Biomass Burning and Global Change

Volume 2

Biomass Burning in South America, Southeast Asia, and Temperate and Boreal Ecosystems, and the Oil Fires of Kuwait

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Introduction

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Our planet and global environment are witnessing the most profound changes in the brief history of the human species. Human activity is the major agent of those changes—depletion of stratospheric ozone, the threat of global warming, deforestation, acid precipitation, the extinction of species, and others that have not become apparent.

This statement is from the introduction to the report, *Global Change and Our Common Future*, published by the National Research Council in 1989. The processes of global change identified in the statement—depletion of stratospheric ozone, the threat of global warming, deforestation, acid precipitation, and the extinction of species—all have one thing in common: they are caused or significantly enhanced by biomass burning. Biomass burning is the burning of the world's living and dead vegetation, including grasslands, forests, and agricultural lands following the harvest for land clearing and land-use change. Biomass burning is not restricted to one geographical region, but is rather a truly global phenomenon.

Biomass burning is a significant global source of gaseous and particulate emissions to the atmosphere. Gases produced by biomass burning include (1) greenhouse gases, carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), that lead to global warming, (2) chemically active gases, nitric oxide (NO), carbon monoxide (CO), methane, and hydrocarbons (NMHCs), which lead to the photochemical production of ozone (O_3) in the troposphere, and (3) methyl chloride (CH_3Cl), and methyl bromide (CH_3Br), which lead to the chemical destruction of ozone in the stratosphere (Levine 1985). Particulates produced by biomass burning perturb the transfer of incoming solar radiation through the troposphere, and, hence, impact climate. Recent estimates of atmospheric gases produced by biomass burning are summarized in table 1.1 (see Chapter 27 by Andreae et al.). In addition to these direct effects on atmospheric composition and chemistry and climate, biomass burning perturbs other components and processes in the earth's system, including (1) the biogeochemical cycling of nitrogen (N_2O and NO) and carbon (CO_2, CO, and CH_4) gases from the biosphere to the atmosphere, (2) water run-off and evaporation, and, hence, impacts the hydrological cycle, (3) the reflectivity and emissivity of the land, which in turn changes the radiative properties of the land and hence, impacts climate, and (4) the stability of ecosystems which in turn impacts biological diversity. For these and other reasons biomass burning is an important driver for global change (Levine et al. 1995).

The 84 contributions in these two volumes represent the latest scientific results and technological advances in biomass burning research. Biomass burning is global in scope and the contributors to this volume are also global in scope representing a total of 254 researchers from 20 countries. The chapters here were originally presented at the Chapman Conference on Biomass Burning and Global Change, 13–17 March 1995, in Williamsburg, the colonial capital of Virginia. The conference was organized and sponsored by the American Geophysical Union (AGU), the world's largest professional organization of earth scientists, with membership in excess of 25 000. The conference was coorganized and cosponsored by the National Aeronautics and Space Administration (NASA), the NASA Langley Research Center, the U.S. Environmental Protection Agency, the U.S. Department of Agriculture Forest Service, the International Geosphere-Biosphere Program, and the International Global Atmospheric Chemistry Project. The 1995 conference was the second AGU Chapman Conference on biomass burning. The first conference, the Chapman Conference on Biomass Burning: Atmospheric, Climatic, and Biospheric Implications, took place 19–23 March 1990, again in Williamsburg, Virginia. The conference volume of the same name, was published by The MIT Press in 1991 and contained 63 contributions written by 160 researchers representing 14 countries (Levine 1991). In the field of biomass burning and global change much has happened and much has been learned since the 1990 conference. These two volumes describe what we have learned and point out directions for future research to better assess the role of biomass burning as a driver for global change.

Table 1 "Best guess" estimates of gaseous and particulate emissions from global biomass burning and all anthropogenic sources (including biomass burning) (Assumptions: Total biomass burned = 8910 Tg/yr; total carbon burned = 4100 Tg C/yr) (Andreae et al. chapter 27)

Species	Biomass burning contribution (units are Tg of species per year)	All anthropogenic sources	% Due to biomass burning
CO_2	13 500	33 700[a]	40.1
CO	680	1600[a]	42.5
CH_4	43	275[a]	15.6
NMHC	42	100[b]	42.0
H_2	16	40[c]	40.0
NO	21	70[a]	30.0
N_2O	1.3	5.5[a]	23.6
NH_3	6.7	57[d]	11.8
SO_2	4.8	160[e]	3.0
COS	0.21	0.38[f]	55.3
CH_3Cl	1.1	1.1?	100
CH_3Br	0.019	0.11[g]	17.3
Aerosols			
TPM[h]	90	390[e]	23.1
Carbon	60	90[e]	66.7

a. Houghton et al. 1995
b. Ehhalt et al. 1986
c. Warneck 1988
d. Schlesinger and Hartley 1992
e. Andreae 1995
f. Chin and Davis 1993
g. WMO/UNEP 1995
h. Total particulate matter

Volume 1 is divided into three parts: I. Remote Sensing: Global and Regional Scales, II. Modeling and Inventory Development: Global and Regional Scales, and III. Biomass Burning in Africa. Volume 2 contains parts IV. Biomass Burning in South America, V. Biomass Burning in Southeast Asia, VI. Biomass Burning in Temperate Ecosystems, VII. Biomass Burning in the Boreal Ecosystem, and VIII. Oil Fires in Kuwait. The chapters in parts I and II are more general in nature and refer to regional or global-scale phenomena or processes; the chapters in parts III to VIII are unique to burning in a particular ecosystem or geographical location.

Remote Sensing of Biomass Burning from Space

Perhaps the greatest single challenge to the scientific community studying biomass burning is to accurately assess the spatial and temporal distribution of burning over a given period of time, that is, weeks, months, or a year. Once the spatial and temporal distribution of burning in a particular ecosystem or geographical region is known, this information combined with information obtained during field experiments on the amount of biomass consumed during burning and the gaseous and particulate combustion emissions, can provide reliable estimates of the amount of gaseous and particulate emissions released to the atmosphere during the burning event. This information can be used in developing global budgets of these gaseous and particulate species and to assess their impact on the composition and chemistry of the atmosphere, and on climate. However, the key to assessing the atmospheric and climatic impact of burning is the monitoring of the spatial and geographical distribution of burning. Remote sensing of fires from space provides the only opportunity for this.

A number of new techniques have been developed to study the spatial and temporal distribution of burning from space using existing satellite systems, including the nighttime low-light satellite images obtained with the Defense Meteorological Satellite Program (DMSP) Block 5 satellites (figure I.1), the Advanced Very High Resolution Radiometer (AVHRR) aboard the NOAA operational meteorological satellites (figure I.2), geostationary satellites, and astronaut photography from the Space Shuttle. The general use of these space-based platforms to study and monitor biomass burning is discussed in chapters 2 through 9. Applications of these techniques to biomass burning in specific ecosystems and geographical regions are addressed in chapters 21 and 22 for fires in Africa, chapters 53 and 54 for fires in Brazil, chapter 63 for fires in Southeast Asia, and chapters 75 through 77 for fires in the boreal system. A new NASA Mission to Planet Earth (MTPE) Program Office research initiative in land-cover and land-use change, of which biomass burning is an important process, is discussed in chapter 1. A dedicated small and inexpensive NASA satellite experiment, FireSat, to monitor the global distribution and frequency of biomass burning on a near daily basis is discussed in chapter 12. Biomass burning is a major global source of carbon monoxide in the troposphere. Measurements of tropospheric carbon monoxide obtained with the NASA Measurement of Air Pollution from Satellites (MAPS) aboard the Space Shuttle in 1984 and 1994 are discussed in chapters 10 and 11. Enhanced levels of tropospheric carbon monoxide were found to be associated with biomass burning in South America and Africa.

Modeling and Inventory Development: Global and Regional Scales

Theoretical modeling is a powerful tool to assess the impact of the gaseous and particulate emissions from biomass burning on regional and global atmospheric composition and chemistry. Part II contains chapters that address the biogeochemical and atmospheric

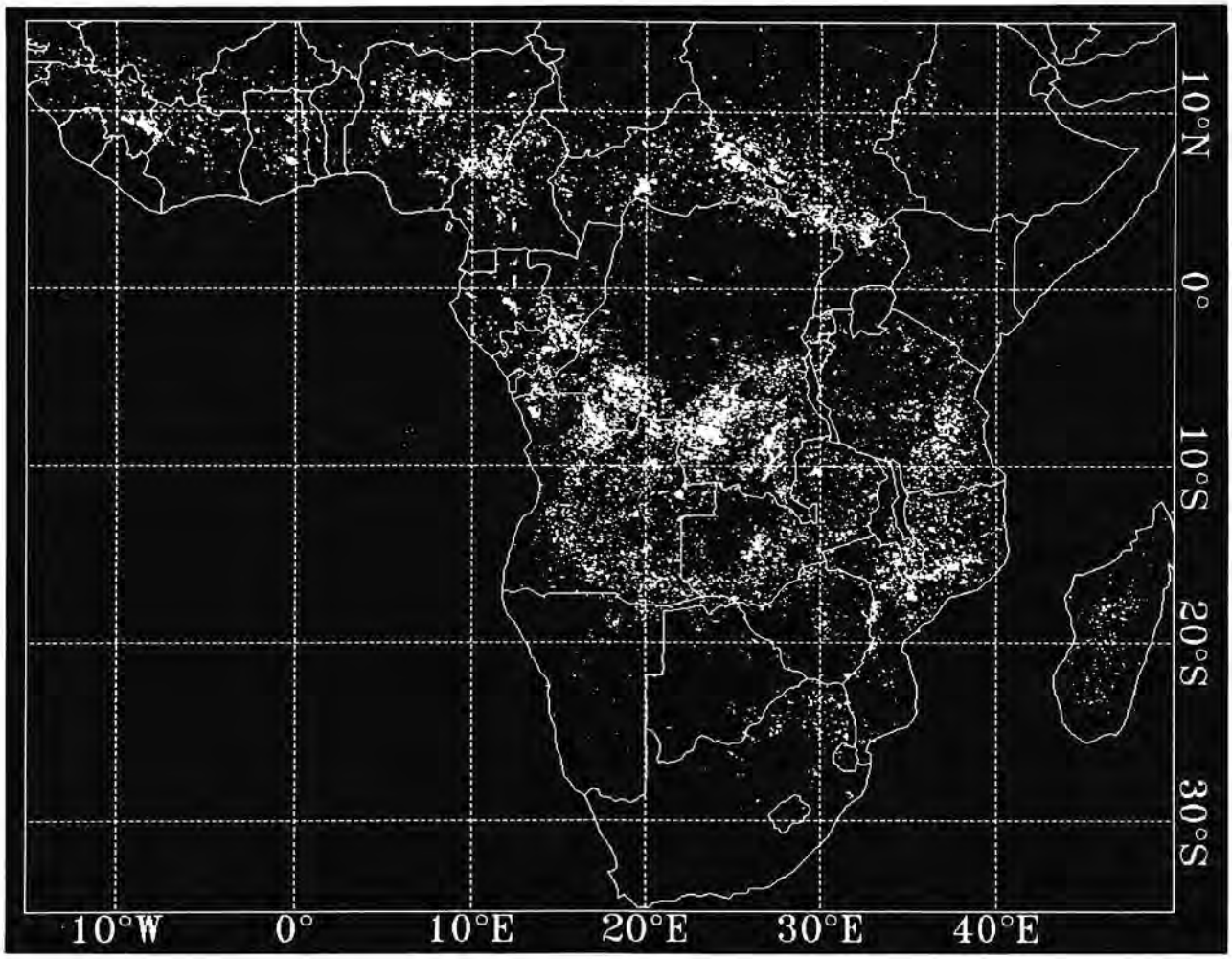

Figure I.1 Extensive burning of Africa's savannas mapped over entire year (1987) based on nighttime images from the Defense Meteorological Satellite Project (DMSP) (Cahoon et al. 1992)

transport modeling and the development of a biomass burning inventory on both global and regional scales. These chapters consider the biomass density for tropical forests, the global carbon dioxide and carbon cycles, and large-scale transport of biomass burning gases and particulates on the regional and global scale. Part II concludes with an approach to the development of an inventory of parameters of biomass burning, that is, spatial and temporal distribution of burning, biomass consumed during burning, and the gaseous and particulate emissions produced during burning.

Field Experiments

Africa and South America

Biomass burning field experiments are important to understand the burning characteristics of very diverse ecosystems, including the amount of biomass consumed during burning, the gaseous and particulate combustion products produced, and the impact of burning on the biogeochemical cycling of gases from the soil to the atmosphere. Since the 1990 conference, a series of international and national field experiments have studied biomass burning in diverse ecosystems including the savannas of southern Africa and Brazil, the tropical rain forests of Brazil, the temperate forests of the United States Pacific Northwest and the boreal forests of Russia. The Biomass Burning Experiment: Impact on the Atmosphere and Biosphere (BIBEX), an activity of the International Global Atmospheric Chemistry (IGAC) Project, part of the International Geosphere-Biosphere Program (IGBP), has organized and coordinated biomass burning field experiments in the grasslands of southern Africa and Brazil, the tropical forests of Brazil, and the boreal forests of Russia

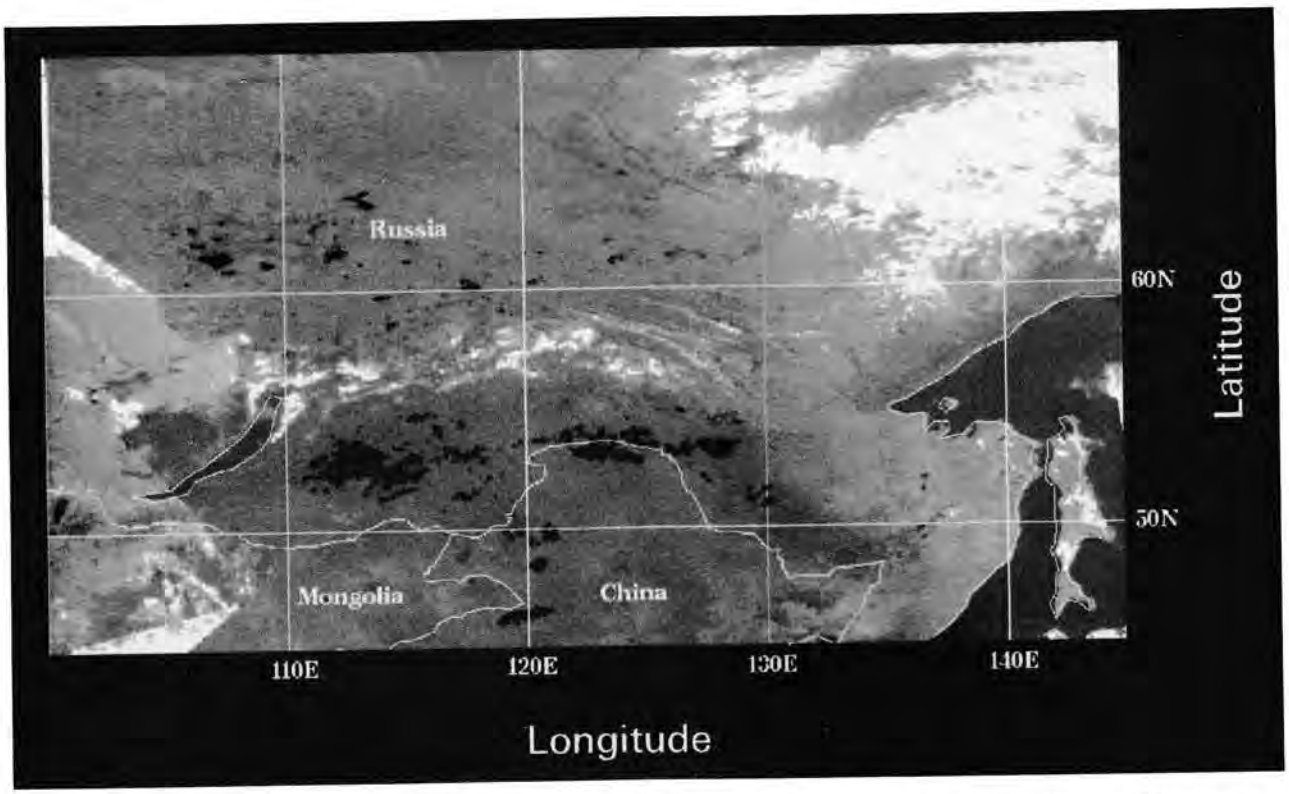

Figure I.2 Fire scars (burned areas) in northern China and southeastern Siberia in 1987 mapped with the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA satellite (Cahoon et al. 1994)

and the former Soviet Union. NASA conducted a field experiment in the forests of the United States Pacific Northwest, the Smoke Cloud, and Radiation (SCAR) Experiment. In 1991, the government of Iraq conducted a large-scale burning experiment in Kuwait.

The first large, coordinated program conducted under BIBEX was the Southern Tropical Atlantic Regional Experiment (STARE). From August to October 1992, after two years of preparation, about 200 researchers participated in this field experiment, using eight aircraft and numerous ground-based measurement systems. STARE had two subcomponents, SAFARI-92 (Southern Africa Fire-Atmosphere Research Initiative-1992) and TRACE-A (Transport and Atmospheric Chemistry near the Equator-Atlantic). SAFARI-92 was planned, organized, and implemented by BIBEX; TRACE-A was planned, organized, and implemented by the NASA Global Tropospheric Experiment Program Office and coordinated with SAFARI-92.

The main objective of SAFARI-92 was the study of burning, fire ecology, and atmospheric chemistry over southern Africa (figure I.3). SAFARI-92 consisted of more than 150 scientists from 14 countries and involved ground-based and airborne measurements. An important aspect of SAFARI-92 was a series of controlled or prescribed fires set at Kruger National Park in the northeast section of South Africa. The controlled fires ranged from more than one dozen small fires covering several acres to two large fires covering about 5000 acres. Ground-based and airborne measurements were obtained before, during, and after the Kruger National Park fires and included such parameters as the rate of fire spread, the amount of biomass consumed, the gaseous and particulate emissions, and the impact of these fires on the biogenic emissions of nitrogen and carbon gases from the soil to the atmosphere. During the SAFARI-92 experiment, measurements of ozone were obtained over Brazzaville, Congo, during a preliminary phase of the Experiment for Regional Sources and Sinks of Oxidants (EXPRESSO). Results from the SAFARI and EXPRESSO experiments form the largest number of contributions to these two volumes and are described in part III (chapters 21 through 46). Chapters 47 through 51 in part III deal with the general physics and chemistry of aerosols produced during biomass burning in Africa and in other locations.

Figure I.3 Burning of the savannas in Kruger National Park, South Africa, in September 1992 during SAFARI-92 (Photograph courtesy Joel S. Levine)

The main objective of TRACE-A was the exploration of the large-scale atmospheric composition of the region extending from Brazil over the South Atlantic to southern Africa. TRACE-A centered around airborne atmospheric chemistry and meteorological measurements obtained with the NASA DC-8 instrumented aircraft. The results of the TRACE-A experiment over Brazil are described in part IV (chapters 53 through 61). Studies on historic fires in Africa and South America are presented in chapters 52 and 62, respectively.

The Temperate Ecosystems

In September and October 1994, the NASA Smoke, Clouds and Radiation-C (SCAR-C) Project was conducted in the US Pacific Northwest. The experiment consisted of three prescribed fires. The measurements included the characterization of the nature and consumption rates of the fuels, fire behavior, and airborne in situ and remote-sensing measurements of the gaseous and particulate emissions. The SCAR-C results are summarized in chapters 65 through 67 in part VI. Other chapters in part VI include biomass burning measurements in other temperate ecosystems: in eastern North America (chapter 69), the southeastern United States (chapter 68), China (chapters 70 through 72), Spain (chapter 73), and Australia (chapter 74).

The Boreal Forests

Biomass burning can no longer be considered only a tropical phenomenon. Since 1990, there has been new interest in biomass burning in the world's boreal forests, particularly in the boreal forests of China, Siberia, Canada, and Alaska. Not long ago it was believed that on average, only about 4 million acres of boreal forest burned each year (Seiler and Crutzen 1980). At the

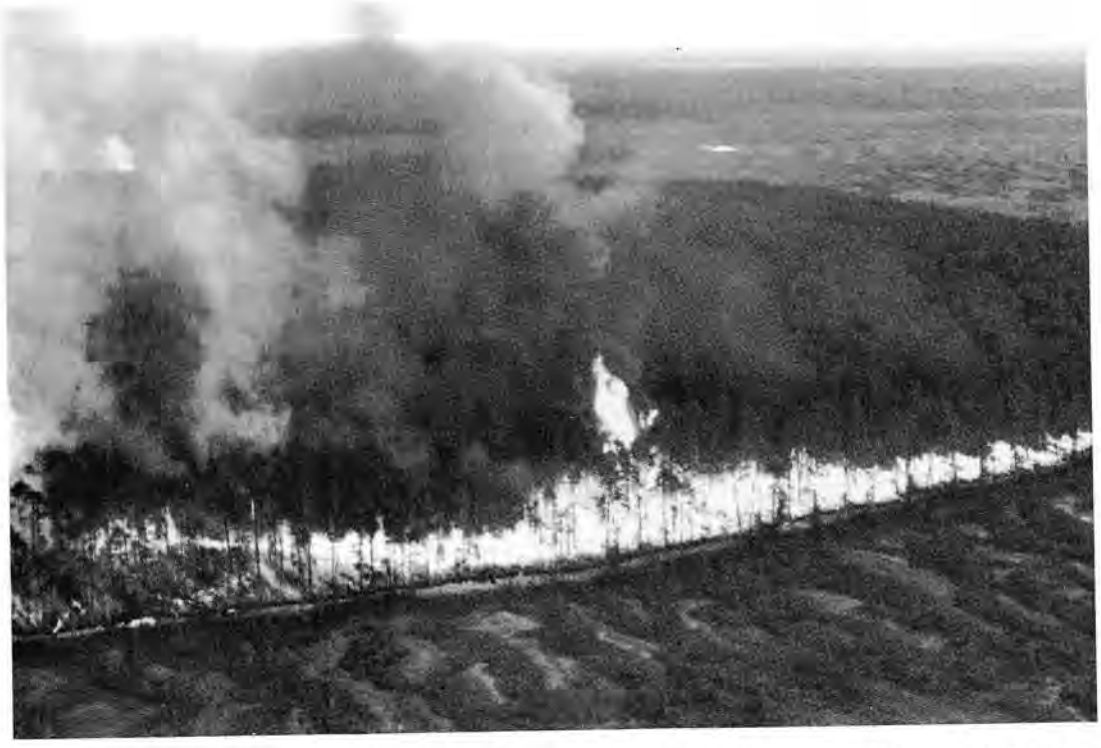

Figure I.4 Burning of the boreal forest during the Bor Forest Island Experiment in Krasnoyarsk, Russia, in July 1993 (Photograph courtesy Wesley R. Cofer)

1990 conference, it was reported that an average of about 20 million acres of boreal forests may burn each year, with significant year-to-year fluctuations (Stocks 1991). A recent study based on satellite measurements indicated that in 1987 about 36 million acres burned in the boreal forests of Asia alone (Cahoon et al. 1994). The estimates of biomass burning in boreal forests, which have increased by a factor of 10 over the last two decades highlight two things: the great geographical extent of biomass burning in the world's boreal forests and the power of satellite measurements to provide accurate information on the geographical extent of burning.

On 6 July 1993 BIBEX and the International Boreal Forest Research Association (IBFRA) organized a boreal forest biomass burn experiment, the Bor Forest Island Experiment, in Krasnoyarsk, Russia, the first phase of the Fire Research Campaign Asia-North (FIRESCAN) (figure I.4). Thirty researchers from eight countries studied fire behavior and the gaseous and particulate emissions from this fire. Measurements obtained during this experiment suggested that gases and particulates produced during biomass burning in the boreal forest may be directly transported to the upper troposphere and, perhaps, even into the lower stratosphere. The very hot boreal forest fire may generate sufficient energy to permit very strong upward convective currents to traverse the entire vertical extent of the troposphere (see chapters 79 and 81).

The boreal system contains about 25% of the world's forests and is very susceptible to climate change. Calculations with General Circulation Models (GCMs) suggest that warming of the earth will result in warmer and drier boreal forests and, in turn, an enhanced frequency of fires. The release of large amounts of carbon dioxide by these fires will amplify the greenhouse warming. There is new interest in biomass burning in the world's boreal forest, which is evident by no fewer than seven chapters on this subject (chapters 75 through 81).

Biomass Burning, Methyl Bromide, and Stratospheric Ozone Depletion

The SAFARI, TRACE-A and Bor Forest Island Experiments led to an important scientific discovery—significant amounts of methyl bromide (CH_3Br) were produced during biomass burning (Mano and Andreae 1994 and chapter 56 by Blake et al.). Methyl bromide releases atomic bromine, which leads to the

catalytic chemical destruction of stratospheric ozone, which is very similar to the catalytic destruction of stratospheric ozone by atomic chlorine. A major anthropogenic source of stratospheric chlorine is the photolysis of chlorofluorocarbons (CFCs), which were used mainly in aerosol sprays. The use of these CFCs is now banned by the Montreal Protocol. On an atom-to-atom basis, bromine is about 50 times more efficient in destroying stratospheric ozone than is chlorine.

Bromine is carried into the stratosphere in various forms such as halons and hydrocarbons, of which methyl bromide (CH_3Br) is the predominant form. The chemistry of bromine in the stratosphere is very interesting because of a chlorine-bromine synergism with respect to ozone depletion. A coupling reaction between BrO and ClO produces Br and Cl atoms, both of which react with ozone forming a catalytic cycle for ozone destruction (Wayne 1991):

$$BrO + ClO \rightarrow Br + Cl + O_2 \quad (I.1)$$

$$Br + O_3 \rightarrow BrO + O_2 \quad (I.2)$$

$$Cl + O_3 \rightarrow ClO + O_2 \quad (I.3)$$

$$\text{Net Reaction: } 2O_3 \rightarrow 3O_2 \quad (I.4)$$

There are no known efficient reservoirs for Br or BrO, in contrast to the case for Cl and ClO, because HBr and $BrONO_2$ are rapidly photolyzed. Other bromine reactions that impact the chemical destruction of stratosphere include:

$$BrO + BrO \rightarrow 2Br + O_2 \quad (I.5)$$

There are two further channels for the BrO + ClO reaction:

$$BrO + ClO \rightarrow Br + OClO \quad (I.6)$$

$$BrO + ClO \rightarrow BrCl + O_2 \quad (I.7)$$

The branching ratios into the three channels for reactions (I.1), (I.6), and (I.7) are 0.45, 0.43, and 0.12, respectively, at room temperature (Wayne 1991). The discovery that methyl bromide is an important combustion product of biomass burning identified a previously unknown and very important connection between biomass burning and the chemical destruction of stratospheric ozone.

A few months after the conference, the Nobel Committee announced that the 1995 Nobel Prize in chemistry would be shared by three atmospheric scientists for their important contributions to our understanding of the chemical destruction of stratospheric ozone. The winners of the 1995 Nobel Prize in Chemistry were Paul J. Crutzen, Mario J. Molina, and F. Sherwood Rowland. Two of these winners, Crutzen and Rowland, participated in the conference and their contributions are included in this volume (Crutzen is an author of chapter 16 and Rowland as an author of chapter 56).

The Oil Fires in Kuwait

One of the consequences of Iraq's invasion of Kuwait was the ignition of more than 700 oil wells, storage tanks, and refineries in February 1991 (figure I.5). These fires initially consumed more than 600 barrels of oil per day. The combustion of this oil produced a tremendous flux of gaseous and particulate emissions into the atmosphere. While not biomass burning in its strictest definition (although in the very distant past, petroleum was indeed biomass!), the Kuwaiti oil fires presented an opportunity for many in the biomass burning community to assess the impact of this act of environmental terrorism on the local and regional atmosphere. The results of several studies are described in chapters 82 through 84.

Public Education and Outreach

As part of the public education and outreach aspect of the conference, a free public symposium, "Biomass Burning and Global Change" took place at the Williamsburg Lodge, the conference site, on Monday, 13 March 1995. The symposium speakers included M. O. Andreae (Max Planck Institute for Chemistry, Mainz, Germany), S. Brown (U.S. Environmental Protection Agency, Corvallis, Oregon), P. J. Crutzen (Max Planck Institute for Chemistry, Mainz, Germany), R. C. Harriss (Director, Science Division, NASA Mission to Planet Earth Program Office), J. S. Levine (NASA Langley Research Center, Hampton, Virginia), J. E. Penner (Lawrence Livermore National Laboratory, Livermore, California), R. G. Prinn (Chair, International Global Atmospheric Chemistry [IGAC] Project, Massachusetts Institute of Technology, Cambridge, Massachusetts), and F. S. Rowland (University of California, Irvine, California). The symposium audience consisted of science teachers and educators from all over Virginia. Public Television local affiliate, WHRO/TV in Norfolk, Virginia, videotaped the entire public symposium and, shortly thereafter, produced a one-hour program entitled "Biomass Burning and Global Change." This program was telecast across the United States on the Public Television Network on 25 April 1995, to coincide with the twenty-fifth annual celebration of Earth Day.

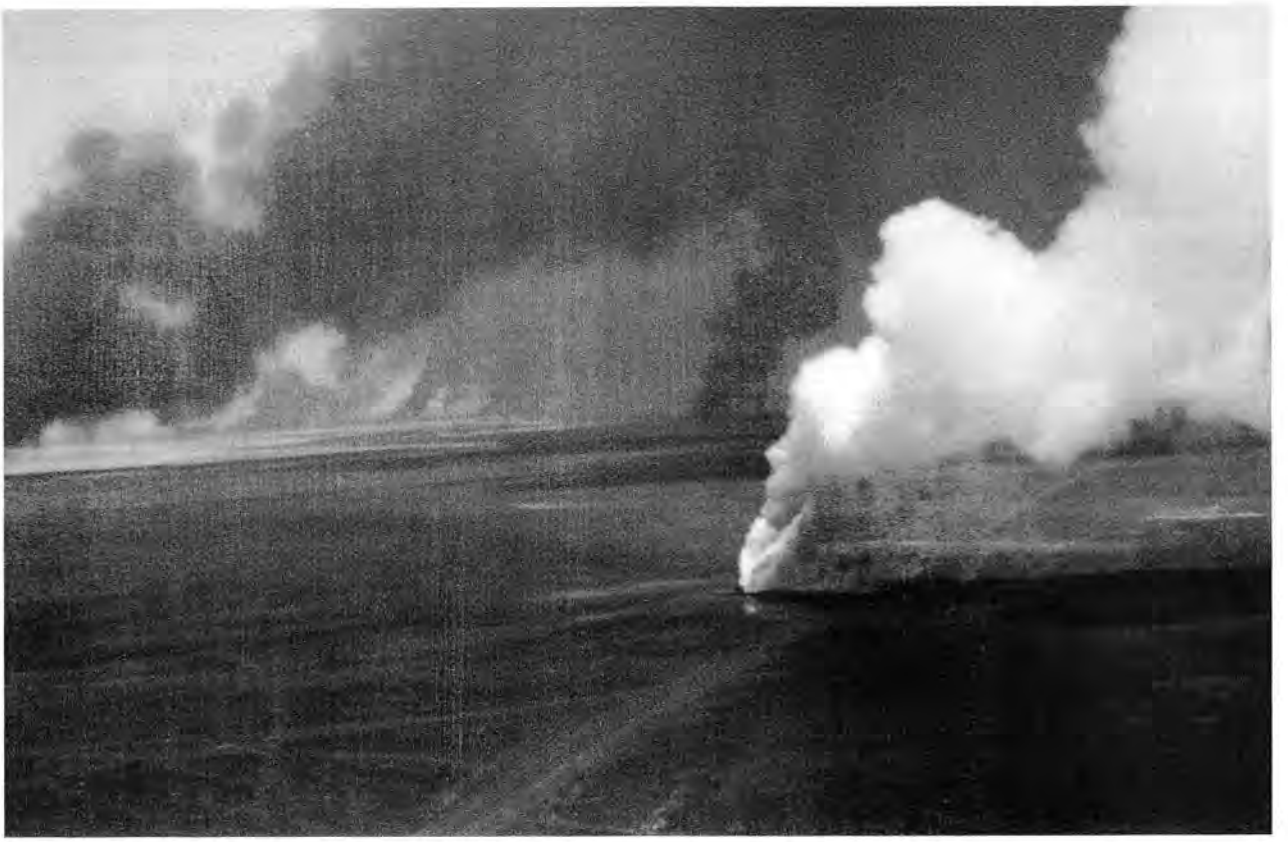

Figure I.5 Burning of Kuwaiti oil wells in July 1991 (Photograph courtesy Wesley R. Cofer).

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Conclusion

Once again, it seems most appropriate to conclude the introduction to this volume with a quote from Stephen J. Pyne, fire historian at Arizona State University:

We are uniquely fire creatures on a uniquely fire planet, and through fire the destiny of humans has bound itself to the destiny of the planet.

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