

ANNEXURE II

WILDLAND FIRE EMISSIONS FROM AFRICA AND THEIR IMPACT ON THE GLOBAL ATMOSPHERE

Mary Scholes
Meinrat O. Andreae

1 INTRODUCTION

In this paper we synthesize and review information on pyrogenic emissions from Africa and their impact on the global atmosphere. In a way, this task would have been much easier some six years ago, before various campaigns, such as STARE, TRACE-A and SAFARI (1, 2), took place, as there was then very little published data on this subject. Data available were mostly associated with biomass burning in the moist savannas of West Africa. Data collected during the project Fire of Savannas / Dynamique et Chimie Atmosphérique en Forêt Équatoriale (FOS/DECAFE) (3-6), together with satellite-based information focused attention on Africa as a possible source of high levels of ozone, carbon monoxide and other trace gases measured over the central South Atlantic in austral spring. At that time, widespread vegetation fires were also common in both South America and southern Africa (7-11).

The shortage of information on the emission characteristics of fires in dry savannas was one of the main reasons for organising the STARE/TRACE-A/SAFARI campaigns. Although there is a long history of fire research in southern Africa, much of the emphasis of this research had been on ecological and management effects, with little thought given to the regional and global atmospheric implications of savanna fires. Even less attention had been paid to the role of soil microorganisms and savanna vegetation in the production of trace gases. The interactions between the sources of the trace gases and their impact on tropospheric ozone have become extremely topical issues as the data bases and knowledge have grown. This paper will present data on the emissions of trace gases from biogenic sources and biomass burning and discuss some of the impacts of these on the global atmosphere. Much of the data have been collected from particular sites in

particular seasons and attempts have been made by some authors to scale-up these values to give annual regional estimates. Problems associated with this approach will be discussed.

2 ATMOSPHERIC CHEMISTRY

The concentrations of nitrogen and oxygen that make up 99% of the Earth's atmosphere have stayed nearly constant over the last several hundred million years. The remainder of the atmosphere is made up by a variety of trace gases, and it is the concentrations of these gases that are being most significantly influenced by anthropogenic effects. Carbon dioxide (CO_2) is chemically inert in the troposphere, whereas methane (CH_4), carbon monoxide (CO), oxides of nitrogen and sulphur, and ozone (O_3) are all chemically reactive. In addition to these trace gases are other chemically reactive gases that occur in even smaller amounts, including the hydroxyl (OH) and hydroperoxy (HO_2) radicals. These free radicals are considerably more reactive than other trace gas species and, even though they have very short residence times and low average concentrations, they are crucial to gas-phase chemistry and have a particularly significant effect on atmospheric composition (12).

Tropospheric ozone is both a pollutant and an effective greenhouse gas, depending on where it occurs relative to the Earth's surface. Any changes in the processes that may lead to changes in tropospheric ozone concentrations by affecting its sources or sinks are therefore of considerable interest. Most tropospheric ozone is produced in the photochemical reaction sequences of methane and non-methane hydrocarbons (NMHCs) with

OH in the presence of nitrogen oxides (NO_x). While hydrocarbon oxidation by OH results in ozone formation in the presence of high levels of NO_x , the oxidation process in a low NO_x environment leads to ozone destruction (13).

In addition to gaseous components, the atmosphere also contains suspended solid particles, or aerosols, that have an important function in the regulation of global climate (14). They are chemically significant primarily because many gas phase molecules are removed from the atmosphere by incorporation into aerosols or by reactions occurring on particle surfaces (15).

3 EMISSIONS FROM WILDLAND FIRES

3.1 Quantity of Biomass Burned in Southern Africa

Estimates of the amounts of vegetative matter (in the following referred to as biomass) burned each year around the globe suggest that savanna fires are the single largest source of pyrogenic emissions. They are believed to be a significant source of aerosol and trace gas inputs to the global atmosphere (16-24). The primary reason for the high incidence of fires is the seasonality of the rainfall over most of the savannas areas, which allows the fuel accumulated in the growing season to become dry and prone to burning. The dry season in southern Africa lasts from May to October each year. The biomass burned annually in African savannas has been estimated at 2000 Tg dm yr^{-1} , and the area exposed to fire covers 440 million hectares (25). Estimates for Africa, south of the equator are 1200 Tg dm yr^{-1} (23). These estimates have been obtained using the

classification method, which involves using the total amount burned as the sum over the vegetation types of the product of the estimated area burned, fuel load, and fraction consumed per type.

The trend in biomass burning studies has been toward decreasing estimates of biomass burned as ecologists with local expertise have been drawn into the estimation process. For example, Menaut et al. (26) halved the estimate for west Africa by applying lower fuel loads in the extensive arid Sahelian savannas. The main reasons for these decreases are the improved estimates of the area burned when calibrated satellite data are used and the lower estimate of fuel load obtained when aridity, herbivory and decay are considered. Constraining the fuel load, by understanding the determinants of the vegetation composition and biomass, to what can be accumulated under the prevailing climate regime accounts for a further substantial part of the reduction. This approach to estimating fuel loads is termed the modelling method (27). When this method is applied to southern Africa, the estimate of the quantity of biomass burned annually and its range of uncertainty are reduced substantially relative to estimates based on extrapolation of a few point data on fuel loads to large areas and reliance on anecdotal data for estimation of the area burned.

The amount of biomass consumed annually in Africa south of the equator by vegetation fires (excluding those used for forest clearing, agricultural waste burning, and domestic biomass fuel consumption) has been estimated to average $177 \pm 87 \text{ Tg dm yr}^{-1}$ (27). Hao and Liu (28) estimated that about 2.5 times more biomass is burned in shifting cultivation in Africa than that in

deforestation. However, it is expected that this value will be much smaller when the modelling method is applied. Estimates made by Scholes et al. (27) were for a period of drought and are lower than what would be expected under normal rainfall conditions. The estimation of burned area based on detection of active fires by AVHRR or other remote sensing technologies is still in need of refinement. Regardless of source, biomass burning in the tropical forests and savannas of Africa is an important source of many of the trace gases in the atmosphere.

3.2 Emissions of Trace Gases and Aerosols from Savanna Fires in Africa

Two-thirds of tropical savannas are located in Africa, 60% of which lie south of the equator. A modelling approach has been used to estimate the emissions of CH_4 , CO , NO_x and particulate matter with a diameter smaller than $2.5 \mu\text{m}$ from vegetation fires in the region (21). The results are summarised by country in Table 1. The emissions are strongly concentrated during July–September, the Southern Hemisphere dry winter season.

Only countries completely within the study area are individually listed in the table. Note that the coarse simulation scale makes the estimates for small countries unreliable. The data are for an average year, nominally 1989, and do not include emissions from domestic fuelwood and charcoal or the burning of agricultural wastes.

The amount of CO_2 that is exchanged with the atmosphere annually owing to vegetation fires in southern Africa is very large, somewhere in the region of 20% of net primary production,

Table 1. Pyrogenic emissions of trace gases per country in Africa south of the equator (21).

Country	CO ₂ Tg/yr	CH ₄ Tg/yr	CO Tg/yr	NO _x Tg/yr	N ₂ O Gg/yr
Angola	63.5	0.068	2.229	0.160	68.0
Botswana	13.2	0.013	0.434	0.030	7.8
Burundi	3.4	0.006	0.174	0.012	7.7
Lesotho	0.4	0.000	0.011	0.001	0.4
Malawi	7.1	0.007	0.248	0.017	11.7
Mozambique	25.6	0.033	1.035	0.072	40.3
Namibia	4.4	0.004	0.138	0.010	0.3
Rwanda	1.0	0.004	0.090	0.006	1.2
South Africa	11.4	0.015	0.449	0.031	5.8
Swaziland	0.1	0.000	0.000	0.000	0.0
Tanzania	41.0	0.015	1.623	0.114	49.5
Zambia	53.6	0.084	2.502	0.175	73.7
Zimbabwe	7.2	0.008	0.265	0.019	6.7
Others (partly included)	92.1	0.207	5.714	0.398	171.6

thus a relatively small perturbation to the fire regime could have significant consequences for the net global carbon budget. The pyrogenic methane emissions are of the same order of magnitude as emissions resulting from enteric fermentation in large mammal herbivores in the same region. The carbon monoxide emitted represents about 1% of the global CO budget and is approximately equal to the annual industrial CO emissions from the one partly industrialized country in the region, South Africa, (29). Regional pyrogenic emissions of NO_x are a significant portion of the global NO_x budget.

Estimates of the emissions of trace gases and aerosols from savanna fires in the whole of Africa and worldwide are presented in Table 2. Emission factors were calculated from the emission ratio using a mean CO₂ emission factor of 1640 g CO₂ kg⁻¹ dry fuel. The estimates of biomass burned are based on the assessments of Hao et al. (23) and Andreae (24). As noted above, investigations carried out using remote sensing and an ecosystem data base (27, 21), have resulted in much lower estimates of biomass burned in the region. However, when pyrogenic CO emissions much below those proposed in Table 2 are used as boundary

Table 2. Best guess emission factors and emission rates for savanna fires, and estimates for emissions from African and global savanna fires, all biomass burning, and all human sources (including biomass burning) (30).

Species	Molar emission ratio [10 ³]	Emission factor g species/kg dry fuel	African savannas Tg species per year	Global savannas	Biomass burning	All human sources
Biomass burned	2000	3700	8910	-		
Carbon burned	1000	1660	4100	-		
CO ₂	1000	1640	3280	6070	13500	33700
CO	62	65	130	240	680	1600
CH ₄	4	2.4	5	9	43	275
NMHC	6	3.1	6	11	42	100
H ₂	10	0.75	1.5	2.8	16	40
NO _x ¹	2.8	3.1	6	11	21	70
NO _x ²	3.5	3.9	8	14	-	-
NO	0.09	0.15	0.03	0.56	1.3	5.5
NH ₃	1.5	1	2	3.7	3.7	57
SO ₂	0.25	0.6	1.2	2.2	4.8	160
COS	0.01	0.02	0.04	0.07	0.21	0.38
CH ₃ O ¹	0.75	0.09	0.17	0.32	1.1	1.1?
CH ₃ Br ¹	0.007	0.002	0.004	0.007	0.019	0.11
CH ₃ I ¹	0.0026	0.001	0.002	0.004	0.008	?
Aerosols						
TPM		10	20	37	90	390
PM _{2.5}		5	10	19	-	240
Carbon		7	14	26	60	90
Black Carbon		0.8	1.6	3	9	20
K		0.33	0.7	1.2	1.4	-
CCN		1.1·10 ¹³	22·10 ²⁷	4·10 ²⁷	35·10 ²⁷	?

¹ emission ratios relative to CO₂, the other emission ratios relative to CO₂ as NO_x

conditions in atmospheric chemistry/transport models, unrealistically low CO concentration are obtained for stations in the tropics (15). Future studies to resolve these issues need to be carried out.

Based on the estimates of Andreae (24) savanna fires in Africa and the world account for about 22% and 42% of the biomass burned globally. However, due to the relatively clean, flaming-dominated combustion typical of savanna fires, the emission of reduced trace gases (CO, CH₄, NMHC) is less than expected from the fraction of global biomass burning that takes place in savannas. In the case of CO, savanna fires produce only 35% of the global pyrogenic emission, and in the case of CH₄, the savanna contribution is only 21%. In contrast, species that are connected to flaming combustion are favoured in savanna fires, which therefore are responsible for some 52% of pyrogenic NO_x emissions. One consequence of this flaming-dominated emission profile of savanna fires is that the ratio NO_x/NMHC in the smoke plumes is relatively high. For this reason, higher specific ozone production can take place in savanna fire plumes than in forest fire emissions (31).

Hydrogenated species (e.g. CH₄, NMHCs, CH₃Cl and CH₃Br) as well as other important trace gases (e.g., CO) are produced predominantly in smouldering conditions characterized by insufficient O₂ supply. Methyl bromide and methyl chloride play significant roles in stratospheric O₃ destruction as sources of bromine and chlorine atoms (32). Savanna fires contribute to methyl halide emissions roughly in proportion to their fraction of biomass burned, since the lower

methylation fraction due to the small amount of smouldering is compensated for by the high halogen element concentration in the savanna biomass as compared to forest biomass (30). Table 3 summarises the available information on emission ratios for CH₃Cl and CH₃Br from fires in various environments. It shows that relatively consistent results were obtained from savanna fires in different regions of Africa and South America, giving a fair degree of confidence in the accuracy of these estimates. On the other hand, the largest uncertainties regarding pyrogenic methyl halide emissions prevail in the humid tropics, where highly divergent results have been found. Future investigations need to address emissions from deforestation fires in particular.

Emission ratios are very useful for providing estimates of the biomass burning contribution to the budgets of different trace gases regionally and globally. Ratios of CO/CO₂ of 0.062 obtained during the SAFARI-92 and TRACE-A campaigns seem typical of savanna fires worldwide. Thus the emission ratios from these campaigns were employed in Table 2 to make some rough estimates of pyrogenic source strength from savannas for various gases, including the methyl halides (37, 1, 42). Worldwide estimates presented were obtained using estimates of global pyrogenic CO₂ and CO emissions of 3660 Tg C yr⁻¹ and 290 Tg C yr⁻¹, respectively (24). Even though large uncertainties are associated with data extrapolation, the calculations of savanna and worldwide emission rates for methyl halides based on these data support significant roles for the biomass burning contributions to CH₃Cl and CH₃Br to their total global emissions. The CH₃I

Table 3. Emission ratios of methyl halide species from fires in various ecosystems.

Environment	CH ₃ Cl/CO *10 ³	CH ₃ Cl/CO ₂ *10 ³	CH ₃ Br/CO *10 ³	CH ₃ Br/CO ₂ *10 ³	CH ₃ Br/CH ₃ Cl *10 ³	Reference
<i>Mid/High Latitude Forest</i>						
Colorado, USA		23				(33)
Various, N. America	160	12				(34)
Siberia		61		1.30	19.0	(35)
Finland	246	32	5.4	0.65	22.2	
Average	203	32	5.4	0.98	20.6	
<i>Tropical/subtropical Forest</i>						
Eucalypt Forest, Australia		290				(36)
Drakensberg, S. Africa	940	99				(37)
Humid forest, Indonesia	200	10	3.2	0.15	15.6	
Best guess	560	55		0.63		
<i>Savanna, Grassland</i>						
West Africa	500	43				(38)
Southern Africa	950	20	8.3	0.11	8.3	(37)
Southern Africa	550	30	4.1	0.23	7.5	(39)
Brazil	980	32	8.7	0.20	8.9	(39)
Average	750	31	7.0	0.21	6.2	
<i>Agricultural Wastes</i>						
Sugar cane	1050	19				(37)
<i>Laboratory Fires</i>						
Various fuels	1600	120				(40)
Various fuels		120				(41)
Savanna grass				0.29	3.4	(35)

emissions from biomass burning are more difficult to quantify, but they are likely to be insignificant in affecting global CH_4 levels compared to the large oceanic source for this gas.

Aerosols are an important by-product of biomass combustion. Recently, there has been an upsurge of interest in the potential of smoke particles to alter the radiative and chemical balance of the tropical and even global troposphere. Although smoke aerosols contain both inorganic compounds and black carbon, they consist predominantly of organic substances (43, 3, 44-46). Depending on the relative proportions of dark (e.g. soot) and non-light-absorbing components, they have the potential to create a cooling of the atmosphere by scattering incoming solar radiation, or a warming by absorbing radiation (47, 48). Furthermore, they are good cloud condensation nuclei (CCN) due to the presence of hydrophilic organic material in the particles (49, 50). Therefore, at tropical latitudes biomass burning aerosols are likely to modify the albedo and lifetime of the cloud cover (51, 52).

The production and characterisation of aerosols was studied at two sites in Africa, the Kruger National Park, South Africa, and the Lamto Research Station, Ivory Coast (45); the data collected are presented in Table 4.

Among the several trace elements detectable in biomass burning aerosols the notable and quite constant enrichment of two metals, potassium and zinc, can serve as biomass burning indicators. Chlorine and sulphur are also found in significant concentrations but their variable abundance probably reflects variable inputs of pre-deposited dust and therefore precludes any possibility for these

elements to serve as biomass burning tracers (53, 45, 46). Large uncertainties remain in the emission factor estimates for aerosols for most types of fires. This applies even more to the production of CCN from fires, therefore the values given in Table 2 must be considered as very preliminary estimates of CCN emissions. Even so, these results indicate that fires may be the largest source of CCN in the tropics (30).

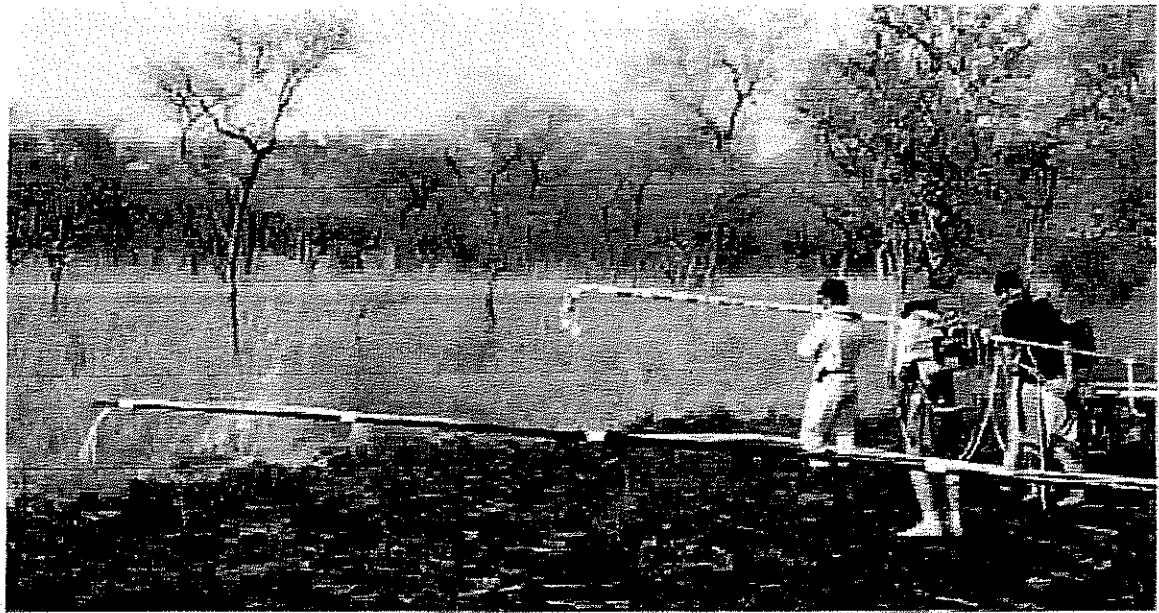
4 GENERAL DISCUSSION AND CONCLUSIONS

Savanna fires are a highly significant source of trace gases and aerosol species. Due to the seasonal and regional concentration of these fires, centred on the dry tropics during the dry season, their impact is even more conspicuous. The low incidence of rain during the fire season also enhances the atmospheric lifetime of the pyrogenic pollutants, and allows them to be dispersed over long distances.

In order to generate realistic patterns of dispersal and transformation, atmospheric chemistry and climate models require trace gas and particle flux estimates for large regions, but with finer spatial and temporal resolution than current methods deliver. Reasonably accurate emission factors have now been determined for many important species. The estimates of fuel loads and emissions given by Scholes et al. (21, 27) and those used to calculate the emissions by Andreae (30) in Table 2 show how important it is to reduce the uncertainties, associated with the amount and composition of the vegetation that will burn, if we are to make accurate predictions about impacts on the atmosphere. The modelling

Table 4. Characterisation of biomass burning aerosols sampled during the two savanna experiments at Kruger National Park (KNP) and Lamto (45).

		Back fire	Head fire	Post-head fire	Smoldering fire (tree)
Fine/total TPM (%)	KNPLamto mean	84 ± 6 74 ± 8 79	80 ± 1073 ± 12 77	71 ± 13 36 54	- -
Cl/TPM (%)	KNPLamto mean	46 ± 1 58	37 ± 12 7053	43 ± 243	-
Ch/Ci (%)	KNPLamto mean	9.5 ± 1.7 2.611	10.7 ± 211.7 ± 3.311.2	11.4 ± 2 3 87	7.0 ± 0.1 7.1 7.0
K fine/K total (%)	KNPLamto mean	94 ± 289 ± 492	88 ± 1070 ± 279	71 ± 207271	64 ± 30-64
K/Cb	KNPLamto mean	1.14 ± 0.48 ± 1.51.4	0.98 ± 0.33 0.91.2	0.32 ± 0.170.400.36	0.011 - 0.011
Zn fine/Zn total (%)	KNPLamto mean	858183	897683	735564	*
Zn/Cb (%)	KNPLamto mean	6.7 ± 5.43.7 ± 2.15.2	4.8 ± 2.46.2 ± 3.05.5	3.35 ± 1.84.74.0	0.005-0.005
Cl fine/Cl total (%)	KNPLamto mean	91 86 89	88 77 83	61 62 61	41 - 41
Cl/Cb	KNPLamto mean	1.10 ± 0.57 ± 1.50.77	0.84 ± 0.300.33 ± 0.120.59	0.17 ± 0.160.370.27	0.005-0.005
S fine/ S total (%)	KNPLamto mean	7610988	717975	70 86 78	48 - -
S/Cb	KNPLamto mean	0.22 ± 0.70.036 ± 0.025-	0.19 ± 0.040.044-	0.20 ± 0.140.16	0.01 - -



method described by Scholes et al. (21, 27) may be one way to pursue this issue. Modelling approaches to scale-up the biogenic emissions to a sub-continental scale are currently being developed. In the scenario of carbon emission limits, taxes and credits, which are now becoming very real, it will be tempting to suppress all fires in the frequently burned vegetation types (if that were practical), in order to sequester carbon. The short-term carbon gains would be substantial but insecure. In the longer term the small but steady increase in soil elemental carbon, about 400 Gg yr^{-1} , in Africa south of the equator, would no longer occur (21).

Pyrogenic emissions are mostly concentrated in the dry season from August to October, whereas the biogenic emissions are continuous throughout the year. Fire seems to have little effect on the biogenic emissions of the globally most important greenhouse gases, CO_2 , CH_4 and

N_2O , whereas precipitation/soil moisture seems to have a much higher influence. The annual amount of biogenic emissions may be greater for some gases (e.g. NMHCs) than the annual pyrogenic emissions. These data will only become available as biogenic models develop. The timing of the peak of the biogenic emissions, at the onset of the spring rains, relative to the pyrogenic emissions may be important in understanding the timing of the mid-Atlantic tropospheric ozone anomaly.

The seasonal tropospheric ozone enhancement is a result of biomass burning on both sides of the South Atlantic. Modelling of biomass burning influences at a pan-tropical scale suggests that photochemical ozone production and destruction in the tropics are enhanced by 35% and 25%, respectively, causing an increase in ozone abundance in the tropical and subtropical troposphere of at least 15%. These findings have considerable

Ground-based measurements of fire emissions during the Southern Africa Fire-Air Atmosphere Research Initiative (SAFARI-92) were conducted in the Kruger National Park, South Africa, in August-September 1992. (Photo: J.G. Goldammer)

implications for our understanding of the role of fire in prehistoric times and of the implications of land use change and changed fire frequencies in the future.

REFERENCES

1. Andreae, M.O., J. Fishman, and J. Lindsey. 1995. The Southern Tropical Atlantic Region Experiment (STARE): Transport and Atmospheric Chemistry near the Equator - Atlantic (TRACE-A) and Southern African Fire/Atmosphere Research Initiative (SAFARI): An introduction. *J. Geophys. Res.* 101, 23, 519-23, 520.
2. Lindsey, J.A. 1997. African savanna fires, global atmospheric chemistry and the Southern Tropical Atlantic Regional Experiment. In: *Fire in the Southern African Savanna: Ecological and Environmental Perspectives* (B.W. van Wilgen, M.O. Andreae, J.G. Goldammer and J.A. Lindsey, eds.), 1-15. Witwatersrand University Press, Johannesburg.
3. Cachier, H., J. Chazot, M.-P. Brémond, V. Yoboue, J.-P. Lacaux, A. Gaudichet and J. Baudet. 1991. Biomass burning in a savanna region of the Ivory Coast. In: *Global biomass burning: atmospheric, climatic and biospheric implications* (J.S. Levine, ed.), 174-180. MIT Press, Cambridge, Mass.
4. Andreae, M.O., A. Chapuis, B. Cros, J. Fontan, G. Helas, C. Justice, Y.J. Kaufman, A. Minga and D. Nganga. 1992. Ozone and Aitken nuclei over equatorial Africa. Airborne observations during DECAFE 88. *J. Geophys. Res.* 97, 6137-6148.
5. Lacaux, J.-P., H. Cachier and R. Delmas. 1993. 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*. P.J. Crutzen and J.G. Goldammer, eds.), 159-191. John Wiley, Chichester.
6. Lacaux, J.-P., M. Brunet, R. Delmas, J.-C. Monnet, L. Abbade, B. Borsang, H. Cachier, J. Baudet, M.O. Andreae and G. Molas. 1995. 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.
7. Fishman, J., R. Minnis and H.C. Reichle. 1986. Use of satellite data to study tropospheric ozone. *J. Geophys. Res.* 91, 14, 451-14,465.
8. Logan, J.A. and V.W.J.H. Kirchhoff. 1986. Seasonal variations of tropospheric ozone at Natal, Brazil. *J. Geophys. Res.* 91, 7875-7881.
9. Fishman, J., C.E. Watson, J.C. Larsen and J.A. Logan. 1990. Distribution of tropospheric ozone determined from satellite data. *J. Geophys. Res.* 95, 3599-3617.
10. Fishman, J., K. Fakhruzzaman, B. Cros and D. Nganga. 1991. Identification of widespread pollution in the southern hemisphere deduced from satellite analyses. *Science* 252, 1693-1696.
11. Cahoon, D.R., B.J. Stocks, J.S. Levine, W.R. Cofer and K.P. O'Neill. 1992. Seasonal distribution of African savanna fires. *Nature* 359, 812-815.
12. Seinfeld, J.H. and S.N. Pandis. 1998. *Atmospheric chemistry and physics: From air pollution to climate change*. John Wiley, New York.
13. Crutzen, P.J. 1995. Overview of tropospheric chemistry: Developments during the past quarter century and a look ahead. *Faraday Discuss.* 100, 1-21.
14. Andreae, M.O. 1995. Climatic effects of changing atmospheric aerosol levels. In: *World survey of climatology, Vol. 16: Future Climates of the World* (A. Henderson-Sellers, ed.), 341-392. Elsevier, Amsterdam.
15. Andreae, M.O. and P.J. Crutzen. 1997. Atmospheric aerosols: Biogeochemical sources and role in atmospheric chemistry. *Science* 276, 1052-1056.
16. Delmas, R.A., A. Marengo, J.P. Tathy, B. Cros and J.G.P. Baudet. 1991. Sources and sinks of methane in the African savanna. CH₄ emissions from biomass burning. *J. Geophys. Res.* 96, 7287-7299.

17. Delmas, R.A., A. Marengo, J.P. Tathy, B. Cros and J.G.R. Baudet. 1991. Sources and sinks of methane in the African savanna. CH₄ emissions from biomass burning. *J. Geophys. Res.* 96, 7287-7299.
18. Scholes, R.J. and B.H. Walker. 1993. *An African savanna: Synthesis of the Nylsvley study*. Cambridge University Press, Cambridge.
19. Sefer, W and R. Conrad. 1987. Contribution of tropical ecosystems to the global budgets of trace gases, especially CH₄, H₂, CO and N₂O. In: *The geophysiology of Amazonia* (R.E. Dickinson, ed.), John Wiley, New York.
20. Huntley, B.J. and B.H. Walker. 1982. *Ecology of tropical savannas*. Springer-Verlag, New York.
21. Scholes, R.J., D. Ward and C.O. Justice. 1996. Emissions of trace gases and aerosol particles due to vegetation burning in southern-hemisphere Africa. *J. Geophys. Res.* 101, 23, 677-23, 682.
22. Crutzen, P.J. and M.O. Andreae. 1990. Biomass burning in the tropics: Impact on atmospheric chemistry and biogeochemical cycles. *Science* 250, 1669-1678.
23. Hao, W.-M., M.-H. Liu and P.J. Crutzen. 1990. Estimates of annual and regional releases of CO₂ and other trace gases to the atmosphere from fires in the tropics, based on the FAO statistics for the period 1975-1980. In: *Fire in the tropical biota: Ecosystem processes and global challenges* (J.G. Goldammer, ed.), 440-462. Springer-Verlag, Berlin.
24. Andreae, M.O. 1993. The influence of tropical biomass burning on climate and the atmospheric environment. In: *Biogeochemistry of global change: Radiatively active trace gases* (R.S. Oremland, ed.), 113-150. Chapman & Hall, New York.
25. Hao, W.-M., D.E. Ward, G. Oibu and S.P. Baker. 1996. Emissions of CO₂, CO and hydrocarbons from fires in diverse African savanna ecosystems. *J. Geophys. Res.* 101, 23, 577-23, 584.
26. Menaut, J.-C., L. Abbadie, F. Laveru, P. Loudjani and A. Podaine. 1991. Biomass burning in West African savannas. In: *Global biomass burning: atmospheric, climatic and biospheric implications* (J.S. Levine, ed.), 133-142. MIT Press, Cambridge, Mass.
27. Scholes, R. J., J. Kendall and C.O. Justice. 1996. The quantity of biomass burned in Southern Africa. *J. Geophys. Res.* 101, 23, 667-23, 676.
28. Hao, W.-M. and M.-H. Liu. 1994. Spatial and temporal distribution of tropical biomass burning. *Global Biogeochem. Cycles*, 8, 495-503.
29. Scholes, R. J. and M.R. van der Merwe. 1994. Greenhouse gas emissions from South Africa. Forastek, CSIR, Pretoria.
30. Andreae, M. O. 1997. Emissions of trace gases and aerosols from savanna fires. In: *Fire in the Southern African Savanna: Ecological and Environmental Perspectives* (B.W. van Wilgen, M.O. Andreae, J.G. Goldammer, and J.A. Lindsey, eds.), 161-183. Witwatersrand University Press, Johannesburg.
31. Andreae, M.O., B.E. Anderson, D.R. Blake, J.D. Bradshaw, J.E. Collins, G.L. Gregory, G.W. Sachse and M.C. Shiptam. 1994. Influence of plumes from biomass burning on atmospheric chemistry over the equatorial Atlantic during CITE-3. *J. Geophys. Res.* 99, 12, 793-12, 808.
32. WMO/UNEP 1995. *Scientific Assessment of Ozone Depletion: 1994*. World Meteorological Organisation, Geneva.
33. Crutzen, P.J., L.E. Heidt, J.P. Krzianec, W.H. Pollock and W. Seifer. 1979. Biomass burning as a source of atmospheric gases CO, H₂, N₂O, NO, CH₄, and COS. *Nature* 282, 253-256.
34. Laursen, K.K., P.V. Hobbs, L.F. Radke and R.A. Rasmussen. 1992. Some trace gas emissions from north American biomass fires with an assessment of regional and global fluxes from biomass burning. *J. Geophys. Res.* 97, 20, 687-20, 701.
35. Manó, S. and M.O. Andreae. 1994. Emission of methyl bromide from biomass burning. *Science*, 263, 1255-1257.
36. Tassios, S. and D.R. Packham, D.R. 1985. The release of methyl chloride from biomass burning in Australia. *J. Air Pollut. Contr. Assoc.* 35, 41-42.

37. Andreae, M.O., E. Atlas, G.W. Harris, G. Helas, A. de Kock, R. Koppmann, W. Maenhaut, S. Manó, W.H. Pollock, J. Rudolph, D. Scharffe, G. Schebeske and M. Welling. 1996. Methyl halide emissions from savanna fires in southern Africa. *J. Geophys. Res.* 101, 23, 603-23, 613.
38. Rudolph, J., A. Khedim, R. Koppmann and B. Bonsang. 1995. Field study of the emissions of methyl chloride and other halocarbons from biomass burning in western Africa. *J. Atmos. Chem.* 32, 67-80.
39. Blake, N.J., D.R. Blake, B.C. Sive, T.Y. Chen, F.S. Rowland, J.E. Collins, G.W. Sachse and B.E. Anderson. 1996. Biomass burning emissions and vertical distribution of atmospheric methyl halides and other reduced carbon gases in the South Atlantic region. *J. Geophys. Res.* 101, 24151-24164.
40. Lobert, J.M., D.H. Schaeffle, W.-M. Hao, T.A. Kuhlbusch, R. Seuwann, P. Warneck and P.J. Crutzen. 1991. Experimental evaluation of biomass burning emissions: Nitrogen and carbon containing compounds. In: *Global biomass burning: atmospheric, climatic and biospheric implications* (J.S. Levine, ed.), 289-304. MIT Press, Cambridge, Mass.
41. Rasmussen, R.A., L.E. Rasmussen, M.A.K. Khalil and R.W. Dailige. 1980. Concentration distribution of methyl chloride in the atmosphere. *J. Geophys. Res.* 85, 7350-7356.
42. Blake, N.J., D.R. Blake, J.E. Collins, G.W. Sachse, B.E. Anderson, J.A. Brass, P.J. Riggan and F.S. Rowland. 1996. Biomass burning emissions of atmospheric methyl halide and hydrocarbon gases in the South Atlantic region. In: *Biomass burning and global change* (J.S. Levine, ed.), 575-594. MIT Press, Cambridge, Mass.
43. Andreae, M.O., E.V. Browell, M. Garstang, G.L. Gregory, R.C. Harris, G.F. Hill, D.J. Jacob, M.C. Pereira, G.W. Sachse, A.W. Szezer, P.L.S. Dias, R.W. Talbot, A.L. Torres, and S.C. Wofsy. 1988. Biomass-burning emissions and associated haze layers over Amazonia. *J. Geophys. Res.* 93, 1509-1527.
44. Cachier, H. 1995. Combustion carbonaceous aerosols in the atmosphere: implications for ice-core studies. In: *Ice-core studies of biogeochemical cycles* (R. Delmas, ed.), 313-346. Springer-Verlag, Berlin.
45. Cachier, H., C. Liousse, M.-H. Pertuisot, A. Gaudichet, F. Echalar and J.-P. Lacaux. 1996. African fire particulate emission and atmospheric influence. In: *Biomass burning and global change* (J.S. Levine, ed.), 428-440. MIT Press, Cambridge, Mass.
46. Andreae, M.O., T.W. Andreae, H. Annegarn, F. Bear, H. Cachier, W. Elbert, G.W. Harris, W. Maenhaut, J. Salma, R. Swap, F.G. Wienhold and T. Zenker. 1998. Airborne studies of aerosol emissions from savanna fires in southern Africa. 2. Aerosol chemical composition. *J. Geophys. Res.* 103, 32, 119-32, 128.
47. Hobbs, P.V., R.J.S. Reid, R.A. Kotchenrathner, R.J. Ferrel, and R. Weiss. 1997. Direct radiative forcing by smoke from biomass burning. *Science* 275, 1776-1778.
48. Penner, J.E., C.C. Chuang and K. Grant. 1998. Climate forcing by carbonaceous and sulfate aerosols. *Climate Dynamics* 14, 839-851.
49. Rogers, C.F., J.G. Hudson, B. Zieleska, R.L. Tanner, J. Hallett and J.G. Watson. 1991. Cloud condensation nuclei from biomass burning. In: *Global biomass burning: atmospheric, climatic and biospheric implications* (J.S. Levine, ed.), 431-438. MIT Press, Cambridge, Mass.
50. Novakov, T. and C.E. Corrigan. 1996. Cloud condensation nucleus activity of the organic component of biomass smoke particles. *Geophys. Res. Lett.* 23, 2141-2144.
51. Penner, J.E., R.E. Dickenson and C.A. O'Neill. 1992. Effects of aerosol from biomass burning on the global radiation budget. *Science* 256, 1432-1434.
52. Kaufman, Y.J. and R.S. Fraser. 1997. The effect of smoke particles on clouds and climate forcing. *Science* 277, 1636-1639.
53. 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. 1996. Trace gas and aerosol emissions from savanna fires. In: *Biomass burning and global change* (J.S. Levine, ed.), 278-295. MIT Press, Cambridge, Mass.