

International Geosphere-Biosphere Programme/International Global Atmospheric Chemistry SAFARI-92 field experiment: Background and overview

J. A. Lindesay,^{1,2} M. O. Andreae,³ J. G. Goldammer,⁴ G. Harris,⁵
H. J. Annegarn,⁶ M. Garstang,⁷ R. J. Scholes,⁸ and B. W. van Wilgen⁹

Abstract. The International Geosphere-Biosphere Programme/International Global Atmospheric Chemistry (IGBP/IGAC) Southern Africa Fire-Atmosphere Research Initiative (SAFARI-92) field experiment was conducted in the 1992 dry season in southern Africa. The objective of the experiment was a comprehensive investigation of the role of vegetation fires, particularly savanna fires, in atmospheric chemistry, climate, and ecology. During SAFARI-92 experimental fires were conducted in Kruger National Park, South Africa, and at some sites in Zambia, in order to study fire behavior and trace gas and aerosol emissions. Regional studies on atmospheric chemistry and meteorology showed that vegetation fires account for a substantial amount of photochemical oxidants and haze over the subcontinent, and that the export of smoke-laden air masses contributed strongly to the ozone burden of the remote atmosphere in the southern tropical Atlantic region. The relationships between fire, soil moisture status, and soil trace gas emissions were investigated for several climatically and chemically important gases. Remote sensing studies showed that advanced very high resolution radiometer/local area coverage (AVHRR/LAC) imagery was valuable for fire monitoring in the region and in combination with biomass models could be used for the estimation of pyrogenic emissions.

Introduction

Since the first suggestions that biomass burning could be a significant factor in global emissions of atmospheric trace gases [Crutzen *et al.*, 1979], the available evidence has increasingly indicated that biomass burning in its various forms represents a major perturbation of atmospheric chemistry comparable in magnitude to the effects of fossil fuel burning (see reviews in work by Crutzen and Andreae [1990] and Andreae [1991, 1993]). Trace gas emissions from biomass burning make substantial contributions to atmospheric NO_x, NMHC, CO, CH₄, and other species. Vegetation fires thus produce radiatively and

chemically important trace gases, including the precursors for tropospheric ozone formation, and are a source of aerosols, including black carbon, which also are of climatic importance. Besides their atmospheric effects, there is a complex interaction between vegetation fires and the ecology of ecosystems, including the impacts of fire on the distribution of plant species, the mobilization of the plant biomass nutrient pool, and the soil-atmosphere trace gas fluxes associated with the microbial ecology of soils.

Many aspects of the interrelationships of biomass burning with the atmosphere, biota, and soils have been reported in some detail for a variety of tropical, subtropical, and temperate ecosystems [e.g., Goldammer, 1990, 1991; Levine, 1991; Crutzen and Goldammer, 1993]. In Africa, extensive work on biomass burning in moist savanna ecosystems in west Africa has been undertaken as part of the Fire of Savannas/Dynamique et Chimie Atmosphérique en Forêt Équatoriale (FOS/DE-CAFE) project [e.g., Cachier *et al.*, 1991; Lacaux *et al.*, 1993, 1995]. In the southern African/South Atlantic region, however, although there is a long history of ecological and management fire research in a range of biomes (reviewed by van Wilgen *et al.* [1990, 1992]), there had been no integrated investigation of the ecology, chemistry, and regional atmospheric implications of savanna fires prior to 1992. In that year a suite of observational campaigns and theoretical scientific studies, designed to address the issue of the impact of biomass burning on the atmosphere and biosphere in the South America-South Atlantic-southern African region, was launched under the Southern Tropical Atlantic Regional Experiment (STARE). STARE, the first interdisciplinary, international, intercontinental fire experiment, was a subprogram of the International Geosphere-Biosphere Programme's (IGBP) International Global Atmospheric Chemistry (IGAC) project [Andreae *et al.*, 1994] and

¹Climatology Research Group, University of the Witwatersrand, Johannesburg, South Africa.

²Now at Geography Department, School of Resource and Environmental Management, Australian National University, Canberra, Australia.

³Biogeochemistry Department, Max Planck Institute for Chemistry, Mainz, Germany.

⁴Biogeochemistry Department, Fire Ecology and Biomass Burning Research Group, Max Planck Institute for Chemistry, Freiburg, Germany.

⁵Centre for Atmospheric Chemistry, York University, North York, Ontario, Canada.

⁶Schonland Research Centre for Nuclear Sciences, University of the Witwatersrand, Johannesburg, South Africa.

⁷Department of Environmental Sciences, University of Virginia, Charlottesville.

⁸Division of Water, Environment and Forest Technology (Environmentek), Council for Scientific and Industrial Research, Pretoria, South Africa.

⁹Division of Forest Science and Technology (Forestek), Council for Scientific and Industrial Research, Stellenbosch, South Africa.

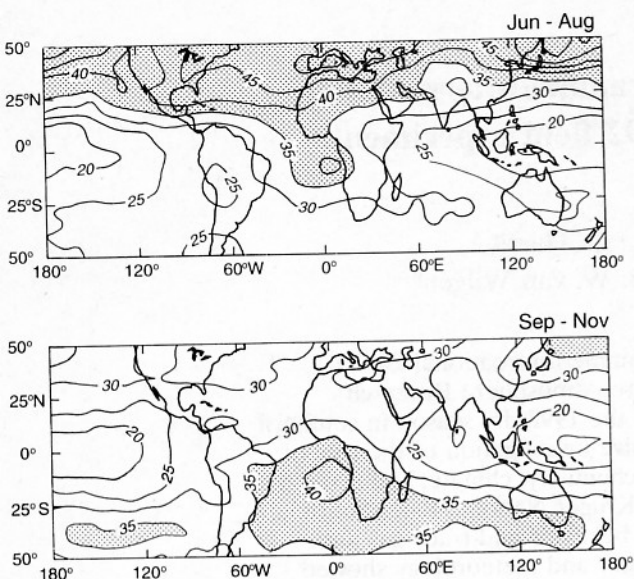


Figure 1. The climatological distribution of the integrated tropospheric residual of ozone in the seasons June–August and September–November (southern hemisphere winter and spring) 1979–1987. Tropospheric ozone concentrations greater than 35 Dobson units are shaded [after Fishman *et al.*, 1990].

addresses a key IGAC research focus: the chemistry of the tropical atmosphere [Prinn, 1994; Pszenny and Prinn, 1994]. The two major components of STARE were the Transport and Atmospheric Chemistry near the Equator–Atlantic (TRACE A) mission, part of NASA's Global Tropospheric Experiment, and the Southern African Fire–Atmosphere Research Initiative (SAFARI) field campaign. Results from TRACE A are also presented in this special section of the *Journal of Geophysical Research* [Fishman *et al.*, this issue]. Numerous papers in the proceedings volume from the Second Chapman Conference on Biomass Burning and Global Change [Levine, 1996] also report on results from the STARE/TRACE A/SAFARI campaigns.

The research papers in this special section present results from the SAFARI-92 field campaign, an investigation of the role of biomass fires in the savanna of southern Africa in the atmospheric chemistry, climate, and ecology of the region. The aim in this introductory paper is to provide a context for the detailed research results presented in the papers on aspects of the fire ecology, climate, and atmospheric chemistry of the southern African region that were explored during SAFARI-92. The rationale behind and the structure of SAFARI are discussed in the context of the STARE project and of the global significance of biomass burning for atmospheric chemistry. The paper also includes a synopsis of the research results of SAFARI-92, which have significantly advanced the understanding of the role of fire in the southern African savanna in regional and global atmospheric chemistry.

The Context: STARE and TRACE A STARE

STARE was inspired by satellite observations of a significant large-scale phenomenon: high concentrations of O_3 , CO, and other trace gases in the troposphere in the South Atlantic region [Fishman *et al.*, 1986, 1990, 1991; Newell *et al.*, 1989;

Watson *et al.*, 1990]. These observations showed large seasonal accumulations of O_3 and CO in some regions, particularly over the South Atlantic Ocean between Brazil and southern Africa and extending across the southern Indian Ocean (Figure 1). The O_3 plume in this region, although of the same magnitude as the fossil fuel combustion-based plumes emanating from North America, Europe, and Asia, is produced in the absence of comparable industrial sources; it also occurs in austral spring (September–October), when widespread vegetation fires are common in both South America and southern Africa [e.g., Logan and Kirchhoff, 1986; Cahoon *et al.*, 1992]. In addition, vertical profiles of O_3 through the tropical troposphere (Figure 2) show that the high O_3 concentrations of more than 50 ppb are found not only predominantly in the South America–South Atlantic–southern African region, but also in the lower levels of the troposphere at altitudes between 1.5 and 4 km. This clearly indicates a surface source rather than, for example, stratospheric injection of O_3 . Coupled with the fact that the O_3 and CO typically occur together, this evidence led to the hypothesis that biomass burning emissions and subsequent photochemical processes may be responsible for the observed high concentrations of the trace gases. What was not clear was whether the principal source for the South Atlantic region of enhanced O_3 was biomass burning emissions in Brazil or in southern Africa. STARE was therefore designed to characterize the emissions from biomass burning in the source regions on either side of the Atlantic, the transport of air masses from these source regions to the atmosphere over the Atlantic, and the chemical transformations occurring in the air masses.

The development of STARE took place under the overall umbrella of IGBP. Tropical atmospheric chemistry and the role of biomass burning was identified as a priority area in the IGBP's IGAC program, leading to the development of an international Biomass Burning Experiment (BIBEX). The STARE project was adopted as a formal BIBEX activity, joining other projects such as the FOS/DECAFE (Fire of Savannas/Dynamique et Chimie Atmosphérique en Forêt Équatoriale) experiment in west Africa, reported by Lacaux *et al.*

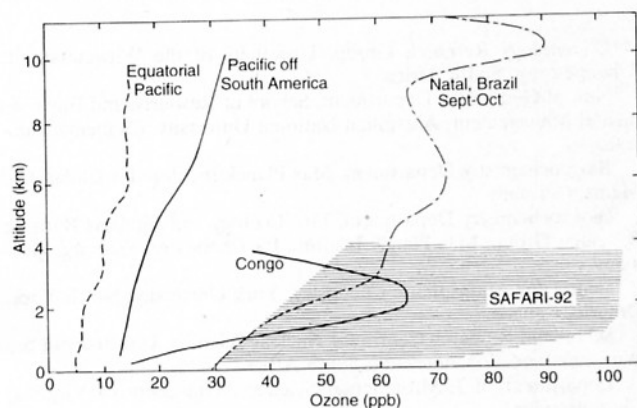


Figure 2. Vertical distribution of ozone in the tropics. There is no biomass burning influence over the equatorial Pacific, some influence of transport off the west coast of South America, and strong ozone enrichment by photochemical production in biomass burning plumes over Brazil and the Congo. The SAFARI-92 data (shaded) are the highest regional ozone levels recorded anywhere in the tropics and subtropics to date [after Andreae *et al.*, 1994].

[1993], and the Fire Research Campaign Asia-North (FIRES-CAN) in Siberia [FIRESCAN Science Team, 1994]. While the first major STARE activity took place in August–October 1992, and it is results from that project that are presented here, STARE and related BIBEX activities are continuing [Pszenny and Prinn, 1994].

Organizationally, STARE in 1992 consisted of two major components which were integrated to form the overall scientific program (Figure 3): TRACE A addressed the source regions in Brazil and the long-range transport and large-scale distribution of pyrogenic pollutants over the southern tropical Atlantic and southern Africa; SAFARI investigated the emissions from savanna fires in southern Africa, their transport across the African continent, and the relationship between fires and southern African savanna ecology.

TRACE A

The TRACE A project was founded principally on collaboration between the space agencies of the United States (NASA) and Brazil (Instituto de Pesquisas Espaciais (INPE)) and involved some 200 scientists from five countries. The research in TRACE A centered largely on the NASA DC-8 instrumented research aircraft, which operated from a base in Brasilia, Brazil, for the western part of its flights, from Ascension Island for the flights over the central Atlantic Ocean, from Johannesburg, South Africa, for flights over the African continent, and from Windhoek, Namibia, for the flights over the South Atlantic off the African west coast (flight tracks and measurement locations are shown in Figure 4). An overview of TRACE A and the results of the field mission is provided by Fishman *et al.* [this issue]. A suite of trace gas and aerosol measurements was made on all these flights, together with meteorological observations that among other things, allowed characterization of the effect of cumulus convection on the vertical transport of biomass burning products over Brazil [Wang *et al.*, this issue]. The key trace gases measured during STARE were O_3 , CO , CO_2 , NMHC, CH_4 , NO , NO_2 , NO_y , N_2O , NH_3 , PAN, H_2O_2 , and various organohalides, covering the range of radiatively and chemically significant trace gases [Heikes *et al.*, this issue; Blake *et al.*, this issue; Browell *et al.*, this issue]. As part of TRACE A, the large-scale distribution of O_3 in the region during the 1992 STARE field campaign was determined using remote sensing from a satellite platform (total ozone mapping spectrometer (TOMS)) [Olson *et al.*, this issue; Thompson *et al.*, this issue (a)]. The remotely sensed information was complemented by the results from a large-scale ozonesonde network with launch sites in Natal, Brazil; Ascension Island, in the tropical South Atlantic Ocean; Brazzaville, Congo; and, in collaboration with SAFARI, Pretoria, South Africa, and the Etosha National Park, Namibia (locations in Figure 4) [Baldy *et al.*, this issue; Diab *et al.*, this issue (b); Jury *et al.*, this issue; Olson *et al.*, this issue; Thompson *et al.*, 1996, this issue (a); Tyson *et al.*, 1996]. Detailed modeling studies investigated the combined effects of pyrogenic emissions from the South American and African continents, meteorological transport mechanisms, and chemical reactions in the atmosphere on the composition of the atmosphere in the study region [Loring *et al.*, this issue; Fuelberg *et al.*, this issue; Jacob *et al.*, this issue; Thompson *et al.*, this issue (a)].

SAFARI

SAFARI-92 was the southern African component of the STARE program (Figure 3), and it involved a principal col-

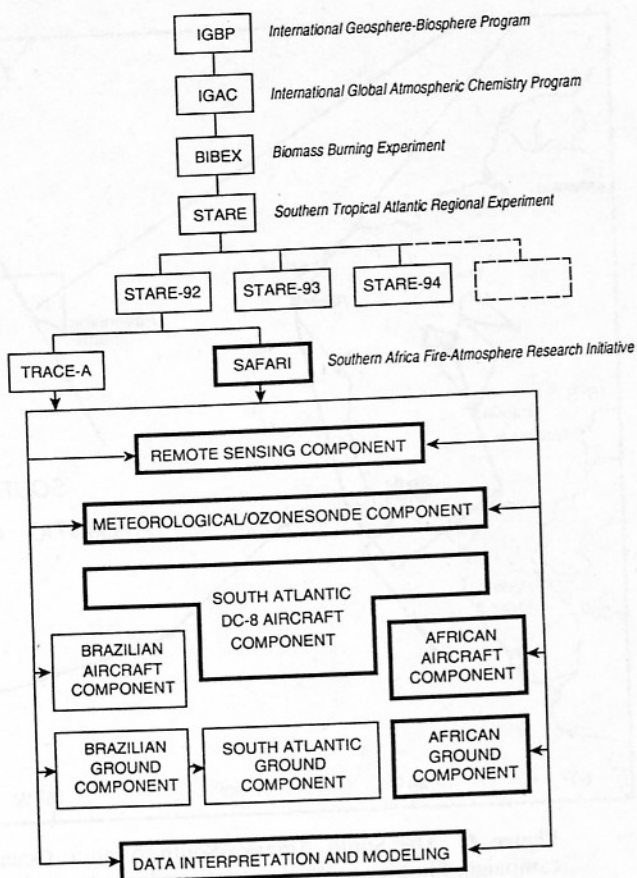


Figure 3. The organizational structure of the Southern Tropical Atlantic Regional Experiment (STARE) and the Southern African Fire-Atmosphere Research Initiative (SAFARI-92).

laboration between European, North American, and South African researchers. The largest international experiment ever conducted in southern Africa and the most comprehensive analysis of fire emissions ever undertaken in a field campaign, SAFARI-92 included more than 150 scientists from 14 countries: South Africa, Namibia, Botswana, Zimbabwe, Swaziland, the Congo, Germany, France, Belgium, Great Britain, Brazil, the United States, and Canada. The project was truly interdisciplinary in nature, with research groups representing atmospheric chemistry, biogeochemistry, fire ecology, microbiology, soil science, pasture science, forestry, meteorology, and climatology. During the period of the field campaign, August–October 1992, these research groups focused their attention on three main sites (Figure 4): the Kruger National Park (South Africa), Etosha National Park (Namibia), and Victoria Falls (Zimbabwe). Some observations were also undertaken in Zambia. Together these sites represent the best possible spatial representation of conditions with a limited number of observation points.

SAFARI was timed to coincide with the usual season for natural and human-induced burning in late winter/spring; the various components of SAFARI operated in southern Africa from mid-August to mid-October 1992. Probably the most anomalous condition affecting the field campaign was the severe drought that occurred in the summer of 1991/1992 in association with an El Niño–Southern Oscillation event. Rain-

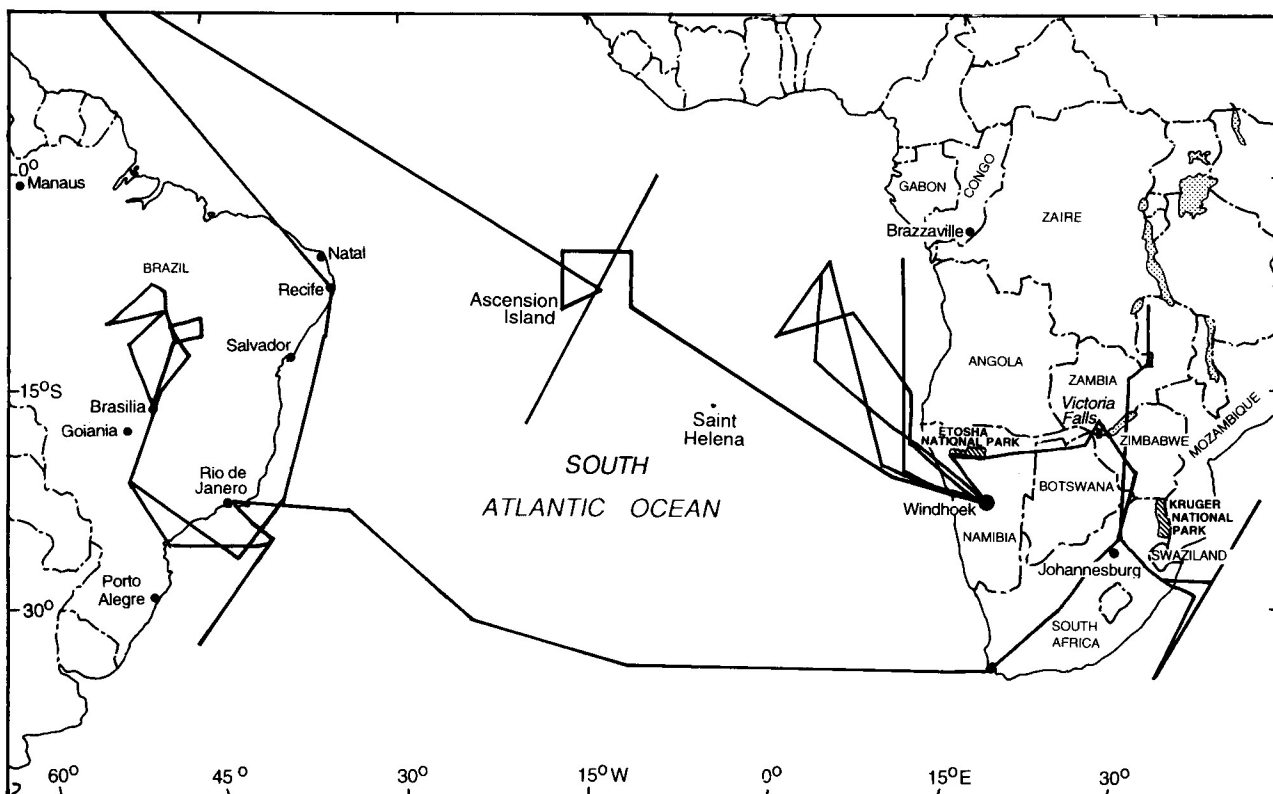


Figure 4. The South America-South Atlantic Ocean-southern Africa region of interest in the STARE campaign. Shown are places mentioned in text, including the Kruger National Park (South Africa), Etosha National Park (Namibia), and Victoria Falls bases for most of the SAFARI studies. Flight tracks of the TRACE A platform, the NASA DC-8 instrumented aircraft, during September-October 1992 are also shown.

fall throughout southern Africa was significantly below normal during the summer growing season (October 1991 through April 1992), which impacted the quantity and status of the biomass in all the field observation areas and across most of the subcontinent. The campaign nevertheless proceeded, with much of the activity taking place around a number of controlled fires in the Kruger National Park south of Skukuza (Figure 5). The history and ecology of fire in Kruger Park have been well documented for many years, providing an ideal location for the SAFARI work.

The SAFARI-92 field program was structured to cover the scientific objectives of assessing the relationships between fires and savanna ecology in southern Africa, determining the emissions from savanna fires in the region, and studying the transport of pyrogenic emissions across the subcontinent and adjacent oceanic areas. The four main components of the project were, accordingly, (1) a ground component which included work on biomass characterization in southern African savannas, trace gas emissions before, during, and after fires, fire behavior and fire ecology, and aerosol emissions and transport (the first time that a significant investigation of biomass burning emissions had included the characterization of fuels and fire dynamics); (2) an airborne component which included sampling of pyrogenic trace gases and particulates to determine plume contents, transformations, and transports using instrumented helicopters, light aircraft (Cessnas), a Learjet, and a DC-3; (3) a meteorological component which covered the use and supplementation of existing rawinsonde and ozonesonde networks in southern Africa, the installation of

additional meteorological stations to monitor boundary layer characteristics during the field phase, meteorological facilities for flight planning, and climatological and meteorological analysis pre- and post-SAFARI; and (4) a remote sensing section in which satellite data were used to investigate the distribution and size of fires in southern Africa prior to and during SAFARI and to map fuel loads and characteristics in the southern African savanna.

Review of SAFARI-92 Results

The focus for SAFARI ground-based monitoring of trace gas fluxes, fire behavior and fire ecology, and boundary layer meteorology during August and September 1992 was eight small controlled burns in the Kruger National Park. The climax of the experiments was the two large fires (>2000 ha each) in the Kruger National Park during September. These burns made possible the integration of ecological work at ground level and measurement of emissions both on the ground and from research helicopters and aircraft. Planned controlled fires in the Etosha National Park, Namibia, had to be canceled due to severe drought conditions in northern Namibia, but a joint South African/United States team based at Okaukuejo (Figure 5) conducted measurements of dust aerosol composition; meteorological parameters including temperature, humidity, and wind using tethersondes, radiosondes, and pilot balloons; and both total column O_3 and profiles of O_3 using ozonesondes. In addition, a set of airborne measurements of ozone and meteorological parameters were made over northern Namibia by a

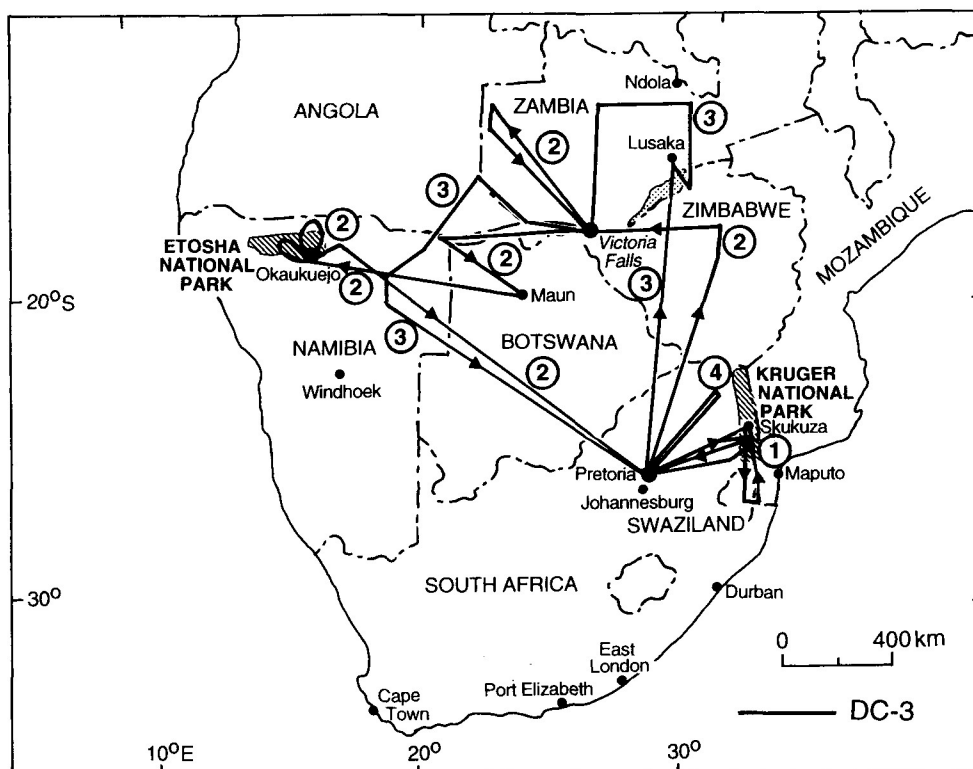


Figure 5. The southern African region, with the bases of operation for SAFARI and the flight tracks of the DC-3 instrumented aircraft shown. Numbers indicate different observation missions.

South African group. At a station at Victoria Falls, Zimbabwe, a joint team from Germany, South Africa, and Zimbabwe monitored ground-level O_3 , aerosols, and boundary layer meteorology and also conducted some airborne observations in an instrumented light aircraft.

The results obtained during SAFARI-92 are reviewed here in four sections corresponding with the four project components: (1) fire behavior, fire ecology, and ground-based emission measurements, including fire and soil emissions; (2) airborne sampling of trace gases and aerosols; (3) meteorology and transport of pyrogenic emissions and ozone observations; and (4) satellite remote sensing of fires and biomass.

Fire Behavior, Fire Ecology, and Ground-Based Emission Measurements

The necessity of documenting fire behavior and the ecological responses to fire and of characterizing the ground-based sources of fire emissions by assessing biomass characteristics and soil emissions of trace gases was recognized in SAFARI for the first time in a biomass burning investigation. Details of the fuel loads, biomass characteristics, and fire behavior for the SAFARI controlled fires in the Kruger National Park are given for the small fires (approximately 7 ha) by *Trollope et al.* [this issue], and for the two large (>2000 ha) fires by *Stocks et al.* [this issue]. All of these parameters were impacted by the prevailing drought conditions, and the results should be viewed in that context. Ground-based energy release measurements and convection column monitoring for the two large SAFARI fires [*Stocks et al.*, this issue] showed that although the energy release rates and convection column development varied greatly between the two fires, it was possible to relate fire behavior in these fires to their atmospheric impact. Unlike

boreal forest fires with their greater fuel loads, savanna fires are unable to generate sufficiently high, sustained energy releases to produce convection columns above 3–4 km. Therefore their emissions are confined to the lower troposphere unless they are entrained by independently generated large-scale convective activity, for example, after transport into the Intertropical Convergence Zone (ITCZ) region.

Comparative measurements of fuel biomass, combustion factors, fire behavior, and emission factors were made in the savanna grassland sites in South Africa and in savanna woodlands in Zambia [*Shea et al.*, this issue; *Ward et al.*, this issue; *Andreae et al.*, 1996; *Lacaux et al.*, this issue; *McKenzie et al.*, 1996; *Susott et al.*, 1996]. These studies highlight the complex nature and variability of African savannas, where vegetation composition, environmental conditions, land-use patterns, and fire regimes influence the characteristics of fuels and therefore the ignition potential, behavior of fires, combustion efficiency, and chemistry of emissions. Fuel biomass estimation for these ecosystems, essential for emissions estimations, is thus complicated. Nevertheless, *Ward et al.* [this issue] and *Hao et al.* [this issue] report the development, for the African savannas, of a range of models integrating biomass and combustion factors and allowing the calculation of emission factors for a range of alkanes, alkenes, and aromatic compounds, based on the emission ratios to CH_4 . Wider applicability of these models is suggested. Combustion efficiency is the same in the different savanna types, and African savanna biomass burning is found to be a significant source of atmospheric CO , some hydrocarbons, and benzene, amounting to between 25 and 75% of global industrial production [*Hao et al.*, this issue]. *Scholes et al.* [this issue (b)] extend a modeling method for estimating the

amounts of biomass burned in southern Africa (reported by *Scholes et al.* [this issue (a)]) to the estimation of regional biomass burning emissions of CO, CH₄, NO_x and aerosols. Calculated emissions are significant, but considerably less than those previously estimated [*Hao and Liu*, 1994] and are concentrated in the dry winter season between 5° and 20°S.

Studies of soil emissions of trace gases during SAFARI-92 concentrated on NO_x, NO, and N₂O and on trace carbon gases. NO_x emissions from both nutrient-rich and nutrient-poor savanna soils in southern Kruger National Park were primarily in the form of NO [*Parsons et al.*, this issue]. Highest emission rates in the absence of burning (20 ng N-NO m⁻² s⁻¹) were related to soil total N content and N nitrification rate, and seasonal variations in NO emissions were ascribed to the effect of seasonally varying rainfall on soil water contents in semiarid savanna areas. Whereas small wetting events following protracted dry periods, such as those that occur at the end of the dry season, produce large increases in NO emissions [*Levine et al.*, this issue], larger amounts of rainfall during the wet season may inhibit NO emissions. Detailed investigation of the impact of wetting and burning on microbial soil emissions of NO and N₂O [*Levine et al.*, this issue] showed a significant enhancement of NO emissions on both wetted and burned sites, with the highest emissions (around 75 ng N m⁻² s⁻¹) from sites which were wetted after burning. It is suggested that African savanna soils can provide a significant source of NO either with or without burning, depending on their moisture status and the seasonal timing of rainfall events. The lack of detectable N₂O emissions from the African savanna soils studied is highlighted for further investigation.

Soil fluxes of CO₂ measured during SAFARI-92 in the semiarid savanna of the Kruger National Park showed little influence of burning but were also strongly affected by the availability of moisture [*Zepp et al.*, this issue], increasing by an order of magnitude with heavy rain and maintaining elevated values for at least a week. In contrast, CO fluxes (which were considerably higher than those previously measured in southern African savannas) were insensitive to moisture changes but responded positively to burning. Soil-atmosphere fluxes of CH₄ were found to be small.

The emission of particulate matter from biomass burning in southern Africa is addressed by *Maenhaut et al.* [this issue], who report on the analysis of size-fractionated aerosol samples from background sites and from prescribed fires in the Kruger National Park for particulate mass, black carbon, and a range of other elements. Results show a combination of mineral (soil) dust, sulfate, and sea salt with biomass burning products, some of which originated to the north of the study area in central southern Africa. The dominant sources of the sulfate aerosols are probably industrial activities in the highveld region west of Kruger Park. A detailed investigation of black carbon formation associated with the prescribed fires in the Kruger National Park [*Kuhlbusch et al.*, this issue] shows that the ratio of black carbon produced to the carbon exposed to fire is lower than in laboratory studies, probably owing to less complete combustion under field conditions. The results allow an estimation of global black carbon formation from savanna fires (10–26 Tg C yr⁻¹), more than 90% of which is thought to remain on the ground as a net sink of biospheric carbon.

Airborne Sampling of Trace Gases and Aerosols

The airborne component of SAFARI included the sampling of trace gases and aerosols and the collection of some meteorological data over the southern African region as a whole. It

also comprised direct sampling of biomass burning products in the plumes from prescribed experimental fires and other fires in the region. The results from the fire emission studies conducted during SAFARI are summarized by *Andreae et al.* [this issue]. The instrumented aircraft used during the field campaign included a helicopter for low-level sampling above the fires in the Kruger National Park, two Cessna light aircraft (one in Kruger Park and one at Victoria Falls) used for in-plume sampling and short-range regional measurements, and an instrumented Learjet used to measure O₃ over northern Namibia. The principal aircraft platform was an instrumented DC-3, used for sampling in the vicinity of plumes from the large prescribed fires in Kruger Park and also for a number of long-distance regional measurement flights (Figure 5) designed to assess the impact of biomass burning on the atmospheric composition over the subcontinent as a whole [*Zenker et al.*, 1996]. This component of SAFARI, in particular, was planned to coincide with the presence of the TRACE A DC-8 in southern Africa so as to allow comparative observations; unfortunately, scheduling changes in TRACE A allowed only minimal overlap. However, in those cases where equivalent air masses were sampled by the two platforms, the results are in excellent agreement [*Anderson et al.*, this issue; *Andreae et al.*, 1996; *Blake et al.*, this issue; *Le Canut et al.*, this issue]. At the near-fire scale, low-level helicopter sampling of smoke plumes from the two large prescribed fires in the Kruger National Park [*Cofer et al.*, this issue] allowed the determination of CO₂-normalized emission ratios for CO, H₂, CH₄, NMHC, and N₂O during the flaming and smoldering combustion phases directly over the source of the emissions.

At the landscape scale, low-altitude observations during one of the regional DC-3 flights revealed substantial emissions of NO_x from a savanna region in northern Namibia following a rainfall event in the area (G. Harris et al., manuscript in preparation, 1996). These results, which support the ground-based observations reported by *Levine et al.* [this issue], suggest that soil microbial processes could provide a significant source of NO_x for ozone formation in these semiarid savanna areas, where sporadic rainfall occurs during and at the end of the dry season. Observations of lower- to mid-tropospheric O₃ over northern Namibia using a Learjet [*Jury et al.*, this issue] provide evidence for relatively high concentrations (>90 ppb) at several levels and indicate the importance of regional synoptic-scale atmospheric circulation patterns in the development of these concentrations.

On the subcontinental scale the DC-3 was used to obtain regional air samples and samples of smoke from savanna fire plumes. *Andreae et al.* [this issue] report on the analysis of these samples for CH₃Cl, CH₃Br, and CH₃I, all three species being present in enhanced concentrations in the smoke plumes relative to the regional background air. The results indicate that biomass burning makes a significant contribution to the atmospheric budget of CH₃Cl and CH₃Br and that these pyrogenic emissions should be considered as contributing to stratospheric ozone depletion. Measurements of aerosol number and mass emission ratios relative to CO and CO₂ from SAFARI-prescribed fires in the Kruger National Park, sugar cane fires in southern Swaziland (south of Kruger Park), and grassland "fires of opportunity" in the southern African region [*Le Canut et al.*, this issue] showed that annual savanna fire releases of aerosol particles in the size range 0.1–3.0 μm are between 11 and 18 Tg, somewhat less than the amount emitted

from tropical forest fires but nevertheless an important contribution to total loadings of aerosols and cloud condensation nuclei. Pyrogenic emissions of aerosols were shown to have a significant impact on the radiative properties of the atmosphere over the entire region from South America to southern Africa [Anderson *et al.*, this issue; Browell *et al.*, this issue; Gregory *et al.*, this issue; Le Canut *et al.*, 1996].

Meteorology and Transport of Pyrogenic Emissions and Ozone Observations

Meteorological and climatological work in SAFARI was focused on defining the fields of motion at various scales, from the turbulent to the synoptic and planetary, which influence fires and determine the dispersion and transport of pyrogenic emissions. The meteorological objectives included basic questions of atmospheric process (e.g., whether large-scale atmospheric fields of motion over southern Africa are markedly different in dry years and wet years) as well as questions combining meteorology and the chemistry of fire products (e.g., the trace gas chemistry of the fire products, their horizontal distribution, and their deposition and role in marine and terrestrial ecosystems well removed from the location of the fires). A second objective was to provide operational meteorological support and a comprehensive description of meteorological conditions prevailing during the experiment.

Recognizing that the fate of biomass burning products, including chemical reactions in the presence of insolation, clouds (liquid water), and humidity (water vapor), is largely dependent upon atmospheric fields of motion, the effort of the meteorological program in SAFARI-92 concentrated on transport processes in the surface and convective boundary layers. During spring, anticyclonic flow is dominant over the subcontinent south of 15°S [Tyson, 1986], and the atmosphere is characterized by inversions and stable layers that inhibit the development of penetrative moist convection and thus trap pyrogenic material in the lower atmosphere. Once burning products break through the mixed layer they are again trapped by midtropospheric stable layers [Garstang *et al.*, this issue]. Only deep convection associated with periodic disturbances or with the start of the wet season (around October) can elevate these products above that level enhancing their effective transport out of the region [e.g., Connors *et al.*, 1991; Garstang *et al.*, this issue].

Boundary layer conditions during SAFARI were monitored in the Kruger National Park [Held, this issue] and the Etosha National Park [Zunckel *et al.*, this issue (b)]; both sets of observations indicate the presence of surface temperature inversions and low-level wind maxima just above the inversions on most nights. Both phenomena were more strongly developed in the arid Namibian environment. Simultaneous tethered observations of meteorological parameters and O₃ at Etosha showed an increase in O₃ concentrations with enhanced thermal stratification following inversion development. It is suggested [Zunckel *et al.*, this issue (a)] that the low-level wind maximum may provide a partial mechanism for westward transport of O₃ in that area. Surface local-scale circulation and temperature characteristics along a section of the Namibian coast were also investigated during SAFARI-92 [Brimelow and van Heerden, this issue], showing that nocturnal surface inversion formation is common and that the coastal surface circulation is dominated by diurnally varying thermotopographic effects.

A significant part of the SAFARI meteorological analysis

has been devoted to transport determination using trajectory calculations. The results, which must be interpreted in the context of the drought conditions at the time, are discussed by Garstang *et al.* [this issue] and Swap *et al.* [this issue]. Classification of each day of the experiment into one of four synoptic classes together with the associated expected transport fields permits rapid assessment of any of the transport which might have occurred on any experiment day or period [Garstang *et al.*, this issue].

Chemical, kinematic, and thermodynamic analyses indicate that aerosols and trace gases transported into the region originate from vegetation and soils as well as from biomass burning [Swap *et al.*, this issue]. The bulk of air transported to the lower and middle troposphere over the tropical South Atlantic originates over western tropical Africa, with transport from the west (South America) less important and at higher altitudes. A classification of atmospheric transport fields over southern Africa based on trajectory analyses [Garstang *et al.*, this issue] shows that the high concentrations of trace gases and aerosols observed over the subcontinent in spring can be ascribed to the combined effects of atmospheric stability and the predominant anticyclonic circulation in that season. Together these can produce recirculation of air and pyrogenic products over long periods, before the air masses exit to the west over the Atlantic Ocean (around the equatorial margin of the anticyclone) or to the east over the Indian Ocean under the influence of westerly wave disturbances further south. These trajectories correspond closely with satellite-based observations of enhanced tropospheric O₃ in the region (see Figure 1).

Ozone concentrations in the southern Africa region before and during SAFARI-92 were monitored using both remote sensing [Thompson *et al.*, this issue] and ozonesondes [Thompson *et al.*, this issue (b); Diab *et al.*, this issue (b)]. Subsequent to the field campaign, data from a series of ozonesonde launches covering the STARE observation period have become available from Isle Reunion in the Indian Ocean [Baldy *et al.*, this issue], extending the ozonesonde data to cover much of the area of interest. While remote sensing of O₃ can lead to overestimation of concentrations, particularly in areas of persistent low-level cloud such as the tropical South Atlantic [Thompson *et al.*, 1993], this remains the best method for obtaining a regional-scale view. The expected seasonal maxima in tropospheric O₃ were observed during SAFARI-92 from TOMS data, but total O₃ levels were exceptionally low during 1992/1993 [Thompson *et al.*, this issue (b)]. Tropospheric O₃ exhibits a latitudinal gradient [Diab *et al.*, this issue (b); Thompson *et al.*, this issue (b)], being highest over the tropical South Atlantic (downwind of the African source region) and lower at sites further south where concentrations depend on variations in synoptic-scale atmospheric circulation. The influence of prevailing large-scale circulation patterns on O₃ as observed from ozonesonde profiles in Namibia is discussed in detail by Diab *et al.* [this issue (b)]. Predominant anticyclonic and westerly wave disturbance conditions are highlighted as being dominant during SAFARI-92, both characterized by an O₃ maximum layer between 9 and 12 km that is ascribed to biomass burning.

Satellite Remote Sensing of Fires and Biomass

Satellite data are an invaluable source of information on the timing and distribution of fires and provide the basis for estimates of the areal extent of burning [e.g., Cahoon *et al.*, 1992]. The remote sensing activity in SAFARI-92 was designed to develop and test algorithms for fire detection, to assist esti-

mates of fuel loads, to supply inputs to transport modeling studies, and to assess the potential contribution of satellite data to regional trace gas emission estimates. Aspects of this part of the campaign are discussed by Justice *et al.* [this issue], who found the advanced very high resolution radiometer (AVHRR) 1-km data suitable for monitoring fire occurrence and its relationship to vegetation state in the region. Most fires were found to occur in the period July–September 1992, with a peak in August, placing the SAFARI-92 field campaign well within the main burning season. Comparison with a wetter year (1989) showed that burning was reduced by approximately 50% in 1992 in the area between 20° and 30°S, a result ascribed to the effect of the severe drought of 1991/1992 on available biomass. A related study [Scholes *et al.*, this issue] reported the development of a method for estimating biomass consumed by fire in the tropics, based on some known fuel-constraining factors and using satellite data to estimate the area burned. The new estimates of the average quantity of biomass burned annually in Africa south of the equator, that is, 177 ± 87 Tg of dry matter per year, are less than previous estimates based on extrapolation from point data. It is suggested that emissions during 1992 could have been as much as 30% lower than this estimate, owing to the prevailing drought conditions.

Summary and Conclusions

During SAFARI-92, experimental vegetation fires were conducted in Kruger National Park, South Africa, and at some sites in Zambia and Swaziland. These experiments provided a broad set of data on trace gas and aerosol emissions, from which emission factors for fires in dry savannas and related biomes could be derived. The relationships between fuel characteristics, burning conditions, and fire behavior were elucidated. Regional studies on atmospheric chemistry and air mass transport showed that savanna fires in southern Africa account for a substantial amount of photochemical oxidants and haze over the subcontinent and that the export of smoke-laden air masses contributed strongly to the burden of ozone and other trace gases and aerosols over the tropical oceans surrounding Africa. Investigations on the relationships between fire, soil moisture status, and soil trace gas showed that moisture played a crucial role but that fire history also had an important influence on the emission of several trace gases. Remote sensing studies confirmed that AVHRR/LAC (1-km) imagery was a useful tool for fire monitoring in the region. In combination with biomass models the remote sensing data could be used for the estimation of the seasonal and geographical distribution of pyrogenic emissions.

The results from SAFARI confirm that it is justified to consider biomass burning as a significant contributor to the overall increase in greenhouse gases that has occurred over the last 150 years, accounting for some 10–25% of current emissions [Lashof, 1991; Andreae, 1993]. In order to establish accurately the global budgets of trace gases, reliable source strength and distribution estimates are needed. At present, the uncertainties associated with budget calculations are necessarily large, owing to the often inadequate quantification of individual sources and the problems associated with extrapolating from a number of poorly known sources to achieve a global estimate. The contribution of vegetation fires in the savanna regions of southern Africa has been one such poorly quantified source, despite the fact that savannas are recognized as one of the most significant biomes in terms of global biomass burning

emissions [Andreae, 1993], and that a large proportion of the African savanna burns each year [Hao and Liu, 1994]. It will now be possible to refine these estimates on the basis of results from SAFARI-92. Modeling studies incorporating the emission data, meteorological information, and the chemical measurements made during STARE/TRACE A/SAFARI indicate that the fires on the African and South American continents are indeed a major source of the gaseous and particulate pollutants found in the troposphere over the study region [Jacob *et al.*, this issue; Thompson *et al.*, this issue (a); Zenker *et al.*, 1996].

STARE/SAFARI-92 was an innovative project in many ways. As well as being the largest international, interdisciplinary investigation of biomass burning and its emissions to the atmosphere ever undertaken, it also represented the first time that a large-scale fire emission measurement campaign included as an integral component the characteristics of the biomass, the fire ecology, and the fire dynamics in the area. This integration constitutes a recognition of the significant link between fire behavior and emissions to the atmosphere. The success of the project as an example of interdisciplinary science is clearly reflected in this special section.

Acknowledgments. We thank the staffs of the Kruger National Park, South Africa (particularly S. Joubert, W. Gertenbach, A. Potgieter, and N. Zambatis), of the Etosha National Park, Namibia (particularly M. Linde and the team from the Etosha Ecological Institute), and of the Zimbabwe Meteorological Services at Victoria Falls for their generous cooperation. We are particularly indebted to L. van Rensburg at the University of the Witwatersrand and L. Trollope in the Kruger National Park for their invaluable logistical support. We are grateful to the pilots and crews of the SAFARI-92 research aircraft for their assistance during the research flights. We appreciate the logistical, technical, and scientific help of a large number of colleagues, whose names are given in the authors' lists and acknowledgments of the primary publications in this special volume. We acknowledge the permission of various government agencies in Angola, Botswana, Namibia, South Africa, Swaziland, Zambia, and Zimbabwe for permission to conduct research in these countries or to use the airspace over these countries. Participation in SAFARI was made possible by various funding agencies which are acknowledged in the papers in the special section.

References

- Anderson, B. E., et al., Aerosols from biomass burning over the tropical South Atlantic region: Distributions and impacts, *J. Geophys. Res.*, this issue.
- Andreae, M. O., Biomass burning: Its history, use and distribution and its impact on environmental quality and global climate, in *Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications*, edited by J. S. Levine, pp. 3–21, MIT Press, Cambridge, Mass., 1991.
- Andreae, M. O., The influence of tropical biomass burning on climate and the atmospheric environment, in *Biogeochemistry of Global Change: Radiatively Active Trace Gases*, edited by R. S. Oremland, pp. 113–150, Chapman and Hall, New York, 1993.
- Andreae, M. O., et al., Biomass burning in the global environment: First results from the IGAC/BIBEX field campaign STARE/TRACE-A/SAFARI-92, in *Global Atmospheric-Biospheric Chemistry*, edited by R. G. Prinn, pp. 83–101, Plenum, New York, 1994.
- Andreae, M. O., E. Atlas, H. Cachier, W. R. Cofer III, G. W. Harris, G. Helas, R. Koppmann, J. P. Lacaux, and D. E. Ward, Trace gas and aerosol emissions from savanna fires, in *Biomass Burning and Global Change*, edited by J. S. Levine, MIT Press, Cambridge, Mass., in press, 1996.
- Andreae, M. O., et al., Methyl halide emissions from savanna fires in southern Africa, *J. Geophys. Res.*, this issue.
- Baldy, S., G. Ancellet, M. Bessafi, A. Badr, and D. Lan Sun Luk, Field observations of the vertical distribution of tropospheric ozone at the island of La Reunion (southern tropics), *J. Geophys. Res.*, this issue.
- Blake, N. J., D. R. Blake, B. C. Sive, T.-Y. Chen, F. Rowland, J. E.

- Collins Jr., G. W. Sachse, and B. E. Anderson, Biomass burning emissions and vertical distribution of atmospheric methyl halides and other reduced carbon gases in the South Atlantic region, *J. Geophys. Res.*, this issue.
- Brimelow, J. C., and J. van Heerden, Surface temperature and wind fields over the Skeleton Coast (Namibia) and adjacent interior during SAFARI-92, *J. Geophys. Res.*, this issue.
- Browell, E. V., et al., Ozone and aerosol distributions and air mass characteristics over the South Atlantic basin during the burning season, *J. Geophys. Res.*, this issue.
- Cachier, H., J. Ducret, M.-P. Brémond, V. Yoboué, J.-P. Lacaux, A. Gaudichet, and J. Baudet, Biomass burning in a savanna region of the Ivory Coast, in *Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications*, edited by J. S. Levine, pp. 174–180, MIT Press, Cambridge, Mass., 1991.
- Cofer, W. R., III, J. S. Levine, E. L. Winstead, D. R. Cahoon, D. I. Sebach, J. P. Pinto, and B. J. Stocks, Source compositions of trace gases released during African savanna fires, *J. Geophys. Res.*, this issue.
- Cahoon, D. R., B. J. Stocks, J. S. Levine, W. R. Cofer, and K. P. O'Neill, Seasonal distribution of African savanna fires, *Nature*, 359, 812–815, 1992.
- Connors, V. S., D. R. Cahoon, H. G. Reichle, E. G. Brunke, M. Garstang, W. Seiler, and H. E. Scheel, Savanna burning and convective mixing in Southern Africa: Implications for CO emissions and transport, in *Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications*, edited by J. S. Levine, pp. 147–154, MIT Press, Cambridge, Mass., 1991.
- Crutzen, P. J., and M. O. Andreae, Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles, *Science*, 250, 1669–1678, 1990.
- Crutzen, P. J., and J. G. Goldammer (Eds.), *Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires*, John Wiley, New York, 1993.
- Crutzen, P. J., L. E. Heidt, J. P. Krasnec, W. H. Pollock, and W. Seiler, Biomass burning as a source of atmospheric gases CO, H₂, N₂O, NO, CH₃Cl, and COS, *Nature*, 282, 253–256, 1979.
- Diab, R. D., M. R. Jury, J. M. Combrink, and F. Sokolic, A comparison of anticyclone and trough influences on the vertical distribution of ozone and meteorological conditions during SAFARI-92, *J. Geophys. Res.*, this issue (a).
- Diab, R. M., A. M. Thompson, M. Zunckel, G. J. R. Coetzee, J. B. Combrink, G. E. Bodeker, J. Fishman, F. Sokolic, D. P. McNamara, C. B. Archer, and D. Nganga, Vertical ozone distribution over southern Africa and adjacent oceans during SAFARI-92, *J. Geophys. Res.*, this issue (b).
- FIRESCAN Science Team, Fire in boreal ecosystems of Eurasia: First results of the Boreal Forest Island Fire Experiment, Fire Research Campaign Asia North (FIRESCAN), *World Resour. Rev.*, 6, 499–523, 1994.
- Fishman, J., P. Minnis, and H. G. Reichle, Use of satellite data to study tropospheric ozone, *J. Geophys. Res.*, 91, 14,451–14,465, 1986.
- Fishman, J., C. E. Watson, J. C. Larsen, and J. A. Logan, Distribution of tropospheric ozone determined from satellite data, *J. Geophys. Res.*, 95, 3599–3617, 1990.
- Fishman, J., K. Fakhruzzaman, B. Cros, and D. Nganga, Identification of widespread pollution in the southern hemisphere deduced from satellite analyses, *Science*, 252, 1693–1696, 1991.
- Fishman, J., J. M. Hoell Jr., R. J. Bendura, V. W. J. H. Kirchhoff, and R. J. McNeal, NASA GTE TRACE A experiment (September–October 1992), *J. Geophys. Res.*, this issue.
- Fuelberg, H. E., J. D. Van Ausdall, E. V. Browell, and S. P. Longmore, Meteorological conditions associated with vertical distributions of aerosols off the west coast of Africa, *J. Geophys. Res.*, this issue.
- Garstang, M., P. D. Tyson, R. Swap, M. Edwards, P. Källberg, and J. A. Lindesay, Horizontal and vertical transport of air over southern Africa, *J. Geophys. Res.*, this issue.
- Goldammer, J. G. (Ed.), *Fire in the Tropical Biota: Ecosystem Processes and Global Challenges*, Springer-Verlag, New York, 1990.
- Goldammer, J. G., Tropical wild-land fires and global changes: Pre-historic evidence, present fire regimes, and future trends, in *Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications*, edited by J. S. Levine, pp. 83–91, MIT Press, Cambridge, Mass., 1991.
- Gregory, G. L., H. E. Fuelberg, S. P. Longmore, B. E. Anderson, J. E. Collins Jr., and D. R. Blake, Chemical characteristics of tropospheric air over the tropical South Atlantic Ocean: Relationship to trajectory history, *J. Geophys. Res.*, this issue.
- Hao, W.-M., and M.-H. Liu, Spatial and temporal distribution of tropical biomass burning, *Global Biogeochem. Cycles*, 8(4), 495–503, 1994.
- Hao, W.-M., D. E. Ward, G. Olbu, and S. P. Baker, Emissions of CO₂, CO, and hydrocarbons from fires in diverse African savanna ecosystems, *J. Geophys. Res.*, this issue.
- Harris, G. W., T. Zenker, F. G. Wienhold, M. Welling, U. Parchatka, and M. O. Andreae, Airborne measurements of trace gas emission ratios from southern African veld fires, *J. Geophys. Res.*, 1996, in preparation.
- Heikes, H., et al., Ozone, hydroperoxides, oxides of nitrogen, and hydrocarbon budgets in the marine boundary layer over the South Atlantic, *J. Geophys. Res.*, this issue.
- Held, G., Wind and temperature profiles in the boundary layer above the Kruger National Park during SAFARI-92, *J. Geophys. Res.*, this issue.
- Jacob, D. J., et al., Origin of ozone and NO_x in the tropical troposphere: Photochemical analysis of aircraft observations over the South Atlantic basin, *J. Geophys. Res.*, this issue.
- Jury, M. R., E. Brunke, and M. Schormann, Aircraft section measurements of meteorology and ozone in northern Namibia during SAFARI-92, *J. Geophys. Res.*, this issue.
- Justice, C. O., J. D. Kendall, P. R. Dowty, and R. J. Scholes, Satellite remote sensing of fires during the SAFARI campaign using NOAA AVHRR data, *J. Geophys. Res.*, this issue.
- Kuhlbusch, T. A. J., M. O. Andreae, H. Cachier, J. G. Goldammer, J.-P. Lacaux, R. Shea, and P. J. Crutzen, Black carbon formation by savanna fires: Measurements and implications for the global carbon cycle, *J. Geophys. Res.*, this issue.
- Lacaux, J.-P., H. Cachier, and R. Delmas, Biomass burning in Africa: An overview of its impact on atmospheric chemistry, in *Fire in the Environment: The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires*, edited by P. J. Crutzen and J. G. Goldammer, pp. 159–191, John Wiley, New York, 1993.
- Lacaux, J. P., J. M. Brustet, R. Delmas, J. C. Menaut, L. Abbadie, B. Bonsang, H. Cachier, J. Baudet, M. O. Andreae, and G. Helas, Biomass burning in the tropical savannas of Ivory Coast: An overview of the field experiment Fire of Savannas (FOS/DECAFE '91), *J. Atmos. Chem.*, 22, 195–216, 1995.
- Lacaux, J.-P., R. Delmas, C. Jambert, and T. Kuhlbusch, NO_x emissions from African savanna fires, *J. Geophys. Res.*, this issue.
- Lashof, D. A., The contribution of biomass burning to global warming: An integrated assessment, in *Global Biomass Burning: Atmospheric, Climatic and Biospheric Implications*, edited by J. S. Levine, pp. 441–444, MIT Press, Cambridge, Mass., 1991.
- Le Canut, P., M. O. Andreae, G. W. Harris, F. G. Wienhold, and T. Zenker, Aerosol optical properties over southern Africa during SAFARI-92, in *Biomass Burning and Global Change*, edited by J. S. Levine, MIT Press, Cambridge, Mass., in press, 1996.
- Le Canut, P., M. O. Andreae, G. W. Harris, F. G. Wienhold, and T. Zenker, Airborne studies of emissions from savanna fires in southern Africa, 1, Aerosol emissions measured with a laser-optical particle counter, *J. Geophys. Res.*, this issue.
- Levine, J. S. (Ed.), *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, 569 pp., MIT Press, Cambridge, Mass., 1991.
- Levine, J. S. (Ed.), *Biomass Burning and Global Change*, MIT Press, Cambridge, Mass., in press, 1996.
- Levine, J. S., E. L. Winstead, D. A. B. Parsons, M. C. Scholes, and R. J. Scholes, W. R. Cofer III, D. R. Cahoon Jr., and D. I. Sebach, Biogenic soil emissions of nitric oxide (NO) and nitrous oxide (N₂O) from savannas in South Africa: The impact of wetting and burning, *J. Geophys. Res.*, this issue.
- Logan, J. A., and V. W. J. H. Kirchhoff, Seasonal variations of tropospheric ozone at Natal, Brazil, *J. Geophys. Res.*, 91, 7875–7881, 1986.
- Loring, R. O., Jr., H. E. Fuelberg, J. Fishman, M. V. Watson, and E. V. Browell, Influence of a midlatitude cyclone on tropospheric ozone distributions during a period of TRACE A, *J. Geophys. Res.*, this issue.
- Maenhaut, W., I. Salma, J. Cafmeyer, H. J. Annegarn, and M. O. Andreae, Regional atmospheric aerosol composition and sources in the Eastern Transvaal, South Africa, and impact of biomass burning, *J. Geophys. Res.*, this issue.
- McKenzie, L. M., D. E. Ward, and W.-M. Hao, Chlorine and bromine in the biomass of tropical and temperate ecosystems, in *Biomass*

- Burning and Global Change*, edited by J. S. Levine, MIT Press, Cambridge, Mass., in press, 1996.
- Newell, R. E., H. G. Reichle, and W. Seiler, Carbon monoxide and the burning earth, *Sci. Am.*, 260, 82–88, 1989.
- Olson, J. R., J. Fishman, and V. W. J. H. Kirchhoff, Analysis of the distribution of ozone over the southern Atlantic region, *J. Geophys. Res.*, this issue.
- Parsons, D. A. B., M. C. Scholes, R. J. Scholes, and J. S. Levine, Biogenic NO emissions from savanna soils as a function of fire regime, soil type, soil nitrogen, and water status, *J. Geophys. Res.*, this issue.
- Prinn, R. G., Global atmospheric-biospheric chemistry, in *Global Atmospheric-Biospheric Chemistry*, edited by R. G. Prinn, pp. 1–18, Plenum, New York, 1994.
- Pszenny, A. A. P., and R. G. Prinn (Eds.), *International Global Atmospheric Chemistry (IGAC) Project: The Operational Plan, Global Change Rep. 32*, Int. Geosphere-Biosphere Programme, Stockholm, 1994.
- Scholes, R. J., J. Kendall, and C. O. Justice, The quantity of biomass burned in southern Africa, *J. Geophys. Res.*, this issue (a).
- Scholes, R. J., D. Ward, and C. O. Justice, Emissions of trace gases and aerosol particles due to vegetation burning in southern hemisphere Africa, *J. Geophys. Res.*, this issue (b).
- Shea, R. W., B. W. Shea, J. B. Kauffman, D. E. Ward, C. I. Haskins, and M. C. Scholes, Fuel biomass and combustion factors associated with fires in savanna ecosystems of South Africa and Zambia, *J. Geophys. Res.*, this issue.
- Stocks, B. J., B. W. van Wilgen, W. S. W. Trollope, D. J. McRae, J. A. Mason, F. Weirich, and A. L. F. Potgieter, Fuels and fire behavior dynamics on large-scale savanna fires in Kruger National Park, South Africa, *J. Geophys. Res.*, this issue.
- Susott, R. A., S. P. Baker, G. Olbu, D. E. Ward, and J. B. Kauffman, Carbon, hydrogen and nitrogen content of tropical ecosystem fuels, in *Biomass Burning and Global Change*, edited by J. S. Levine, MIT Press, Cambridge, Mass., in press, 1996.
- Swap, R., M. Garstang, S. A. Macko, P. D. Tyson, W. Maenhaut, P. Artaxo, P. Källberg, and R. Talbot, The long-range transport of southern African aerosols to the tropical South Atlantic, *J. Geophys. Res.*, this issue.
- Thompson, A. M., D. P. McNamara, K. E. Pickering, and R. D. McPeters, Effect of marine stratocumulus on TOMS ozone, *J. Geophys. Res.*, 98, 23,051–23,057, 1993.
- Thompson, A. M., et al., Where did tropospheric ozone over southern Africa and the tropical Atlantic come from in October 1992?: Insights from TOMS, GTE/TRACE A and SAFARI-92, *J. Geophys. Res.*, this issue (a).
- Thompson, A. M., R. D. Diab, G. E. Bodecker, M. Zunkel, G. J. R. Coetzee, C. B. Archer, D. P. McNamara, K. E. Pickering, J. B. Combrink, F. Sokolic, J. Fishman, and D. Nganga, Ozone over southern Africa during SAFARI-92/TRACE A, *J. Geophys. Res.*, this issue (b).
- Thompson, A. M., T. Zenker, G. E. Bodeker, and D. P. McNamara, Ozone over southern Africa: Patterns and influences, in *Fire in the Southern African Savanna: Ecological and Environmental Perspectives*, edited by B. W. van Wilgen, M. O. Andreae, J. G. Goldammer, and J. A. Lindesay, Witwatersrand Univ. Press, Johannesburg, South Africa, in press, 1996.
- Trollope, W. S. W., L. A. Trollope, A. L. F. Potgieter, and N. Zambatis, SAFARI-92 characterization of biomass and fire behavior in the small experimental burns in the Kruger National Park, *J. Geophys. Res.*, this issue.
- Tyson, P. D., *Climatic Change and Variability in Southern Africa*, Oxford Univ. Press, New York, 1986.
- Tyson, P. D., M. Garstang, R. J. Swap, E. V. Browell, R. D. Diab, and A. M. Thompson, Transport and vertical structure of ozone and aerosol distributions over southern Africa, in *Biomass Burning and Global Change*, edited by J. S. Levine, MIT Press, Cambridge, Mass., in press, 1996.
- van Wilgen, B. W., W. S. W. Trollope, and C. S. Everson, Fire management in southern Africa: Some examples of current objectives, practices and problems, in *Fire in the Tropical Biota: Ecosystem Processes and Global Challenges*, edited by J. Goldammer, pp. 179–215, Springer-Verlag, New York, 1990.
- van Wilgen, B. W., D. M. Richardson, F. J. Kruger, and H. J. van Hensberge (Eds.), *Fire in South African Mountain Fynbos: Species, Community and Ecosystem Response in Swartboskloof*, vol. 93, Springer-Verlag, New York, 1992.
- Wang, Y., W.-K. Tao, K. E. Pickering, A. M. Thompson, J. S. Kain, R. F. Adler, J. Simpson, P. R. Keehn, and G. S. Lai, Mesoscale model (MM5) simulations of TRACE A and PRESTORM convective systems and associated tracer transport, *J. Geophys. Res.*, this issue.
- Ward, D. E., W. M. Hao, R. A. Susott, R. A. Babbitt, R. W. Shea, J. B. Kauffman, and C. O. Justice, Effect of fuel composition on combustion efficiency and emission factors for African savanna ecosystems, *J. Geophys. Res.*, this issue.
- Watson, C. E., J. Fishman, and H. G. Reichle, The significance of biomass burning as a source of carbon monoxide and ozone in the southern hemisphere tropics: A satellite analysis, *J. Geophys. Res.*, 95, 16,443–14,450, 1990.
- Zenker, T., A. M. Thompson, D. P. McNamara, T. L. Kuscera, G. W. Harris, F. G. Wienhold, P. Le Canut, M. O. Andreae, and R. Koppmann, Regional trace gas distribution and air mass characteristics in the haze layer over southern Africa during the biomass burning season (Sep./Oct. 92): Observations and modeling from the STARE/SAFARI '92/DC-3, in *Biomass Burning and Global Change*, edited by J. S. Levine, MIT Press, Cambridge, Mass., in press, 1996.
- Zepp, R. G., W. L. Miller, R. A. Burke, D. A. B. Parsons, and M. C. Scholes, Effects of moisture and burning on soil-atmosphere exchange of trace carbon gases in a southern African savanna, *J. Geophys. Res.*, this issue.
- Zunkel, M., G. Held, R. A. Preston-Whyte, and A. Joubert, Low-level wind maxima and the transport of pyrogenic products over southern Africa, *J. Geophys. Res.*, this issue (a).
- Zunkel, M., Y. Hong, and S. O'Beirne, Characteristics of the nocturnal boundary layer: Okaukejo, Namibia, during SAFARI-92, *J. Geophys. Res.*, this issue (b).

M. O. Andreae, Biogeochemistry Department, Max Planck Institute for Chemistry, Box 3060, 55020 Mainz, Germany. (e-mail: moa@mpch-mainz.mpg.de)

H. J. Annegarn, Schonland Research Centre for Nuclear Sciences, University of Witwatersrand, Johannesburg 2050, South Africa.

M. Garstang, Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22903.

J. G. Goldammer, Biogeochemistry Department, Fire Ecology and Biomass Burning Research Group, 79085 Freiburg, Germany.

G. Harris, Centre for Atmospheric Chemistry, York University, 4700 Keele St., North York, Ontario, M3J 1P3 Canada.

J. A. Lindesay, Geography Department, School of Resource and Environmental Management, Australian National University, Canberra ACT 0200, Australia.

R. J. Scholes, Division of Water, Environment and Forest Technology (Environmentek), CSIR, P.O. Box 395, Pretoria 0001, South Africa.

B. W. van Wilgen, Division of Forest Science and Technology (Forestek), CSIR, Private Bag X5011, Stellenbosch 7600, South Africa.

(Received April 24, 1996; revised May 12, 1996; accepted May 15, 1996.)