Environment Information and Assessment Technical Report

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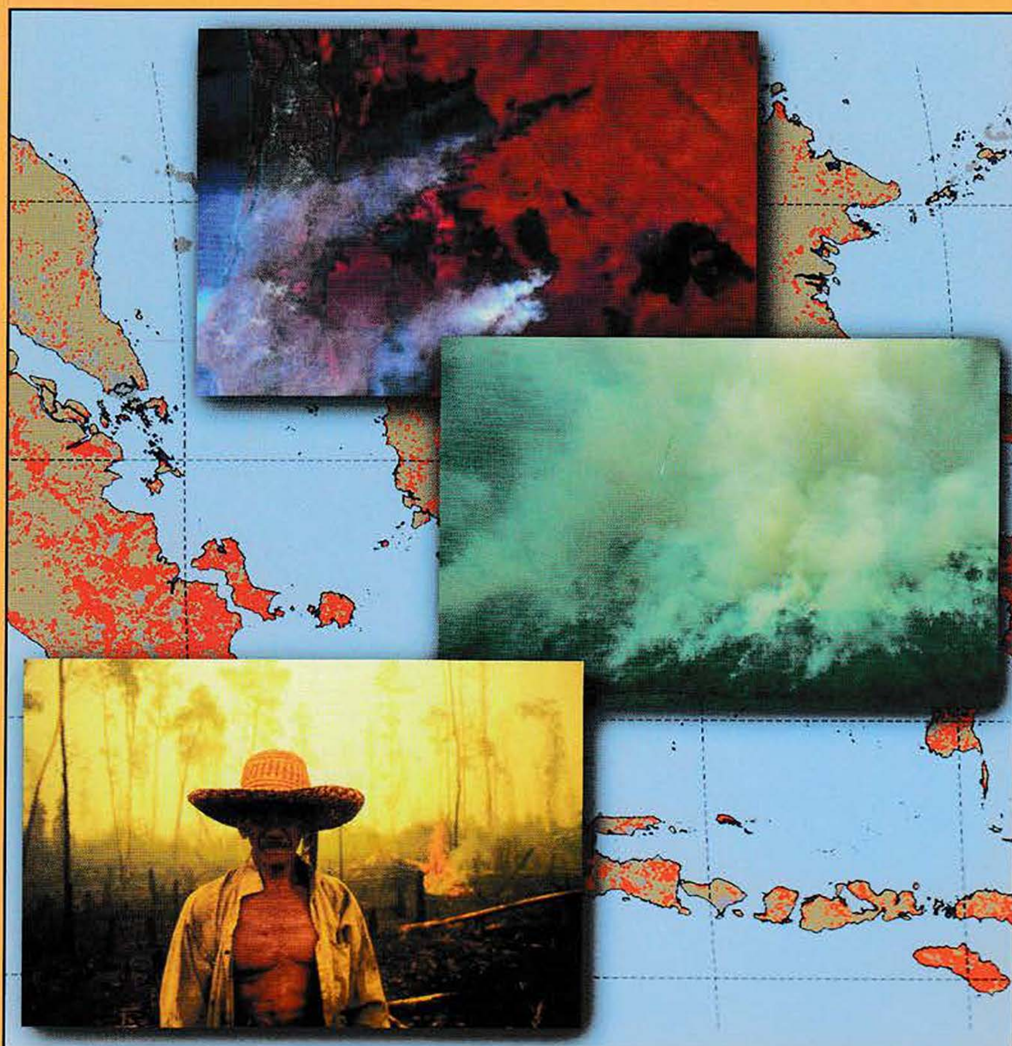
UNEP/DEIA&EW/TR.99-1

Wildland Fires and the Environment: a Global Synthesis



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Wildland Fires and the Environment: a Global Synthesis

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1999

List of Acronyms

AVHRR: Advanced Very High Resolution Radiometer
CGIAR: Consultative Group for International Agricultural Research
DMSP: Defense Meteorological Satellite Program
EEPSEA: Economy and Environment Programme for South East Asia
ENSO: El Niño Southern Oscillation
FPI: Fire Potential Index
GAC: Global Area Coverage (data from NOAA/AVHRR)
GRID: Global Resource Information Database
NASA: National Aeronautics and Space Administration
NFDRS: National Fire Danger Rating System
NOAA: National Oceanic and Atmospheric Administration
OCHA: UN's Office for the Coordination of Humanitarian Affairs
TOMS: Total Ozone Mapping Spectrometer
UNEP: United Nations Environment Programme
USDA/FS: United States Department of Agriculture/Forest Service
USGS: United States Geological Survey
WWF: World Wildlife Fund
See also Appendix 3

ISBN: 92-807-1742-1

For bibliographic and reference purposes this publication should be referred as:

UNEP (1999). Levine, J.S., Bobbe, T., Ray, N., Singh, A. and R.G. Witt. Wildland Fires and the Environment: a Global Synthesis. UNEP/DEIAEW/TR.99-1.

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Acknowledgement

This report was produced through the cooperation of UNEP, NASA, USFS and USGS. The authors are grateful to a number of colleagues who critically reviewed and helped in the preparation of the report. Special thanks are due to Steve Howard, Zhi-Liang Zhu, Gene Fosnight, Rachel Clement and Dawn Buehner of USGS/EROS Data Center for their valuable comments and support in finalizing the report. From UNEP/DEIA&EW/GRID-Geneva, special thanks to Dr. Behnaz Zand for her technical help and Pascal Peduzzi for his valuable comments. We also thank Jean-Luc Ray for his comments on the photographs, and Sipi Jaakkola of UNEP's regional Office of Europe for reading the report with a critical eye.

Joel Levine would like to acknowledge Dr. Teresa D. Edwards (Spelman College), Ms. Theresa E. McReynolds (College of William and Mary), and Mr. Charles W. Dull (USDA Forest Service), for their research into the area burned during the Indonesian fires and Dr. Lawrence Mtetwa (College of William and Mary) for general scientific discussions during the course of this research. This research was funded by the Global Change Program of the U. S. Environmental Protection Agency under Interagency Agreement DW 80936540-01-1.

Executive summary

During 1997 and 1998, relatively small-scale, human-initiated fires for land clearing and land-use change quickly developed into uncontrolled large-scale and widespread fires. These fires occurred in Southeast Asia, South and Central America, Africa, Europe, Russia, China and the United States. These uncontrolled and widespread wildfires were a consequence of extreme drought conditions apparently brought about by the 1997 El Niño. On a daily basis, these wildfires were reported on the front pages of the world's newspapers and on television and radio throughout the world. Internet websites described the daily, and in some cases hourly progress of these wildfires.

The extensive and widespread wildfires of 1997 and 1998 made the world aware of the environmental and human health impacts associated with these fires. In Southeast Asia alone, tens of millions of people were exposed to high levels of fire-produced gases and particulates for weeks at a time. The poor atmospheric visibility resulting from these fires was responsible for the crash of a commercial airplane and the collision of two ships at sea in Southeast Asia. In general, the countries of the world were not prepared to react in a timely and effective way to these fires. Fire control and air quality monitoring systems did not provide the information needed for government officials and others responsible to make decisions and take related action. Thus, the wildfires of 1997 and 1998 were a learning experience for many environmental managers.

Natural fires induced by atmospheric lightning were a regular phenomenon even before humans were present. Such naturally-induced fires remain a vital process that initiates natural cycles of vegetation succession and maintains ecosystem viability. In the tropical regions and elsewhere, human-initiated fires have also become an important and widespread tool for land clearing and land-use change. Fires initiated by human activities (which may account for as much as 90% of all fires) can have a negative impact on the composition and chemistry of the global and regional atmosphere, on our planet's climate and on human health.

Fires are a significant source of gases and particulates to the atmosphere: environmentally important gases produced by fire include carbon dioxide, carbon monoxide, methane, non-methane hydrocarbons and oxides of nitrogen. Fire also produces large amounts of small, solid particles or "particulate matter", which absorb and scatter incoming solar radiation, and hence impact the climate of our planet, as well as provoking a variety of human health problems.

This report, Wildland Fires and the Environment: a Global Synthesis was prepared to better inform decision makers about fires, their environmental and health risks, as well as those technologies available to monitor and hopefully reduce the impacts of fires in the future.

1 Introduction

Fire has been an agent of disturbance for thousands of years. Forest and wildland fires have occurred long before the advent of humans, shaping landscape structure, pattern and ultimately the species composition of ecosystems. The ecological role of fire is to influence several factors such as plant community development, soil nutrient availability and biological diversity. Forest and wildland fire is a vital and natural process that initiates natural cycles of vegetation succession and maintains ecosystem viability. Uncontrolled or misused fires can, however, cause tremendous adverse impacts on the environment and human society.

A combination of climate and human activity account for the majority of wildland fires. The contribution of natural fires such as those caused by lightning is insignificant in comparison to the number of fires started by humans. The vast majority of wildfires are intentionally set fires in forests, savannas, grasslands and other wildland areas for timber harvesting, land conversion, slash-and-burn agriculture, and socio-economic conflicts over questions of property and land use rights. In recent years extended droughts, together with the rapidly expanding exploitation of tropical forests and the demand for the conversion of forests to other land uses, have resulted in a dramatic increase in wildfire size, frequency and related environmental impacts. During 1997 and 1998, a combination of drought conditions brought on by El Niño and uncontrolled burning practices caused unprecedented levels of wildland fires across the globe.

Recent wildfires had an immense impact in Indonesia, Brazil, Mexico, Canada, USA, France, Turkey, Greece and Italy. In the latter country, for example, the government declared a state of emergency in parts of the southern mainland and the islands of Sicily and Sardinia during 1997-98. Large scale forest fires and fire hazards were also reported in eastern parts of the Russian Federation, and in China's northeastern Inner Mongolia Autonomous Region.

The number and extent of uncontrolled wildland fires during 1997 and 1998 captured the attention of the media and helped increase public awareness of issues such as biomass burning and greenhouse gases, loss of habitat for threatened and endangered plant and wildlife species, international haze and air pollution, and public health and safety. Uncontrolled fires and haze also have adverse economic impacts through the loss of industrial and agriculture production, the destruction of commercial timber, decline in tourism and increased health care costs. Yet despite the intense media attention, and dozens of international evaluation and assistance programs, a limited reliable scientific data exist to describe the extent of recent burning and its affect on the environment. The purpose of this report is to highlight global fire issues and identify opportunities to coordinate international wildland fire prevention, suppression and rehabilitation programs.

2 Significance of fire to the global environment

Forest fires, controlled or uncontrolled, have profound impacts on the physical environment including: land cover, land use, biodiversity, climate change and forest ecosystems. They also have enormous implications for human health and on the socio-economic system of affected countries.

Economic costs are hard to quantify, but a conservative estimate by the Economy and Environment Programme for Southeast Asia (EEPSEA/WWF, 1998b) put the cost of damages stemming from the Southeast Asian fires (all causes) at more than $4 billion.

Health impacts are often serious. Estimates suggest 20 million people were in danger of respiratory problems from fires in Southeast Asia (EEPSEA/WWF, 1998a). In 1997 smoke and air pollution from fires in Mexico, Honduras and Guatemala drifted across much of the US Southeast, prompting officials to issue a health warning to residents.

A major consequence of forest fires is their potential effects on climate change. Only in the past decade have researchers realized the important contributions of biomass burning to the global budgets of many radiatively and chemically active gases such as carbon dioxide, carbon monoxide, methane, nitric oxide, tropospheric ozone, methyl chloride and elemental carbon particulates.

Biomass burning is now recognized as a significant global source of emissions, contributing as much as 40% of gross carbon dioxide and 38% of tropospheric ozone (Andreae, 1991).

The major components of biomass burning are forests (tropical, temperate and boreal); savannas; agricultural lands after the harvest; and wood for cooking, heating and the charcoal production. The burning of tropical savannas is estimated to destroy three times as much dry matter per year as the burning of tropical forests. Most of the world's burned biomass matter is from savannas, and because two-thirds of the Earth's savannas are in Africa, that continent is now recognized as the "burn center" of the planet. Biomass burning is generally believed to be a uniquely tropical phenomenon, because most of the information we have on its geographical and temporal distribution is based on observations of the tropics. Because of poor satellite coverage, among other things, little information is available on biomass burning in boreal forests, which represent about 29% of the world's forests.

One of the largest fires ever measured occurred in the boreal forests of Heilongjiang Province, northeastern China, in May 1987. In less than four weeks, more than 1.3 million hectares were burned. At the same time, extensive fire activity occurred across the border in Russia, particularly east of Lake Baikal between the Amur and Lena rivers. Estimates based on National Oce-

anic and Atmospheric Administration/Advanced Very High Resolution Radiometer (NOAA/ AVHRR) imageries indicated that 14.4 million hectares in China and Siberia were burned in 1987. Knowledge of the geographical and temporal distribution of burning is critical for assessing the emissions of gases and particulates to the atmosphere. Biomass is 45% carbon by weight (Andreae, 1991). Estimates for the release of carbon (in units of teragrams of carbon, TgC/year, where 1 teragram equals 10^{12} grams or 10^{6} metric tons) into the atmosphere from biomass burning for different ecosystems are summarized in Table 1.

One of the important discoveries in biomass burning research over the past years, based on a series of field experiments, is that fires in diverse ecosystems differ widely in the production of gaseous and particulate emissions. Emissions depend on the type of ecosystem; the moisture content of the vegetation; and the nature, behavior and characteristics of the fire.

Source of burning	**Biomass burned (Tg dry matter/year)**	**Carbon released (TgC/year)**
Savannas	3690	1660
Agricultural waste	2020	910
Tropical forests	1260	570
Fuel wood	1430	640
Temperate and boreal forests	280	130
Charcoal	20	30
World total	8700	3940

Table 1. *Global estimates of annual amounts of biomass burning and of the resulting release of carbon into the atmosphere*

Source: *Andreae et al., 1991*

3 Global wildland fires: current status and trends

Globally, no reliable statistics about the exact location and annual areas burned by forest fires are available. Estimates of area burned annually are based on two sources. Statistics related to forest fires for each country, mostly for Europe and North America, are compiled and disseminated by the United Nations Food and Agricultural Organization (FAO). Some estimates are derived using satellite data. In any case at the global scale there are large uncertainties in both sources. Statistics related to forest fires are not generally collected and maintained in most of developing countries. The current satellite systems used to deduce information about the area burned have problems that make it difficult to determine information on the area and duration of forest fires.

The natural role of fire in shaping and maintaining ecosystems is changing, since humans have introduced burning into areas that normally do not burn, and have suppressed fire from areas that have regularly burned in the past. The general outcome over the past several decades has been a global surge in uncontrolled wildland fires from Siberia to Indonesia, and in Amazonia, Africa, Australia, Canada, Mexico and the United States. Uncontrolled forest, wildland and prescribed fires now occur in all vegetation ecosystems of the world. It is estimated that fires annually burn 10-15 million hectares of boreal and temperate forest, 20-40 million hectares of tropical forests due to land development, forest conversion and escaped agriculture fires, and up to 500 million hectares of tropical and subtropical savannas, woodlands and open forests (Goldammer, 1995).

The percent increase in recent catastrophic wildland fires is closely related to the El Niño climatic phenomenon. The El Niño Southern Oscillation (commonly known as ENSO) is a periodic climatic phenomenon caused by the interaction between the atmosphere and abnormally warm sea surface water in the eastern Pacific Ocean off the coast of South America (Figure 1). During an El Niño event, the surface of the water becomes warmer and alters trade wind patterns which in turn influence the surface temperature over vast areas of the Pacific Ocean. ENSO events typically occur every three to ten years and have influences around the world. El Niño has caused extreme weather patterns throughout the tropics and has been linked to droughts in tropical locations such as eastern Australia, central and eastern Pacific Islands, the coast of northern Peru, New Zealand, Indonesia, India and southern Africa. 20 ENSO events have been recorded since 1887. Some evidence show that these El Niño events have become more frequent and intense during the past twenty years (Trenberth and Hoar, 1997).

During 1997 and 1998, wildland fires burned extensive areas in Indonesia, Australia, Brazil, Mexico, Canada, Russia and the southern United States. Many of these fires were severe in nature due to drought conditions caused by El Niño. Despite the interest generated by these fires, the full extent of the areas burned and associated environmental impacts have not been determined. In

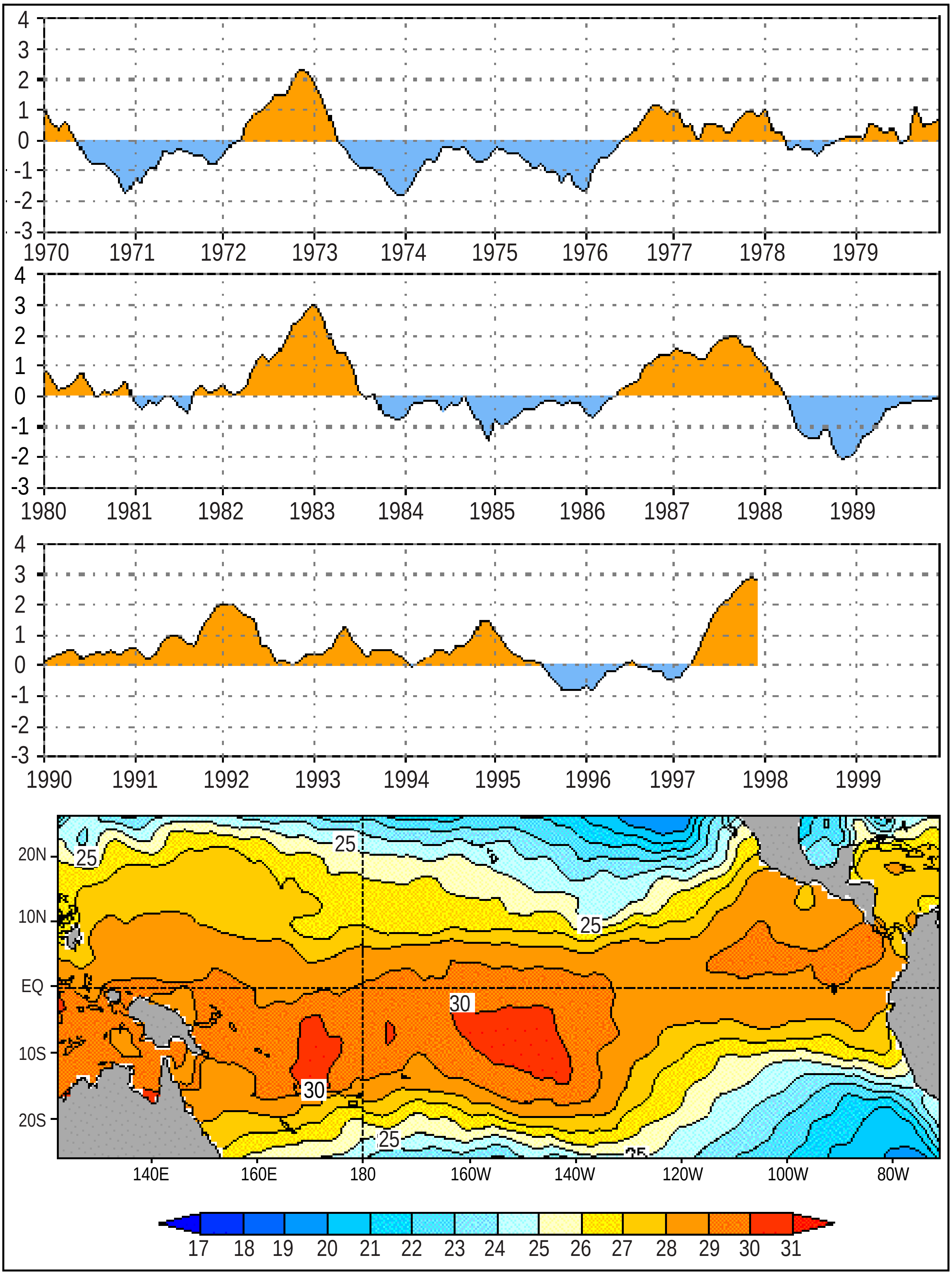

Figure 1. *Sea surface temperature anomalies, known as El Niño Southern Oscillations, since 1970, and observed sea surface temperature (^0C) in central Pacific Ocean based on a 7-day average centered on 7 January 1998.*

Source: NOAA/NCEP/Climate Prediction Center and NOAA/NCEP/Climate Modeling Branch

most cases, estimates of fire area and resulting damage vary widely. However, a number of international organizations and countries have provided assistance and conducted studies to determine the extent and impacts of wildland fires in Indonesia. The fires in Indonesia serve as a case study to examine the issues and impacts related to uncontrolled burning.

4 Overview of wildland fires in Indonesia during 1997 and 1998

Indonesia received unaccustomed attention in the world's headlines during 1997 and 1998 as a result of extensive wildland fires, social unrest, and political and economic instability. In 1997, despite official warnings about high fire danger, burning activities were continued by farmers, plantation and forest concession holders in the traditional manner.

Swidden or shifting agriculture has been widely practiced in Indonesia for thousands of years. Burning is a low-cost way of clearing the land for agriculture, and the ash provides a source of nutrients including nitrogen, carbon, phosphorus, potassium, magnesium and sodium. The nutritional content of the soil increases immediately after burning, but the nutrients deplete rapidly through rainfall leaching. Traditional shifting agriculture is thought to have little long-term impact on forest ecosystems, but may change vegetation composition in intensively used areas. The current trend is to develop larger plots for longer periods, giving the natural vegetation less time to recover between rotation periods. After one or two growing seasons, the agricultural plots must be shifted into new areas which will then also be cleared and burned.

Extensive land clearing is also conducted by private and government companies. Fires are started to reduce logging slash, and to prepare areas for rubber and palm oil plantations (Figure 2). The increasing demand for forest products such as lumber, paper pulp, rubber and palm oil has escalated the pressure in remaining tropical forest. The combination of a growing population and increased development by logging and plantation companies has resulted in growing social pressure to use a limited land base. The population of many forest areas has increased dramatically as farmers have followed logging roads into forests. Local rural populations regard the forest as a resource for their use. When concessions for logging and plantations are granted to private and government owned companies, access to forest areas is often restricted, which causes resentment among local populations. The lack of clear land tenure laws, uncertain land status and poor relationships between concessionaires and local people often results in fires being started intentionally.

During the El Niño 1997 event, the dry conditions persisted long enough for standing forests to burn as fires spread and escaped land clearing activities. The President of Indonesia declared on September 9th that all land clearing activities were to be terminated. On September 25th the President declared the fires a national disaster and ordered the mobilization of the people to put the fires out. Extensive uncontrolled burning continued during September, October and November of 1997 in Kalimantan and Sumatra. Uncontrolled wildland fires diminished during rains that started in late November.

Concerns escalated again as fires resumed in early 1998 after an abnormally short wet season. The fires burned out of control again in 1998, the second year of a pronounced El Niño-related

Figure 2. *Extensive land clearing/planting of palm oil trees in the smoke from forest fires. Riau, South Sumatra, Indonesia, 1997.*
Source: WWF-Canon/Tantyo Bangun

drought. The burning filled the region with smoke and haze which blanketed Indonesia, Malaysia, Singapore, southern Thailand and the Philippines. The extent of the smoke and haze covering much of Indonesia and neighboring countries indicated an unprecedented amount of burning. However, it was difficult to accurately determine how much area had burned or where fire were burning due to smoke, haze and cloud cover. Figure 3 shows large area of smoke haze over Borneo in early 1998.

Estimates of area burned vary substantially among the different government agencies and international support group. In early September, the government provided an estimate of 3,000 km^2 of burnt forest (Jakarta Post 1st Sep 1997). In early October the estimate was 6,000 km^2 (Jakarta Post 6th Oct 1997). The Ministry of Forestry (MoF) officially stated that 1,650 km^2 of designated forest land burned during 1997 (Siswanto, 1997). This estimate does not include fires on land under the jurisdiction of other Ministries. The State Ministry of Environment estimated that approximately 4,000 km^2 of forest and other land burned in 1997 (KLH, 1998). The report indicates that 85% of the burning was caused by logging operations and palm oil and industrial plantations.

During the Southeast Asia fires, the US Department of Agriculture (USDA) Forest Service prepared a series of 77 maps showing the locations of active fires and burned areas in Sumatra, Kalimantan and Java, Indonesia for October and November 1997, and February and March 1998, for use in fire-fighting operations. These maps offer high spatial resolution coverage of the areas of both active fires and burned areas, identifying these areas against a geographical grid showing provincial and city boundaries and topographic features. As these maps were prepared for fire suppression activities and cover the regions of intense fires, they do not provide complete coverage of all of the fires and burned areas in Kalimantan, Sumatra and Java.

It is important to re-emphasize that the 77 USDA Forest Service maps only cover burned areas in Kalimantan, Sumatra and Java. Indonesia is a nation that consists of more than 13,000 islands

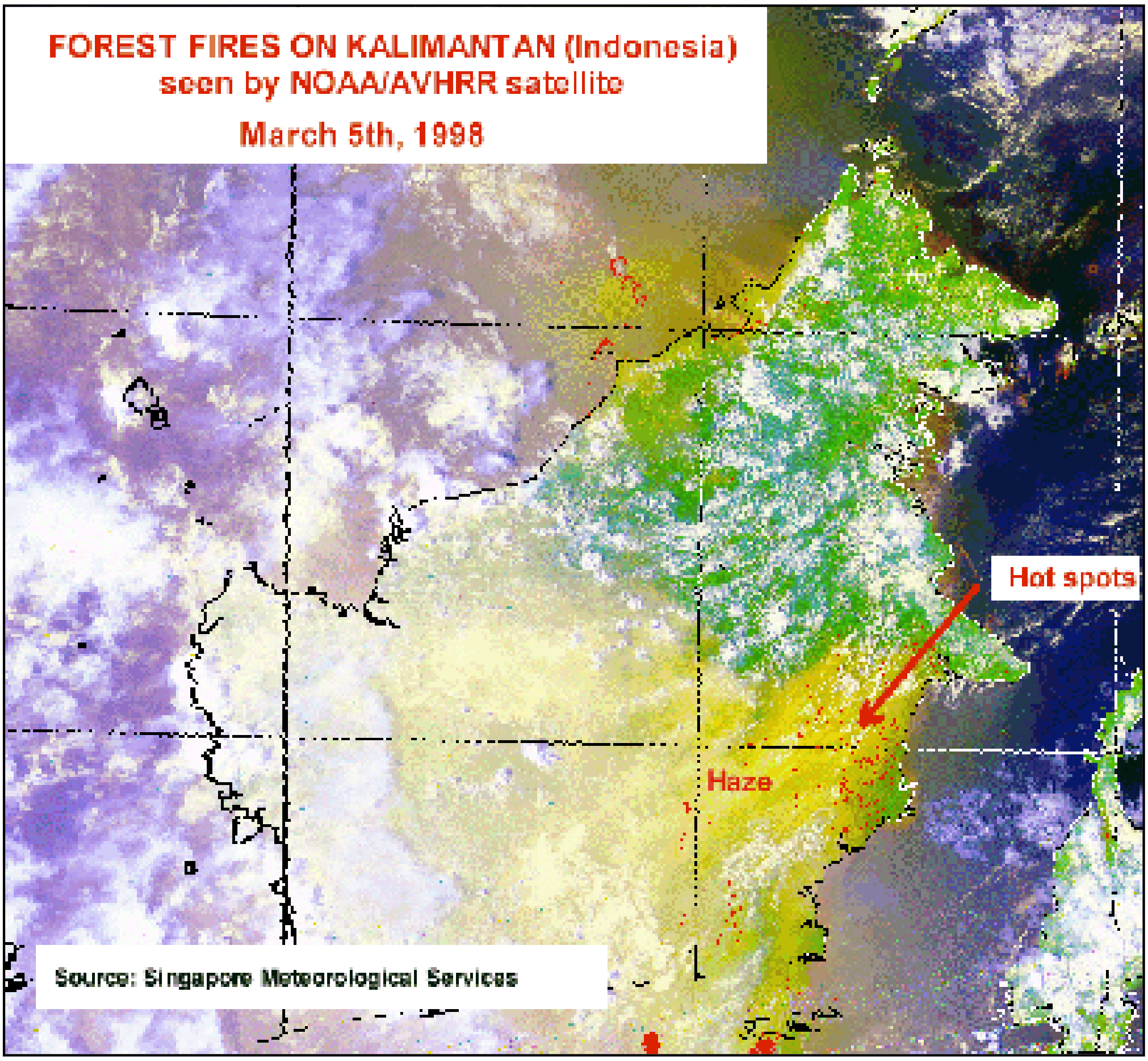

Figure 3. *Kalimantan satellite image (AVHRR,) showing fire "hot spots" and smoke haze.* Source: NOAA.

(some reports cite more than 17,000 islands), only 6,000 of which are inhabited. These islands cover a total of 1,826,440 km^2 between the Indian and Pacific Oceans, linking the continents of Asia and Australia. The main Indonesian islands are Kalimantan (539,460 km^2), Sumatra (473,606 km^2), Irian Jaya (421,981 km^2), Sulawesi (189,216 km^2) and Java (132,187 km^2). Indonesia shares the islands of Kalimantan with Malaysia and Irian Jaya with Papua New Guinea.

The 77 Forest Service fire maps have been used to calculate the area burned for the fires in Sumatra, Kalimantan and Java, Indonesia, for these four months (October - November 1997 and February - March 1998). The burned area in Sumatra was calculated to be 12,933.85 km^2, the burned area in Kalimantan was 12,334.73 km^2 and the burned area for Java was 362.96 km^2. The total burned area for all three Indonesian islands was 25,632 km^2 (Levine *et al.,* 1998). A summary of the burned area determined from these maps is included in Appendix 1. However, this burned area estimate represents only a lower limit of the area burned in Kalimantan, Sumatra and Java.

Liew *et al.* (1998) analyzed 766 SPOT "quick-look" images with almost complete coverage of Kalimantan and Sumatra from August to December 1997. The SPOT "quick-look" images have a spatial resolution of 100 m. Liew *et al.* (1998) estimate the burned area in Kalimantan to be 30,600 km^2 and the burned area in Sumatra to be 15,000 km^2, for a total burned area of 45,600 km^2. Since the SPOT images provided more complete coverage of Kalimantan and Sumatra than the Forest Service fire maps, the total burn area of 45,600 km^2 is considered more accurate. Even the estimate of Liew *et al.* (1998) represents only a lower limit estimate of the area burned in Southeast Asia, since the SPOT data only covered Kalimantan and Sumatra in 1997, and did not include fires on the other Indonesian islands of Irian Jaya, Sulawesi, Java, Sumbawa, Komodo, Flores, Sumba, Timor and Wetar or the countries of Malaysia (land area of 328,550 km^2) and Brunei (land area of 5,270 km^2), all areas of active fires.

4.1 Impacts on wildlife and habitat biodiversity

The fires in Indonesia posed a serious threat to wildlife. Wildlife are killed directly by the heat and smoke of fires, or may subsequently die from the lack of food and water or habitat degradation and loss. Small slow-moving animals are the highest risk to be killed directly from flames and smoke. Other wildlife with specific food, habitat or climate requirements are at risk immediately after wildland fires if they cannot find suitable habitat. Fire can destroy critical wildlife habitat or alter the biodiversity of remaining tropical forest areas.

According to the World Conservation Monitoring Center (Gilbert, 1997), the fires in Indonesia threatened at last 19 protected areas including a World Heritage site, Ujung Kulon in Java, a Ramsar Wetland, Berbak in Sumatra and the Biosphere Reserve of Tanjung Puting in Kalamantan. These sites are considered especially valuable for wildlife because they include richly biodiverse

Figure 4. *Burnt Orang Utan in trees surrounded by smoke. Tanjung Puting National Park, Kalimantan, Indonesia, 1997.*
Source: WWF-Canon/Tantyo Bangun

areas. Fruit-eating animals and birds, such as orangutans and hornbills, are vulnerable since the trees they rely on for food take many years to mature and develop fruit.

The 1997 and 1998 fires had a severe impact on Bornean orangutans in East and Central Kalimantan (Schweithelm, 1998). In addition to destroying remaining valuable habitat, flames and smoke as well as a lack of food and water drove many orangutans from forest areas (Figure 4). Fleeing orangutans were killed by villagers as the animals sought food and water in agricultural fields. Young orangutans were captured to be sold as pets. Many captured orangutans die of illness or injuries sustained as they were caught.

4.2 Loss of lives and property

Besides destroying valuable habitat, wildfires pose an severe risk to people living in or near affected areas. Thousands of people have suffered from respiratory diseases as a result of smoke and haze generated from the fires. Prolonged fires and droughts have destroyed crops and caused rivers and other water sources to dry up, making food and water scarce in areas hardest hit by wildfires.

It is generally believed that the health of approximately 20 million people in the region was adversely affected by the smoke, particularly through upper respiratory tract infections and asthma. Skin and eye diseases were also prevalent. The economies of Indonesia, Singapore and Malaysia were seriously affected through business shut-downs, and absenteeism, airport delays, accidents and depressed tourism revenues.

Figure 5. *Smoke as a health problem in Indonesia. Pelembang street scene in the haze, south Sumatra, 1997.*
Source: WWF-Canon/Tantyo Bangun

Smoke and haze from the uncontrolled fires covered Indonesia and neighboring countries. Poor visibility due to the thick haze (Figure 5) caused land, air and sea transport accidents. Fatalities included 29 people who were killed in a ship collision in the Straits of Malacca. A commercial airliner crash in North Sumatra that killed 222 people is thought to be partially due to the inability of the pilot to see the mountainous terrain. Figure 6 shows the extent of the smoke haze on 15 April 1998 with associate aerosol index (AI). This index is a directly calculated quantity from the measured backscattered radiances from TOMS. There is no specific relationship between AI and human health. However, anything that can block more than 50% of the sun's radiation in the UV (AI = 1.5) is considered a hazard.

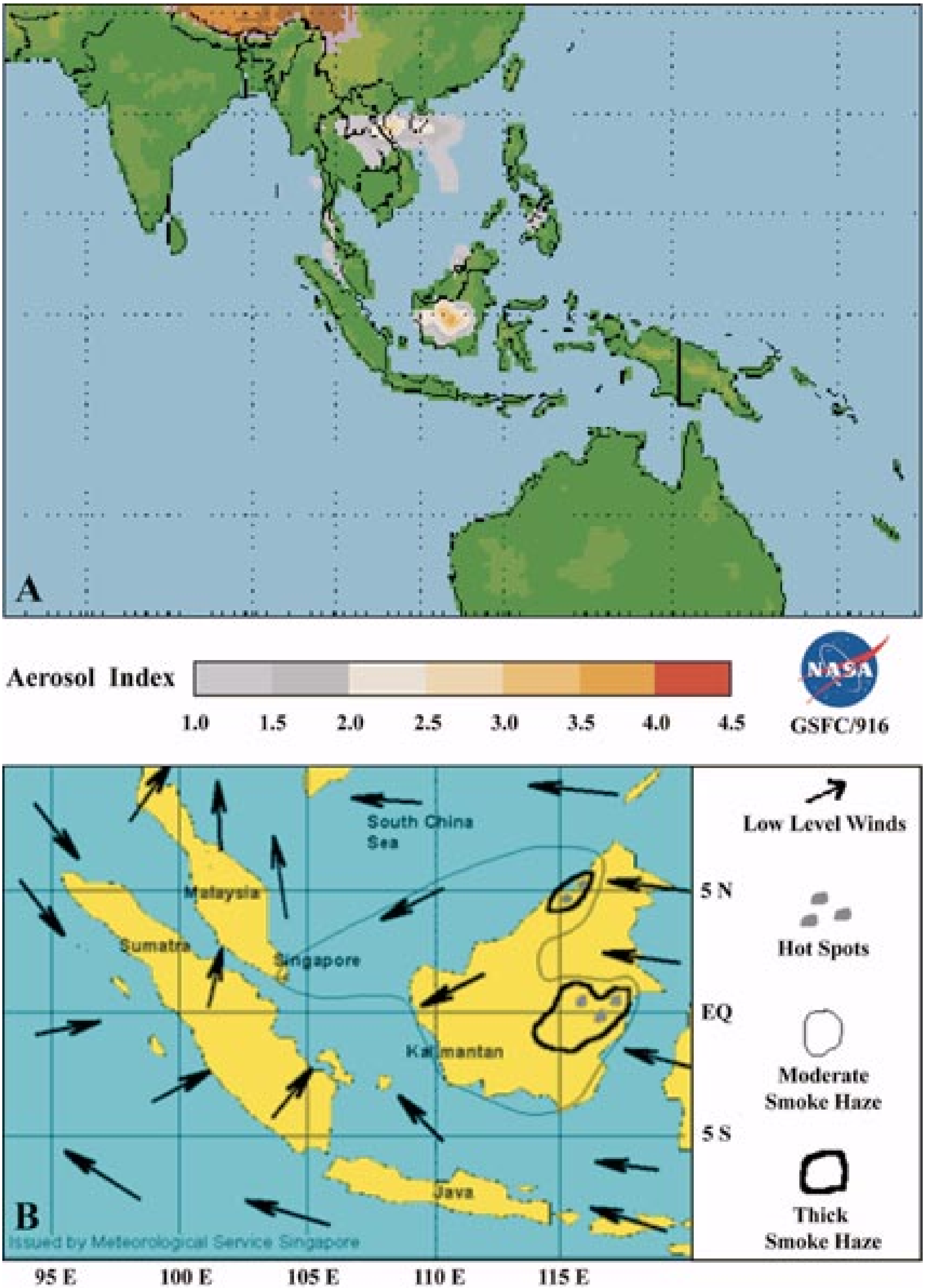

Figure 6. *Large area of smoke haze due to fires in Borneo on 15 April 1998.*

Notes: A: image from NASA/Total Ozone Mapping Spectrometer (TOMS) with associate Aerosol Index. B: Surface winds map showing fire hot spots and associated smoke haze. Prepared by Meteorological Service Singapore (MSS).

Source: NASA/TOMS and MSS.

4.3 Regional economic impacts

Measuring the economic impacts of the 1997 and 1998 uncontrolled fires requires reliable information about the amount, type and quality of crop and forest land that burned. In October 1997, the World Wildlife Fund (WWF) and the Economy and Environment Programme for South East Asia (EEPSEA) started an effort to quantify the economic impacts in Indonesia, Malaysia and Singapore for the period of August through October 1997. The interim results were released in February 1998 (EEPSEA/WWF, 1998a). The economic cost of the 1997 smoke and haze was estimated to be approximately US$ 1.4 billion. These costs do not include the loss of forest resources or the impacts of long-term health care. Of the US$ 1.4 billion, Indonesia experienced the greatest loss estimated at US$ 1.0 billion. The majority of this cost was attributed to short-term health care treatment. An additional US$ 90 million was lost as a result in tourism decline. The economic impact to Malaysia was estimated to be US$ 300 million primarily due to loss of tourism and decline in industrial production. The economic impact to Singapore was estimated to be US$ 60 million largely from loss of tourism.

In May 1998 EEPSEA and WWF released an updated report that includes the economic impacts of fire damages (EEPSEA/WWF, 1998b). The 1997 fires were estimated to have a total cost of US$ 3.0 billion in fire damages, bringing the total economic loss to US$ 4.4 billion including fire and haze damages. These losses include US$ 493.7 million in timber, US$ 705.0 million in direct forest benefits (non-timber forest products: food and raw materials), US$ 470.4 million in agriculture (plantations), US$ 1,077.1 million in indirect forest benefits (water supply, erosion control, soil and nutrient loss), US$ 30 million in biodiversity, US$ 272.1 million for carbon release, and US$ 25.1 million in fire fighting costs.

The total 1997 cost of US$ 4.4 billion dollars was calculated using the best available data at the time of the analysis. Actual costs may exceed this estimate, especially if long-term health costs and impacts to biodiversity and wildlife could be accurately accounted for. However, these estimates give an indication of the massive economic impacts of uncontrolled fires.

For a detailed scientific analysis of the atmospheric impacts and overall areas burned in Indonesia by the 1997-1998 fires, please see Appendix 2.

5 Forest fire potential, detection, monitoring and assessment

The inability to detect wildland fires during initial stages and take rapid and aggressive action on new fires is perhaps the most limiting factor in controlling such wildland Indonesia fires. This is especially true for fires in areas with limited access. Another constraint to effective wildfire control is the imbalance between increasing fire risks due to extended drought and the limited ability to raise the concern among local people, plantation and logging managers involved in land clearing and burning activities.

Providing an effective response to wildland fires requires four stages of analysis and assessment: 1) determining fire potential and risk, 2) detecting fire starts, 3) monitoring active fires, and 4) conducting post-fire assessments (Klaver *et al.*, 1998).

Information requirements for each stage of fire analysis vary significantly. Fire potential quantifies the likelihood of a fire when there is ignition. Fire potential requires collecting baseline vegetation information, daily to weekly monitoring of vegetation condition or vigor, daily monitoring of weather conditions and acquiring risk management information. Fire detection requires daily monitoring for fire starts. Fire monitoring requires daily monitoring of fire scars and of smoke and haze during the burn. Fire assessment requires analysis of fire burns and periodic monitoring of the vegetation transitions in the fire burns.

5.1 Fire potential

Fire potential depends on the amount of dead and live vegetation and moisture content in each. The amount of dead and live vegetation is estimated from a high quality land cover map derived from (ideally) a high-resolution sensor, such as the Landsat Thematic Mapper (TM) or SPOT multispectral scanner or from a lower resolution sensor, such as National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (AVHRR) or NASA Moderate Resolution Imaging Spectrometer (MODIS). Given this baseline land cover map, low-spatial and high-temporal resolution satellites, such as AVHRR, can be used to monitor changes in the vegetation vigor, which is correlated with the moisture of the live vegetation. The moisture in the dead vegetation is estimated from knowledge of local weather conditions. Thus, a baseline land cover map and immediate estimate of the vegetation condition are needed.

Ideally local firefighters try to control wildland fires before they become too large to suppress quickly. Immediate suppression action is essential to prevent large wildland fires. In order to minimize the threat of catastrophic wildfires, fire managers must be able to plan protection strategies that are appropriate for local areas. A prerequisite for this planning is the ability to assess and map, for broad areas, the local potential for a major fire to occur. Using such geospatial information,

managers can establish priorities for prevention activities to reduce the risk of wildfire spread and for allocating suppression forces to improve the probability of quickly controlling fires in areas of high concern.

The Canadian Forest Service has developed a Fire Behaviour Prediction System (FBPS) that includes fuel maps, fire weather information, fire behaviour prediction methods, sensitive area maps and fire occurrence. The US Geological Survey (USGS) EROS Data Center, in cooperation with the USDA Forest Service Intermountain Fire Laboratory and the Pan American Institute of Geography and History (PAIGH), developed a method to assess and map broad areas to estimate the potential for fires.

Burgan *et al.* (in press) and Klaver *et al.* (1997) developed a Fire Potential Index (FPI). This index is based on the moisture of live vegetation, the moisture of dead vegetation and the amount of live and dead vegetation. The moisture of the live vegetation is derived from the relative

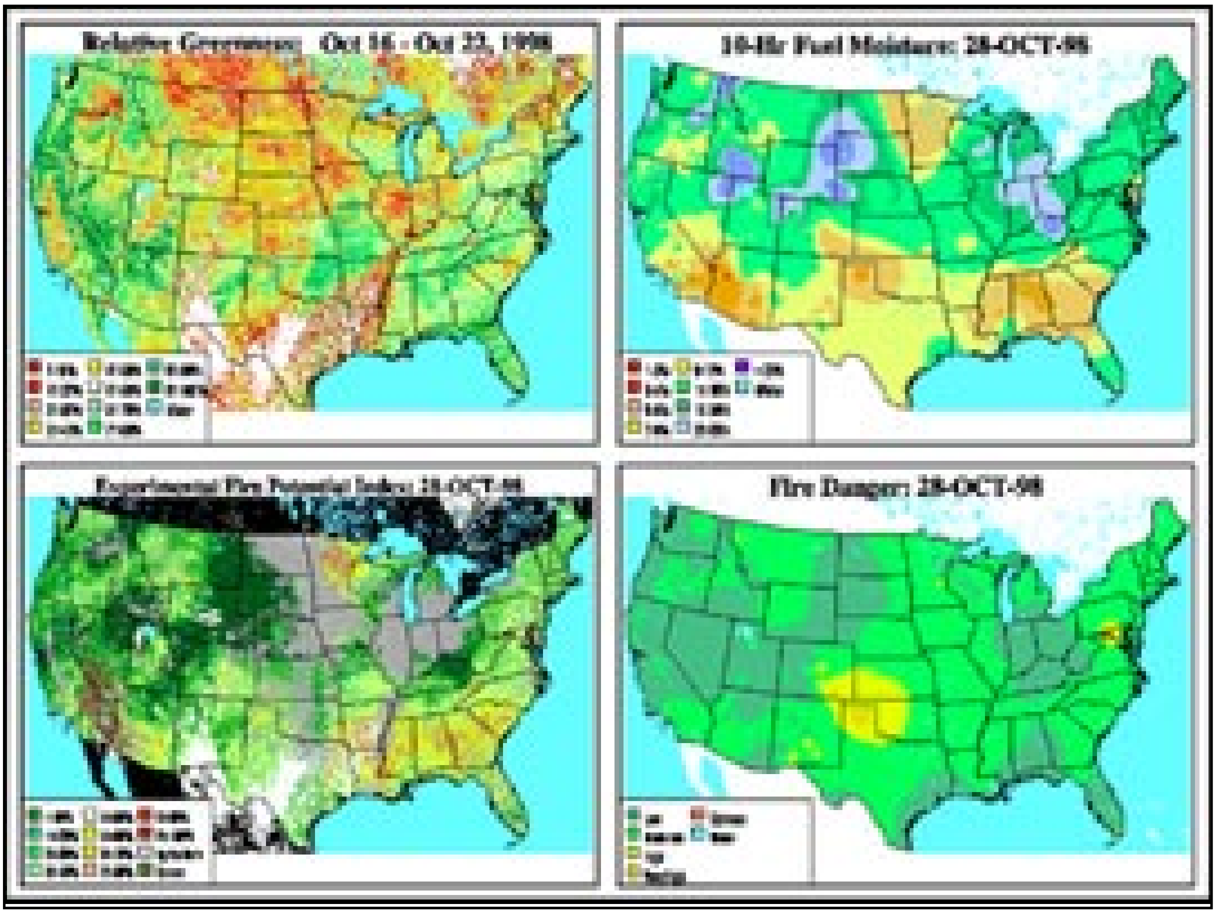

Figure 7. *Fire Potential Index (FPI) in the US*
Notes: This graphic shows the relative greenness and 10-hr fuel moisture used to calculate the Fire Potential Index (FPI) for 2 October 1997. The lower-right graphic shows the traditional National Fire Danger Rating System (NFDRS). The FPI is of higher spatial resolution than the NFDRS. Available at: http://www.fs.fed.us/land/wfas/exp_fp_4.gif
Source: USDA Fire Service

greenness of the Normalized Difference Vegetation Index (NDVI) from the AVHRR sensor (Burgan and Hartford, 1993). The moisture of the dead vegetation is calculated from temperature, relative humidity and weather (Fosberg and Deeming, 1971). The amounts of live and dead fuels are derived by reclassifying existing baseline land cover maps to the National Fire Danger Rating System's (NFDRS) fuel models (Deeming *et al.*, 1978), which provide information on the loadings of live and dead fuels (Bradshaw *et al.*, 1984). The USDA Forest Service calculated FPI daily for the 1997 fire season (Figure 7).

The fire potential and actual fires need to be modeled in concert with socioeconomic information, such as population and land use, to determine costs to the human population in the actual burned areas and in neighboring areas affected direct by the smoke and haze, as well as indirectly by economic losses such as reductions in forest or range productivity and tourism.

5.2 Fire detection

Satellite-borne sensors can detect fires in the visible, thermal and mid-infrared bands. Active fires can be detected by their thermal or mid-infrared signature during the day or night or by the light from the fires at night. For their detection the sensors must also provide frequent overflights, and the data from the overflights must be available fast. Satellite systems that have been evaluated for fire detection include AVHRR, which has a thermal sensor and makes daily overflights, the Defense Meteorological Satellite Program (DMSP) Optical Linescan System (OLS) sensor, which makes daily overflights and routinely collects visible images during its nighttime pass, and the NOAA Geostationary Operational Environmental Satellite (GOES) sensor, which provides visible and thermal images every 15 minutes over the United States and every 30 minutes elsewhere. A brief summary of operational satellite systems having the capability to detect and monitor burned areas is given in Appendix 3.

An evaluation of all three satellite systems for fire detection was conducted in New Mexico, United States (Elvidge *et al.*, 1997c). This evaluation compared the fire detection capabilities of each satellite system with fire reports collected on the ground by the USDA Forest Service. Each satellite system provides unique capabilities and coverage for fire detection. Results from this evaluation indicate that a program dedicated to either early fire detection or monitoring of fire activity would achieve its best results by using data from all three systems in concert.

Data from the OLS sensor must be adjusted to account for the locations of persistent sources of light, such as city lights or gas fires in oil fields (Elvidge *et al.*, 1997a, 1997b). Once these light sources have been identified, the remaining signal can reasonably be associated with vegetation fires (Cahoon *et al.*, 1992). These fires comprise a combination of controlled agricultural-related fires and wildfires. In the Indonesian example, the city lights on Java are clearly visible, and a comparison of the population distribution with the location of many of the detected lights in

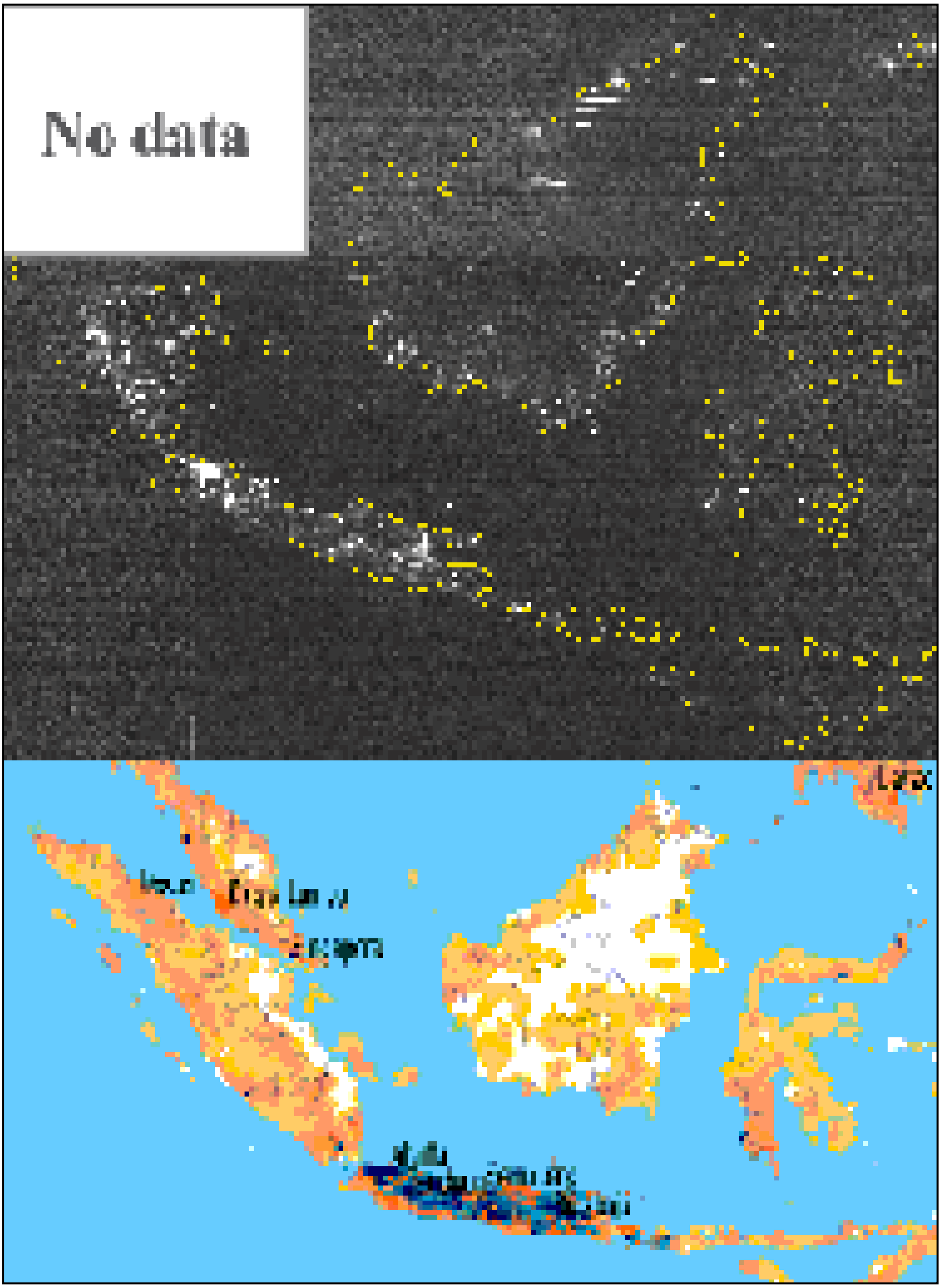

Figure 8. *DMSP OLS night-time visible image from 30 September 1997, available at NOAA WWW site (http://www.ngdc.noaa.gov/dmsp/dmsp.html) and estimated 1995 population density, (http://grid2.cr.usgs.gov/globalpop/).*

Borneo and Sumatra suggests the locations of the wildfires (Figure 8).

AVHRR has been used for detecting and monitoring wildfires. The mid-infrared and thermal bands of AVHRR have been investigated for fire detection (Robinson 1991; Langaas, 1992; Chuvieco and Martin, 1994; Kennedy *et al.*, 1994; Malingreau and Justice, 1997; Pozo *et al.*, 1997). As with OLS images, significant agricultural fires were detected. These controlled agricultural fires can often be excluded through the use of nighttime thermal images. An inspection of a composite of the AVHRR bands produced by NOAA shows both the extent of the smoke and haze from the fire and many of the actual fire locations (Figure 9).

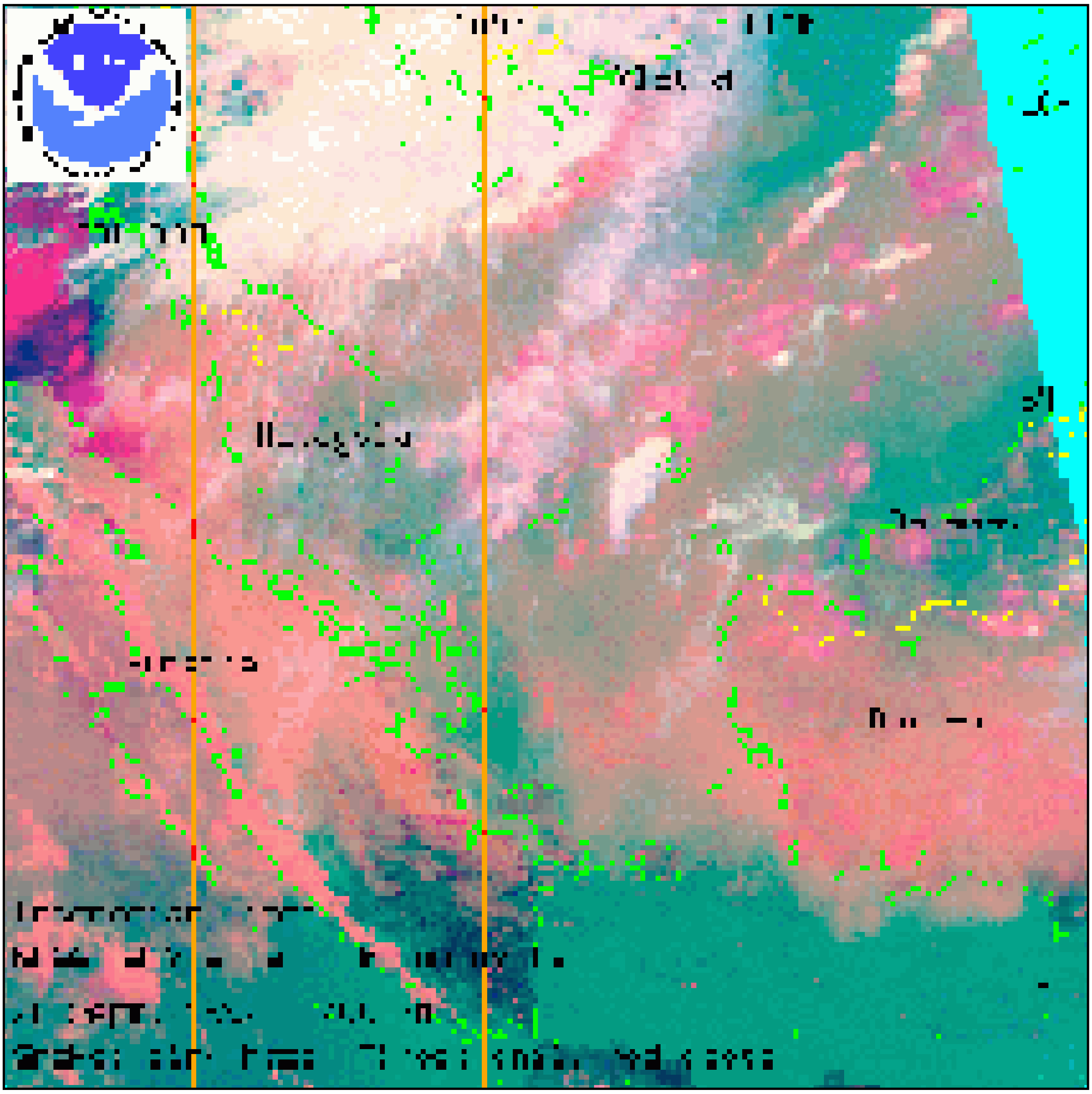

Figure 9. *26 September 1997 AVHRR/GAC image showing smoke haze (pink) and fires (small red spots). AVHRR images can be acquired at http://www.saa.noaa.gov/*
Source: NOAA

5.3 *Fire monitoring*

Fire monitoring differs from fire detection in timing and emphasis rather than in the methods used to process the satellite image information. Fire monitoring measures and delineates the extent of known fires. Fire monitoring includes mapping the growth and change of active fire perimeters and tracking smoke plumes.

Monitoring active fires is similar to fire detection since thermal and nighttime visible imagery is effective for mapping active fire areas. Monitoring the extent of the smoke plume requires analysis of visible and near-infrared wavelengths (Figure 10). Tracking the smoke plume allows the impact of fires on neighboring human populations to be estimated.

Satellite sensors typically provide coarse resolution fire maps which show the general location and extent of wildland fires. Detailed fire suppression mapping requires the use of higher resolution airborne thermal infrared sensors to accurately map small fire hot-spots and active fire perimeters. Higher-resolution fire maps are needed to deploy fire suppression crews and aerial water or retardant drops. Since fire conditions can change rapidly, fire maps derived from airborne thermal sensors need to be delivered to fire managers within a few hours after the flight.

5.4 *Fire assessment*

Once fires are extinguished, a combination of low-resolution images (AVHRR) and higher-resolution images (SPOT, Landsat and radar) can be used to assess the extent and impact of the fire (Figure 11). Radar has proved effective in monitoring and assessing the extent and severity of fire scars in the boreal forests (Kasischke *et al.*, 1994), for quantifying biomass regeneration in tropical forests (Luckman *et al.*, 1997) and for modeling ecosystem recovery in Mediterranean climates (Viedma *et al.*, 1997). Low-resolution visible and infrared sensors such as AVHRR have proved useful for automated fire mapping (Fernandez *et al.*, 1997) and for evaluating the impact of fire on long-term land cover change (Ehrlich *et al.*, 1997). Multi-resolution studies incorporating both AVHRR and Landsat images reveal the scale-related influences of analyzing post-fire vegetation regeneration (Steyaert *et al.*, 1997).

Information related to new fire scars and vegetation succession within the scars can be used to update the baseline vegetation map used for fire prediction. Continued monitoring of the fire scars provides extensive information on land cover transitions involving changes in productivity and biodiversity, which in turn influence fire potential. Knowledge of the extent and intensity of the fire scars provides important information for the rehabilitation of the burn areas.

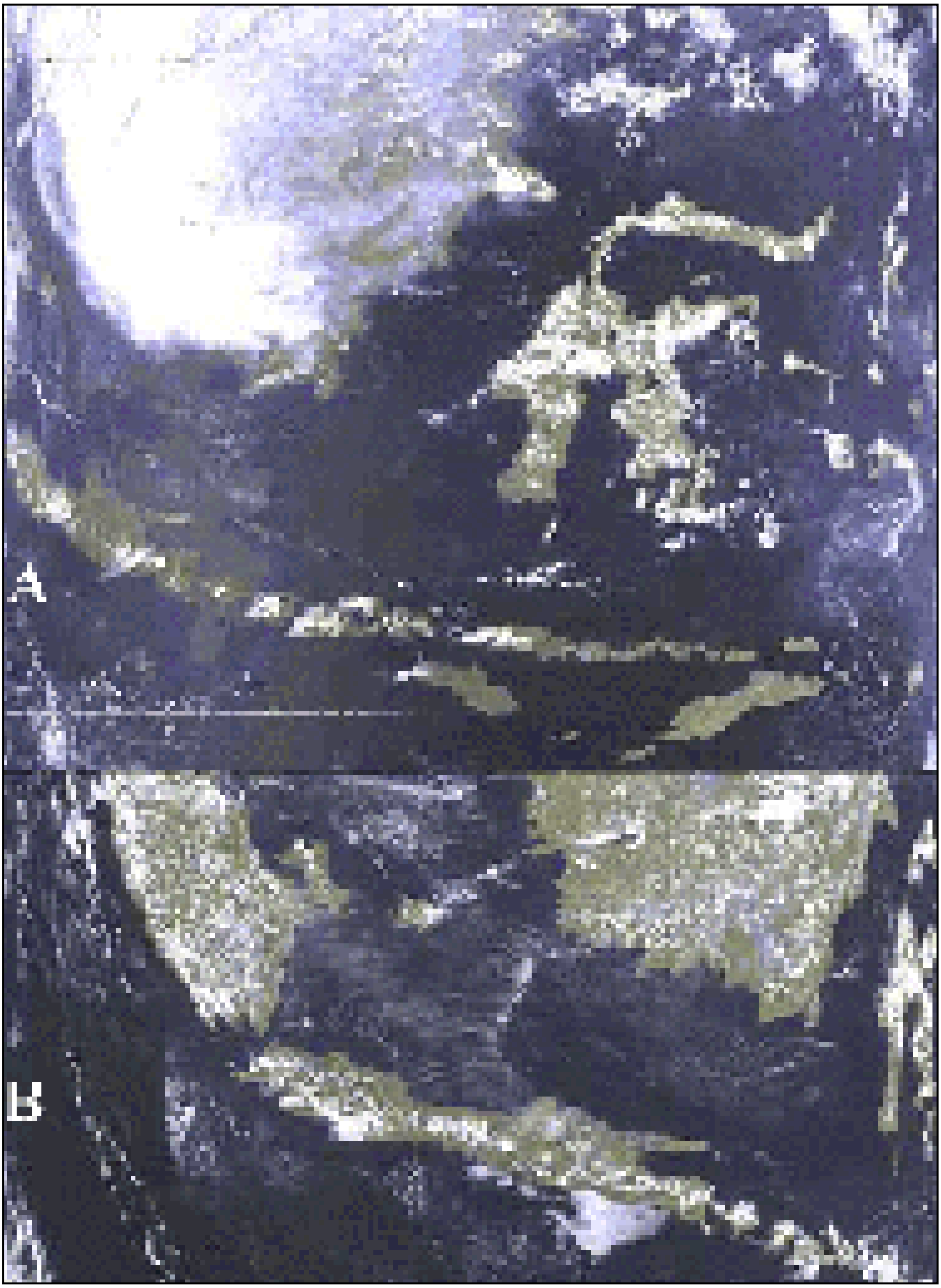

Figure 10. *4 August 1997 (B) and 22 September 1997 (A) AVHRR browse images.*
Source: Satellite Remote Sensing Services, Department of Land Administration, Australia.

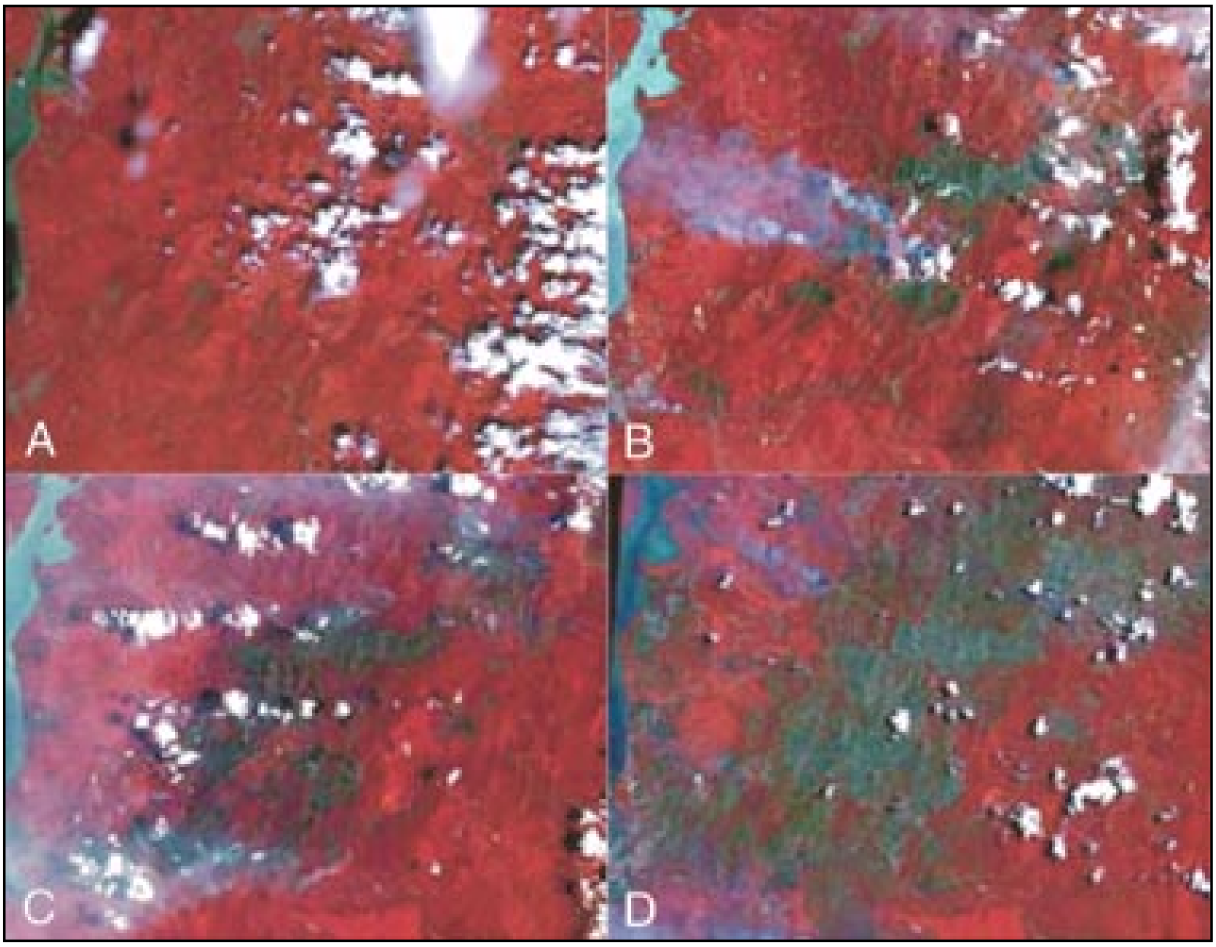

Figure 11. *Fires and smoke haze along the western coast of Sabah, in the northern part of Borneo.*
Notes: A: A reduced resolution SPOT quicklook image covering about 40 km by 30 km. Acquired 20 September 1997.
B: Image of the same area in February 1998, the town of Sipitang is located to the right of the image. Acquired 24 february 1998.
C: Image of the same area two weeks later. Acquired 8 Mars 1998.
D: Large burnt scars (blackish areas) are visible on the image. Acquired 4 April 1998.
Source: All images are acquired by the SPOT satellites. Copyright of images belongs to CNES (Centre National d'Etudes Spatiales). Images are acquired and processed by the Centre for Remote Imaging, Sensing and Processing, National University of Singapore.

6 Global responses

Within the United Nations system, the United Nations Environment Programme (UNEP) was asked to coordinate the international community's response to the forest fires emergency in Indonesia. Donors responded, both with cash and direct assistance, to a joint appeal for emergency assistance to the region made by UNEP and the UN's Office for the Coordination of Humanitarian Affairs (OCHA) earlier in the year. An appeal, made on the basis of recommendations from a fire-fighting experts' meeting in Geneva in April 1998, was made at a time when fires raged in large parts of Indonesia's East Kalimantan province, threatening much of the region with smog. With the twin objectives of containing and preventing the recurrence of fires in priority areas, aid priorities were identified as fire-fighting packages and other specialized equipment, expert advice, training, aerial surveillance and enhanced communications.

Countries in the region had also taken steps to help mitigate the problem. Singapore, for example, provided communications equipment, and Malaysia trained Indonesian fire-fighters as part of the Sub-Regional Fire-fighting Arrangement worked out among the countries most affected by the disaster.

The extensive wildland fires during 1997 and 1998 highlight the need to coordinate international fire detection, suppression and rehabilitation efforts. Several government agencies and relief organizations provided assistance to countries such as Indonesia, Brazil and Mexico. In the case of Indonesia, support came from many countries including: Australia, Canada, Denmark, Finland, France, Germany, Japan, Malaysia, New Zealand, Norway, Singapore, Sweden, South Korea, the United Kingdom and the United States. In addition, the United Nations Disaster Assessment and Coordination team led by UNEP, and other international organizations such as the European Union, the Asian Development Bank, the Center for International Forestry Research and the World Wide Fund for Nature provided assistance and technical assessments.

6.1 Emergency response to forest fires

The fires in Indonesia prompted many international assistance programs to help mobilize people and equipment to extinguish the flames and prevent further damage to the forest ecosystem, and public health, and to minimize effects on neighboring countries. However, the efforts to extinguish the fires proved costly and difficult. Cloud seeding to induce rain, use of helicopters and fixed-wing aircraft for water bombing and ground attack all had minimal effect in controlling the fires. The fires were too large and widespread to use conventional fire suppression techniques effectively. Fires in zones where forests and agricultural areas overlie deposits of peat are especially difficult to extinguish. These fires burn deep into the thick layers of peat and smolder for a long time even after repeated attempts to extinguish the fire with aerial water drops.

6.2 GRID's activities relating to the forest fires situation

The numerous fires in 1997 and 1998 have resulted in a demand that information be available to help provide a quick response. GRID-Sioux Falls created the first WWW site (http://grid2.cr.usgs.geov/globalfire/start.html) within the UN to raise awareness about the Indonesian forest fires, reviewed the methodology for forest fire potential. The Klaver *et al.* (1997) paper on "Global Forest Fire Watch" is available on the site (http://grid2.cr.usgs.gov/globalfire/indofire/firepaper.html). At GRID-Geneva, a methodology was set up to produce a weekly report including documents such as maps and satellite images downloaded from the WWW and further refined or produced by GRID-Geneva itself (*e.g.* Figure 12). Theses reports are now collectively available, and continue to be updated weekly, at GRID-Geneva's website (http://www.grid.unep.ch/fires/). Satellite imagery and associated GIS data have already been shown to offer a time- and cost-effective way of evaluating situations during and after a natural disaster. They can often provide information on the precise location of the disaster, its evolution, access to a given area and local impacts on inhabitants, wildlife and flora. This was important during the forest fires in the Russian Federation in 1998 (UNDAC, 1998b; *e.g.* Figure 13).

These activities and the production of similar image products, maps and reports on the forest and wildfires of the last two years (by European Space Agency (ESA), Integrated Forest Fire Management Project (IFFM), NASA, National Space Development Agency (NASDA), NOAA, Singapore Meteorological Service (SMS), UNEP/GRID *et al.*) highlight the need for greater coordination of such efforts at the international level. A global overview of fire events, accompanied by relevant, up-to-date images, maps and local situation reports, produced in a consistent format and issued on a regular basis, could become a key tool for the international community in general and decision-makers in particular, and to focus public attention on this issue. Appendix 4 gives relevant websites for fire monitoring and assessment.

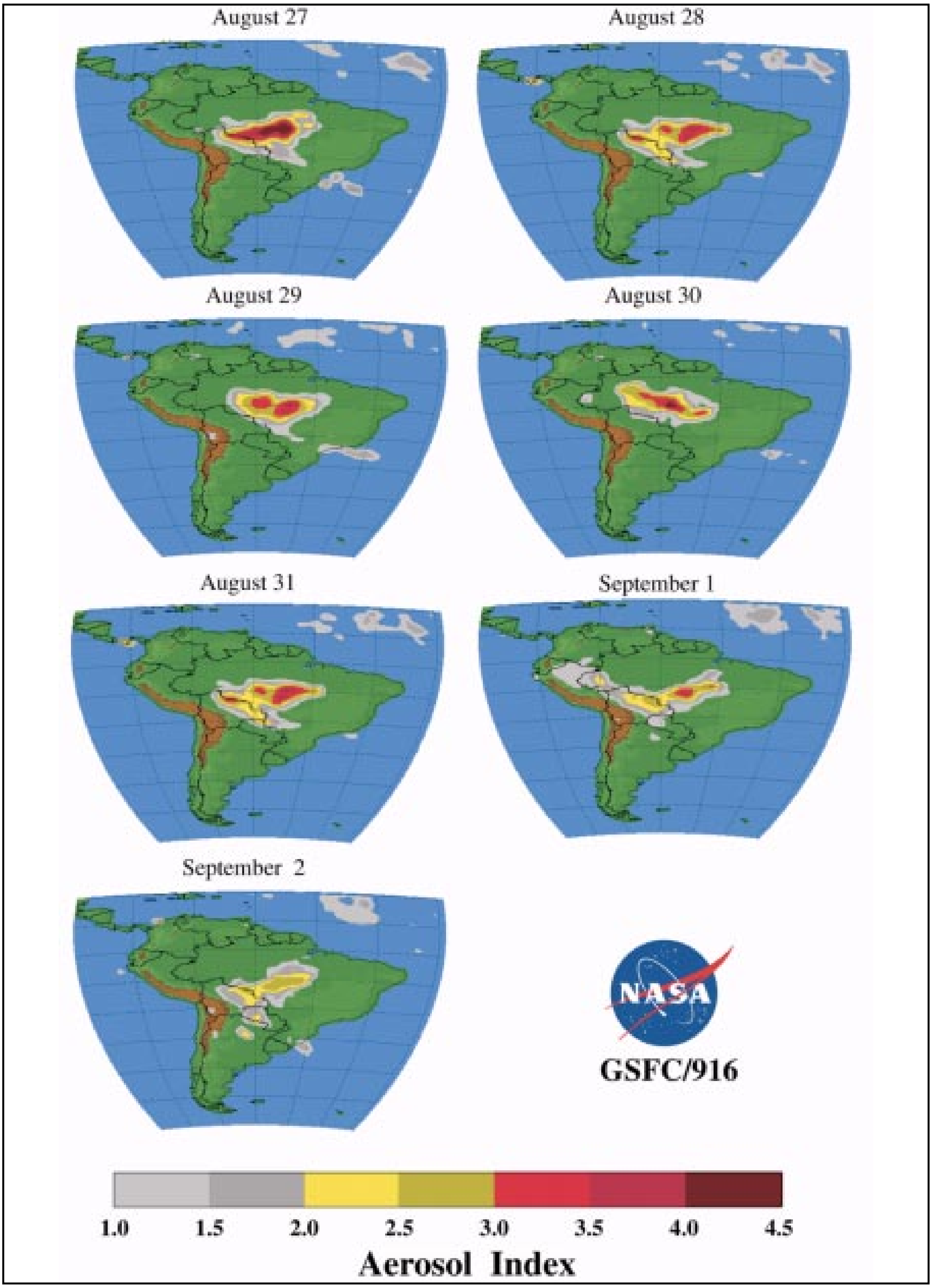

Figure 12. *Smoke over South America. Evolution from 27 August until 2 September 1998.*
Source: NASA/TOMS Earth Probe.

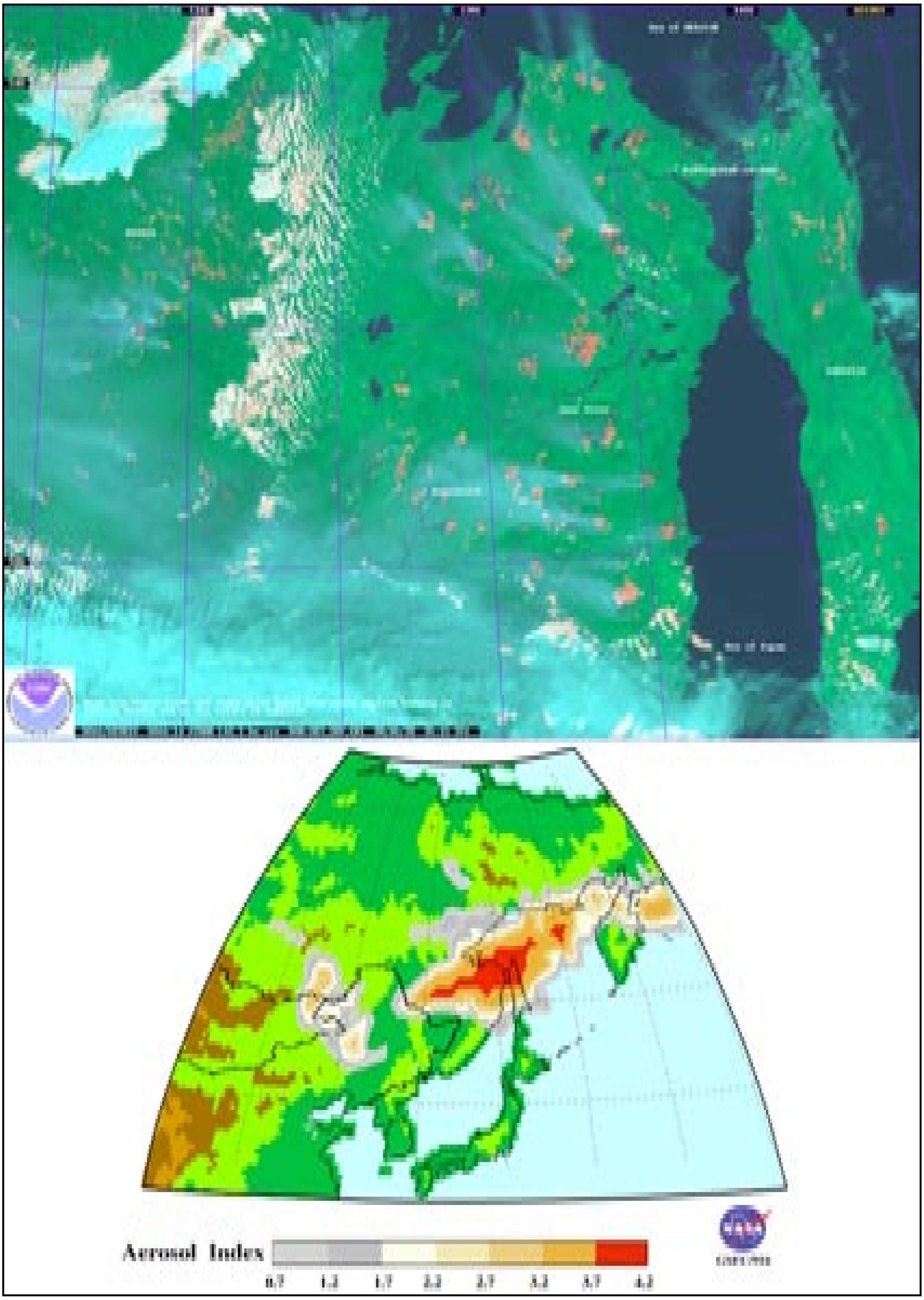

Figure 13. *Wildland fires in the Russian Federation in 1998.*
Notes: Above image: NOAA/AVHRR multichannel image from 6 August 1998 showing heat signatures (red) and smoke (blue haze) from areas of fire in eastern Russia and on the Island of Sakhalin. Below figure: Smoke over Russia, with associate Aerosol Index, from 16 August 1998.
Source: NOAA and NASA/TOMS Earth Probe.

7 Recommendations

There is a need for an international fire coordination centre, to provide to provide leadership and direction in coordinating international fire prevention, training, monitoring, suppression and assessmen. The centre could address the following activities:

a. Coordinate efforts to monitor global fire risk:

Monitor and predict drought conditions that lead to unusual fire danger;

Map risk according to vegetation and fuel types;

Report fire risk danger to local fire management and forestry offices responsible for activating land use and fire restrictions based on fire danger rating.

b. Coordinate development of a global satellite fire detection and reporting system:

Use the combination of AVHRR, GOES, and DMSP satellite systems to identify fire starts early on;

Identify communication protocol and requirements to convey fire start information to local fire management offices responsible for fire suppression response.

c. Coordinate development of a global fire monitoring system:

Develop a dedicated fire monitoring system from satellite data to provide immediate information on fires to the affected countries. Such a system would utilize satellite and ancillary data (existing GIS data and available airborne imagery) to prepare daily fire perimeter maps, to be used by local fire management offices to coordinate fire suppression efforts;

Utilize remotely sensed imageries to map fire extent, smoke plumes and fire intensity to assess environmental impacts.

d. Support fire suppression coordination efforts:

Serve as a clearinghouse to distribute information, geospatial data and international contacts to determine available fire suppression resources;

Provide training in fire suppression techniques.

e. Fire prevention:

Assist in developing guidelines for regulation of agriculture burning, logging, land clearing and other land uses that create uncontrolled fires;

Establish guidelines for management of combustible fuels;

Coordinate development of technology transfer and training methods to raise public awareness of fire danger risks and the benefits of preventing uncontrolled burning.

8 Conclusions

It is possible to reduce both the risk of forest fires and the cost of these disasters when they do occur, through better application of information technology to forest fire management. Some developed countries like Canada and the United States have installed an operational Fire Danger Rating System to produce daily national maps of “fire weather” and fire danger. There is a need to develop a “Global Forest Fire Watch” system that would provide fire potential ratings including early warning and risk assessment, fire detection, fire monitoring and fire assessment on a regular basis. The creation of such a system will require high-quality vegetation maps, near real-time inexpensive satellite images, weather information and a local requirement for fire-related services and products. There is also a pressing need to improve technical capabilities and information infrastructure in developing countries to support regional, national and local decision-making capabilities related to fire management, and also to improve communication, coordination and rapid response to forest fires.

The extensive fires in Indonesia and other developing countries are in part due to the increased pressure of expanding human populations and demands for agricultural and forest products. Ultimately, the solution for preventing a recurrence of large-scale uncontrolled burning relies on the ability of local government agencies to regulate land development and enforce restrictions to use fire as a land-clearing tool. Since the majority of uncontrolled wildland fires are caused by local rural populations, an effective fire prevention and control program will require a complete understanding of the cultural and socio-economic values, background and livelihoods of local peoples. Successful prevention of uncontrolled wildland fires requires the understanding by local populations of the economic and ecological benefits of fire prevention, and the securing of a strong commitment on their part to prevent intentional and carelessly started fires.

At the same time, the annual re-occurrence of local and even wide-spread forest and grassland fires in more developed countries, typically as "natural" events, reminds us this is a global phenomenon to be dealt with in many countries (for statistics of forest fire in developed countries, see ECE/TIM, 1997). Further international cooperation and sharing of expertise and technology would certainly benefit all of those affected, and help to control or dampen the worst impacts of such fires on both humankind and nature.

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Appendix 1. Area burned in Sumatra, Kalimantan and Java, Indonesia.

October-November, 1997 and February-March, 1998 (Based on USDA Forest Service fire maps) (Levine *et al.*, 1998)

Region	Date	Total Area (km^2)
Sumatra		
Jambi	15-Oct-97	199.39
Muaraenim	15-Oct-97	898.35
Sukarami	15-Oct-97	730.87
Jambi	19-Oct-97	169.86
Rengat South	19-Oct-97	245.71
Sukarami	19-Oct-97	403.86
Lahat	21-Oct-97	319.95
Sukarami	27-Oct-97	4.40
Buluranriding River	30-Oct-97	330.76
Talang Gelumbang	30-Oct-97	947.70
Talang Kubuan	30-Oct-97	2281.34
Kotabumi	04-Nov-97	693.02
North Kotaagung	04-Nov-97	242.82
Kotabumi	07-Nov-97	73.32
Bulau River	09-Nov-97	258.30
East Karangagung	09-Nov-97	733.23
Jambi	09-Nov-97	35.00
Sukadana	09-Nov-97	169.59
Bandar	11-Nov-97	86.21
Kasui	11-Nov-97	274.53
Kotabumi	11-Nov-97	183.79
Sukadana	12-Nov-97	79.00
Sukadana	12-Nov-97	82.44
Bandar	13-Nov-97	15.29
Kotabumi	13-Nov-97	115.73
Surabaja	13-Nov-97	404.90
Bandar	14-Nov-97	90.93
Kasui	14-Nov-97	165.15
Sukadana	14-Nov-97	37.03
Bandar	15-Nov-97	31.45
Sukadana	15-Nov-97	93.19
Kasui	16-Nov-97	35.80
Kotabumi	16-Nov-97	605.02
Surabaja	16-Nov-97	47.65
Bandar	17-Nov-97	62.63
Surabaja	17-Nov-97	54.81
Bujut	19-Nov-97	124.02
Kotabumi	19-Nov-97	229.04
Bujut	20-Nov-97	47.69
Sukadana	22-Nov-97	381.61

Region	Date	Total Area (km^2)
Kotabumi	23-Nov-97	11.34
Surabaja	23-Nov-97	360.47
Kasui	28-Nov-97	113.29
Bandar	30-Nov-97	25.28
Surabaja	30-Nov-97	351.27
Kampar	6-Mar-98	42.60
Kampar	10-Mar-98	44.22
Subtotal		***12933.85***
Kalimantan		
Batuwinang	27-Oct-97	557.28
Matua	27-Oct-97	1140.87
Satui	27-Oct-97	852.12
Bapuju	28-Oct-97	805.28
West Batuwinang	29-Oct-97	791.05
Batuwinang	25-Nov-97	75.30
Nanang	7-Feb-98	209.27
Susang	7-Feb-98	75.42
Santan	13-Feb-98	328.26
Melintang	19-Feb-98	967.49
Susang	19-Feb-98	9.22
Mahakam	20-Feb-98	422.57
Penawai	20-Feb-98	208.22
Sidulang	20-Feb-98	95.07
Saliki	21-Feb-98	142.88
Sambodja	21-Feb-98	99.97
Penawai	22-Feb-98	152.16
Mengangau	23-Feb-98	209.45
Susang	23-Feb-98	19.30
Gitan	24-Feb-98	306.44
Djambu	25-Feb-98	66.04
Bontang	27-Feb-98	325.93
Sedulang	27-Feb-98	562.44
Guntung	28-Feb-98	973.46
Sangatta	3-Mar-98	670.15
Sideman	4-Mar-98	208.41
Rapak	13-Mar-98	2050.68
Subtotal		***12334.73***
Java		
Malang	6-Oct-97	76.19
Madium	22-Oct-97	277.77
Blitar	23-Oct-97	9.00
Subtotal		***362.96***
Total		**25631.54**

Appendix 2. Analysis of the atmospheric impacts and overall areas burned in Indonesia by the 1997-1998 fires.

A2-1. Calculation of gaseous and particulate emissions from the forest and peat fires in Kalimantan and Sumatra

A recent study conducted by the Atmospheric Sciences Division, NASA/Langley Research Center has examined the fires in Kalimantan and Sumatra, Indonesia to determine gaseous and particulate emissions. Biomass burning, the burning of living and dead vegetation for land-clearing and land-use change, has been identified as a significant source of gases and particulates to the regional and global atmosphere (Crutzen *et al.*, 1979; Seiler and Crutzen, 1980; Crutzen and Andreae, 1990; Levine *et al.*, 1995). The bulk of the world's biomass burning occurs in the tropics, primarily in the tropical forests of South America and Southeast Asia and in the savannas of Africa and South America. The majority of biomass burning (perhaps as much as 90%) is believed to be human-initiated, natural fires triggered by atmospheric lightning accounting for the rest (Andreae, 1991).

Over the last few years, books have documented much of the scientific understanding of biomass burning, including the remote sensing of fires, fire ecology, fire measurements and modeling, fire combustion, gaseous and particulate emissions from fires, the atmospheric transport of these emissions and the chemical and climatic impacts of burning. These volumes include: Goldammer (1990), Levine (1991), Crutzen and Goldammer (1993), Goldammer and Furyaev (1996), Levine (1996a), Levine (1996b) and van Wilgen *et al.* (1997).

The major gases produced during the biomass burning process include carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), oxides of nitrogen (NO_x = nitric oxide (NO) + nitrogen dioxide (NO_2)) and ammonia (NH_3). Carbon dioxide and methane are greenhouse gases, which trap Earth-emitted infrared radiation could possibly lead to global warming. Carbon monoxide, methane, and the oxides of nitrogen lead to the photochemical production of ozone (O_3) in the troposphere. In the troposphere, ozone is an irritant and harmful pollutant, and in some cases is toxic to living systems. Nitric oxide leads to the chemical production of nitric acid (HNO_3) in the troposphere. Nitric acid is the fastest growing component of acidic precipitation. Ammonia is the only basic gas that neutralizes the acidic nature of the troposphere. Particulates, small solid particles (usually about 10 micrometers or smaller), such as smoke or soot particles, are also produced by burning and released into the atmosphere. These particulates absorb and scatter incoming sunlight and hence impact the local, regional and global climate. In addition, these particulates (specifically particulates 2.5 micrometers or smaller) can lead to various human respiratory and general health problems when inhaled. The gases and particulates produced during biomass burning lead to the formation of *smog*. The word *smog* was coined as a combination of smoke and fog and is now used to describe any smoky or hazy pollution in the atmosphere.

Appendix 2

To assess environmental impacts of forest burning, the gaseous and particulate emissions produced during the fire and released into the atmosphere must be calculated. To illustrate the procedures to calculate the gaseous and particulate emissions produced during forest fires and peat fires, the widespread forest and peat fires in Kalimantan and Sumatra, Indonesia, in 1997 was considered (Figure 14). The calculation includes the relevant mathematical relationships for calculating total mass burned and the various gases and particulates produced, and makes use of the following information: area burned, biomass burned, biomass loading, fire efficiency and the various species emission ratios.

Figure 14. *Fields burning in peat moss area. Kuala Kapuas. Central Kalimantan, Indonesia. 1997.*

The gaseous emissions from tropical forest and peat fires can be calculated using an expression from Seiler and Crutzen (1980):

$$(1)\ M = A * B * E$$

where M = total mass of forests or peat consumed by burning (tons), A = area burned (km^2), B = biomass loading ($tons/km^2$), and E = burning efficiency.

Since carbon represents about 45% of the mass of the tropical forests, the total mass of carbon

(M(C)) released to the atmosphere during forest burning is related to M by the following expression:

$$(2)\ M(C) = 0.45\ M\ \text{(Units of tons of carbon)}$$

For burning of tropical forests, about 90% of the carbon is in the form of CO_2 (Andreae, 1991) and the mass of CO_2 ($M(CO_2)$) released to the atmosphere is related to M(C) by the following expression:

$$(3)\ M(CO_2) = 0.90\ M(C)\ \text{(Units of tons of carbon in the form of } CO_2\text{)}$$

About 50% of the mass of peat is in the form of carbon (Yokelson *et al.*, 1997). During the burning of peat, about 77% of the released carbon is in the form of CO_2 (Yokelson *et al.*, 1997). Hence, the mass of CO_2 ($M(CO_2)$) released to the atmosphere is related to M, the mass of the peat, by the following expression:

$$(4)\ M(CO_2) = (0.50)\ (0.77)\ M\ \text{(Units of tons of carbon in the form of } CO_2\text{)}$$

Once the mass of CO_2 produced by burning is known, the mass of any other species, X_i ($M(X_i)$), produced by burning and released to the atmosphere can be calculated with knowledge of the CO_2-normalized species emission ratio ($ER(X_i)$). The emission ratio is the ratio of the production of species X_i to the production of CO_2 in the fire. The mass of species, X_i, is related to the mass of CO_2 by the following expression:

$$(5)\ M(X_i) = ER(X_i) * M(CO_2)\ \text{(Units of tons of element } X_i\text{)}$$

In these calculations, X_i = CO, CH_4, NO_x, NH_3 and O_3. It is important to note that O_3 is not a direct product of biomass burning. However, O_3 is produced via photochemical reactions of CO, CH_4, and NO_x, all of which are produced directly by biomass burning. Hence, the mass of ozone resulting from biomass burning may be calculated by considering the ozone precursor gases produced by biomass burning. Values of CO_2 and CO_2-normalized gaseous species emission ratios for tropical forests and peatlands are given in Table 2. The tropical forest fire emission ratios for gases in Table 2 are based on the measurements of Andreae (1991), Andreae *et al.* (1988) and Blake *et al.* (1996). These emission measurements were obtained for burning tropical forests in South America, not Southeast Asia. However, studies indicate that the emission ratios from tropical forests in South America should be comparable to those in Southeast Asia (see, for example, Andreae, 1991 and Brown and Gaston, 1996).

The peat fire emission ratios for gases in Table 2 are based on the measurements of Yokelson *et al.* (1997). These emission measurements were obtained for burning peat from Minnesota and

Alaska. Because emissions measurements for burning Indonesian peat are rare in the literature, values from Yokelson *et al.* (1997) were used. Yokelson *et al.* (1997) did not obtain emission ratios for either NO_x or O_3 from burning peat. To estimate the emission ratio for NO_x from peat fires, the expression for the production ratio of NH3/NO_x = 14 x (1 - MCE), was used where MCE is the modified combustion efficiency (Yokelson *et al.*, 1996). For NH_3 = 1.28% (Yokelson *et al.*, 1997), the value of NO_x is 0.457%. CO, CH_4 and NO_x are the precursors in the photochemical production of O_3. For peat fires, the emission ratios for CO, CH_4 and NO_x are 18.15%, 1.04% and

Species	Tropical Forest	Reference	Peat Fires	Reference
CO_2	90.00%	Andreae (1991)	77.05%	Yokelson *et al.* (1997)
O	8.50%	Andreae *et al.* (1988)	18.15%	Yokelson *et al.* (1997)
CH_4	0.32%	Blake *et al.* (1996)	1.04%	Yokelson *et al.* (1997)
NO_x	0.21%	Andreae *et al.* (1998)	0.46%	Derived from Yokelson *et al.* (1997); see text
NH_3	0.09%	Andreae *et al.* (1998)	1.28%	Yokelson *et al.* (1997)
O_3	0.48%	Andreae *et al.* (1998)	1.04%	Derived from Yokelson *et al.* (1997); see text
TPM	20 tons/kiloton	Ward (1990)	35 tons/kiloton	Ward (1990)

Table 2. *Emission Ratios for Tropical Forest Fires and Peat Fires*
Notes: Total particulate matter (TPM) emission ratios are in units of tons/kiloton (tons of total particulate matter/kiloton of biomass or peat material consumed by fire).

0.457% (Yokelson *et al.,* 1997). NO_x is the reaction-limiting species in the photochemical production of O_3. To estimate the emission ratio of O_3 for peat fires, we have assumed that the ratio of emission ratio of O_3 to NO_x in forest fires is comparable to that ratio in peat fires. For these assumptions, the emission ratio of O_3 from peat fires is found to be 1.0653%.

To calculate the total particulate matter (TPM) released from tropical forest fires and peat fires, the following expression is used (Ward, 1991):

$$(6)\ TPM = M * C$$

where C is the conversion of biomass matter or peat matter to particulate matter during burning.

For tropical forest burning, C = 20 tons of TPM per kiloton of biomass consumed by fire. For peat burning, it is assumed that C = 35 tons of TPM per kiloton of biomass consumed by fire (Ward, 1991). Ward (1991) gives a value of 35 tons of TPM per kiloton of burned 25% organic soil. In the absence of a value of C for peat burning this value has been used.

A2-2. Total area burned and biomass consumed

Perhaps the major uncertainties in the calculation of gaseous and particulate emissions resulting from fires involve poor or incomplete information about four fire parameters: (1) The area burned (A), (2) The ecosystem or terrain that burned, *i.e.*, forests, grasslands, agricultural lands, etc., and (3) The biomass loading (B), *i.e.*, the amount of biomass per unit area of the ecosystem prior to burning, and (4) The fire efficiency (C), *i.e.*, the amount of biomass in the burned ecosystem that was actually consumed by burning.

Indonesia ranks third, after Brazil and Democratic Republic of Congo, in its area of tropical forest. Of Indonesia's total land area of 1.9 million km^2, current forest cover estimates range from 0.9 to 1.2 million km^2, or 48% to 69% of the total. Forests dominate the landscape of Indonesia (Makarim *et al.*, 1998). Large areas of Indonesian forests burned in 1982 and 1983. In Kalimantan alone, the fires burned from 2.4 to 3.6 million hectare (ha) of forests (Makarim *et al.*, 1998). It is interesting to note that there is an uncertainty of 1.2 million ha or an uncertainty of 50% in our knowledge of the burned area of fires that occurred 16 years ago.

As already noted, analyses using two different techniques for the determination of the area burned in 1997 have been reported (Levine *et al.*, 1998 and Liew *et al.*, 1998). Levine *et al.* (1998) calculated the burned area in Sumatra and Kalimantan for 1997 from fire maps of regions of the highest density of fires prepared by the USDA Forest Service. For 1997, Levine *et al.* (1998) found a burned area of 12, 847 km^2 in Sumatra and 4221.90 km^2 in Kalimantan, for a total burned area of 17,068.93 km^2.

Liew *et al.* (1998) analyzed 766 SPOT "quicklook" images with almost complete coverage of Kalimantan and Sumatra from August to December 1997. Liew *et al.* (1998) estimate the burned area in Kalimantan to be 30,600 km^2 and the burned area in Sumatra to be 15,000 km^2, for a total burned area of 45,600 km^2. The Liew *et al.* (1998) area estimate is a factor of 2.7 greater than the area estimate of Levine *et al.* (1998). This is not surprising since the Liew *et al.* (1998) estimate is based on almost complete coverage of Kalimantan and Sumatra, while the Levine *et al.* (1998) estimate is based on the USDA Forest Service maps prepared for only the very highest density fire regions in Kalimantan and Sumatra. For the calculations reported in this paper the Liew *et al.* (1998) estimate has been used for total burned area in Kalimantan and Sumatra of 45,600 km^2. It is important to emphasize that accurate estimates of the total area burned is difficult and very time consuming. The estimate of Liew *et al.* (1998) represents only a lower limit estimate of the area

burned in Southeast Asia in 1997, since the SPOT data only covered Kalimantan and Sumatra and did not include fires on the other Indonesian islands of Irian Jaya, Sulawesi, Java, Sumbawa, Komodo, Flores, Sumba, Timor and Wetar or the fires in the neighboring countries of Malaysia and Brunei.

What is the nature of the ecosystem and terrain that burned in Kalimantan and Sumatra? In October 1997, NOAA satellite monitoring produced the following distribution of fire hot spots (UNDAC, 1998a): agricultural and plantation areas: 45.95%; bush and peat soil areas: 24.27%; productive forests: 15.49%; timber estate areas: 8.51%; protected areas: 4.58%; and transmigration sites: 1.20%. The three forest/timber areas add up to a total of 28.58% of the area burned. While the distribution of fire hot spots is not an index for area burned, the NOAA satellite-derived hot spot distribution is quite similar to the distribution of burned area deduced by Liew *et al.* (1998) based on SPOT images of the actual burned areas: agricultural and plantation areas: 50%; forests and bushes: 30%; and peat swamp forests: 20%. Since, the terrain burned estimates of Liew *et al.* (1998) were based on actual SPOT images of the burned area, their estimates were adopted in the calculations.

1. Total Area Burned in Kalmantan and Sumatra, Indonesia in 1997: 45,600 km^2

2. Distribution of:		**Burned Areas**	**Biomass Loading**	**Combustion Efficiency**
A.	Agricultural and plantation areas	50%	10,000 tons/km^2	0.20
B.	Forests and bushes	30%	5,000 tons/km^2	0.20
C.	Peat swamp forests	20%	97,500 tons/km^2	0.50

Table 3. *Parameters Used in Calculations*

What is the biomass loading for the three terrain classifications identified by Liew *et al.* (1998)? The biomass loading for tropical forests in Southeast Asia ranges from 5,000 to 55,000 tons/km^2, with a mean value of 23,000 tons/km^2 (Brown and Gaston, 1996). However, in the calculations a value of 10,000 tons/km^2 has been used to be conservative. The biomass loading for agricultural and plantation areas (mainly rubber trees and oil palms) of 5,000 tons/km^2, is also a conservative value (Liew *et al.*, 1998). Nichol (1997) has investigated the peat deposits of

Kalimantan and Sumatra and used a biomass loading value of 97,500 tons/km^2 (Supardi *et al.*, 1993) for the dry peat deposits 1.5 m thick as representative of the Indonesian peat in her study. The combustion efficiency is estimated at 0.20 for forests, and at 0.50 for peat (Levine and Cofer, 1999). Based on the discussions presented in this section, the values for burned area, biomass loading and combustion efficiency used in the calculations are summarized in Table 3.

A2-3. Results of calculations: gaseous and particulate emissions

The calculated gaseous and particulate emissions are summarized in Table 4. For each of the seven species listed, the emissions due to agricultural burning (A), forest burning (F), and peat burning (P) are given. The total (T) of all three components (A+F+P) is also given. The total emissions are summarized as: CO_2: 191.485 million metric tons of C (MtC); CO: 32.80 MtC; CH_4: 1.845 MtC; NO_x: 5.898 MtN; NH_3: 2.585 MtN; O_3: 7.100 MtO_3; and total particulate matter:

Species	Emissions		Species	Emissions	
CO_2	A:	9.234	CH_4	A:	0.030
	F:	11.080		F:	0.035
	P	171.170		P:	1.780
	T:	191.485		T:	1.845
CO	A:	0.785	NO_x	A:	0.023
	F:	0.942		F:	0.027
	P:	31.067		P:	5.848
	T:	32.794		T:	5.898
NH_3	A:	0.010	O_3	A:	0.177
	F:	0.012		F:	0.213
	P:	2.563		P:	6.710
	T:	2.585		T:	7.100
TPM	A:	0.046			
	F:	0.547			
	P:	15.561			
	T:	16.154			

Table 4. *Gaseous and particulate emissions from the fires in Kalimantan and Sumatra in 1997 (For total burned area = 45,600 km^2)*

Notes: Units of emissions: Million metric tons(Mt) of C for CO_2, CO and CH_4; Mt of N for NO_x and NH_3; Mt of O_3 for O_3; Mt of particulates; 1 million metric tons = 10^{12} grams = 1 Teragram, Tg.
Total particulate matter (TPM) emission ratios are in units of tons/kiloton (tons of total particulate matter/kiloton of biomass or peat material consumed by fire).
(A = Agricultural/Plantation Fire Emissions, F = Forest Fire Emissions, P = Peat Fire Emissions, T = Total Fire Emissions = A + F + P)

16.154 MtC. It is important to re-emphasize, however, that these emission calculations represent lower limit values since the calculations are only based on burning in Kalimantan and Sumatra in 1997. The calculations do not include burning in Java, Sulawesi, Irian Jaya, Sumbawa, Komodo, Flores, Sumba, Timor and Wetar in Indonesia or in neighboring Malaysia and Brunei.

It is interesting to compare the gaseous and particulate emissions from the Kalimantan and Sumatra fires with those from the Kuwait oil fires of 1991, described as a major environmental catastrophe. Laursen *et al.* (1992) have calculated the emissions of CO_2, CO, CH_4, NO_x and particulates from the Kuwait oil fires in units of metric tons per day. The Laursen *et al.* (1992) calculations are summarized in Table 5. To compare these calculations with the calculations presented in this paper for Kalimantan and Sumatra (Table 4), the calculations have been normalized by the total number of days of burning. The SPOT images (Liew *et al.*, 1998) covered a period of 5 months (August-December 1997) or about 150 days. For comparison with the Kuwait fire emissions, the calculated emissions were divided by 150 days. These values are summarized in Table 5. The gaseous and particulate emissions from the fires in Kalimantan and Sumatra significantly exceeded the emissions from the Kuwait oil fires. The 1997 fires in Kalimantan and Sumatra were a significant source of gaseous and particulate emissions to the local, regional and global atmosphere.

Species	**Indonesian Fires**	**Kuwait Oil Fires**[1]
CO_2	1.28×10^6	5.0×10^5
CO	2.19×10^5	4.4×10^3
CH_4	1.23×10^4	1.5×10^3
NO_x	3.93×10^4	2.0×10^2
Particulates	1.08×10^5	1.2×10^4

Table 5. *Gaseous and particulate emissions: the Indonesian fires and the Kuwait oil fires*
Notes: Units of emissions: Million metric tons of C for CO_2, CO; million metric tons for particulates.
1 million metric tons = 10^{12} grams = 1 Teragram, Tg
Source: [1] Laursen *et al.*, 1992

Appendix 3. Operational Satellite Fire Monitoring Systems

The following summary lists the current operational satellite systems used in fire monitoring.

1. NOAA (National Oceanic and Atmospheric Administration)/AVHRR (Advanced Very High Resolution Radiometer):

Global 1-km imaging systems. Monitors active fires and burned area.

2. DMSP (Defense Meteorological Satellite Program)/OLS (Operational Linescan System):

Global night-time low light sensor. Monitors active fires.

3. GOES (Geostationary Operational Environmental Satellite)Imager:

Continental high temporal frequency, coarse spatial resolution geostationary imaging. Monitor active fires and smoke.

4. ERS (European Remote Sensing Satellite)/ATSR (Along-Track Scanning Radiometer) (European Space Agency):

Global 1-km imaging. Monitors active fires and burned areas.

5. ERS (European Remote Sensing Satellite /JERS (Japanese Earth Resources Satellite) SAR (Synthetic Aperture Radar) (European Space Agency /NASDA (National Space Development Agency of Japan):

Global microwave high resolution system. Monitors burned area.

6. LANDSAT (Land Satellite) TM (Thematic Mapper)/MSS (Multispectral Scanner System):

Local, high spatial frequency, low temporal frequency. Monitors burned area.

7. SPOT (Systeme Pour l'Observation de la Terre (CNES) (Centre National d'Etudes Spatiales) :

Local, high spatial frequency, low temporal frequency. Monitors burned area.

8. IRS (Indian Remote Sensing Satellites)

Local, high spatial frequency, low temporal frequency. Monitors burned area

9. RADARSAT

Global microwave high resolution system, Monitors burned area

Appendix 4. Most relevant websites for fire detection and monitoring

http://hazard1.wwb.noaa.gov/

Most reliable site on environmental disasters from NOAA. Daily updated images and summary. Best used for fires evaluation worldwide, especially for America and Russia.

http://www.gov.sg/metsin/hazed.html

Most reliable site for fires and haze survey over Indonesia and Southeast Asia. Provides daily maps of the general situation and the most recent available NOAA images of Sumatra and Borneo.

http://shark1.esrin.esa.it/cgi-bin/ATSR_FIRE_RUSH_HOME

Interesting site from the European Space Agency (ESA), with maps of hot spots and latitude/longitude coordinates. Not regularly updated.

http://wwwnotes.reliefweb.int/websites/rwdomino.nsf/VNaturalDisastersTheLatest

Text-only information about environmental disasters.

http://toms.gsfc.nasa.gov

Site providing smoke and haze coverage, as well as dust in the atmosphere from the major events. Display of information is linked the event's importance.

http://smd.mega.net.id/iffm/hotspots_map.htm

Interesting project with map of 'hot spots'. Not regularly updated.

http://earth1.esrin.esa.it/ew/

Archive on all type of envionmental disasters. Not regularly updated.

Cover

Pictures from top to down:

- SPOT image from the 30th March 1998 showing fires impacts on Sarawak vegetation, in the eastern part of Malaysia. Copyright belong to CNES
- Forests on fire in Tanjung Lumut area, Indonesia, 1997. WWF-Canon/Tantyo Bangun
- Forest on fire. Farmer on foreground. Tanjung Puting Nat. Park, Kalimantan, Indonesia, 1997. WWF-Canon/Tantyo Bangun
- Background map: DMSP image showing areas of fire during July-December 1997. National Geophysical Data Center