JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. D19, PAGES 23,973–23,981, OCTOBER 30, 1996

Overview of an aircraft expedition into the Brazilian cerrado for the observation of atmospheric trace gases

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Abstract. Tropospheric trace gases were measured from an aircraft platform. The flights were organized to sample air masses from the geographic area of central Brazil, where the vegetation, a savanna-type environment with the local name of "cerrado", is subject to burning every year, especially through August, September, and October. These measurements were made as a Brazilian local contribution to the international field campaign organized by NASA, the Transport and Atmospheric Chemistry Near the Equator–Atlantic (TRACE A) mission, and the Southern African Fire Atmospheric Research Initiative (SAFARI). The major NASA TRACE A mission used the NASA DC 8 aircraft, with most flights over the South Atlantic Ocean region. In Brazil, missions using small aircraft measured ozone and carbon dioxide continuously, and carbon monoxide, nitrous oxide, and methane using grab sampling. In addition, ground-based measurements were made continuously over most of the dry months of 1992, and ozonesondes were launched at three different sites. Geostationary Operational Environment Satellite-East (GOES E) images and a special network of radio soundings provided meteorological information, and advanced very high resolution radiometer (AVHRR) images indicated the distribution of fire pixels in the region of interest. Most of the biomass burning in 1992 occurred in the state of Tocantins, with about 22% of all the burning in Brazil. The state of Mato Grosso was second, with 19% of all burning. The Brazilian aircraft was used mostly in these two states, near the cities of Porto Nacional and Cuiabá, for in situ sampling; 31 vertical profiles were made in air masses considered to be well mixed, that is, not in fresh plumes. Although the major interest was the dry season, sampling was also made during the previous wet season period in April 1992 for comparison; 10 vertical profiles were obtained using the same aircraft and measurement techniques. There is a clear difference between these two opposite seasonal periods, most evident in the O_3 and CO data. Both Cuiabá and Porto Nacional show some 30–60 parts per billion by volume (ppbv) larger methane concentrations, for example, during the dry season, in comparison to the wet season, the difference at Cuiabá being larger. The methane data for the wet season show no significant differences between Cuiabá and Porto Nacional mixing ratios, which seems to exclude the existence of significant sources or sinks at these sites during this wet season. The ozone mixing ratios vary around 15 ± 5 ppbv in the wet season, and from a minimum of 35 to a maximum of 70 ± 10 ppbv, depending on height, in the dry season. The largest variability is seen in the carbon monoxide mixing ratios which vary from 90–100 ppbv in the wet season to maxima of 300 at 3.3 km and 600 ppbv at 1.2 km height in the dry season.

Introduction

Biomass Burning

Brazil is one of the tropical countries that still has a large population growth rate; its population has doubled in the last 50 years. This causes pressure to search for new land, modulated by the country's economic situation. Years ago the federal government of Brazil created incentives for people to move especially from the poor northeast states to the Amazonian states, for basic development. This caused considerable population migrations, with large rates of deforestation, especially in the state of Rondonia, and the south of Pará, well documented by the press. Forest land became pasture and several new cities were created. Much of the deforested areas were immediately burned to clear the land. Deforestation rates then were about 20,000 $km^2\ yr^{-1}$. Presently, federal incentives are no longer in effect and the migrations have decreased considerably. Although there is still significant deforestation estimated at about 10,000 $km^2\ yr^{-1}$ by 1995, the deforestation trend has been decreasing consistently over the last 7 years. Most of the biomass burning has turned to the savanna-type environments, known as the cerrado of central Brazil. Biomass burning in Brazil has a strong seasonal cycle (from wet to dry, or vice versa) with almost no burning from January to May, and strong burning activity in July to October. For September of 1992, for example, it is shown that 22% of all burning in Brazil occurred in the state of Tocantins. The definition of wet and dry seasons is generally subjective, but can be defined quantitatively as shown by *Kirchhoff et al.* [1992].

Biomass burning introduces several gases into the lower atmosphere modifying its natural composition [*Crutzen et al.*,

Paper number 95JD03029.
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Table 1. Flight Locations, Types and Data Obtained During Major TRACE A Mission Period (Dry Season, Total of 31 Aircraft Profiles)

September, 1992	Location	Flight Sites*	Flight Type and Number	Data Obtained
8	SJC-CBA		transit 1	O_3, CO, N_2O, CO_2
9	CBA	1, 2	profiles 1, 2	O_3, CO, N_2O, CO_2, CH_4
10	CBA	3, 4	profiles 3, 4	O_3, CO, N_2O, CO_2, CH_4
13	CBA	5	profile 25	O_3, CO, N_2O, CO_2, CH_4
15	CBA-PN	7	profile 5	O_3, CO, N_2O, CO_2, CH_4
16	PN	10, 11	profiles 6, 7	O_3, CO, N_2O, CO_2, CH_4
17	BG	5	profile 8	O_3, CO, N_2O, CH_4
18	PN	8	profile 9	O_3, CO, N_2O, CH_4
19	PN	9, 8, 9	profile 10, 11, 12	O_3, CO, N_2O, CH_4
20	PN	7, 10, 12	profile 13, 14, 15	O_3, CO, N_2O, CO_2, CH_4
21	PN	7, 10, 12	profile 16, 17, 18	O_3, CO, N_2O, CO_2, CH_4
22	PN	7, 10, 11	profile 19, 20, 21	O_3, CO, N_2O, CO_2, CH_4
23	PN	7, 10, 12	profile 22, 23, 24	O_3, CO, N_2O, CO_2, CH_4
26	SJC-PN		transit 2	O_3
27	PN-AF	7, 6	profiles 26, 27	O_3, CO, N_2O, CH_4
28	PN	7, 10, 12	profile 28, 29, 30	O_3, CO, N_2O, CH_4
29	PN	11	profile 31	O_3, CO, N_2O, CH_4

*These refer to flight sites shown in Figure 5

Most flights are made between 1000 LT and 1400 LT. Location shorts are as follows: São José dos Campos, SJC; Cuiabá, CBA; Porto Nacional, PN; Barra do Garças, BG; Alta Floresta, AF.

1979]. This fundamental concept has received increasing attention, both from a purely theoretical (photochemical) perspective [*Jacob and Wofsy*, 1988; *Logan*, 1985] as well as from the observational point of view. A number of new observational groups developed facilities to measure atmospheric trace gases [*Cros et al.*, 1987, 1988; *Kirchhoff et al.*, 1989; *Kirchhoff and Marinho*, 1990] and several field expeditions were organized to measure these effects in the tropics, using aircraft [*Crutzen et al.*, 1985; *Delany et al.*, 1985; *Gregory et al.*, 1988; *Browell et al.*, 1988, 1990; *Andreae et al.*, 1992; *Anderson et al.*, 1993; *Hoell et al.*, 1993; *Andreae et al.*, 1994]. In the late 1980s, J. Fishman and coworkers developed a new technique to study tropospheric ozone distributions from simultaneous observations of two satellites, and these studies detected a large ozone bulge in the South Atlantic Ocean, near the African coast [*Fishman et al.*, 1990, 1991; *Watson et al.*, 1990]. Preliminary studies at Natal, for example [*Kirchhoff and Nobre*, 1986] and later for the South Atlantic by J. Fishman and coworkers, indicated that this large ozone bulge could be the result of transport and chemistry induced by biomass burning in the nearby South American and African regions. This early hypothesis was confirmed by this special field mission. Not only are the source regions in Brazil and Africa strong and efficient enough for the chemical production [*Jacob et al.*, this issue; *Pickering et al.*, this issue] but also detailed trajectory analyses [*Fuelberg et al.*, this issue] show that the Brazilian sources contribute to the South Atlantic tropical portion of the ozone bulge at the higher levels, above about 500 hPa, whereas the lower portions of the troposphere in the South Atlantic region, from coast to coast, receive the burning products from Africa [see also *Thompson et al.*, this issue].

The TRACE A Mission

A large field campaign with a strong focus on international cooperation and participation was organized by NASA's Global Tropospheric Experiment (GTE) program, and was called the Transport and Atmospheric Chemistry Near the Equator–Atlantic (TRACE A) experiment. The NASA DC 8 was programed to fly over the South Atlantic region, Africa, and Brazil [*Fishman et al.*, this issue] and, in addition, field missions were organized in Africa and Brazil by independent groups. A group from Europe worked in Africa under the Southern Africa Fire Atmospheric Research Initiative (SAFARI), and in Brazil the Instituto Nacional de Pesquisas Espaciais (INPE) group organized special ground-based work and two aircraft missions described in this report.

The Brazilian Component of TRACE A

Two aircraft experiments were organized in 1992, one in the wet season and one in the dry season. In addition, ground-based observations were made at Cuiabá (16° S, 56° W), Porto Nacional (10.5° S, 48° W), and Natal (6° S, 35° W). For the major dry season mission, aircraft flights were organized initially such that the timing would correspond to the major NASA TRACE A campaign, but technical problems with the NASA DC 8 caused delays and changed the original plans. The Brazilian aircraft flights are shown in Table 1. Most of the actual sites for profiling were located close to Cuiabá in the state of Mato Grosso, and near Porto Nacional in the state of Tocantins (see Figure 5). These sites are part of the cerrado environment, but Cuiabá has the influence of the rain forest area to the north and west, and possibly from the Pantanal area in the south-southwest. Thus the fuel type being burnt is grass, shrubs, and small trees, with flaming combustion prevailing over smoldering. However, when the winds blow from the forest areas, near Cuiabá, there may be a significant contribution from smoldering fires. Most of the new fires are lit in the afternoon, around 1500 to 1600 LT, and they usually last for about 1 to 2 hours, depending on the local fuels. Some smoldering goes on during the night, but by the morning of the next day the fires disappeared and what is left is a rather uniform smoglike-filled atmosphere. From the aircraft, at certain heights near 2 km where strong inversions are common, the visibility is normally so bad that the horizon cannot be seen.

Previous INPE Measurements

The INPE group has made ground observations of O_3 and CO at Cuiabá for several years [*Kirchhoff and Rasmussen*, 1990;

Kirchhoff et al., 1992; *Kirchhoff and Marinho*, 1994], and a long-term program for obtaining ozonesonde data at Natal, in collaboration with NASA, has investigated, for example, the possible influence from biomass burning in Africa [*Kirchhoff and Nobre*, 1986; *Logan and Kirchhoff*, 1986]. As mentioned, this was again a major issue of TRACE A. A special report on ozone observations, ground based and using sondes, during TRACE A, is presented in a companion paper [*Kirchhoff et al.*, this issue].

Also more recently, greenhouse gases have been measured in Brazil. Previous work on atmospheric methane has shown that flooded areas act as methane sources, injecting significant fluxes of methane into the atmosphere [*Bartlett and Harris*, 1993]. There are several large flooded areas in Brazil. The largest natural areas are probably the Amazon River complex, in the Brazilian states of Amazonia and Pará, and the Pantanal area in the states of Mato Grosso, and Mato Grosso do Sul (a significant part extending into Bolivia and Paraguay). In addition to these, there are also many artificially created flooded areas for the generation of electricity. Besides the flooded areas as potential sources to increase atmospheric methane concentrations in Brazil, there is another methane source active in the dry season of central Brazil, which is biomass burning [*Jacob and Wofsy*, 1988, 1990; *Goldammer*, 1991; *Levine et al.*, 1991]. The instrument for methane measurements has been described by *Oliveira et al.* [1993].

Objective of Present Work

The objective of this work is to describe an overview of the INPE Bandeirante aircraft mission that took place in April and September of 1992 in the Brazilian cerrado region of central Brazil. Highlight observations are reported of the atmospheric trace gases methane, nitrous oxide, carbon dioxide, carbon monoxide, and ozone, their concentrations and variations in the lower troposphere (below 5 km) during the NASA GTE/TRACE A mission.

Specific objectives are as follows: (1) obtain representative and average mixing ratios of trace gases in wet and dry season periods, in the remote biomass burning areas of central Brazil; (2) compare wet season and dry season mixing ratios; (3) observe the spatial distribution of carbon dioxide, and compare mixing ratios over savanna and over forests; (4) investigate and compare sources for methane and nitrous oxide; and (5) correlate precipitation and fire pixels to measured trace gases.

This work considers items (1) and (2) above and other following papers consider the remaining items. A companion paper describes the ozone soundings that were made during TRACE A [*Kirchhoff et al.*, this issue]. In addition, a second independent Brazilian aircraft mission that measured radon, soot carbon, and aerosols will be described elsewhere.

Experiment

Aircraft

The INPE aircraft is a two engine Bandeirante, model EMB 110. It has increasingly been used for obtaining in situ measurements of atmospheric trace gases, but has also been used for aerophotogrammetry. The aircraft is shown in Figure 1 (external view in three positions: side, top, and front) and Figure 2 (internal view from the side and top, and position of some of its instruments). Its total length is 14.79 m. The passenger seats can be removed as needed. One of the shortcomings of this facility is that it is not pressurized, which limits its normal use to below about 4–5 km. For special requirements, oxygen masks are available for crew and operators, but its use is generally avoided.

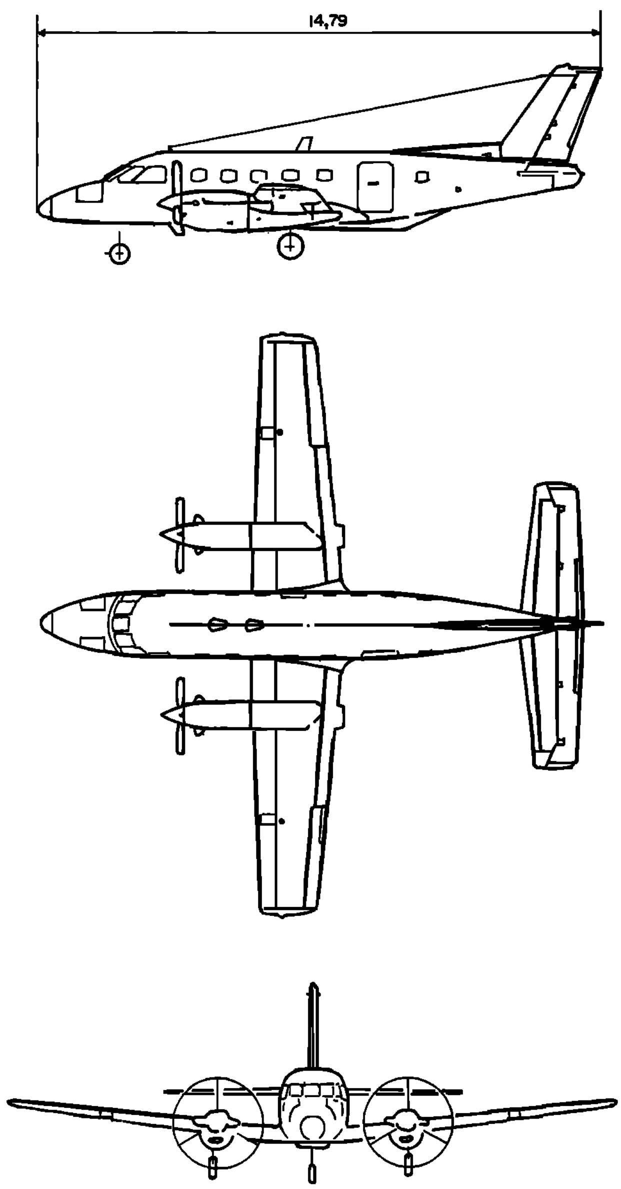

Figure 1. External characteristics of the INPE Bandeirante aircraft used for obtaining in situ samples of trace gases in Brazil during the TRACE-A mission. Three positions are shown: from the side, top, and front.

Flight Patterns

Figure 3 describes the general flight patterns used by the INPE aircraft. Basically, three different approaches are followed, depending on the objectives of flight. For obtaining vertical profiles, the pattern of Figure 3a is often used. At a fixed given height, as previously determined, the pilot flies into the prevailing wind. The flight leg at any given height takes about 10 min, which is generally enough for obtaining all the parameters that are measured. In case of large variability or other problems, another leg at the same height may be considered, and this is in general flown along the wind direction. The redundancy leg, shown in Figure 3b, is used when the real time instrumentation shows results that are unusual or when

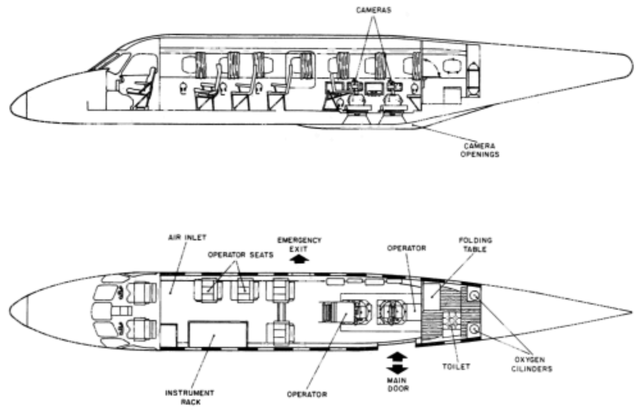

Figure 2. Internal view of the Bandeirante aircraft, in two positions: side and top views.

the operators have trouble. Finally, the option shown in Figure 3c is used when a spatial survey is made at fixed height.

Instruments and Methods

Methane, nitrous oxide, and carbon monoxide concentrations in air were measured by gas chromatography. The first methane observations by the INPE group, as well as a description of the measurement facility, were presented by *Oliveira et al.* [1993], describing the column arrangement of the gas chromatograph and the flame ionization detector (FID). The nitrous oxide chromatography was developed by *Marinho* [1993], using basic chromatographic separation with a Porapak-q column, operated at 50°C, and Electron Capture Detector (ECD) detection. *Kirchhoff and Marinho* [1990] described the carbon monoxide instrumentation, which uses a chromatographic separator followed by a mercury oxide detector. The measurements are made in our laboratory in São José dos Campos, São Paulo, Brazil. For these long-lived gases, grab samples are collected in special stainless steel flasks, internally electropolished, by a method developed by R. Rasmussen. The 800-mL cans are handled according to international standards, being evacuated immediately after analysis. The samples are kept in the cans for only short time periods, in general not more than about a week. For the aircraft work, the cans are filled in flight by special air pumps, to a pressure of about 30 psi, a procedure that takes about 2 to 3 min at selected height levels. The samples of this report were obtained in the biomass burning area of central Brazil, especially near Cuiabá and Porto Nacional. The accuracy of the chromatographic measurements depends on the standards used, provided by other international laboratories, and the precision is 0.6% for methane, 0.5% for nitrous oxide, and 0.2% for carbon monoxide.

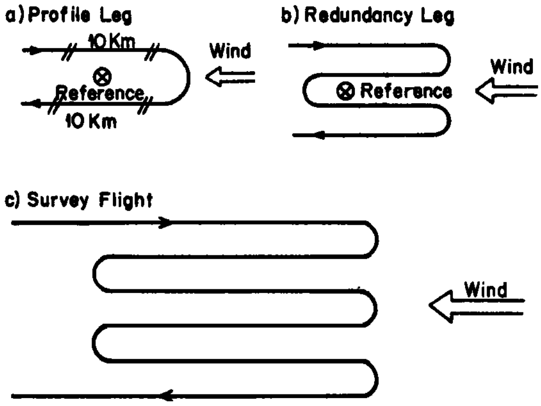

Figure 3. Typical flight paths used in the September 1992 mission. In **a**, a profile leg is made into or along the wind direction and has typically a length of 10 km, or less. In case there are difficulties, the operator may choose a redundancy leg, as in **b**; a and b legs may be stacked up to obtain vertical profiles; another option that has been used is the survey flight in which a large area is covered at the same height, as in **c**.

Ozone and carbon dioxide have been measured continuously. For ozone the UV absorption technique is used which provides measurements at about 15-s intervals. This technique has been widely used for many years and results of it have been described in considerable detail in the literature. The accuracy of the measurements is tested or adjusted at regular intervals, generally a year, by comparison with international standards, and the precision is nearly 2 or 3 ppbv. The carbon dioxide measurements use the technique of nondispersive infrared absorption, and provide observations at about 10-s intervals. This technique has recently achieved excellent performance, providing reliable observations and small size instrumentation that can be easily carried to the field or set up on towers and aircraft.

Atmospheric Conditions

The Cuiabá site had much higher precipitation rates in September and October 1992 than one would expect, on the basis of its climatological mean. This is shown in the companion paper, Figure 2 of *Kirchhoff et al.* [this issue]. The data for Cuiabá (and Goiânia) clearly show that in September 1992 the precipitation intensity was about 3 times as large as the "climatological" average. For October the precipitation amount was also considerably larger than the average. Evidently, the

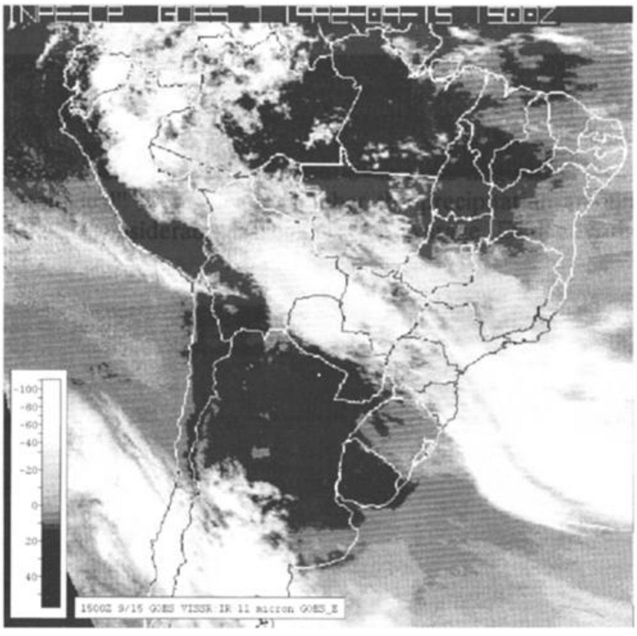

Figure 4. GOES E satellite image in the infrared, showing the strong cold front that was almost stationary over the continent reaching over to Cuiabá (which received much larger precipitation rates than its climatological mean) but not as far as Porto Nacional, in the state of Tocantins (which received less rain in September than its climatological mean).

high precipitation rates in September and October 1992 at Cuiabá (and Goiânia) affected the overall results in terms of biomass burning intensity in the region, and the aircraft avoided this part of the savanna, concentrating its efforts near Porto Nacional. It is noteworthy that the months of July and August 1992 were effectively very dry months at Cuiabá (and Goiânia), contrary to September and October.

The station Porto Nacional, contrary to what occurred at Cuiabá, was quite dry during September 1992. The strong cold fronts that were able to reach Cuiabá (and Goiânia) dissipated before they could propagate as far north as Porto Nacional, leaving the precipitation rate for September at slightly less than one half of the "climatological" mean, defined with an 11-year data sequence available from 1977 to 1987 (see the companion paper for details). In a period of 1 year, one may notice a very long dry period, of almost 5 months, when precipitation amounts to less than 50-mm per month, but which has less than 10-mm per month in at least 3 months of this dry period. Also, the transition time between wet (300-mm per month) and dry periods is rather short (about 1 month).

Examination of several satellite images show an almost cloudless panorama over central Brazil during the dry August–September period in the Brazilian cerrado. This was also the case for 1992 during August but in September cold fronts advanced from the southwest as far as Cuiabá, but not reaching Porto Nacional, as can be seen for example, in the GOES E image for September 15, 1992, at 16 UT, shown in Figure 4. Note that the state of Tocantins is essentially cloudless on this day, and on most of the observation days in September.

Satellite Observation of Fires

Figure 5 shows the approximate location of the sites over which most of the flights were made, as listed in Tables 1 and 2. Figure 6 shows the largest fire percentages in a sequential way. The sequence by state is Tocantins (TO, 22%), Mato Grosso (MT, 19%), Pará (PA, 13%), Maranhão (MA, 12%), and then Goiás (GO, 8%). Thus the profiles described in this aircraft mission were obtained in the geographical area where most of the biomass burning was taking place.

Table 2. Flight Locations, Dates, and Data Obtained During Wet Season Period (Total of 10 Aircraft Profiles)

April 1992	Location	Flight Site*	Flight Type	Data Obtained
1	GO	A	profile	O_3, CO, N_2O, CH_4
2, 2	GO	A, B	profiles	O_3, CO, N_2O, CH_4
3	CBA	C	profile	O_3, CO, N_2O, CH_4
4, 4	CBA	C, D	profiles	O_3, CO, N_2O, CH_4
5	PN	E	profile	O_3, CO, N_2O, CH_4
6, 6	PN	E, F	profiles	O_3, CO, N_2O, CH_4
7	GO	A	profile	O_3, CO, N_2O, CH_4

*These refer to flight sites shown in Figure 5

Location shorts are as follows: Goiânia, GO; Cuiabá, CBA; Porto Nacional, PN.

Overview of Measurement Results

Ozone

The ozone measurements are summarized in Figure 7 showing the wet and dry season averages, minima and maxima. As mentioned, the data reflect results for an aged (generally about 24 hours) and mixed air mass, a characteristic that can be easily identified by the naked eye. Open fires and fresh smoke plumes were avoided, since the objective of the flights was to obtain a characterization of the mixed atmosphere. The flight times of most of the profiles was near local noon, when dry convection activity is largest, providing generally good mixing of the atmosphere. On most occasions, mixed conditions in one height

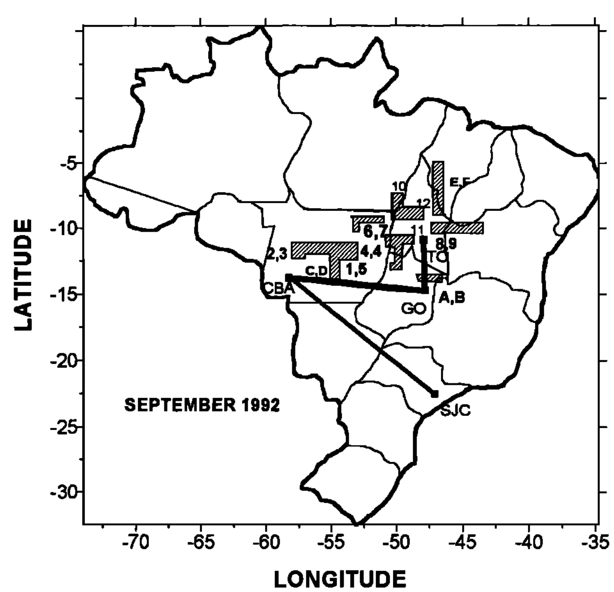

Figure 5. Map of Brazil showing most of the aircraft sites where profiles have been made. Also shown are the percentages of the total number of fires detected by NOAA AVHRR, per state, during the period of this experiment. The Brazilian states most affected are Tocantins (TO), Mato Grosso (MT), where most of the flights were made.

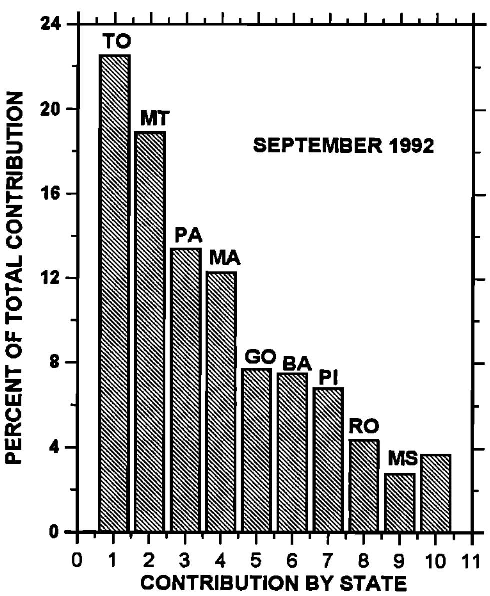

Figure 6. Sequential decrease in the percentage of total fire counts per state for Brazil, in September 1992. The figures are respectively for the states of Tocantins (TO), Mato Grosso (MT), Pará (PA), Maranhão (MA), Goiás (GO), Bahia (BA), Piauí (PI), Rondônia (RO), and Mato Grosso do Sul (MS). The unlabeled bar represents the contribution of the rest of the states.

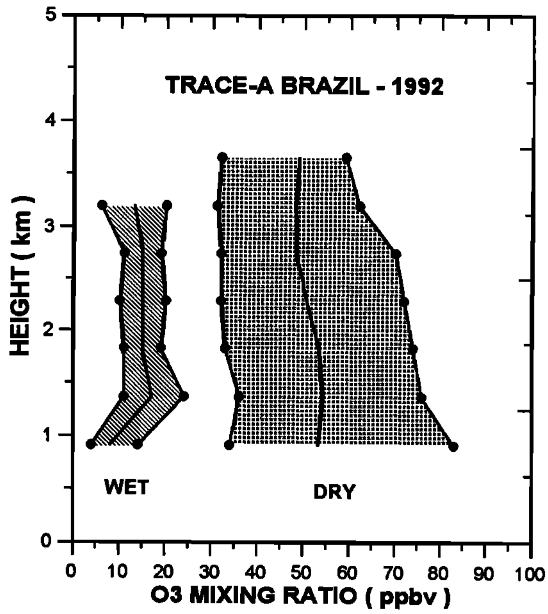

Figure 7. Averages, maximum and minimum plot for ozone mixing ratios for wet and dry season experiments, 1992.

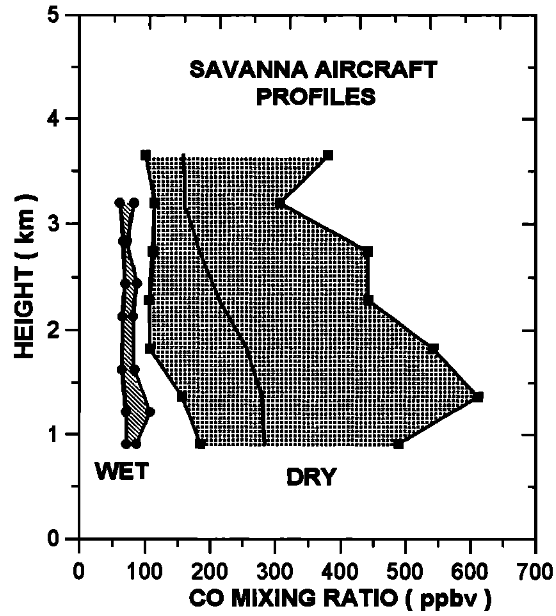

Figure 8. Averages, maximum and minimum plot for carbon monoxide mixing ratios for wet and dry season experiments, 1992.

level also meant same conditions in the other height levels. The clear distinction between the wet and dry season results is a confirmation of previous results of ozone measurements in biomass burning regions [*Kirchhoff and Rasmussen*, 1990; *Andreae et al.*, 1992, 1994; *Jacob*, this issue].

The absolute values of the ozone average concentrations in Figure 7 seem to be lower than the ozone concentrations observed by other techniques, but the reason for the differences may be largely due to the different sampling procedures. In the aircraft experiment one was looking for a mixed atmosphere to obtain observations that could be compared with a wet season average. For the ozonesonde launches a very specific airmass is being sampled. Thus, occasionally, large ozone concentrations were observed, for example, at Porto Nacional where near the ground concentrations of 80 ppbv were seen [*Kirchhoff et al.*, this issue].

Carbon Monoxide

The CO measurements with an overall average, minima and maxima, are summarized in Figure 8. The measurements show a distinct separation of the wet season results and the much larger dry season concentrations, which may be larger by factors of from 4 to 6. This result for the aboveground atmosphere is also in agreement with previous results for ground-based measurements [*Kirchhoff et al.*, 1989; *Kirchhoff and Rasmussen*, 1990]. In the dry season, the present data indicate a CO mixing ratio decreasing with height. This seems to be a natural consequence, since the CO is the result of the direct injection from fires, especially in the smoldering combustion stage, where the source is directly on the ground. In the wet season the CO profile has no strong source at the ground, and the mixing in the atmosphere is stronger, which gives the profile an almost constant mixing ratio. The dry season CO may be 3 times as large as the wet season typical value of about 100 ppbv, at the lower height level of 1 km, but values larger than a factor of 6 have also been observed. It should be added that observations in 1990, also in the cerrado area, gave even larger CO concentrations, in which CO reached a mixing ratio of 1000 ppbv.

Nitrous Oxide

The effect of biomass burning on nitrous oxide seems to be small, in comparison to ozone and carbon monoxide. Figure 9 shows the variability of the mixing ratio of this gas, from about 310 to less than 320 ppbv (only 10 ppbv in 310, or 3%). The dry season averages are slightly larger than the wet season averages, but within the standard deviations of the mean (not shown in Figure 9).

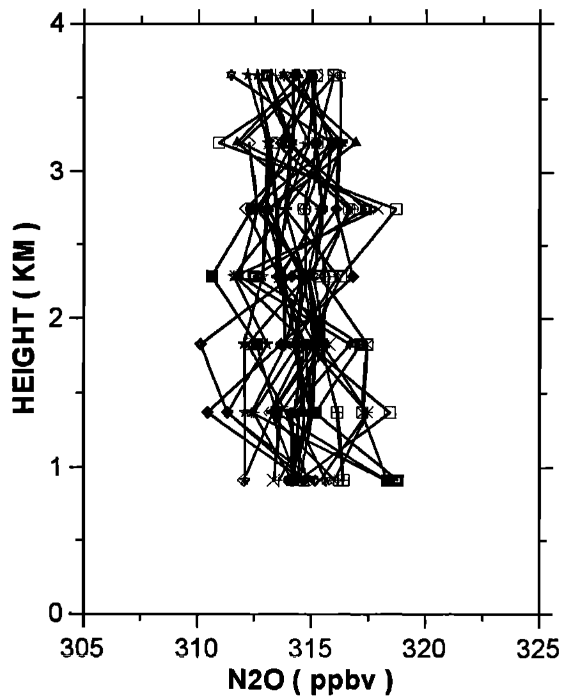

Figure 9. Mass plot of nitrous oxide mixing ratio obtained during the experiment in 1992 (not all data is shown).

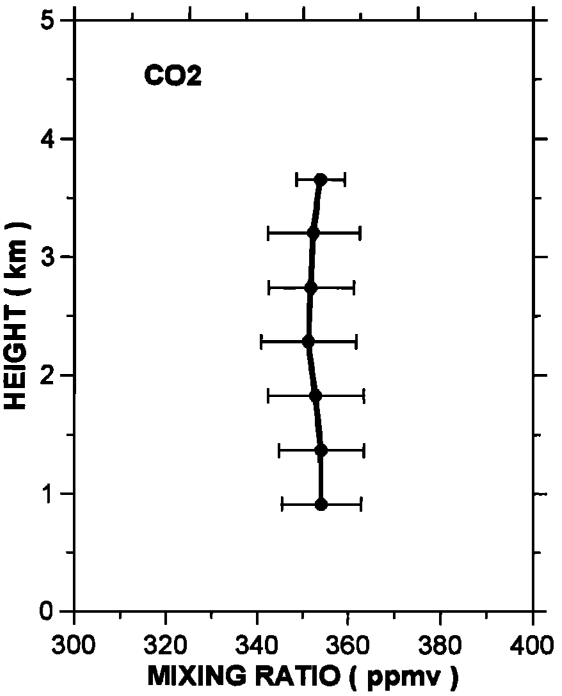

Figure 10. Average carbon dioxide mixing ratio and standard deviations of the mean, all profiles of 1992.

Carbon Dioxide

Mixing ratio averages for carbon dioxide, seen in Figure 10, show a rather uniform profile, indicating a well-mixed troposphere below 4 km, with an overall average close to 353 ppmv. However, considerable lower and larger mixing ratios have been observed, and will be described elsewhere. The horizontal bars are the standard deviations from the means at the different heights.

Methane

Results for methane are shown in Figure 11. The left panel shows results for Cuiabá, and the right panel shows results for Porto Nacional. Both panels show larger concentrations in the dry season. Contrary to the ozone and carbon monoxide data, there are no other databases with which the nitrous oxide, the carbon dioxide, and the methane may be compared.

The larger concentrations of methane observed near 1.8 km at Cuiabá (Figure 11) are probably the result of sampling inside an inversion layer that is often formed near this height, produced by dynamic vertical motions in the lower atmosphere, as previously described for ozone observations [*Kirchhoff and Marinho*, 1994]. Another apparent feature in Figure 11 is that methane concentrations at Porto Nacional and Cuiabá are significantly larger during the dry season. This confirms the general idea that during the dry season, biomass burning is responsible for an increase of methane concentrations in the environment; in this case by about 40 ppbv. Larger concentrations at Cuiabá relative to Porto Nacional may be caused by a larger smoldering combustion component near Cuiabá [*Griffith et al.*, 1991]. A closer inspection of Figure 11 shows that there is no significant difference in the methane mixing ratios at Cuiabá and Porto Nacional, during the wet season. This leads to the conclusion that the present Cuiabá data are not influenced by the Pantanal area.

Summary

This work describes results of a field campaign organized by INPE, using a Brazilian made Bandeirante aircraft, showing the first observations of carbon dioxide, nitrous oxide, and methane obtained by the INPE group in the biomass burning region of central Brazil. Profiles of ozone and carbon monoxide were also obtained. The aircraft expedition was organized in April and September of 1992 in Brazil in cooperation with the major NASA TRACE A mission. General characteristics of the biomass burning behavior of the Brazilian cerrado in 1992 are shown. The INPE aircraft crew was instructed to avoid the direct sampling of source areas, so that the observed profiles should reflect reasonably well-mixed air, not burning plumes.

Vertical profiles during the wet and dry seasons are shown at sites of the remote savanna regions in central Brazil. The smallest variability between wet and dry seasons is observed in

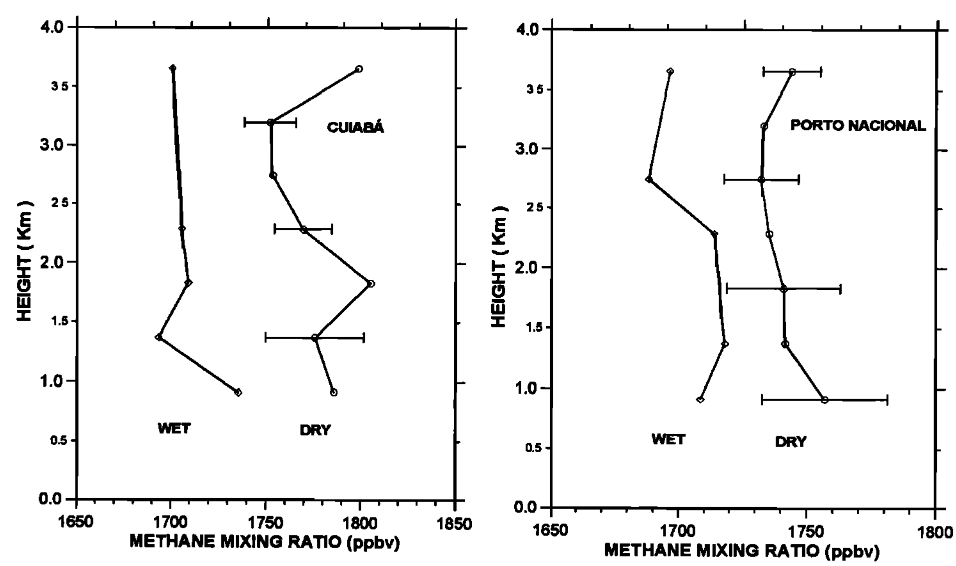

Figure 11. Methane mixing ratios for Cuiabá and Porto Nacional, for dry and wet season periods of 1992.

the nitrous oxide data, which in terms of mixing ratios, vary between 310 and 320 ppbv. The carbon dioxide mixing ratios average around 353 ppmv, and show an almost constant mixing ratio with height, but show spatial variability probably associated to local sources.

For ozone and carbon monoxide the results confirm earlier sonde and ground-based data that show consistent mixing ratio increases between wet and dry season periods. Ozone may increase from 15 ppbv in the wet period to 80 ppbv in a dry season observation. The factor of increase is even larger for CO, which shows, consistently, concentrations in the small range of 80 to 100 ppbv in the wet period, and values up to 600 ppbv in the dry season observation period. The vertical profiles made at Cuiabá and Porto Nacional indicate consistently larger concentrations of methane in the dry season. Cuiabá shows between 15 and 40 ppbv larger concentrations in the dry season than Porto Nacional, which may be the result of smoldering fires north of the Cuiabá station.

Acknowledgments. The authors are grateful to local support at INPE Cuiabá, especially to José Roberto Chagas, and to Ermelinda deLamonica Freire of the University of Mato Grosso. At Porto Nacional, support was offered by the local state university, UNITINS. The technical team at Natal headed by José Ribeiro Alves includes Adauto Motta, Francisco Raimundo da Silva, and Carlos Roberto da Silva. At São José dos Campos the technicians headed by Marcelo Araújo are Luiz Mangueira, Vitor Portezani, and Angelica de Jesus. Special thanks are due to the aircraft crew Pedro Celso Santos and Luiz Monteiro. The authors are grateful to Maria A. O. da Silva for her collaboration with the methane measurements, to Randy Cofer and Glen Sachse of NASA Langley Research Center for calibration gases that were generously provided, to the TRACE A mission team, especially R. J. McNeal of NASA Headquarters, and to J. M. Hoell of NASA Langley Research Center for their encouragement and support, and to CNPq and FAPESP for financial support.

References

Anderson, B. E., G. L. Gregory, J. D. W. Barrick, J. E. Collins, G. W. Sachse, C. H. Hudgins, J. D. Bradshaw, and S. T. Sandholm, Factors influencing dry season ozone distributions over the tropical South Atlantic, *J. Geophys. Res.*, *98*, 23,491–23,500, 1993.

Andreae, M. O., A. Chapuis, B. Cros, J. Fontan, G. Helas, C. Justice, Y. J. Kaufman, A. Minga, and D. Nganga, Ozone and Aitken nuclei over Equatorial Africa: Airborne observations during DECAFE 88, *J. Geophys. Res.*, *97*, 6137–6148, 1992.

Andreae, M. O., B. E. Anderson, D. R. Blake, J. D. Bradshaw, J. E. Collins, G. L. Gregory, G. W. Sachse, and M. C. Shipham, Influence of plumes from biomass burning on atmospheric chemistry over the equatorial and tropical South Atlantic during CITE 3, *J. Geophys. Res.*, *99*, 12,793–12,808, 1994.

Bartlett, K. B., and R. Harris, Review and assessment of methane emissions from wetlands, *Chemosphere*, *26*(1–4), 261–320, 1993.

Browell, E. V., G. L. Gregory, R. C. Harriss, and V. W. J. H. Kirchhoff, Tropospheric ozone and aerosol distributions across the Amazon Basin, *J. Geophys. Res.*, *93*, 1431–1451, 1988.

Browell, E. V., G. L. Gregory, R. C. Harriss, and V. W. J. H. Kirchhoff, Ozone and aerosol distributions over the Amazon Basin during the wet season, *J. Geophys. Res.*, *95*, 16,773–16,788, 1990.

Cros, B., R. Delmas, B. Clairac, and J. Loemba-Ndembi, Survey of ozone concentrations in an Equatorial region during the rainy season, *J. Geophys. Res.*, *92*, 9772–9778, 1987.

Cros, B., R. Delmas, D. Nganga, and B. Clairac, Seasonal trends of ozone in Equatorial Africa: Experimental evidence of photochemical formation, *J. Geophys. Res.*, *93*, 8355–8366, 1988.

Crutzen, P. J., L. E. Heidt, J. P. Krasnec, W. L. Pollock, and W. Seiler, Biomass burning as a source of atmospheric gases CO, H2, N2O, NO, CH3Cl, and COS, *Nature*, *282*, 253–256, 1979.

Crutzen, P. J., A. C. Delany, J. Greenberg, P. Haagenson, L. Heidt, R. Lueb, W. Pollock, W. Seiler, A. Wartburg, and P. Zimmerman, Tropospheric chemical composition measurements in Brazil during the dry season, *J. Atmos. Chem.*, *2*, 233–256, 1985.

Delany, A. C., P. Haagenson, S. Walters, A. F. Wartburg, and P. J. Crutzen, Photochemically produced ozone in the emission from large-scale tropical vegetation fires, *J. Geophys. Res.*, *90*, 2425–2429, 1985.

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. Fakhruzzman, 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. D. Bendura, V. W. J. H. Kirchhoff, and R. J. McNeal, The NASA GTE TRACE A experiment (September–October, 1992), *J. Geophys. Res.*, this issue.

Fuelberg, H. E., R. O. Loring Jr., M. V. Watson, M. C. Sinha, K. E. Pickering, A. M. Thompson, and D. P. McNamara, Trace A trajectory intercomparison, 2, Isentropic and kinematic methods, *J. Geophys. Res.*, this issue.

Goldammer, J., Tropical wild-land fires and global changes: Prehistoric evidence, present regimes, and future trends, in *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, edited by J. S. Levine, pp. 83–91, MIT, Cambridge, Mass., 1991.

Gregory, G. L., E. V. Browell, and L. S. Gahan, Boundary layer ozone: An airborne survey above the Amazon Basin, *J. Geophys. Res.*, *93*, 1452–1468, 1988.

Griffith, D. W. T., W. G. Mankin, M. T. Coffey, D. E. Ward, and A. Riebau, FTIR remote sensing of biomass burning emissions of CO2, CO, CH4, CH2O, NO, NO2, NH3, and N2O, in *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, edited by J. S. Levine, pp. 230–239, MIT, Cambridge, Mass., 1991.

Hoell, J. M., et al., Operational overview of the NASA GTE/CITE 3 airborne instrument intercomparisons for sulfur dioxide, hydrogen sulfide, carbonyl sulfide, dimethyl sulfide, and carbon disulfide, *J. Geophys. Res.*, *98*, 23,291–23,304, 1993.

Jacob, D. J., and S. C. Wofsy, Photochemistry of biogenic emissions over the Amazon forest, *J. Geophys. Res.*, *93*, 1477–1486, 1988.

Jacob, D. J., and S. C. Wofsy, Budgets of reactive nitrogen, hydrocarbons, and ozone over the Amazon Forest during the wet season, *J. Geophys. Res.*, *95*, 16,737–16,754, 1990.

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.

Kirchhoff, V. W. J. H., and E. V. A. Marinho, Surface carbon monoxide measurements in Amazonia, *J. Geophys. Res.*, *95*, 16,933–16,943, 1990.

Kirchhoff, V. W. J. H., and C. M. Nobre, Atmospheric chemistry research in Brazilozone measurements at Natal, Manaus, and Cuiabá, *Geofisica*, *24*, 95–108, 1986.

Kirchhoff, V. W. J. H., and R. A. Rasmussen, Time variations of CO and O_3 concentrations in a region subject to biomass burning, *J. Geophys. Res.*, *95*, 7521–7532, 1990.

Kirchhoff, V. W. J. H., A. W. Setzer, and M. C. Pereira, Biomass burning in Amazonia, *Geophys. Res. Lett.*, *16*, 469–472, 1989.

Kirchhoff, V. W. J. H., Y. Nakamura, E. V. A. Marinho, and M. M. Mariano, Excess ozone production in Amazonia from large scale burnings, *J. Atmos. Terr. Phys.*, *54*, 583–588, 1992.

Kirchhoff, V. W. J. H., and E. V. A. Marinho, Layer enhancements of tropospheric ozone in regions of biomass burning, *Atmo. Environ.*, *28*(1), 69–74, 1994.

Kirchhoff, V. W. J. H., J. R. Alves, F. R. da Silva, and J. Fishman, Observations of ozone concentrations in the Brazilian Cerrado during the TRACE A field expedition, *J. Geophys. Res.*, this issue.

Levine, J. S., W. R. Cofer, E. L. Winstead, R. P. Rhinehart, D. R. Cahoon Jr., D. I. Sebacher, S. Sebacher, and B. J. Stocks, Biomass burning: Combustion emissions, satellite imagery, and biogenic emissions, in *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications*, edited by J. S. Levine, pp. 264–271, MIT, Cambridge, Mass., 1991.

Logan, J. A., Tropospheric ozone: Seasonal behavior, trends, and anthropogenic influence, *J. Geophys. Res.*, *90*, 10,463–10,482, 1985.

Logan, J. A., and V. W. J. H. Kirchhoff, Seasonal variation of tropospheric ozone at Natal, Brazil, *J. Geophys. Res.*, *91*, 7875–7881, 1986.

Marinho, E. V. A., Medidas de óxido nitroso em ecossistemas naturais do Brasil, Ph.D. thesis, IAG, The University of Sao Paulo, Sao Paulo, Brazil, 1993.

Oliveira, M. A. S., V. W. J. H. Kirchhoff, and P. C. Alvalá, Performance of a monitor for atmospheric methane measurements, *Rev. Bras. Geofis.*, *11*(1), 57–64, 1993.

Pickering, K. E., et al., Convective transport of biomass burning emissions over Brazil during TRACE A, *J. Geophys. Res.*, this issue.

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.

Watson, C. E., J. Fishman, and H. G. Reichle Jr., 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*, 16,443–16,450, 1990.

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(Received March 21, 1995; revised July 21, 1995;
accepted September 13, 1995.)