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Satellite Remote Sensing of Fires: Potential and Limitations

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ABSTRACT

This chapter outlines the role of remote sensing in the study of fires in the environment. A brief description is given of the current and planned sensing systems relevant to fire-related studies. Past and present efforts to develop operational fire-monitoring products are discussed, and an outline is given of some of the current trends in this field of research.

INTRODUCTION

Satellite remote sensing can make an important contribution to the study of fires in the environment, its ecological, climatic, and atmospheric chemical effects. Current estimates of trace gas emissions from biomass burning are severely constrained by the lack of reliable statistics on fire distribution and frequency, and the lack of accurate estimates of area burned, fuel load, and fuel moisture content. Regional ecological studies could benefit from an accurate multiyear record of the distribution, timing, and frequency of fires. Modeling of the transport and the role of the products of biomass burning in global and regional atmospheric chemistry would be enhanced by the incorporation of reliable information on the source location and volume of emissions. In addition, the task of fire management can be facilitated by an indication of the susceptibility of fire, an early warning, and monitoring of wildfire events. Satellite remote sensing can contribute to satisfying these information needs providing a unique source of repetitive, synoptic data on fire distribution, burned area, vegetation state and fire products.

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No one satellite system meets all the spatial and temporal requirements for mapping and monitoring these different phenomena. At present it is necessary to use a combination of the available sensing systems and a variety of analysis techniques to meet our information needs. Summary descriptions of these satellite sensing systems are provided by Pease (1991). A comprehensive review of the contribution from infrared remote sensors to fire studies is provided by Robinson (1991). A bibliography of remote sensing of wildland fires has also been produced by the California Department of Forestry and Fire Protection (1990).

SATELLITE SENSING SYSTEMS FOR FIRE-RELATED STUDIES

The high spatial resolution Landsat Thematic Mapper (TM) includes a middle infrared channel (2.08-2.35 μm) with a 30 m spatial resolution, which permits active fires to be detected. A 700 K fire that occupies 20% of the 30 m pixel will saturate the middle infrared TM channel. In addition, visible and near-infrared channels designed specifically for vegetation studies permit the detection of burn scars and the assessment of vegetation state through the use of vegetation indices (Chuvieco and Congleton 1988; Pereira and Setzer 1992). A recent study using the TM 1.6 μm channel has provided some interesting preliminary results, estimating fire intensity through interpretation of the spectral response from the resulting ash layer (J. Brass, pers. comm.). The repeat cycle of 16 days and the high cost of data limit the use of TM data to local sampling rather than regional monitoring. The visible and near-infrared channels of the Landsat Multispectral Scanner (MSS) are also suitable for mapping burn scars (Milne 1988). The historical record of MSS data over the last twenty years may also provide a useful source of information on recent fire history (Minich 1983). The utility of the historical record will be limited to those areas where there has been a program of long-term systematic MSS acquisition. The Systeme Probatoire pour l'Observation de la Terre (SPOT) also provides high spatial resolution data for vegetation, and burn scar mapping and assessment of vegetation state. The 10 m panchromatic sensor provides the highest spatial resolution currently available from commercial sensing systems. SPOT data are also constrained by the high cost of data.

The NOAA Advanced Very High Resolution Radiometer (AVHRR) provides daily global data at a sampled resolution of ca. 4 km (GAC) and acquisition of a limited amount of 1 km data (LAC) on request from the on-board tape recorder (Justice et al. 1985). In addition, 1 km data are available from a number of ground receiving stations with NOAA High Resolution Picture Transmission (HRPT) capability (IGBP 1992). The middle infrared (3.7 μm) and thermal channels (10.8 μm) provide the means to detect active flaming fires (Lee and Tag 1990). Theoretical studies have shown that flaming fires, as small as 10 m × 10 m, can be detected by the AVHRR sensors (Kaufman et al. 1990). Experience in the Amazon has shown that the actual size of fires needed to saturate an AVHRR pixel may be much larger than previously thought (Setzer and Pereira 1992). The saturation of the sensors at ca. 320 K, however, presents a serious limitation in the accurate calculation of fire size or temperature. Comparison of the middle-infrared and thermal-infrared brightness temperatures permits the discrimination of saturation resulting from warm surfaces, such as bare soil and active fires. Matson and Dozier (1981) described a method to derive sub-pixel fire size and temperature under controlled conditions from the AVHRR 1 km data; however, the method has limitations for operational implementation at a regional scale. In particular, the method requires an accurate estimate of the background surface temperature of the fire pixel. A preliminary evaluation of the use of AVHRR fire counts for estimating burned area using high spatial resolution TM data is given by Pereira et al. (1992). The study shows that estimate of burned area made directly from the AVHRR fire counts is subject to several errors, including those related to sub-pixel size fires, diurnal sampling, and the occurrence of smoke and clouds. The visible and near-infrared channels of the AVHRR permit the direct identification of burn scars and the monitoring of vegetation state (Fredericksen et al. 1990; Lopez et al. 1991; Paltridge and Barber 1988; Malingreau 1990). In a preliminary study of burn scars in the boreal forest of Alaska, Kasischke et al. (1993) reported that they were able to detect 89.5% of all fires with sizes greater than 2000 ha by using AVHRR vegetation indices. The AVHRR time series data can also be used to estimate above-ground biomass for savanna vegetation (Prince 1991; Menaut et al. 1991). While techniques for estimating biomass production in annual grasslands are showing some promising results, the methods have yet to be developed for other savanna systems (Prince 1991). Similarly, the use of AVHRR time series data for measuring the rate of plant regrowth, following burning in different ecosystems, has yet to be fully quantified. It is also possible to monitor the products of biomass burning with the visible and near-infrared channel of the AVHRR through the determination of the single scattering albedo of smoke (Kaufman et al. 1990). The direction of the dispersal of smoke and associated gases in the lower atmosphere can be ascertained from examination of the pattern of smoke plumes.

In summary, the limitations of the AVHRR system for fire monitoring include the low saturation level of the sensors, the sensor noise in the 3.7 μm channel, and the overpass time of 2.30 am and pm for even-numbered NOAA satellites and 7.30 am and pm for odd-numbered satellites, which effectively sample the diurnal cycle of fire activity. In addition dense clouds will prevent detection of the surface by the visible and infrared sensors and will obscure active fires. The utility of the NOAA AVHRR, which is currently the instrument of choice for regional fire detection and monitoring, will be reduced if current plans to replace the operation of the 3.7 μm channel on the pm satellites by a 1.6 μm channel for snow and ice monitoring are realized for the NOAA K, L, and M series due for launch in 1994. As of today, the international fire research community has not made representations to NOAA strong enough to adjust the decision to its particular interest.

The NASA manned missions and, in particular, the Space Shuttle program has provided an interesting series of hand-held photographs of biomass burning at a range of scales and view angles. These photographs can be used to obtain an indication of the distribution of fires and smoke for the periods of observation (Helfert and Lulla 1990). The sporadic timing of the manned missions and their short duration make this data set of limited use for deriving comprehensive regional estimates.

The recent launch of the European Resource Satellite (ERS-1) provides two sensors that may contribute to the study of fire. The Synthetic Aperture Radar (SAR) will give additional information concerning changes in vegetation structure as a result of burning (Kasischke et al. 1992). The Along Track Scanning Radiometer (ATSR) will provide sensing in the middle and thermal infrared. Results from studies using these sensing systems, which address aspects associated with fires, have yet to be published.

The Defense Meteorological Satellite Program (DMSP) has a broad-band panchromatic low-light sensor that has been used to detect visible light sources at night, including fires. This sensing system has been operational since 1974; however, the intensities measured by the system are not well calibrated (Sullivan 1989).

The Geostationary Operational Environmental Satellite (GOES) Visible Infrared Spin Scan Radiometer Atmospheric Sounder (VAS) system provides high temporal frequency coverage every 30 minutes; however, its coarse spatial resolution of 16 km permits only the largest of fires to be detected (Menzel et al. 1991). Application of the sub-pixel fire technique described by Matson and Dozier (1981) provides a means to estimate fire size and temperature, yet as with the AVHRR, there are serious limitations to applying the method on a regional scale. The unique contribution from geostationary sensing systems is their ability to monitor the diurnal cycle of fire activity. Knowledge of the diurnal distribution of fire activity will help quantify the error associated with fire detection by the diurnal sampling provided by the polar orbiting systems. Preliminary results examining the diurnal pattern of fire distribution in the Amazon, using the GOES data, show a 20% decrease in the detected fire frequency between 3.30 pm and 6.30 pm (Prins and Menzel 1992). The decrease in fire activity late in the day and during the night in the Tropics indicates that nighttime sensing alone may result in a significant underestimate of fire occurrence. This diurnal cycle of fire activity is corroborated by field observations of controlled agricultural burning (Malingreau 1990). Preliminary results of the analyses of Meteosat data from West Africa have shown the thermal dynamics of a savanna landscape as it relates to biomass burning (Citeau et al. 1988). In addition to fire monitoring, the visible channels from the existing network of operational geostationary satellites offer considerable potential for regional monitoring of smoke plumes.

Satellite monitoring of tropospheric ozone, a secondary product of biomass burning, can be undertaken using a combination of data from the Total Ozone Mapping System (TOMS) and the Stratospheric Aerosol and Gas Experiment (SAGE) stratospheric ozone sensor. This method provides a mapping of tropospheric ozone with an accuracy of better than 10% in the Tropics and 15% in northern latitudes (Fishman et al. 1990). A peak in tropospheric ozone off the Atlantic coast of Africa, identified by this satellite system, has been linked to biomass burning during the Southern Hemisphere dry season in Africa.

The above list of satellite systems and their sensor characteristics relevant for fire studies gives an indication of the potential utility of satellite remote sensing data. It is worth noting that none of the current systems has been designed specifically for fire monitoring and that in most cases the use of these systems for fire-related studies requires further research and development.

Examples of the current research and development priorities associated with the different remotely sensed phenomena are as follows:

1. *Fires.* Assess the accuracy of satellite fire detection for different fire/vegetation/land-use systems for the AVHRR 1 km and 4 km data products, and the DMSP, Meteosat and GOES data products. Determine the contribution from the reflective component of the 3.7 μm channel to the brightness temperature from different surfaces and different sensor geometries that result in saturated pixels. Evaluate the sensitivity of sub-pixel fire estimation techniques for operational regional fire monitoring.
2. *Burn Scars.* Evaluate the relationships between temporal, spatial, and spectral characteristics of burn scars and the temporal, spatial, and spectral characteristics of the AVHRR, Landsat, and SPOT sensing systems for different fire/vegetation/land-use systems. The feasibility of producing regional estimates of burned area by satellite detection must be systematically assessed for a range of ecosystems. Evaluate the feasibility of using remote sensing techniques to estimate burning efficiency on a local and regional scale, through the spectral analysis of burned areas. The efficiency parameter should reflect the conditions in a mosaic of patches of land burned at different levels of intensity. Scene-based spectral radiometric models will have to be developed to quantify the efficiency parameter.
3. *Smoke.* Develop and test improved methods for estimating the mass of smoke produced from fires characteristic of different fire/vegetation/land-use systems. Develop a better understanding of the relationship between particle emissions and trace gas emissions.
4. *Clouds.* Examine the relationship between fire events and cloud generation as a means of better understanding the role of convective clouds in the transport of the products of biomass burning.
5. *Fuel Load.* Develop and test methods for regional estimation of biomass and fuel moisture content as well as seasonal evolution of fuel loading conditions using time series of vegetation indices derived from AVHRR data. Evaluation of high spectral resolution procedures to determine fuel chemical characteristics. Compilation of collateral information on land cover and burning practices in a geographic information system will provide an important contribution to regional emission estimates.

Although there is a large amount of research and development needed to refine the existing satellite techniques, it is apparent that the synergistic use of data from the current geostationary systems, the coarse resolution polar orbiters, and the high spatial resolution sampling systems provide a means by which some of our immediate data needs can be met. The experience acquired to date points to the need to integrate data derived from various sensors operating at various wavelengths and resolutions. Operational approaches that can utilize the synergy of data from different instruments have yet to be developed. These requirements are currently as pressing as the need to develop a new series of sensors. There are, however, some encouraging indications that the needs of the fire research community will be better served by sensors currently planned for service later this decade (Robinson 1991). The Japanese Earth Resources Satellite (JERS-1), launched in 1992 includes an optical sensor system with a spatial resolution of 20 m and spectral bands in the middle infrared. The imager currently being designed for the geostationary Second Generation Meteosat will provide 13 spectral channels with a 3 km resolution, including a 3.7 μm channel and a panchromatic channel with a 1 km resolution imaging every 15 minutes. The Moderate Resolution Imaging Spectrometer (MODIS), planned for launch in 1998 as part of NASA's Earth Observing System (EOS), will have 32 spectral channels at resolutions of 250 m, 500 m, and 1 km and will include a 3.7 μm channel specifically designed for measuring fire temperature and size. The specification for the MODIS includes two 3.7 μm channels: one channel saturates at 335 K, the other at 500 K. In addition, there are plans to operate both morning (10.30 am) and afternoon (1.30 pm) copies of the MODIS instrument. An airborne simulator of the MODIS instrument has been developed and is currently being tested by NASA (M. King, pers. comm.). This simulator will provide data for algorithm development and fire research prior to the launch of MODIS.

In the EOS time frame, additional instruments to MODIS will provide data to study aerosols, particulates, and the products of biomass burning. The Multi-angle Imaging Spectrometer (MISR), the Tropospheric Radiometer for Atmospheric Chemistry and Environmental Research (TRACER), and the Stratospheric Aerosol and Gas Experiment III (SAGE III) will be of particular relevance for biomass burning studies (NASA 1991).

OPERATIONAL FIRE MONITORING

Preliminary satellite investigations of fire occurrence in the Amazon region using 1 km AVHRR data in the mid-1980s gave an indication of the extensive nature of biomass burning in the region and led to a joint project by the Brazilian Space Agency (INPE) and the Brazilian Institute of Natural Resources (IBAMA) to develop an operational fire monitoring program. Preliminary verification of AVHRR-detected fires by systematic observation from light aircraft gave promising results. In 1989 96% of the fires identified by the AVHRR were matched by field-located fire scars or active fires found within 500 m of the given AVHRR fire location. Also, in 1989, daily satellite information concerning the timing and location of fires was used by IBAMA and the Environmental Agency of the State of Sao Paulo (DPRN) as part of a program to combat unauthorized fires and, as a result, several millions of dollars worth of fines were handed out (Setzer and Pereira 1992).

National fire monitoring systems using satellite data are also being developed in Senegal and Guinea in Africa. The growing availability of mobile and relatively low cost AVHRR receiving stations will increase the practicality of directly linking satellite observations with field intervention.

Most of the examples of the use of remote sensing in fire management have been to provide improved maps of fuel type distribution using high resolution satellite data. The AVHRR vegetation indices provide additional information on the timing of "green up," senescence, and vegetation condition through the growing season. Miller et al. (1986) describe how the U.S. Bureau of Land Management in Oregon use AVHRR data to detect, locate, and rank areas according to accumulated biomass and the risk of wildfire. These data are combined with data from an automated lightning detection system, a remote automatic weather system, information on fire protection status and topography as part of a Wildfire Initial Attack Management System. Those concerned with fire management have specific requirements in terms of data timeliness. Weekly information on vegetation condition would clearly play an important role in modeling fire susceptibility. Such information on biomass and fuel loading would, in addition, improve assessments of burning efficiencies and emission estimates.

There have been relatively few studies which demonstrate the contribution of satellite-based fire monitoring to address current research issues. One notable study, developed by Kaufman et al. (1990), provides a demonstration of the satellite contribution to the estimation of regional trace gas emissions. Two techniques are described for estimating trace gas emissions; both rely on the operational monitoring using AVHRR data. One method determines the emission of particulates per fire using the satellite imagery, which is then converted to trace gas emissions. The total emissions are then calculated by multiplying the average per fire emission by the total number of fires observed. The other method computes the total burned biomass by multiplying the biomass burned in an "average fire." The average emission and fire concept needs further refinement. Stratification of a region into vegetation types related to fuel loading, along with field sampling of emissions and the fraction of the biomass burned under different fire conditions and for the different vegetation types, will greatly increase the accuracy of emissions estimates. Remote sensing can be used to develop the regional vegetation stratification using multitemporal classification techniques (Townshend et al. 1987). High resolution satellite data might be used to better estimate the average fire size in a given landscape through analysis of burn scars.

One of the most important data needs from remote sensing is an accurate estimate of the distribution and timing of fires on a global scale. In 1987, NOAA developed a test data product of global fire distribution for one year. The product was generated using the GAC nighttime data and a thresholding of the 3.7 μm and the 10.8 μm band. The data set was subject to several problems resulting from the GAC sampling and received little support from the science community; data collection was discontinued after one year. The full validation of fire distribution using the NOAA GAC data can only be done by understanding the effect of the LAC to GAC sampling on the depiction of fires. Such an assessment is important as the GAC data provides the only currently available long-term global data base with which to study the trend in fire distribution. IGBP-DIS is currently coordinating an international program to create a global 1 km AVHRR product to support the research activities of the IGBP core projects (IGBP 1992). The global 1 km data set will be compiled using data from several international HRPT stations and NOAA acquisitions. The major challenges associated with compiling the data set will be the international coordination of the data acquisition and handling the large data volume of ca. 3.5 terabytes annually. The global 1 km AVHRR data set could be used to develop a much improved global fire product and would avoid some of the more serious deficiencies of the NOAA GAC-derived product. There is now the need for the IGBP International Global Atmospheric Chemistry (IGAC) Core Project to help design the specifications for a new global fire product and to develop the methods by which the interdisciplinary research community can apply the global remote sensing products to address current research questions.

CURRENT RESEARCH TRENDS

Climate change has been given increased importance by national and international research programs and is one of the current trends in environmental research. The scientific assessment made by the Intergovernmental Panel on Climate Change (IPCC) has identified the need for improved knowledge on the source and volume of trace gas emissions and their effect on atmospheric chemistry and ultimately on global and regional climate. As part of this activity, national inventories of trace gas emissions are being compiled. The current data on trace gas emissions from biomass burning are inadequate to make reliable national emission estimates and, as a result, research efforts are being initiated to address this question. To achieve the IPCC objective of improved emission estimates and improved understanding of the role of biomass burning in atmospheric chemistry, there is a need for an interdisciplinary approach to the research. A combination of accurate estimates of fire distribution, frequency, and fuel loading from remote sensing, combined with representative ground and laboratory measurements of combustion efficiencies and emission ratios for different fire-vegetation regimes, and linked to studies of particulates and modeling of gas transport would lead to significant improvements in our current understanding (Kaufman et al. 1992). Recent programs proposed and initiated by IGAC, NASA, and EPA have supported such an interdisciplinary approach to the study of biomass burning. For example the Transport and Atmospheric Chemistry Experiment-Atlantic (TRACE -A) and the Southern Africa Fire/Atmosphere Research Initiative (SAFARI) projects planned for September, 1992 will bring together international scientists from different disciplines to address the subject of biomass burning and its impact on regional atmospheric chemistry. Remote sensing components will provide data on fire, and tropospheric ozone distribution will be integral to these experiments. Similarly, the Dynamique et Chimie Atmosphérique en Forêt Equatoriale (DECAFE) and the Savane à Long Terme (SALT) projects adopted an interdisciplinary approach during their 1991 field program (Lacaux et al., this volume).

A further area of research associated with climate change is to improve our understanding of the ecological and management consequences of changes in fire frequency. Fire is a phenomenon that is mainly controlled by three major categories of factors: those related to climate, to vegetation conditions, and to human activity. These three categories are tightly interrelated and are often at the core of issues related to the problems of global change. An improved understanding of global patterns of biomass burning and their trends could shed new light on the evolving relationship between humans, climate, and vegetation. Given the disproportionate effect of biomass burning on the atmosphere and biosphere, relative to the extraordinary efforts required to manage fire effectively within the landscape, the topic of biomass burning assumes a particular relevance (Malingreau 1990). Changes in the frequency and intensity of disturbance by fires can effect the species composition of vegetation, the structure of ecosystems, the availability of soil nutrients, and local hydrology. The new information provided by remote sensing concerning the distribution, pattern, and timing of biomass burning over a range of scales offers new opportunities to examine the relationships between vegetation conditions and burning as a land management practice. Such an understanding is important if we are to chart the impact of burning upon the global system under changing land-use practices (e.g., agricultural expansion, tropical deforestation, ranching). In addition, the consequences of wildfire in areas not normally burned, caused by such factors as extreme climatic conditions or unexpected land-use policies, could be more predictable given improved knowledge of current patterns and trends. The effects of changing fire regimes in response to regional changes in climate or changes in traditional land-use practices is an important topic requiring additional research. Ecological studies addressing the above effects will require an accurate assessment of fire distribution and a long-term record of fire frequency and timing. There is a need for the remote sensing community to understand the information requirements of the ecological community, to address better the research aspects of fire ecology. Similarly, the ecological community needs to understand the new contribution that remote sensing technology can make to such studies.

CONCLUSION

There is little doubt that satellite remote sensing can make a significant contribution to the study of fires in the environment. A number of studies during the last ten years have demonstrated the potential of remote sensing for fire-related studies. There is an urgent need for research to be undertaken to determine fully the accuracy with which such important variables as burned area, fire occurrence, fuel loading, and particulate mass can be quantified by current remote sensing. At the present time there are several obstacles to realizing the full potential of satellite technology. There are serious limitations to the capability of the current satellite sensing systems for studying fire and its related phenomena, and it will only be towards the end of the decade when the next generation of sensing systems are operational that we will see an improvement in the current global sensing capability. There is a need to ensure that the requirements and specifications for instrumentation to provide the necessary data for fire-related studies are included in the current design of these new sensing systems. The problems associated with acquiring and processing data from the current sensing systems, including cost, data volume, and a distributed network of reception stations, act as an obstacle to the wider use of currently available satellite data for fire monitoring. New initiatives by the international science community to make global data sets, including fire products from the current and future systems, more readily available may help alleviate some of these problems. The promise of improvements in sensing capability and data availability gives encouragement for future research. However, it is important that planning for future systems be matched by an immediate and concerted international effort to use the existing satellite sensing systems to provide the information necessary to address the pressing science questions associated with global change.

Specific areas of research must be strengthened to improve the utilization of remote sensing techniques in biomass burning studies:

- Improve fire detection and measurement capabilities; this necessitates the definition and operational implementation of dedicated satellite sensor packages for biomass burning.
- Improve data analysis techniques for a better assessment of vegetation conditions, fuel loading, burning efficiencies, burn scar, and particulate measurements.
- Secure the availability of global data sets for biomass burning related research. This will necessitate international arrangements on data exchange and distribution. Global data sets are a prerequisite for producing global assessments of biomass burning.
- Research needs to be dedicated to the direct measurement of burning emission products, both gases and particulates, through existing and planned spaceborne instrumentation.
- Continuity of spaceborne observations must be secured in order to monitor surface conditions related to biomass burning and interpret them in terms of trends of fire frequency and utilization.
- Improve linkages between remote sensing parameterization of biomass burning and fire products and ground-based measurements.

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