2001 a working group on wildland fire was created within the UNISDR inter-agency task force for disaster reduction. Through this group the various UN specialized agencies, programmes and secretariats of conventions that have a direct or indirect responsibility in matters related to wildland fire shared their views and visions for a collective approach (UNISDR, 2008). In this working group the GOFC-GOLD fire implementation team provided concepts and visions for the coordinated use of satellite remote sensing (RS) of wildland fires. While the UN has to agree on a systematic and standardized approach in developing a global database on wildland fire, there is an increasing demand of countries on the other side to receive guidance and support for developing such databases. The UN and other international organizations also require spaceborne fire information—to mention a few examples:

(1) United nations environment programme (UNEP)—for monitoring the environment effects of wildland fire

(2) UN office for the coordination of humanitarian affairs (UN-OCHA)—for response to wildland fire disasters (with UNEP and GFMC)

(3) FAO—for the regular global forest resources assessments

(4) World health organization (WHO)—for providing guidance on response measures to reduce impacts of smoke pollution on human health and security

(5) World meteorological organization (WMO)—for early warning of wildland fire danger and smoke trajectories

(6) The “Rio conventions”—for the implementation of the mandates of the UN conventions on combat desertification (UNCCD), biological diversity (UNCBD) and the UN framework convention on climate change (UNFCCC)

(7) The United nations forum on forests (UNFF)—for including forest fire management into the multi-year plan of work of the “Non-legally binding instrument on all types of forests” (2007)

(8) The UN office for outer space affairs (OOSA) / UN Committee on the peaceful uses of outer space (COPUOS)—for satellite RS technology transfer to developing countries

(9) The earth observation user Liaison Office for the humanitarian community—for providing accurate information updates on fast evolving situations for humanitarian relief and crisis prevention operations

(10) United Nations University (UNU)—for conducting dedicated targeted research and training

Driven by the interests of countries to create synergies in sharing fire management resources—including fire information systems—the Global Wildland Fire Network was established in 2003 as an outreach programme of UNISDR (GWFNa, 2008). Government and non-government institutions actively organized under the Regional Wildland Fire Networks are aiming at strengthening the dialogue between specialists and government agencies of neighbouring countries. Representatives of the Regional Wildland Fire Networks are members of the UNISDR Wildland Fire Advisory Group which is serving as an advisory body to the United Nations. There is a close working relationship with the regional GOFC-GOLD networks which are focussed on fire observations and monitoring. Both networks are interacting in regional consultations and workshops aiming at the preparation of targeted proposals to the international community, notably the UN family.

Regional network consultations conducted in 2004 came up with recommendations directed to a ministerial conference at FAO (Rome, March 2005) to formulate an International Wildland Fire Accord. The ministerial meeting, however, rejected the proposal for an accord and instead recommended the development of "voluntary guidelines"; at the time of writing this Chapter the overall aims of these guidelines have not yet been defined (GWFNb, 2008). FAO also rejected the GOFC-GOLD proposal to utilize satellite RS products for a consistent global fire assessment within the Global Forest Resources Assessment 2005 (FAO, 2006).

So far all proposals to set up a consistent global wildland fire monitoring programme under the umbrella of the UN have failed. However, the GOFC-GOLD Fire Implementation Team, through its involvement in the Wildland Fire Advisory Group and by facilitation through the Global Fire Monitoring Center (GFMC), continues to push the agenda at the UN level.

23.2.2 To Encourage the Development and Testing of Standard Methods for Fire Danger Rating Suited to Different Ecosystems and to Enhance Current Fire Early Warning Systems

23.2.2.1 Early Warning Systems and Fire Danger

Fire danger rating (FAO, 1986) is a mature science and has long been used as a tool to provide early warning of the potential for serious wildfires. Fire danger rating systems (FDRS) utilize basic weather data to calculate wildfire potential. Fire danger is a general term used to express an assessment of both fixed and variable factors of the fire environment that determine the ease of ignition, rate of spread, difficulty of control, and fire impact (Merrill and Alexander, 1987). FDRS early warning information is often enhanced with satellite data such as hot spots for early fire detection, and spectral data on land cover type and indices of vegetation condition. More recently, remote sensed weather data is also being used to enhance the ground-based network of weather stations. Normally, these systems provide a 4 – 6 hour early warning of the highest fire danger for any particular day that the weather data is supplied. However, by using forecasted weather data, as much has 10 days of early warning can be provided. As well, FDRS indices can be calibrated with local data to provide longer term early warning, such as a 30-day early warning tool developed for SE Asia to indicate the potential for disaster-level haze events from peatland fires (Field et al., 2004).

23.2.2.2 Developing a Global Early Warning System

The science to develop a global early warning system for wildland fire currently exists, but there are some technical issues to overcome. A daily operational global system will need large amounts of data and will require considerable processing capability. There are a number of regional examples demonstrating feasibility, and global implementation is essentially a technical issue of providing complete data coverage for all countries and regions, and scaling-up with standardized products. Implementing a global system will also require regional calibration of early warning indicators using danger level boundaries. This can be done using historical ground-based weather data and remotely sensed fire data such as hotspots and burned area maps.

Advances in measuring spatial precipitation from space would offer the single largest improvement to the development of fire danger monitoring systems. Such advances would reduce or eliminate the need for spatial interpolation of precipitation from ground-based point sources, which in some regions has serious limitations. Even some countries that have established fire danger systems do not have a reliable, comprehensive network of ground-based precipitation stations that cover their fire regions. While it is recognized that space-based precipitation estimates also have limitations, combining those estimates with ground-based data as control points is expected to significantly improve the spatial modeling of this critical fire danger parameter.

Establishing an operational global early warning system for wildland fire will require an international partnership of agencies. A weather data stream from WMO could provide the baseline data necessary to calculate fire danger. The WMO could also provide additional weather-based early warning products such as smoke trajectories and air pollution warnings. Such near real-time products are currently being generated from geostationary satellites. The GOFC-GOLD Fire Implementation Team is involved in exploring the use of satellite data for early warning and fire danger purposes including hot spots for early detection, land cover classification of fuel types, and perhaps spatial weather information (e.g., precipitation) for areas where ground-based weather data is sparse. Fire management data system expertise is needed to develop a system that integrates the disparate data sources and generates early warning indicators.

Establishing a global early warning system for wildland fire provides common criteria for comparing burning conditions and wildfire situations internationally. It also provides a globally-consistent method for quantifying fire danger, an important factor for promoting resource-sharing arrangements between nations. Perhaps most importantly, establishing a global early warning system would provide a formal system for the large number of developing countries that would never have the means to develop their own. It would also provide those countries with a substantial base of information to use in developing their own fire management capabilities.

An immediate contribution that GOFC-GOLD can make to expand the international role of wildland fire danger rating. The first step would to be to promote an international fire weather index (FWI) system that is modeled on a working system. A suitable candidate is the Canadian Forest Fire weather index (FWI) System which has already been implemented in several locations around the world including Southeast Asia (de Groot et al., 2007), Mexico, New Zealand and in some states or fire agencies (Michigan, Minnesota, Alaska) within the USA. The FWI system consists of six components that account for the effects of fuel moisture and wind on fire behavior (Van Wagner, 1987). The system requires four continuous inputs (temperature, 24-hour precipitation, wind speed and relative humidity) to monitor the water balance in forests that are characterized by organic soils. However, the system could be adapted to measure fire danger in any wildland zone.

In response to the request by the UN Secretary General, the Hyogo Framework for Action 2005 – 2015: "Building the Resilience of Nations and Communities to Disasters" and the preparation of the upcoming Third International Early Warning Conference (EWC-III, Bonn, Germany, March 2006) a project proposal on the development of Global Early Warning System for Wildland Fire has been submitted to the United Nations in October 2005.

23.2.3 To Develop an Operational Global Geostationary Fire Network Providing Observations of Active Fires in Near Real Time

The international environmental monitoring and scientific research communities have stressed the importance of utilizing operational satellites to produce routine fire products and to ensure long-term stable records of fire activity. Although a number of geostationary systems cover most of the Earths surface and in some cases with considerable overlap, there has been little coordination to date concerning fire monitoring. An operational global geostationary fire monitoring network would enable monitoring of fires as they occur and capture the diurnal signature of fire activity.

Geostationary systems have an important contribution to make in providing multiple observations per day for active fire and smoke detection and characterization with applications in fire management, emissions and air quality studies, and global change research. A global geostationary fire monitoring network is technically feasible, but must be supported by the operational agencies in order to sustain the activity and produce standardized long-term data records and fire inventories of known accuracy.

In an effort to coordinate international geostationary fire monitoring efforts the

GOFC-GOLD fire monitoring and implementation team and the EUropean organization for the exploitation of METeorological SATellites (EUMETSAT) hosted two workshops on geostationary fire monitoring and applications in Darmstadt, Germany in 2004 and 2006. The 2006 workshop was attended by over 45 representatives from 18 countries in Europe, Africa, Asia and the Americas.

23.2.3.1 Current Status

Currently the Imager on the US geostatationary operational environmental satellites (GOES-East and GOES-West) allows for diurnal fire detection and monitoring throughout the Western Hemisphere. The European Meteosat-9 spinning enhanced visible and infrared imager (SEVIRI) provides diurnal fire monitoring capabilities in Western Europe and Africa. FY-2C and MTSAT-1R were launched in 2004 and 2005, respectively, allowing for nearly global geostationary fire monitoring capabilities. Over the past 2 years, FY-2C/2D and MTSAT-1R have been used to some extent for fire detection and monitoring in Asia and Australia.

The number of countries and research and operational groups involved in geostationary fire monitoring has significantly grown in the last two years, with applications in a variety of areas including hazards, air quality monitoring, climate change, and industrial applications. Applications of GOES-E/-W, Met-8/-9, FY-2C/2D, and MTSAT-1 are demonstrating the capabilities of these operational satellites for fire detection, monitoring, and characterization. Furthermore, several operational agencies (e.g., NOAA/NESDIS, EUMETSAT, UK Met Office, China Meteorological Administration, and India) plan to develop or expand existing geostationary fire detection and monitoring programs.

23.2.3.2 Future Plans

The current configuration of geostationary platforms around the globe leaves a gap in coverage over Eastern Europe and Western Asia to monitor burning in India and the boreal forests of Russia. Within the next 2 years additional geostationary instruments with fire monitoring capabilities will be launched by India (INSAT-3D, 2008), Russia (GOMS Elektro L MSU-GS, 2008) and Korea (COMS, 2009) providing coverage of this region as well. Together with the current suite of meteorological geostationary sensors, these upcoming sensors will enable nearly global geostationary fire monitoring. They will be able to detect, monitor, and characterize sub-pixel fires as they occur with high temporal resolution. NOAA/NESDIS and the UK Met Office plan to implement a real-time global geostationary fire monitoring system in 2008 and 2009, respectively. Furthermore fire detection and monitoring is a requirement for the next generation GOES-R Advanced Baseline Imager (ABI) and the Meteosat Third Generation geostationary platforms.

For algorithm development, operational implementation, and validation there is a need for more involvement from all countries, but especially Africa, Eastern Europe, Asia and Australia, with the recent/near-term launches of FY-2C/2D, MTSAT-1R, INSAT-3D, GOMS Elektro L MSU-GS, and COMS. Research and development is needed in the area of fused polar and geostationary fire products with the goal of improved merged products. This includes fire identification and sub-pixel characterization. Validation activities to date have been on an ad-hoc basis and would benefit greatly from more interaction with the CEOS LPV Working Group to establish systematic validation plans that include efforts to understand cross platform differences. In order to implement a global geostationary fire monitoring network with consistent global fire products, it is necessary to characterize the unique fire monitoring capabilities of each sensing system.

23.2.4 To Establish Operational Polar Orbiters with Fire Monitoring Capability to Provide Operational Moderate Resolution Long-Term Global Fire Products and Enhanced Regional Products from Distributed Ground Stations to Meet User Requirements

23.2.4.1 Current Status

Moderate resolution polar orbiters currently provide data used in detection of vegetation condition, active fires and burn scars. The system having the clearest operational status is the National Oceanic and Atmospheric Administration (NOAA) polar orbiting environmental satellites (POES) advanced very high resolution radiometer (AVHRR). Many of the existing national or regional operational systems for detecting active fires rely on AVHRR data downloaded from direct readout stations (GFMC 2008; GOFC FIRE 2008). The National Aeronautics and Space Administration (NASA) Moderate-resolution imaging spectrometer (MODIS) a research instrument, has demonstrated the value that improved spatial resolution, radiometric calibration, geolocation accuracy, and an extended suite of spectral bands can bring to fire RS (Justice et al., 2002). MODIS sensors are currently flying on NASA’s Terra and Aqua satellites and fire data from these systems is increasingly used by operational agencies. Data from the European space agency (ESA) (Advanced) Along Track Scanning Radiometer ((A)ATSR) have been processed to produce global compilations of night-time active fire and burn scars (Arino et al., 2001). Data from the European Commission SPOT-VEGETATION, sensor have been used to produce annual compilations of global burn scar. The U.S. air force defense meteorological satellite program (DMSP) operational linescan system (OLS) can detect fires at night via low light imaging in the visible wavelength region (Elvidge et al., 2001), a capability used in conjunction with data from other systems, such as AVHRR and MODIS.

23.2.4.2 Future Plans

In the next three years there will be good continuity of primary moderate resolution systems for global fire monitoring, barring system failures (i.e. AVHRR, MODIS, DMSP and AATSR). The NASA/NOAA/DoD visible infrared imaging radiometer suite (VIIRS) instrument, to be flown on the NPOESS preparatory mission (NPP) in 2009 is designed to provide continuity for the MODIS mission and prototype the operational moderate resolution sensor and product data streams from VIIRS during the national polar-orbiting operational environmental satellite system (NPOESS, Townshend et al., 2002) Importantly, the NPP spacecraft will provide direct broadcast of data, continuing the tradition of the NOAA-POES and NASA Terra/Aqua.

The VIIRS is under construction and will provide fire data similar to that of MODIS. An advantage over MODIS will be the inclusion of a suite of imaging bands, centered at 0.64, 0.86, 1.61, 3.74 and 11.4 microns at 400 meter resolution at nadir. This should enable improvements in both active fire and burn scar mapping. (Note that the VIIRS thermal anomaly product will be based on the moderate resolution bands, not the imaging band set). The major problem with the VIIRS bands in the 10.8 um region is that the saturation temperature is set to maximize the discrimination of cloud top temperatures and saturation is expected on large fires. Upon saturation, it will not be possible to estimate fire characteristics, such as size and temperature using the standard 3.7 versus 10.8 μm band algorithm. In addition, on-board aggregation will average values for saturated and unsaturated pixels. It may be possible to make use of other VIIRS bands, such as those placed at 1.61 and 2.25 to characterize fire size and temperature when saturation occurs in the 10.8 μm bands, but this is currently not planned for the operational thermal anomaly product.

In the next ten years it is anticipated that the NPOESS VIIRS will become the primary operational moderate resolution polar orbiting system used in active fire and burn scar RS. This will be augmented by a continuation of the AVHRR data record on the morning MetOp the first of which was launched in October 2006. It is important that the active fire RS user community effectively establish requirements for unsaturated 3.7 μm data, for all but the very largest and hottest fires.

23.2.5 To Develop Long-Term Fire Data Records by Combining Data from Multiple Satellite Sources

Beginning in the 1980’s, various instruments on geostationary and polar platforms have been providing systematic measurements useful for fire mapping and monitoring. The independent development of these systems has led to the generation of a number of single-sensor products. However, the sensors on board operational and experimental satellite platforms have provided data limited to the associated sensor’s spatial and temporal coverage and only for the duration of the specific mission or project. The accuracy of the different products also varies due to sensor characteristics, such as spatial resolution, geolocation accuracy and radiometric characteristics, and algorithm. To generate a long-term, science quality, homogeneous fire data record, a number of issues related to inter-satellite and inter-sensor continuity need to be addressed. In this process the advancement of technology and the consequent improvement of data quality and the availability of an increasing number of sensors need to be considered. Specifics of such dynamic continuity for fire products need to be defined. A fundamental component of this process is product validation, which also allows the linkage of products from different sensors.

23.2.5.1 Active Fire Data Record

The longest data record—25 years-applicable for active fire monitoring is available from AVHRR. In many areas, however, for most of the data record full 1km resolution data are not available. The 4 km Global Area Coverage (GAC) data generated by sampling and averaging the 1km data, are of limited use for fire detection and burned area mapping. In addition, inter-satellite changes, the orbital drift of the NOAA satellites and sensor degradation make the creation of a homogeneous AVHRR-based active fire data record difficult (Csiszar et al., 2003). Nighttime data within the ATSR/AATSR World Fire Atlas (Arino et al., 2001) now provide nearly a decade of systematic record. Science quality daytime and nighttime active fire data have been generated from MODIS since late 2000 (Justice et al., 2002). To establish continuity between these products, differences in detection capabilities and temporal sampling of the diurnal cycle of fire activity need to be analyzed. Multi-year data records from GOES (hemispherically) and TRMM (within the tropics) provide an opportunity for such intercomparisons and the normalization of fire counts. Advances have also been made in the use of coincident fire observations from high resolution sensors—primarily Terra/ASTER—for product validation (Morisette et al., 2005a; 2005b, Csiszar et al., 2006). The creation of true multi-sensor fire products via data fusion—defined as the generation of a single, enhanced product using information from various sensors—is currently still in the exploratory phase.

23.2.5.2 Burned Area Data Record

The production of long-term, large-scale burned area datasets has begun only recently. After pilot projects such as GBA-2000 (Tansey et al., 2004) and GLOBSCAR (Simon et al., 2004) multi-year global datasets from several sensors are being generated within the ESA GLOBCARBON project (GLOBCARBON, 2008). Recently most of the Pathfinder AVHRR Land dataset has been processed into a multi-year burned area product, however a systematic validation of the product has yet to be developed (Carmona-Moreno et al., 2005). Production of the standard MODIS burned area product (Roy et al., 2005a) began in early 2007 and reprocessing of the entire MODIS data record will be completed by mid-2008. Validation of the beta-product has been undertaken in close collaboration with the GOFC-GOLD regional fire networks in Africa, Australia and Russia (Roy et al., 2005b). Regional burned area mapping initiatives, such as TerraNorte for the boreal zone of the Northern Hemisphere (TERRANORTE, 2008) also exist.

Major requirements for the creation of the science quality burned area long term data record are the provision of 1km AVHRR observations and the inclusion of burned area among the systematically generated and validated data products by the various space and operational agencies. GOFC-GOLD Fire can be instrumental in advocating and coordinating the adoption of standard validation protocols and sustained product validation activities.

23.2.5.3 Analysis of Global Fire Dynamics

The emerging products have been used for provisional studies on the spatial and temporal dynamics of fire activity at global (e.g. Dwyer et al., 2000; Csiszar et al., 2005a; Giglio et al., 2006) and regional (e.g. Schroeder et al., 2005) scales. These analyses have revealed some important patterns of fire activity, particularly in remote areas, that will result in a better understanding of fire regimes and the role of human activity in fire dynamics. The data record will enable the analysis of long-term interactions between fire, land use, land cover and other components of the climate system (Csiszar et al., 2005b).

23.2.6 To Establish Operational Polar Orbiters with Fire Monitoring Capability to Provide Operational High Resolution Data Acquisition Allowing Fire Monitoring and Post-fire Assessments

23.2.6.1 Advanced Active Fire Detection and Characterization

The German Bi-spectral InfraRed Detection (BIRD) satellite was successfully exploited as an innovative technology development in an end-to-end demonstration for semi-operational fire detection during the FUEGOSAT Consolidation Phase Step 1 within the FIREBIRD / DEMOBIRD projects in 2003 (Briess et al., 2003; Lorenz et al., 2003). The FUEGOSAT Consolidation Phase is part of the ESA Earth Watch initiative and running since 2002 with funding contributions and participation of the ESA Member States: Spain, Italy, France, and Germany.

Work conducted by DLR and partners (Kings College London (KCL), GFMC, Remote Sensing Solution GmbH (RSS), Ingeneria y Servicios Aerospatiales (INSA) and OHB-Systems) for ESA in the ECOFIRE Study on “Scientific Assessment of Space-borne High Temperature Event Observing Mission Concepts” revealed that active fire data nearly simultaneously obtained by MODIS on Terra and by BIRD complement very well (Wooster et al., 2003; Zhukov et al., 2003). There is a high complementary potential of these two types of Low Earth Orbiting (LEO) IR sensors for innovative and quantitative active fire detection. Wide-swath moderate-resolution spectro-radiometers (MODIS type) on major polar orbiting satellites can provide daily global coverage fire detection, whereas moderate-to-high spatial resolution imagers (BIRD type) flown on micro-satellite constellations and / or on medium-scale satellites allow detailed monitoring and validation of the parameters of fires whose occurrence was detected before by the wide-swath and geostationary sensors.

A conclusion from the above European initiatives is that a dedicated fire-detecting and monitoring instrument with ~200 m spatial resolution would complement the fire detection capability of VIIRS. The accommodation of such an instrument on the GMES satellites (Global Monitoring for Environment and Security; GMES, 2008) Sentinel 2 (Land) and Sentinel 3 (Ocean) is still pending. A market study for FIRES—a prospective micro-satellite constellation with BIRD-type IR sensors, real time on-board fire product generation and broadcast—was conducted in 2005.

23.2.6.2 Role of Burned Area Maps from High Resolution RS Data to Support Global Wildland Fire Management

High resolution (20 – 30 m) RS data support a variety of global wildland fire management programs. Local fire managers require fine scale information for applications such as pre-fire vegetation/fuels mapping, fire risk modeling, burn area mapping, and post-fire assessment and monitoring.

Landsat has historically been the primary source of such high resolution imagery since it provides spectral bands in the visible, near infrared, short wave infrared, and thermal infrared regions and a valuable global archive of imagery from 1972 to the present (Sheffner, 1994). Continuity of the Landsat record is critical to accurately monitor regional and local scale temporal changes in vegetation and land cover and land use both for resource monitoring and global change research. The immediate future of the Landsat program is currently at risk due to the current operating conditions of Landsat 5 and Landsat 7, and the delay in the launch of the Landsat Data Continuity Mission (LDCM) in 2011.

Landsat 5, launched in 1984, and Landsat 7 are currently operating past their original design lives. Several critical mission components on Landsat 5 are presently operating without redundancy (Irons 2005) and instrument problems continue to arise. The fuel remaining onboard Landsat 5 is not sufficient to maintain its orbit through to the beginning of the NPOESS era and data can only be directly downlinked in real-time to a limited number of ground stations (Irons and Ochs, 2004). Landsat 7's ETM+ sensor experienced a failure of the scan line corrector (SLC) in May 2003. The result of this failure causes portions of the area within the scene to be collected redundantly while other areas are missed entirely (Howard and Lacasse 2004). The lost data which are scattered throughout the image except for a narrow central swath, amounts to ~22% of each scene (Irons and Ochs, 2004). In addition to the SLC failure, Landsat 7 lost one of its three gyroscopes in May 2004.

Since the SLC failure, various alternatives have been discussed for Landsat continuity beyond the LDCM, including a free flyer, collocation on the NPOESS platform, a commercial data buy and a micro-satellite imaging constellation. The latter approach which has been proven by the Disaster Monitoring Constellation (DMC) developed by Surrey Satellite Ltd., has considerable appeal as it would enable multiple low cost satellites to be built and launched, increasing temporal coverage and ensuring timely instrument replacement upon failure. With a number of high resolution instruments currently orbit e.g. IRS AWiFS, SPOT, ASTER, EO1, and CBERS, GOFC-GOLD in cooperation with the CEOS Working Group on Information Systems and Services in the framework of the Global Earth Observing System of Systems (GEOSS) is pursuing the coordination of the acquisition from multiple international spaceborne assets to fill this critical gap in global data continuity.

23.2.7 To Enhance Fire Product Use and Access by Developing Operational Multi-source Fire and GIS Data and Making These Available Over the Internet

Recent advances in information technology make it easier integrate RS products and GIS data within web-based GIS systems to provide resource managers with information that is timely, accurate, and delivered in a readily accessible format. Using these technologies NASA Goddard Space Flight Center (GSFC) and the University of Maryland (UMd) are working with GOFC-GOLD partners to improve the way in which active fire locations are disseminated to end users around the world.

23.2.7.1 Delivering MODIS Global Active Fire Data over the Internet

The standard MODIS active fire product can be obtained a few days after satellite data acquisition from the Earth Observation Systems Data Center (EDC) Distributed Active Archive Center (LP DAAC, 2007). However, accessing data from the DAAC requires users to download large files (typically 50 MB), use specialized software, and to possess some expertise to order the data and handle the HDF file format. To better meet the needs of resource managers, two systems were developed as part of NASA's Applications Program, under the umbrella of GOFC-GOLD Fire; the MODIS Land Rapid Response (MLRR) system (MLRR, 2008) and Web Fire Mapper (WFM, 2008).

The MLRR system processes MODIS data in near real-time and serves true color images with active fire locations overlain over the Internet. The active fire locations generated by MLRR are also ingested into Web Fire Mapper and made available to natural resource managers in readily accessible formats; these include interactive Web maps, downloadable GIS layers, and more recently (for selected areas) fire email alerts and cell phone text messages. The development of Web Fire Mapper has been based on an understanding of user needs and providing appropriate delivery systems. Using the Web GIS tools, users can customize a map by selecting from a range of geospatial layers and overlaying them with most recently acquired active fire data. Users can also analyze and query the global database of active fire detections from November 2000 to present. This capacity to integrate fire information with local geospatial information (such as park boundaries, roads and settlements) allows natural resource managers to place active fires in their geographic context.

23.2.7.2 Regional Web Fire Mapping Initiatives

There are a number of regional initiatives that also serve MODIS active fire data from a direct broadcast station. The primary advantage of these initiatives is the reduced time from satellite overpass to data distribution (~40 minutes). Examples of these systems are those operated by: the USDA Remote Sensing Applications Center (USDA, 2005), Sentinel in Australia (SENTINEL, 2007), INPE in Brazil (INPE, 2008), Conabio in Mexico (CONABIO, 2007), Avialesookhrana in Russia (AVIALESOOKHRANA, 2005) and the Satellite Applications Center in South Africa (SACSA, 2008); for a complete list of systems see the monitoring portal of the Global Fire Monitoring Center (GFMC, 2008) and the GOFC-GOLD Fire Implementation Team website (GOFC FIRE, 2008) The regional systems are better placed than centralized, global systems, to combine the active fire locations with regional information such as weather conditions, local GIS datasets and active fire locations from other satellite sensors. For example, INPE integrates fire detections from NOAA-AVHRR and GOES as well as MODIS; the South African system integrates active fire detections from Meteosat-8 G data; and Sentinel adds localized information such as water courses, terrain relief, built up areas and topographic maps.

23.2.7.3 Future

A considerable investment has been made by the space agencies around the World to develop improved satellite monitoring of the planet. To maximize the societal benefit of these systems to support natural resource management and decision-making, there needs to be a continued emphasis on ensuring that the data are converted to useable information and made available in a timely fashion. This process is becoming easier with advances in web technology and improved access to broadband Internet.

Technologies already exist to create interactive web maps that incorporate data from a wide range of servers (in different locations); a key obstacle to improving these maps for active fire managers, is finding suitable data that are up-to-date, accurate, readily available and consistent across regions. For examples, Web Fire Mapper is being updated to serve the MODIS burned area product.

It is expected that future efforts to enhance the delivery of multi-source fire and GIS data will include: XML (extensible markup language) based data feeds (that allow the end user to customize the information they are interested in and have it delivered to them through a web browser), enhanced interoperability (allowing more integration of datasets), improved web technologies (such as Asynchronous JavaScript + XML), emerging open source GIS solutions, and a wider range of Fire Alerts /summary reports in the form of email alerts and cell phone messages, with text only or text and map attachments. Providing these data in a range of formats that are easy to access—even with slow internet connectivity, will continue to improve access to satellite derived information and enhance product use globally.

23.2.8 To Establish an Operational Network of Fire Validation Sites and Protocols, Providing Accuracy Assessment for Operational Products and a Testbed for New or Enhanced Products, Leading to Standard Products of Known Accuracy

The potential research, policy and management applications of satellite fire products place a high priority on providing statements about their accuracy. Inter-comparison of different fire area products provides an indication of gross differences and possibly insights into their causes, however product comparison with independent reference data is needed to determine accuracy (Justice et al., 2000). Validation is defined here, and more generally, as the process of assessing satellite product accuracy by comparison with independent reference data (Morisette et al., 2002; Roy et al., 2002a). Validation is required (i) to provide accuracy information to help users decide if and how to use a product, and (ii) to identify needed product improvements.

Previous studies have revealed large discrepancies in the areal estimates, timing and location among satellite fire products and highlight the need for systematic validation (Korontzi et al., 2004; Boschetti et al., 2004). Despite the large number of experimental and systematically derived satellite fire products, there has been neither rigorous assessment of their accuracy, nor development of systematic methodologies to evaluate their accuracy, arguably because of the limited resources made available for validation and because of the scope and complexity of the task.

Validation of satellite active fire products is difficult because of practical problems in collecting independent reference data that characterize the location and physical properties of actively burning fires. Previous approaches have used data from aircraft observations of prescribed fires and wildfires (Kaufman et al., 1998), but are expensive to undertake in a regionally or globally representative manner and are difficult to coordinate with satellite observations. Similarly, field based measurements are difficult to coordinate and cannot be used to infer active fire product accuracy over large areas (Cardoso et al., 2005). Burned areas identified in high spatial resolution satellite data do not provide a reliable validation if the fires are inactive or cloud-covered at the time of satellite overpass (Pereira and

Setzer, 1996). More recently, high spatial resolution ASTER data collected simultaneously with low resolution MODIS data on the NASA EOS Terra platform have been used to validate the MODIS active fire product (Morisette et al., 2005a; Morisette et al., 2005b; Csiszar et al., 2006).

The validation of burned area products is less sensitive to the need for simultaneous collection of independent reference data with satellite overpasses, as the surface effects of fire persist for a time varying between weeks (grassland ecosystems) to years (typically, forest ecosystems). Consequently, independent reference data derived from high spatial resolution satellite data, such as Landsat, have been used extensively to validate lower spatial resolution burned area products (e.g., Barbosa et al., 1999; Fraser et al., 2000; Roy et al., 2005b; Boschetti et al., 2006).

There are several outstanding issues in the development of robust regional to global scale fire product validation methodologies. These include the need to increase the quality and reduce the cost of validation by developing and promoting an international network of validation sites and by establishing validation standards and protocols (Morisette et al., 2002). Common validation sites would facilitate data sharing and can be expected, with the development of validation protocols, to foster standardization of the validation data and of the product accuracy reporting. Validation protocols are needed not as strict requirements but as suggested baseline approaches (Rasmussen et al., 2001). These issues are more pressing than ever with the prospects of operational fire products, for example from NPOESS data, and with a proliferation of global and regionally generated products.

A strategic GOFC-GOLD fire goal is to advocate and where possible facilitate the development of international validation standards and protocols for the validation of satellite active fire and burned area products, including: independent reference data definition and measurement; validation site selection and exchange of independent reference data collected at validation sites; statistical comparison of independent reference data and products; and product accuracy reporting. Despite the broadening recognition for these needs, and an emerging adoption of validation concepts by the fire product producer community, they have not yet been achieved.

23.2.9 To Operationally Generate Fire Emission Product Suites of Known Accuracy Providing Annual and Near Real-Time Emission Estimates with Available Input Data Sets

23.2.9.1 Current Status

The common approach used in land-based emission quantifications relies on a combination of satellite burned area information, modeled fuel load amounts, estimates of combustion completeness and ground and/or airborne measured emission factors (Hoelzemann et al., 2004; Ito and Penner, 2004; van der Werf et al., 2004). The improvements in spatially and temporally explicit regional to global emissions modeling have been rather incremental and have been hampered by the lack of the reliable underlying datasets. The recent availability of two global satellite-based burned area products, GBA-2000 (Tansey et al., 2004) and GLOBSCAR (Simon et al., 2004) for the year 2000 has provided an opportunity for generating new global emissions estimates. A global MODIS burned area algorithm has also been implemented and validated over several regions in the world (Roy et al., 2002b; 2005a; 2005b). However, several studies have highlighted the pressing need for rigorous validation of these satellite burned area products (see Sect. 23.2.8). Further improvements in the burned area products require biome/regional specific representative information.

Considering the advances in burned area mapping, likely the largest persistent challenge in global emissions modeling is the spatiotemporal quantification of different fuel types available for burning. Interannual variations in fuel loads at regional scales are also largely unknown and require a dynamic modeling approach. Biogeochemical models have been applied to assess fuel loads that are higher when compared with a handful of field measurements in Southern Africa (van der Werf et al., 2003). Satellite measures of global net primary productivity (e.g., MODIS, GLOPEM model) adjusted by region specific available fuel maps (e.g., fuel map of Malaysia and Western Indonesia by Dymond et al., 2004) and validated through regionally representative field measurements can provide the means to estimate fuel loads more accurately.

Current global emission models do not adequately account for burning of organic matter present in peatlands and boreal regions which release significant amounts of carbon into the atmosphere (Page et al., 2002; Soja et al., 2004). The capability to map these low energy peat fires and estimate the fire release energy has been developed locally using the high resolution experimental BIRD Infrared sensor (Wooster et al., 2003; Siegert et al., 2004). Similar mapping methodologies for large scale peatland fire events using suitable operational sensors remain to be developed.

Large woody fuels can be an important fuel load component especially in tropical regions, with significant implications for smoldering emissions (Bertschi et al., 2003). Tree mortality has been incorporated to some extent in current global emissions models but is still highly uncertain. Other forms of potential fuel load alteration whether natural (e.g., herbivory, insects, fuel decay) or anthropogenic (e.g., fuel load removal by humans, forest clearance, agriculture, rangeland management) also warrant improvements in their implementation in fuel load models. Information of fire frequency/return is also pertinent to quantifying fuel accumulation since the last fire event in a particular location. The establishment of consistent time-series of long-term satellite fire records from different sensors is required to investigate fire regimes (see Sect. 23.2.5).

The fire and atmospheric science community has made considerable advances in the knowledge of emission factors for various important atmospheric species from vegetation fires in major biomes (Andreae and Merlet, 2001). Some important gaps exist though. The seasonal variations in emission factors and combustion completeness can be significant and have not been thoroughly addressed in global emissions models partially also due to the very limited number of existing early dry season measurements (Hoffa et al., 1999; Korontzi et al., 2003). The importance of accounting for the seasonal variations in emission factors and combustion completeness has been shown for southern African savanna fires (Korontzi, 2005). A compelling need for the prediction of these seasonal variations is the reliable assessment of the fuel moisture content which can be estimated from satellite observations (Zarco-Tejada et al., 2003; Chuvieco et al., 2004). There is still a lack of adequate field measurements for important compounds, such as acetonitrile and hydrogen cyanide. The improved characterization of nitrogen, sulfur and halogen containing fire emitted compounds requires the development of seasonal fuel chemistry databases.

23.2.9.2 Future Plans

In the future, national or regional fire analysis and data information service centers may provide the institutional environment for the operational production of these emissions model outputs. The methodologies, roles and responsibilities for transferring the experimental emissions estimates to the operational domain are still undeveloped. A critical step in the transition of the emission model outputs to their operational production on a continuous basis will be to determine their accuracy. Rigorous sensitivity analyses at the regional scale can provide explicit information as to which parameters add the most uncertainty (French et al., 2004) and priorities for improvements. The synergistic use of different products made available for the same region has to rely on standard guidelines and protocols for product accuracy assessment intended for optimal use in emissions models. Atmospheric modelers have started to utilize the land based emissions estimates in inverse modeling studies (van der Werf et al., 2004; Arellano et al., 2004). Approaches that integrate land-based emissions models with atmospheric chemistry/ transport models will be the key to improve emissions on a global scale and will be most useful to the community. This is especially true considering the still unresolved discrepancy between these two approaches for emissions estimation.

Other currently experimental satellite based measurements of the fire radiative energy may offer an important new way of directly estimating the amount of fuel consumed which needs to be further explored (Kaufman et al., 1998; 2003; Wooster, 2002; Wooster et al., 2003; Siegert et al., 2004; Ichoku and Kaufman, 2005).These techniques have been successfully tested at local to regional scales and are currently being developed at a global scale. Satellite based techniques for direct estimation of trace gases (e.g., CO, CH_4) (McMillan et al., 2005) and aerosol loading (e.g., Kaufman et al., 1998; 2003) are also being developed.

23.3 Example Contributory Activities from US Agencies

23.3.1 NASA Wildfire Activities

NASA's research, analysis, and applied science activities associated with wildfire fall within both the Research and Analysis and Applied Sciences programs. The NASA Earth Science Division is divided into focus areas with wildfire as an important terrestrial process that cuts across a number of these e.g. carbon cycle, ecosystems and land use change, atmospheric composition, water cycle and land cover . The NASA Land Cover and Land Use change program has been a strong supporter of the GOFC-GOLD Fire program, providing outreach for NASA research and data products and assisting the GOFC regional fire networks to access and utilize NASA data. In the NASA science program, satellite fire data are being used for example, to assess recent trends in global fire activity, to model annual trace gas and particulate emissions, to examine the relationship between fire and climate change, to model land use change and project the future changes in fire regimes (Korontzi et al., 2004; van der Werf et al., 2004). From the atmospheric science perspective NASA is studying the role of particulates generated by fires in cloud formation and global radiative forcing. These science studies are couched within the framework of the US Climate Change Science Program (CCSP) and the US Global Earth Observations (USGEO). In support of these science studies, NASA provides funding for algorithm development, product generation, validation and benchmarking of research results e.g. (Justice et al., 2002). Current emphasis within the science program is to develop long-term data records to enable the study of global change. New techniques are also being developed using airborne Lidar to estimate vegetation structure and fuel load in anticipation of a future spaceborne vegetation Lidar missions.

The NASA Applied Science program has two main themes, transitioning NASA research into the operational domain, and using NASA research results to enhance decision support systems and tools for fire management. To help achieve the goal of integrating data and models into decision support systems, NASA is partnering with the USDA Forest Service Remote Sensing and Applications Center (RSAC). With the Forest Service, emphasis has been given to support the provision of NASA data to the National Interagency Fire Center (NIFC), for example through the MODIS Rapid Response System (see Sect. 3.3). Satellite data along with airborne sensors and platforms are being used for assessing fire danger, monitoring fires in near real time and assessing post-fire impacts. New technologies for improving fire observations have been developed under the recent Sensor Web project. The goal of this project is to link the NASA spaceborne systems in an automated way, so that coarse resolution fire detection systems can direct the acquisition of data from the next high resolution sensor overpass. The prototype for this system was developed using MODIS and Earth Observer (EO-1) sensor. NASA has also been experimenting with the use of Unmanned Aerial Systems (UAS) in support of fire management under the Wildfire Research and Applications Partnership (WRAP) funded by NASA's Research Education and Applications Solutions Network (REASoN Cooperative Agreement). Seamless data from the Shuttle Radar Topography Mission (SRTM) are also integrated to improve geo-correction of sub-orbital data sets. Support was given to the U. S. Forest Service this past fire season and created a Western States Fire Mission that coincidently provided support to the Esperanza and Southern California Fire events in 2003 and 2007, respectively.

23.3.2 NOAA Wildfire Activities

The Hazard Mapping System (HMS; NOAA, 2008), developed and run operationally by NOAA's Satellite Services Division (SSD), is a multiplatform RS approach to detecting fires and smoke over the US and adjacent areas of Canada and Mexico. The system utilizes sensors on seven different NOAA and NASA satellites. Automated fire detections are incorporated into the system from GOES through the Wildfire Automated Biomass Burning Algorithm (WF-ABBA) (Prins and Menzel, 1996), AVHRR (Li et al., 2001) and MODIS (Giglio et al., 2003). Automated detection algorithms are employed for each of the satellites for the fire detects while smoke is delineated by an image analyst. Analyses are quality controlled by an analyst who inspects all available imagery and automated fire detects, deleting suspected false detects and adding fires that the automated routines miss. Graphical, text, and GIS compatible analyses are posted to a web site as soon as updates are performed, and a final product for a given day is posted early the following morning. All products are archived at NOAA's National Geophysical Data Center. Daily fire and smoke analyses are available on-line (NOAA, 2008).

Areal extent of detectable smoke is outlined using animated visible imagery, for input to a dispersion and transport model, the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT), developed by NOAA's Air Resources Laboratory (ARL). Resulting smoke forecasts will be used as input to NOAA's Air Quality forecasts. The GOES Aerosol and Smoke Product (GASP) is an experimental GOES imagery based aerosol optical depth product developed by the NESDIS Office of Research and Applications, being implemented for operational use by the NESDIS Satellite Analysis Branch for use in smoke and volcanic ash monitoring. GASP products are available on-line (GASP, 2004).

NOAA's Operational Significant Event Imagery (OSEI, 2008) program processes satellite imagery of environmentally significant events, including fire, smoke and volcanic ash, visible in operational satellite data. This imagery is often referred to by fire managers and air quality agencies.

NOAA's future plans include the integration of high resolution global data from the European Space Agency's MetOp satellite, integration of more ancillary data layers, and better characterization of fire emissions for input to air quality models. Ongoing research in NESDIS' Center for Satellite Applications and Research (STAR) will provide means to estimate smoke concentrations and trace gas characterization by incorporating data from RS sources as they become available, such as the Ozone Monitoring Instrument (OMI) and VIIRS.

23.3.3 USDA Forest Service Wildfire Activities

The USDA Forest Service is currently using a combination of satellite and airborne RS systems to map and monitor active wildland fires, and to map burn severity for post-fire rehabilitation. RS systems are used to provide national scale—strategic planning level, and local scale—tactical incident level fire maps and products.

National scale, strategic planning fire maps are developed using the NASA MODIS sensor, direct broadcast capability, and Rapid Response System. The system utilizes Western United States MODIS data acquired in real time by the RSAC MODIS Direct Broadcast receiving station in Salt Lake City, Utah and near real time MODIS data for the Eastern United States and Alaska from the NASA GSFC. Both day and night time data are collected. These data are used to prepare active fire maps and geospatial data continuously for the entire United States and Canada. These maps and data are made available to fire managers and the public through the internet and have proved to be useful for monitoring actively burning fires, assisting in planning, allocating fire suppression resources, and informing the public on current fire activity across the nation (USDA, 2005).

National scale active fire maps are intended to provide accurate and current information to assist wildfire managers in strategic planning. The information is used to make decisions on where and when to allocate critical fire suppression resources, such as high resolution airborne thermal infrared fire mapping systems at NIFC. The national scale active fire maps allow managers to prioritize fire mapping needs and prepare flight plans for airborne thermal infrared systems.

For local planning, fire managers require higher spatial resolution fire map products to support decisions such as where to place fire crews or airborne retardant drops. Tactical scale, finer resolution fire maps, and geospatial data are provided to Incident Command fire suppression teams to assist in tactical level planning. A combination of airborne Forward Looking Infrared (FLIR), thermal imagers, and high resolution thermal infrared line scanner systems are used to acquire detailed imagery and data for quick response fire mapping products. These products are used to brief Incident Command staff and support local decisions on where fire suppression assets should be used.

Satellite and airborne RS systems are used to quickly map burn severity and prioritize areas for re-vegetation and erosion control treatments. To mitigate the effects of wildland fire on soil and duff layers, the Forest Service and other federal land management agencies prepare Burned Area Emergency Response (BAER) plans to stabilize soils and return vegetation cover to the burned areas as soon as possible. One of the first steps in the BAER process is the creation of a map that highlights the areas most in need of immediate erosion control and other protection measures. Traditionally this map was created by airborne sketch mapping in combination with field surveys. Recently, techniques have been developed using airborne and satellite RS imagery to derive base maps to improve the accuracy of the initial burn severity product. These base maps have included mosaicked digital camera images and satellite imagery such as IKONOS, SPOT, Landsat TM, ASTER, and MODIS.

RSAC provides field level BAER team members, arriving at an incident, with remotely sensed imagery, Burn Area Reflectance Classification (BARC) maps, and ancillary data. A BARC map is typically created using change detection on a band ratio such as the Normalized Burn Ratio (NBR) and the Normalized Difference Vegetation Index (NDVI). The BARC output is delivered to the field in two forms. One has four classes: High, Moderate, Low, and Unburned. The other has 255 discrete values and allows field users to make their own classification decisions such as altering the threshold values between burn severity categories. The BARC map, when used in conjunction with other geospatial data, provides a synoptic view of the burned area and allows for more consistent mapping decisions. The BARC data and remotely sensed imagery are commonly used to focus the reconnaissance efforts of the BAER team on areas of greatest concern, develop the BAER burn severity map, create 3-dimensional models of the burned area and visualization products, and prepare graphics for public meetings to show areas with increased erosion potential.

23.4 Conclusion

The GOFC-GOLD program has undertaken an ambitious agenda to improve the availability, accessibility and use of earth observation information. The program started from grass-roots concern amongst practitioners that the potential of satellite RS was not being realized, despite the overwhelming demand for environmental information. Since that time there has been a broadening recognition of the need for effective global earth observation. The program activities and structure established by GOFC-GOLD provide an important contribution to the emerging GEOSS which recognizes that in a rapidly changing world, there is the need for timely and up-to-date earth observations and information (GEOSS, 2005). The emergence of systematically generated and validated global fire products also provides the opportunity for a reliable Global Fire Assessment. Such an assessment is currently being coordinated by the GOFC-GOLD Implementation Team and the regional fire networks. The ultimate goal is to put in place sustained systems which are operational, providing reliable and consistent fire information to meet the needs of decision-makers, resource managers and global change scientists. We are a long way from achieving this goal but GOFC-GOLD is making considerable progress and has highlighted some of the necessary near-term and concrete steps to that end. The challenge in this time of limited budgets is for governments to make the necessary commitment to international coordination, utilizing the international programs such as GOFC-GOLD to facilitate and proceed with implementation.

References

Ahern F, Goldammer G, Justice CO, (2001), Global and Regional Vegetation Fire Monitoring From Space: Planning a Coordinated International Effort. SPB Academic Publishing, The Hague, The Netherlands

Andreae M, Merlet P, (2001), Emission of Trace Gases and Aerosols From Biomass Burning. *Global Biogeochemical Cycles*, **15**(4), 955 – 966

Arino O, Simon M, Piccolini I, Rosaz JM, (2001), The ERS-2 ATSR-2 World Fire Atlas and the ERS-2 ATSR-2 World Burnt Surface Atlas projects. In: Proceedings of the 8th ISPRS conference on physical measurement and signatures in remote sensing, http://shark1.esrin.esa.it/ionia/FIRE / references_fire.html

Arellano AF Jr, Kasibhatla PS, Giglio L, van der Werf GR, Randerson JT, (2004), Top-down estimates of global CO sources using MOPITT measurements, Geophysical. Research Letters, 31, L01104, doi:10.1029/2003GL018609

[AVIALESOOKHRANA] Aerial Forest Protection Service. 2005 Jan 2. Avialesookhrana Fire Monitoring home page: http://www.nffc.aviales.ru/engl/main.sht. accessed 2008 Jan 14

Barbosa PM, Stroppiana D, Grégoire JM, Pereira JMC, (1999), An assessment of vegetation fire in Africa (1981 – 1991): Burned areas, burned biomass, and atmospheric emissions. *Global Biogeochemical Cycles*, **13**: 933 – 950

Bertschi I, Yokelson RJ, Ward DE, Babbitt RE, Susott RA, Goode JG, Hao WM, (2003), Trace gas and particle emissions from fires in large diameter and belowground biomass fuels, *Journal of Geophysical. Research*, **108**(D13): 8472, doi:10.1029/2002JD002100

Boschetti L, Eva H, Brivio PA, Grégoire JM, (2004), Lessons to be learned form the intercomparison of three satellite-derived biomass burning datasets. *Geophysical Research Letters*, **31**(21): L21501 10.1029/2004GL021229

Boschetti L, Brivio PA, Eva H, Gallego J, Baraldi A, JM Grégoire, (2006), A Sampling Method for the Retrospective Validation of Global Burned Area Products. *IEEE Transactions on Geoscience and Remote Sensing*, **44**(7): 1765 – 1773 Digital Object Identifier 10.1109/TGRS.2006.874039

Briess K, Jahn H, Lorenz E, Oertel D, Skrbek W, Zhukov B, (2003), Remote Sensing Potential of the Bi-spectral InfraRed Detection (BIRD) Satellite. *International Journal of Remote Sensing*, **24**: 865 – 872

Cardoso MF, Hurtt GC, Moore B, Nobre CA, Bain H, (2005), Field work and statistical analyses for enhanced interpretation of satellite fire data. *Remote Sensing of Environment*, **96**: 212 – 277

Carmona-Moreno C, Belward A, Malingreau J-P, Garcia-Alegre M, Hartley A, Antonovskiy M, Buchshtaber V., Pivovarov V, (2005), Characterizing Inter-annual Variations in Global Fire Calendar Using Data from Earth Observing Satellites. *Global Change Biology*, **11**(9): 1537 – 1555

Chuvieco E, Cocero D, Riaño D, Martin P, Martínez-Vega J, de la Riva J, Pérez F, (2004), Combining NDVI and surface temperature for the estimation of live fuel moisture content in forest fire danger rating. *Remote Sensing of Environment*, **92**(3): 322 – 331

[CONABIO] Comisión nacional para el conocimiento y uso de la biodiversidad. 2007 Jan 10. CONABIO Fire detection home page: http://www.conabio.gob.mx/conocimiento/hotspots/doctos/puntos_calor.html, accessed 14 Jan 2008

Csiszar I, Abdelgadir A, Li Z, Jin J, Fraser R, Hao WM (2003) Interannual changes of active fire detectability in North America from long-term records of the Advanced Very High Resolution Radiometer. *Journal of Geophysical Research* **108**(D2), 4075. doi:10.1029/2001JD001373

Csiszar I, Denis L, Giglio L, Justice CO, Hewson J, (2005a), Global Fire Activity from two years of MODIS data. *International Journal of Wildland Fire*, **14**: 117 – 130

Csiszar I, Justice CO, McGuire AD, Cochrane MA, Roy DP, Brown F, Conard SG, Frost PGH, Giglio L, Elvidge C, Flannigan MD, Kasischke E, McCrae DJ, Rupp TS, Stocks BJ, Verbyla DL, (2005b), Land use and fires. In: Land Change Science: Observing, Monitoring, and Understanding Trajectories of Change on the Earth's Surface. Kluwer Academic Publishers, 329 – 350

Csiszar I, Morisette JT, Giglio L, (2006), Validation of active fire detection from moderate resolution sensors: the MODIS example in Northern Eurasia. *IEEE Transactions on Geoscience and Remote Sensing*, **44**(7): 1757 – 1764

de Groot WJ, Field RD, Brady MA, Roswintiarti O, Mohamad M, (2007), Development of the Indonesian and Malaysian fire danger rating systems. *Mitigation and Adaptation Strategies for Global Change*, **12**: 165 – 180, doi: 10.1007/s11027-006-9043-8

Dwyer E, Pinnock S, Grégoire JM, (2000), Global spatial and temporal distributions of vegetation fire as determined from satellite observations. *International Journal of Remote Sensing*, **21**:1289–1302. doi:10.1080/014311600210182

Dymond CC Roswintiarti O, Brady M, (2004), Characterizing and mapping fuels for Malaysia and western Indonesia. *International Journal of Wildland Fire*, **13**(3) 323 – 334

Elvidge CD, Nelson I, Hobson VR, Safran J, Baugh KE, (2001), Detection of fires at night using DMSP-OLS data. Global and Regional Vegetation Fire Monitoring from Space: Planning a Coordinated International Effort. Edited by Ahern FJ, Goldammer JG, Justice CO. SPB Academic Publishing, The Hague, The Netherlands, 125 – 144

FAO, (1986), Wildland Fire Management Terminology. Food and Agriculture Organization of the United Nations, FAO Forestry Paper, 70 – 257

FAO, (2006), Global Forest Resources Assessment 2005. Food and Agriculture Organization of the United Nations, FAO Forestry Paper, 147

Field, RD, Wang Y, Roswintiarti O, Guswanto, (2004), A drought-based predictor of recent haze events in western Indonesia, *Atmospheric Environment*, **38**: 1869 − 1878

Fraser RH, Li Z, Cihlar J, (2000), Hotspot and NDVI differencing synergy (HANDS): A new technique for burned area mapping over boreal forest. *Remote Sensing of Environment*, **74**: 362 − 376

French NHF, Goovaerts P, Kasischke ES, (2004), Uncertainty in estimating carbon emissions from boreal forest fires. Journal of Geophysical Research 109 D14S08, doi:10.1029/2003JD003635

[GASP] National Oceanic and Atmospheric Administration. 2004 May 21. GOES Aerosol/Smoke Product home page: http://www.ssd.noaa.gov/PS/FIRE/GASP/gasp.html, accessed 2008 Jan 14

[GEOSS] Global Earth Observation System of Systems. Date of latest revision unknown. GEOSS home page: http://earthobservations.org/, accessed 2008 Jan 14

[GFMC]. Global Fire Monitoring Center. Updated daily. Current & Archived Significant Global Fire Events and Fire Season Summaries. Near-Real Time and Daily Updates by GFMC Partners. http://www.fire.uni-freiburg.de/current/globalfire.htm, accessed 2008 Jan 14

Giglio, L, Descloitres, J, Justice, CO, Kaufman, Y, (2003), An enhanced contextual fire detection algorithm for MODIS. *Remote Sensing of Environment*, **87**: 273 − 282

Giglio, L, Csiszar, I, Justice, CO, (2006), Global distribution and seasonality of active fires as observed with the Terra and Aqua MODIS sensors. *Journal of Geophysical Research—Biogeosciences*, **111**, G02016, doi:10.1029/2005JG000142

[GLOBCARBON] European Space Agency. 2008 Jan 9. GLOBCARBON home page: http://dup.esrin.esa.it/projects/summaryp43.asp, accessed 2008 Jan 14

[GMES] European Space Agency. Date of latest revision unknown. Global Monitoring for Environment and Security Living Planet Programme home page: http://www.esa.int/esaLP/LPgmes.html, accessed 2008 Jan 14

[GOFC] Global Observation of Forest Cover/Global Observation of Landcover Dynamics. 2007 Apr 16. GOFC-GOLD home page: http://www.fao.org/gtos/gofc-gold/index.html, accessed 2008 Jan 14

[GOFC FIRE] University of Maryland. Date of latest revision unknown. GOFC-GOLD Fire Implementation Team home page: http://gofc-fire.umd.edu/, accessed 2008 Jan 14

[GTOS] Global Terrestrial Observing System. 2005 May 18. GTOS home page: http://www.fao.org/gtos/, accessed 2008 Jan 14

[GWFNa] Global Fire Monitoring Center. Date of latest revision unknown. Global Wildland Fire Network home page: http://www.fire.uni-freiburg.de/GlobalNetworks/globalNet.html, accessed 2008 Jan 14

[GWFNb] Global Fire Monitoring Center. Date of latest revision unknown. Global Wildland Fire Network: Rationale and Introduction. http://www.fire.uni-freiburg.de/GlobalNetworks/RationaleandIntroduction. html, accessed 2008 Jan 14

Hoelzemann JJ, Schultz MG, Brasseur GP, Granier C, Simon M, (2004), Global Wildland Fire Emission Model (GWEM): Evaluating the use of global area burnt satellite data, Journal of Geophysical Research 109, D14S04, doi:10.1029/2003JD003666.

Hoffa, E, Ward D, Hao WM, Susott R, Wakimoto R, (1999), Seasonality of carbon emissions from biomass burning in a Zambian savanna. *Journal of Geophysical Research* **104**(D11): 13841 – 13853

Howard SM, Lacasse JM, (2004), An Evaluation of Gap-Filled Landsat SLC-Off Imagery for Wildland Fire Burn Severity Mapping. *Photogrammetric Engineering and Remote Sensing*, **70**(8): 877 – 880

[INPE] Instituto Nacional de Pesquisas Espaciais. Updated daily. INPE Fire home page: http://www.cptec.inpe.br/products/queimadas, accessed 2008 Jan 14

Ichoku C, Kaufman Y, (2005), A method to derive smoke emission rates from MODIS fire radiative energy measurements. *IEEE Transactions on Geoscience and Remote Sensing*, **43**(11): 2636 – 2649

Irons JR, Ochs WR, (2004), Status of the Landsat Data Continuity Mission. 2004 IEEE International Geoscience and Remote Sensing Proceedings. Anchorage, AK, September 20 – 24, 2004

Irons JR, (2005), Status of the Landsat Data Continuity Mission. A presentation at NASA's Land Cover Land Use Change Science Team Meeting. College Park, MD, January 11 – 13, 2005

Ito A, Penner JE, (2004), Global estimates of biomass burning emissions based on satellite imagery for the year 2000, *Journal of Geophysical Research*, **109**: D14S05, doi:10.1029/ 2003JD004423

Justice CO, Belward A, Morisette J, Lewis P, Privette J, Baret F, (2000), Developments in the 'validation' of satellite sensor products for the study of land surface. *International Journal of Remote Sensing*, **21**: 3383 – 3390

Justice CO, Giglio L, Korontzi S, Owens J, Morisette JT, Roy DP, Descloitres J, Alleaume S, Petitcolin F, Kaufman YJ, (2002), The MODIS fire products. Remote Sensing of Environment **83**: 244 – 262. doi:10.1016/S0034-4257(02)00076-7

Justice CO, Smith R, Gill M, Csiszar I, (2003), Satellite-based Fire Monitoring: current capabilities and future directions. *International Journal of Wildland Fire*, **12**: 247 – 258

Kaufman YJ, Justice CO, Flynn LP, Kendall JD, Prins EM, Giglio L, Ward DE, Menzel WP, and Setzer AW, (1998), Potential global fire monitoring from EOS-MODIS. *Journal of Geophysical Research*, **103**: 32, 215 – 232, 238

Kaufman Y, Ichoku C, Giglio L, Korontzi S, Chu DA, Hao WM, Li RR, Justice CO, (2003), Fires and smoke observed from the Earth Observing System MODIS instrument: products, validation, and operational use. *International Journal of Remote Sensing*, **24**: 1765 – 1781

Korontzi S, Ward DE, Susott RA, Yokelson RJ, Justice CO, Hobbs PV, Smithwick EAH, Hao WM, (2003), Seasonal variation and ecosystem dependence of emission factors for selected trace gases and PM 2.5 for southern African savanna fires. *Journal of Geophysical Research*, **108**(D24): 4758, doi:10.1029/2003JD003730

Korontzi S, Roy DP, Justice CO, Ward DE, (2004), Modeling and sensitivity analysis of fire emissions in southern Africa during SAFARI 2000. *Remote Sensing of Environment*, **92**(2): 255 – 275

Korontzi S, (2005), Seasonal patterns in biomass burning emissions from southern African vegetation fires for the year 2000. *Global Change Biology*, **11**: 1680 – 1700

Li, Z, Kaufman, Y, Ichoku, C, Fraser, R, Trishchenko, A, Giglio, L, Jin, J, Yu, X, (2001), A review of AVHRR-based fire active fire detection algorithm: Principles, limitations, and recommendations, in Global and Regional Vegetation Fire Monitoring from Space, Planning and Coordinated International Effort (Eds. F. Ahern, J.G. Goldammer, C. Justice) SPB Academic Publishing, The Hague, The Netherlands, 199 – 225

Lorenz E, Briess K, Halle W, Kayal H, Oertel D, Skrbek W, Zhukov B, Leibrandt W, (2003), BIRD—A Technology Demonstrator Dedicated to the Fire Hazard Detection and Monitoring. Proceedings of 30th International Symposium on Remote Sensing of Environment, Information for Risk Management and Sustainable Development, Honolulu, Hawaii, November 10 – 14, 2003

[LP DAAC] US Geological Survey. 2007 Jul 25. Land Processes Distributed Active Archive Center home page: http://edcdaac.usgs.gov/main.asp, accessed 2008 Jan 14

McMillan WW, Barnet C, Strow L, Chahine MT, McCourt ML, Warner JX, Novelli PC, Korontzi S, Maddy ES, Datta S, (2005), Daily global maps of carbon monoxide from NASA's Atmospheric Infrared Sounder. *Geophysical Research Letters*, **32**: L11801, doi:10.1029/2004GL021821

Merrill DF, Alexander ME, (1987), Glossary of forest fire management terms. Fourth edition. National Research Council of Canada, Canadian Committee on Forest Fire Management, Ottawa, Ontario, Publication NRCC No. 26516, 91

[MLRR]. National Aeronautics and Space Administration. Updated daily. MODIS Land Rapid Response System home page: http://rapidfire.sci.gsfc.nasa.gov, accessed 2008 Jan 14

Morisette JT, Privette JL, Justice CO, (2002), A framework for the validation of MODIS land products. *Remote Sensing of Environment*, **83**: 77 – 96

Morisette JT, Giglio L, Csiszar I, Setzer A, Schroeder W, Morton D, Justice CO, (2005a), Validation of MODIS active fire detection products derived from two algorithms. *Earth Interactions* **9**: 1 – 25

Morisette JT, Giglio L, Csiszar I, Justice CO, (2005b), Validation of MODIS active fire product over southern Africa with ASTER data. *International Journal of Remote Sensing*, **26**(10): 4239 – 4264

[NOAA] National Oceanic and Atmospheric Administration. Updated daily. Hazard Mapping System home page: http://www.ssd.noaa.gov/PS/FIRE/hms.html, accessed 2008 Jan 14

[OSEI] National Oceanic and Atmospheric Administration Satellite and Information Service. Operational Significant Event Imagery home page: http://www.osei.noaa.gov/, accessed 14 Jan 2008

Page SE, Siegert F, Rieley JO, Boehm HDV, Jaya A, Limin S, (2002), The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature*, **420** (6911): 61 – 65

Pereira AC, Setzer AW, (1996), Comparison of fire detection in savannas using AVHRR's channel 3 and TM images. *International Journal of Remote Sensing*, **17**: 1925 – 1937

Prins, E.M., and W.P. Menzel, (1996), Investigation of biomass burning and aerosol loading and transport utilizing geostationary satellite data. Biomass Burning and Global Change, edited by J.S. Levine, pp. 65 – 72, The MIT Press, Cambridge, MA

Rasmussen K, Russell-Smith J, Morisette JT, (2001), Establishing a validation site network for remote sensing applications to fire research: a joint activity between GOFC-Fire and the LPV subgroup, White paper available at http://modis.gsfc.nasa.gov/MODIS/LAND/VAL/CEOS_WGCV/GOFC_LPV_fire_sites.pdf

Roy DP, Borak J, Devadiga S, Wolfe R, Zheng M, Descloitres J, (2002a), The MODIS land product quality assessment approach. *Remote Sensing of Environment*, **83**: 2 – 76

Roy DP, Lewis PE, Justice CO, (2002b), Burned area mapping using multi-temporal moderate spatial resolution data—a bi-directional reflectance model-based expectation approach. *Remote Sensing of Environment*, **8**(1 – 2): 263 – 286

Roy DP, Jin Y, Lewis PE, Justice CO, (2005a), Prototyping a global algorithm for systematic fire-affected area mapping using MODIS time series data. *Remote Sensing of Environment*, **97**: 137 – 162

Roy DP, Frost P, Justice CO, Landmann T, Le Roux J, Gumbo K, Makungwa S, Dunham K, Du Toit R, Mhwandagara K, Zacarias A, Tacheba B, Dube O, Pereira J, Mushove P, Morisette J, Santhana Vannan S, Davies D, (2005b), The Southern Africa Fire Network (SAFNet) regional burned area product validation protocol. *International Journal of Remote Sensing*, **26**: 4265 – 4292

[SACSA] Satellite Applications Center South Africa. Updated daily. SACSA home page: http://www.wamis.co.za/eskom/checkboxes/sa.htm, accessed 14 Jan 2008

Schroeder W, Morisette J, Csiszar I, Giglio L, Morton D, Justice CO, (2005), Characterizing Vegetation Fire Dynamics in Brazil Through Multi-Satellite Data: Common Trends and Practical Issues. *Earth Interactions*, **9**: 13

[SENTINEL] Commonwealth Scientific and industrial Research Organization. 2007 Aug 15. Sentinel home page: http://www.sentinel.csiro.au, accessed 14 Jan 2008

Sheffner, EJ, (1994), The Landsat Program: Recent History and Prospects. *Photogrammetric Engineering & Remote Sensing*, LX(6): 735 – 744

Siegert F, Zhukov B, Oertel D, et al., (2004), Peat fires detected by the BIRD satellite. *International Journal of Remote Sensing*, **25**(16): 3221 – 3230

Simon M, Plummer S, Fierens F, Hoelzemann JJ, Arino O, (2004), Burnt area detection at global scale using ATSR-2: The GLOBSCAR products and their qualification. Journal of Geophysical Research 109:D14S02, doi:10.1029/2003JD003622

Soja AJ, Cofer WR, Shugart HH, Sukhinin AI, Stackhouse PW, McRae DJ, Conard SG (2004) Estimating fire emissions and disparities in boreal Siberia (1998 – 2002). Journal of Geophysical Research 109:D14S06, doi:10.1029/2004JD004570

Tansey K, et al., (2004), Vegetation burning in the year 2000: Global burned area estimates from SPOT VEGETATION data. Journal of Geophysical Research **109**: D14S03, doi:10.1029/2003JD003598

[TERRANORTE] Russian Academy of Sciences Space Research Institute. Date of latest revision unknown. TerraNorte home page: http://terranorte.iki.rssi.ru/, accessed 2008 Jan 14

Townshend JRG, Justice CO, (2002), Towards operation monitoring of terrestrial systems by moderate-resolution remote sensing. *Remote Sensing of Environment*, **83**: 351 – 359

Townshend JRG, Justice CO, Skole DL, Belward A, Janetos A, Gunawan I, Goldammer J, Lee B, (2004), Meeting the goals of GOFC: an evaluation of progress and steps for the future. In: Gutman G, Janetos AC, Justice CO et al. (eds) Land Change Science: Observing, Monitoring and Understanding Trajectories of Change on the Earth's Surface. Kluwer Press, pp 31 – 51

[UNISDR] United Nations Interagency Strategy for Disaster Reduction Working Group.

Date of latest revision unknown. Wildland Fire home page: http://www.unisdr.org/eng/task%20force/tf-working-groups4-eng.htm, accessed 14 Jan 2008

[USDA] United States Department of Agriculture. 2005 Aug 8. US Department of Agriculture Forest Service Remote Sensing Application Center MODIS Active Fire Maps page: http://activefiremaps.fs.fed.us, accessed 14 Jan 2008

Van der Werf GR, Randerson JT, Collatz GJ, Giglio L, (2003), Carbon emissions from fires in tropical and subtropical ecosystems. *Global Change Biology*, **9**(4): 547 − 562

Van der Werf, GR, Randerson JT, Collatz GJ, Giglio L, Kasibhatla PS, Arellano AF, Olsen SC, Kasischke ES, (2004), Continental-Scale partitioning of fire emissions during the 1997 to 2001 El Nino/La Nina period. *Science*, **303**: 73 − 76

Van Wagner CE, (1987), Development and structure of the Canadian Forest Fire Weather Index System. Canadian Forest Service, Ottawa, ON. Forestry Technical Report, 35 − 37

[WFM] University of Maryland. Updated daily. Web Fire Mapper home page: http://maps.geog.umd.edu, accessed 14 Jan 2008

Wooster MJ, (2002), Small-scale experimental testing of fire radiative energy for quantifying mass combusted in natural vegetation fires. Geophysical Research Letters, **29**(21): 2027 − 2034

Wooster M, Zhukov B, Oertel D, (2003), Fire radiative energy release for quantitative study of biomass burning: derivation from the BIRD experimental satellite and comparison to MODIS fire products. *Remote Sensing of Environment*, **86**: 83 − 107

Zarco-Tejada PJ, Rueda CA, Ustin SL, (2003), Water content estimation in vegetation with MODIS reflectance data and model inversion methods. *Remote Sensing of Environment*, **85**(1): 109 − 124

Zhukov B, Briess K, Lorenz E, Oertel D, Skrbek W, (2003), BIRD Detection and Analysis of High-temperature Events: First Results. *Proc. SPIE*, **4886**: 160 − 171