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Topical Subject	Atmospheric composition Atmospheric chemistry Ozone production Project TRACE
Geog. Subject	Tropical Atlantic

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NASA GTE TRACE A Experiment (September-October 1992): Overview

Jack Fishman, James M. Hoell Jr., Richard D. Bendura, Robert J. McNeal, Volker W. J. H. Kirchhoff

Abstract. An overview of the Transport and Atmospheric Chemistry near the Equator—Atlantic (TRACE A) field mission is presented. TRACE A was conducted to provide a comprehensive investigation of the chemical composition, transport, and chemistry of the atmosphere over the tropical South Atlantic Ocean and the adjacent South American and African continents. Measurements for TRACE A consisted of a remote sensing component to derive tropospheric ozone and biomass burning patterns, an airborne atmospheric chemistry component to determine the composition of the air in the most pristine areas of our research domain as well as to characterize the photochemistry and transport of trace gas emissions from both fire and biogenic sources, a series of ozonesonde observations, and an enhanced radiosonde network and airborne meteorological measurements that provided information about the transport of trace gases and the physical processes that were responsible for their observed distributions. The data were interpreted through the use of both photochemical and meteorological numerical models. The picture that emerges from TRACE A is that widespread biomass burning in both South America and southern Africa is the dominant source of the precursor gases necessary for the formation of the huge amounts of ozone over the South Atlantic Ocean. In addition, however, the meteorology in this region of the world is favorable for the accumulation of these pollutants over the tropical Atlantic basin so that photochemical processes produce large quantities of ozone in situ. The generation of ozone occurs over scales of thousands of kilometers and is unusually enhanced in the upper troposphere where relatively high concentrations of nitrogen oxides (NO_x) prevail. This latter finding suggests that convective processes (or other lifting mechanisms) may play an important role in the generation of tropospheric ozone or that there may be an additional significant upper tropospheric source of NO_x, such as from lightning.

Introduction

The TRACE A (Transport and Atmospheric Chemistry Near the Equator—Atlantic) field mission conducted in September-October 1992 afforded the scientific community with the first opportunity to explore the atmospheric chemistry and the meteorology over the tropical South Atlantic Ocean. The study was prompted by satellite findings of a region of enhanced tropospheric ozone off the west coast of southern Africa that was at least as large as the enhanced ozone plumes emanating from North America, Europe, and Asia [*Fishman et al.*, 1990, Plate1]. Whereas the high northern hemisphere tropospheric ozone concentrations were most pronounced during the summer, the feature in the southern subtropics was highest during austral spring (September-October).

Enhanced tropospheric ozone concentrations had been reported at Natal, Brazil (6°S, 35°W), by *Kirchhoff* [1984] and *Logan and Kirchhoff* [1986]. The seasonally enhanced ozone in Brazil was hypothesized to be a result of widespread vegetation burning in the cerrado from August to October and there was a suggestion by Logan and Kirchhoff that long-range transport from Africa also contributed to the high ozone amounts measured at Natal. Similarly, widespread vegetation fires are also present in southern Africa during this time of the year [*Cahoon et al.*, 1992]. Thus if the South Atlantic enhancement were a result of the oxidation of emissions coming from widespread burning practices, it was not clear whether the origin of these emissions was from Africa or Brazil. TRACE A was conducted as part of NASA's Global Tropospheric Experiment (GTE), [*McNeal et al.*, 1984] to investigate this feature. Coincident with TRACE A, another group of scientists focused on the ecological and atmospheric chemistry impact of biomass burning in southern Africa through SAFARI (Southern African Fire-Atmosphere Research Initiative), a field experimented coordinated by the International Global Atmospheric Chemistry (IGAC) project [*Andreae et al.*, 1994]. Together, TRACE A and SAFARI formed the core of IGAC's STARE (South Tropical Atlantic Regional Experiment), which addresses one of IGAC's primary research foci, namely, the impact of biomass burning on the biosphere and the atmosphere [*Prinn*, 1994].

Approach

The objectives of the TRACE A mission were (1) to study the relative contributions of the photochemistry and the large- and small-scale circulation features to the enhanced ozone concentrations observed over the tropical Atlantic Ocean; and (2) to characterize/quantify the source and transport of primary and secondary ozone precursors associated with biomass burning in South America and southern Africa. To accomplish these

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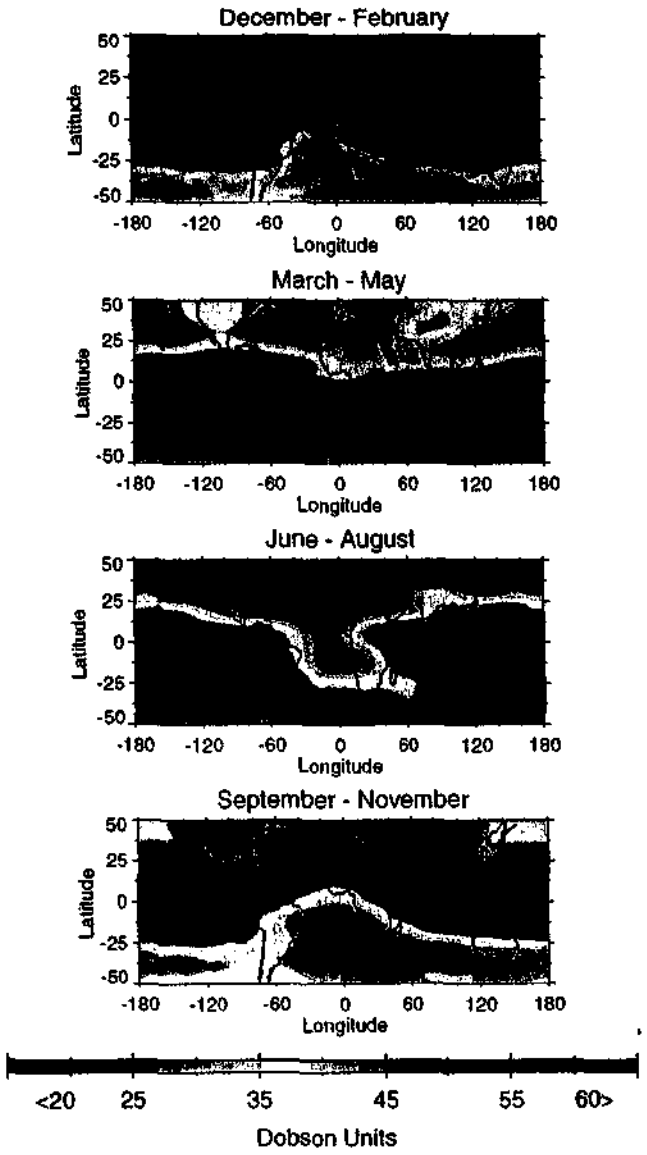

Plate 1. Depiction of climatological satellite data during four seasons. Note the September-November panel showing plume of high-tropospheric ozone in South Atlantic.

objectives, TRACE A was designed to include a pre-TRACE A study employing coordinated ozonesonde launches from three sites spanning the tropical Atlantic region and a focused study during the September-October 1992, time period employing the NASA DC-8 aircraft, two Brazilian aircraft, ground-based measurements in Brazil, an enhanced rawinsonde network in Brazil, and enhanced ozonesonde launches in both Brazil and selected sites in southern Africa. As already noted above, the focused study period of the TRACE A mission was coordinated with SAFARI, an extensive study involving a wide range of ground and airborne measurements in southern Africa [*Andreae et al.*, 1994]. The combined TRACE A and SAFARI missions provided a comprehensive multidisciplinary experiment that spanned spatial scales of less than 1 km to more than 1000 km to provide insight into the potential impact of biomass burning on the oxidizing capacity of the troposphere. Eventually, we hope that the measurements supplied by TRACE A will be used in chemical transport models to attain an understanding as to how these regional- and synoptic-scale processes influence global tropospheric composition.

Figure 1a shows the overall study region, including the DC-8 flight tracks. A summary of the missions is given in Table 1. Figure 1b illustrates, in more detail, the study sites of the TRACE A mission in Brazil, including the rawinsonde sites, Instituto Nacional de Pesquisas Espaciais (INPE) ground stations for trace gas measurements, ozonesonde launch sites, and the INPE aircraft study areas.

Pre-TRACE A Studies

Prior to the TRACE A field deployment, coordinated ozonesondes were launched at Brazzaville, Congo (4°S, 15°E), Ascension Island (8°S, 15°W), and Natal, Brazil (6°S, 35°W). The pre-TRACE A ozonesonde data from 1990 and 1991 [*Cros et al.*, 1992; *Fishman et al.*, 1992] confirmed the presence of high mixing ratios of ozone throughout the troposphere and supported the finding that possible misinterpretation of TOMS data from low-level cloud interference was not a significant reason for elevated total ozone amounts being erroneously measured [*Thompson et al.*, 1993]. During TRACE A these stations remained operational with three additional ozonesonde stations providing data in Brazil [*Kirchhoff et al.*, this issue (b)]. In addition, an ozonesonde site was established at Okaukuejo (19°S, 16°E) in the Etosha National Park in Namibia and the ozone capability at Irene (Pretoria), South Africa (26°S, 28°E), was enhanced [*Diab et al.*, 1996] in support of TRACE A and SAFARI. During TRACE A a coordinated launch schedule was developed to maximize use of these measurements in support of the aircraft observations.

An interpretation of the data from the ozonesonde sites comprising the pre-TRACE A network shows that the onset of higher O_3 concentrations begins two months sooner at Brazzaville than at Natal. The high seasonable ozone values at Ascension Island occur in the middle and upper troposphere and are detached from the boundary layer (<900 mbar) where the seasonal cycle appears to be significantly influenced by photochemistry in the marine boundary layer. *Olson et al.* [this issue] provide a detailed discussion of the ozonesonde measurements from these sites.

A study of the prevailing meteorological conditions was also included as part of Pre-TRACE A and this analysis indicated that ozone could be brought down from the upper troposphere and lower stratosphere during this time of the year [*Krishnamurti et al.*, 1993]. From a global perspective the *Krishnamurti et al* analysis suggested that the return flow from the upward branch of the Walker cell driving the Indian monsoon circulation results in the persistence of the strong subsidence over the South Atlantic during this time of the year. *Krishnamurti et al.* also suggested that some of the emissions from the fires in western Brazil could be transported efficiently by propagating anticyclones at southern middle latitudes. Eventually, these transient circulation patterns would also feed ozone precursors into the region where the high ozone concentrations were observed. Ozone would then be generated photochemically in the region as these emissions accumulated there and "cooked" [*Chatfield and Delany*, 1990]. Whether the origin of this anomaly resulted from chemical generation or from circulation processes could only be resolved by the systematic in situ measurement program that TRACE A uniquely provided. Further insight into the meteorological influences during the specific TRACE A time frame is provided by the modeling study of *Krishnamurti et al.* [this issue] and the analysis presented by *Thompson et al.* [this issue].

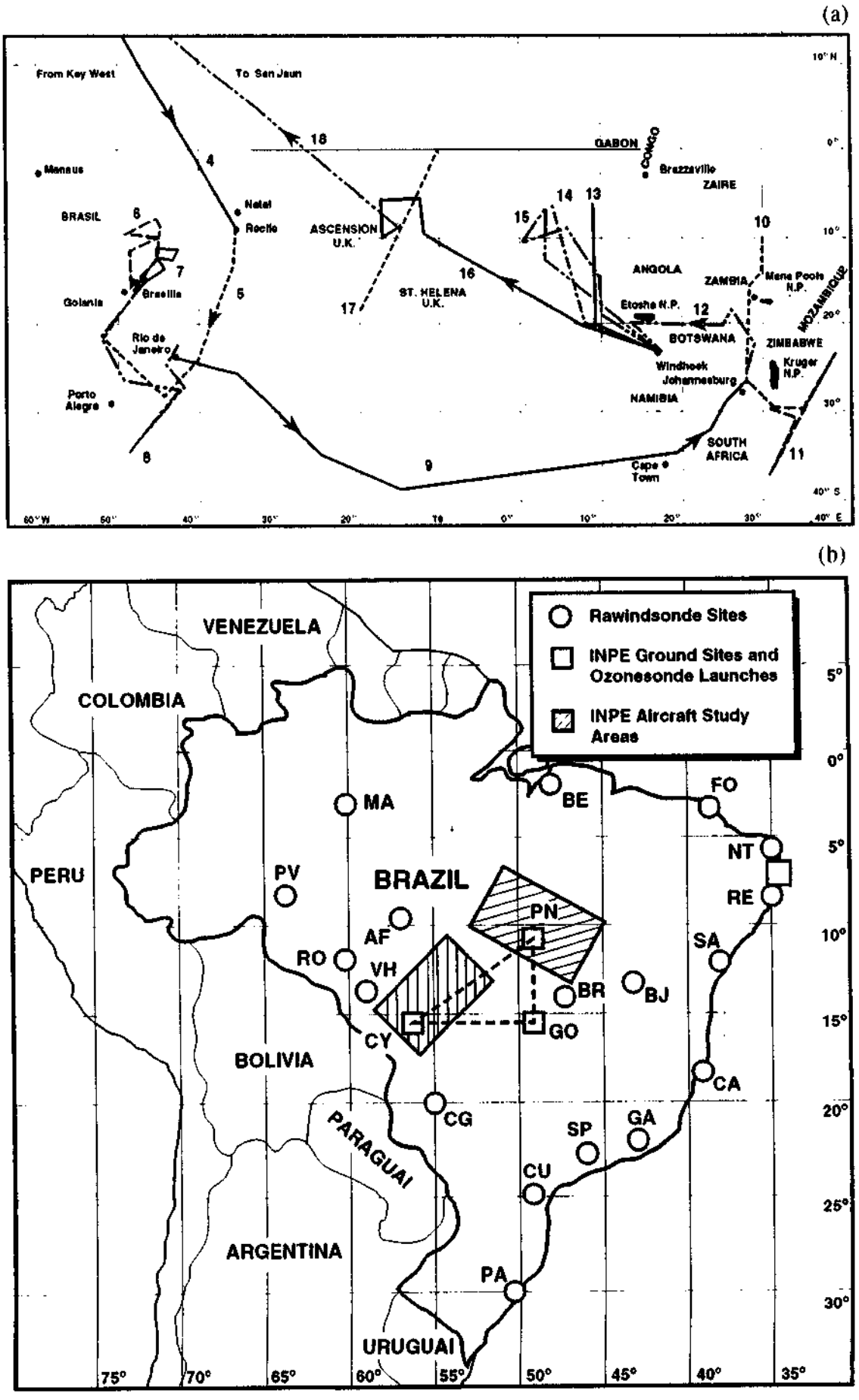

Figure 1. Map of flight tracks. (a) Flight paths of DC-8 and (b) area over Brazil detailed: hatched area is where Brazilian aircraft flew; circles indicate operational rawinsondes during TRACE A; location of INPE ground sites and ozonesonde launches shown by squares.

Table 2. Summary of Missions Conducted During TRACE A

Flight Number	Description	Date	Start Time, GMT	Stop Time, GMT
1	Ames Research Center test flight 1	Aug. 18, 1992	1859	2331
2	Ames Research Center test flight 2	Sept. 18, 1992	1407	1723
3	Transit Ames to Key West survey flight	Sept. 21, 1992	1517	2024
4	Transit Key West to Recife survey flight	Sept. 22, 1992	1201	1935
5	Transit Recife to Brazilia continental overflow	Sept. 24, 1992	1207	1900
6	Brazilia local vertical transport	Sept. 27, 1992	0912	1651
7	Brazilia local sample region affected by biomass burning	Sept. 28, 1992	1400	1922
8	Brazilia to Rio sample region of clean air	Oct. 01, 1992	1207	1923
9	Rio to Johannesburg, SA transect jet stream and sample stratospheric air	Oct. 03, 1992	0746	1600
10	Johannesburg, SA local biomass burning coordinated with SAFARI aircraft	Oct. 06, 1992	0717	1428
11	Johannesburg, SA characterize atmosphere of African East Coast	Oct. 09, 1992	0653	1421
12	Transit Johannesburg to Windhoek survey flight and Estosha pan fly-by	Oct. 11, 1992	0800	1303
13	Windhoek local wall flight-outflow from southern Africa	Oct. 14, 1992	0714	1415
14	Windhoek local wall flight-outflow from southern Africa	Oct. 15, 1992	0722	1504
15	Windhoek, Namibia large-scale divergence over South Atlantic	Oct. 18, 1992	0930	1715
16	transit flight-Windhoek to Ascension quantification of divergence in area of Ascension Island	Oct. 20, 1992	0758	1449
17	local flight from Ascension Island	Oct. 22, 1992	0903	1623
18	Ascension Island to San Juan survey flight	Oct. 24, 1992	0859	1647
19	San Juan to Ames Research Center survey flight	Oct. 26, 1992	1406	2133

TRACE A also attempted to characterize air as pristine as possible so that the relative impact of South American biomass burning emissions could be assessed; this was achieved on October 1 (flight 8), with a flight as far south as possible off the east coast of South America to find an air mass that had not recently been influenced by continental emissions. During the southernmost portions of this flight, NO_x < 18 parts per trillion volume (pptv), CO < 65 ppbv, CH_3Cl < 600 pptv, and C_2H_2 < 45 pptv were measured [*Talbot et al.*, this issue], indicating that the air had likely not been influenced by continental emissions for more than 10 days [*Gregory et al.*, this issue]. Analysis of the continental outflow from Brazil (flights 4, 7, and 8) shows that the air sampled also contained emissions from urbanized areas [*Blake et al.*, this issue; *Talbot et al.*, this issue].

African Component

The prolonged drought in southern Africa, called by many the worst drought of the century, resulted in less biomass loading throughout the region and, therefore probably reduced the amount of burning relative to what would have taken place during a more representative year. Nonetheless, vegetation burning did occur, primarily farther north than what had been anticipated. While based in Johannesburg, the DC-8 traveled to northern Zambia (~1300 km) to find a region of widespread burning. The series of photographs in Plate 3 shows representative views of what was seen from the DC-8 in Zambia and Brazil. The top picture shows how dirty the air appeared in Zambia relative to the air encountered in Brazil (middle). The bottom picture shows the charred areas that were overflown by the DC-8 in Zambia. Such charred expanses are indicative of the widespread nature of the recently burned areas not only in Zambia but also in Zaire, Tanzania, Angola, and Mozambique, countries that were logistically difficult to obtain measurements in. In these polluted regions, high concentrations of many trace gases were encountered up to altitudes of ~3000 m. Not surprisingly, high concentrations of every compound were found: O_3 generally ranged 60–80 ppbv; NO, 0.15–0.20 ppbv; NO_2, 1.1–1.4 ppbv; PAN, ~4 ppbv; H_2O_2, ~5 ppbv; HNO_3, ~1 ppbv; HCOOH, 7–8 ppbv; and CH_3OOH, 0.7–0.8 ppbv (for further details, see

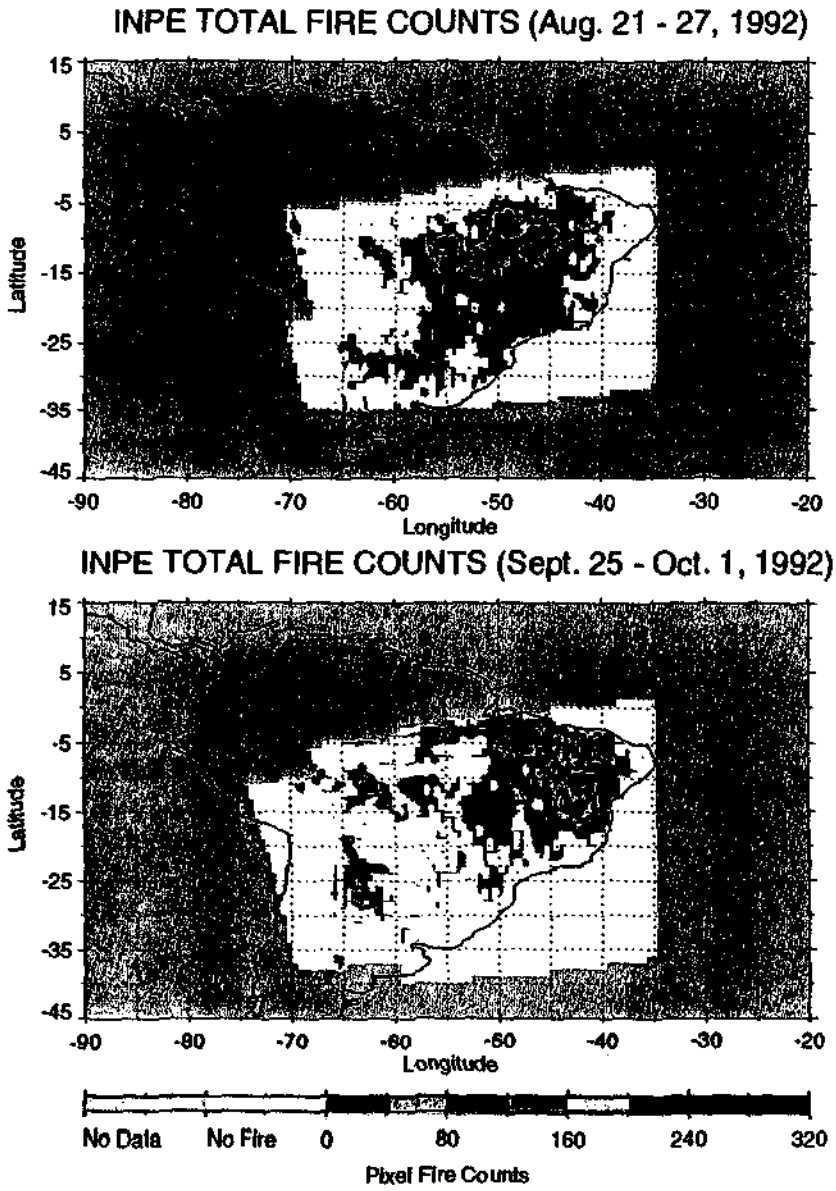

Plate 2. AVHRR imagery over Brazil; top half shows week of August 21–27, when TRACE A measurement program over Brazil had been planned; bottom half shows week of September 25 to October, when flights over Brazil actually took place (figure courtesy of A. Setzer and V. Brackett). Unexpected delay was caused by major repair that was needed for the DC-8.

papers in this issue by *Gregory et al.*, *Smyth et al.*, *Heikes et al.*, *Talbot et al.*, *Singh et al.*). All hydrocarbons, CO, CH_4, N_2O, and CO_2, were also elevated well above their background concentrations, and emission ratios of these species can be computed [*Blake et al.*, this issue; *Anderson et al.*, this issue]. Although O_3 concentrations were high in the same region as the most intense smoke, higher mixing ratios were observed above the boundary layer. In a layer generally situated between 4–7 km, the UV-DIAL measured mixing ratios often in the 80–120 ppbv range [*Browell et al.*, this issue].

Another flight was conducted to investigate the composition of air that had not been influenced by any emissions from the continent and was carried out primarily over the Indian Ocean off the east coast of South Africa. Having such measurements, we had planned to quantify the continental influence of biomass burning emissions. The meteorology, however, was considerably more complicated than anticipated and it is not obvious from our analyses that emissions over southern Africa are immediately transported off the east coast of southern Africa. The emissions may recirculate and waft for a considerable length of time before being advected to the east [e.g., *Garstang et al.*, 1996], while at other times, trajectories show that air in the upper troposphere can travel substantial distances with little influence from continental sources [*Bachmeier and Fuelberg*, this issue].

Tropical Atlantic Component

While based in Windhoek, Namibia, two flights were conducted parallel to the African west coast to characterize the composition of the air exiting the continent. During these two flights, we employed the strategy of overflying the study region at the DC-8 cruising altitude as far as possible (based on a total

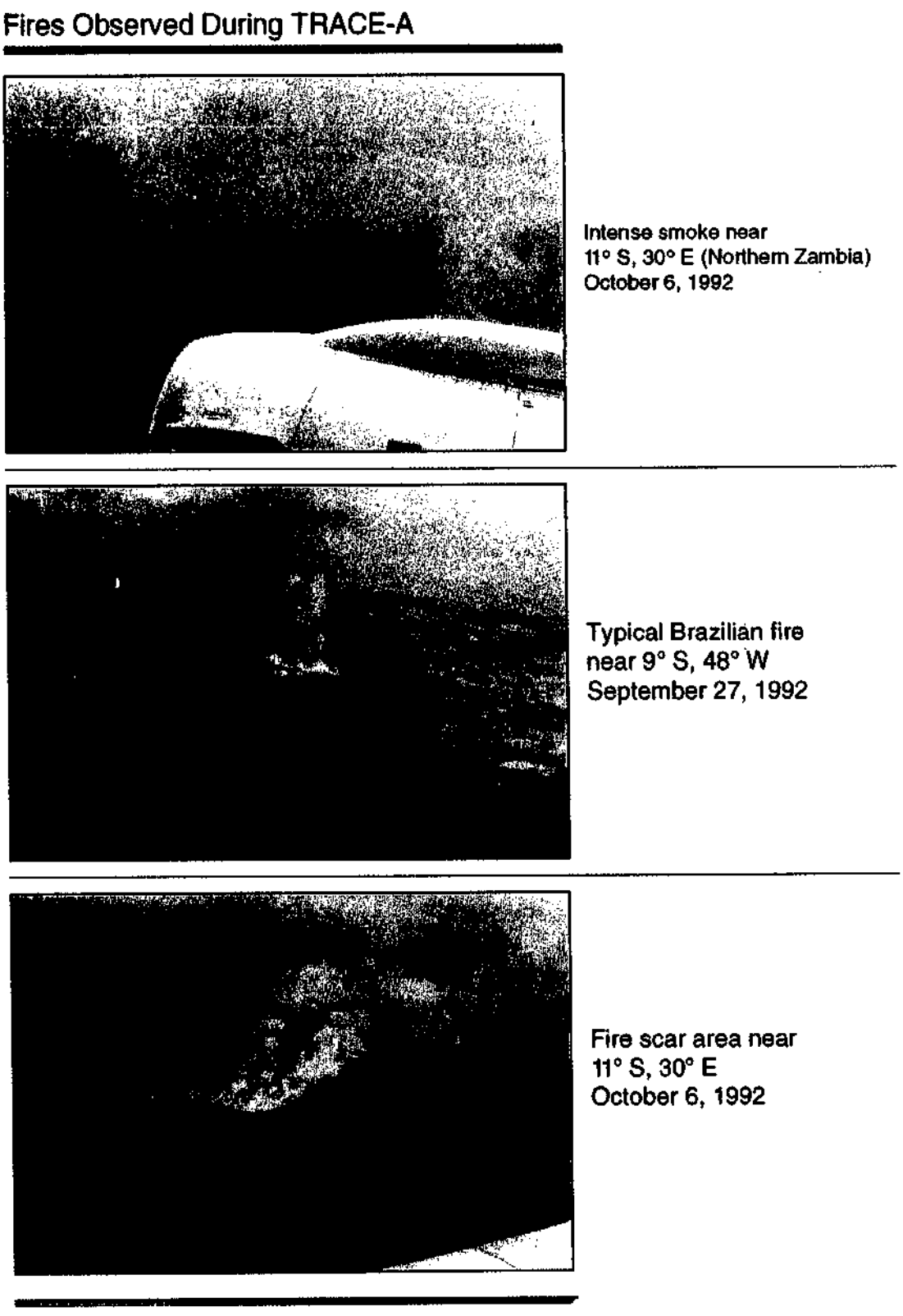

Plate 3. Photographs from DC-8 showing burning in Africa and Brazil.

flight-time constraint of 8 hours) to characterize the aerosol and ozone distribution below the aircraft with the Ultraviolet Differential Absorption Lidar (UV-DIAL) [*Browell*, 1989]. After reaching the northern terminus of the flight, the UV-DIAL information was used to define the particular altitudes for the return portion of the flight. The onboard real-time UV-DIAL data were frequently used to redefine subsequent flight altitudes. The first of these was a north-south transect along the 9°E meridian.

The aerosol scattering depiction in the top portion of Plate 4 clearly defines the location of the plume coming from continental

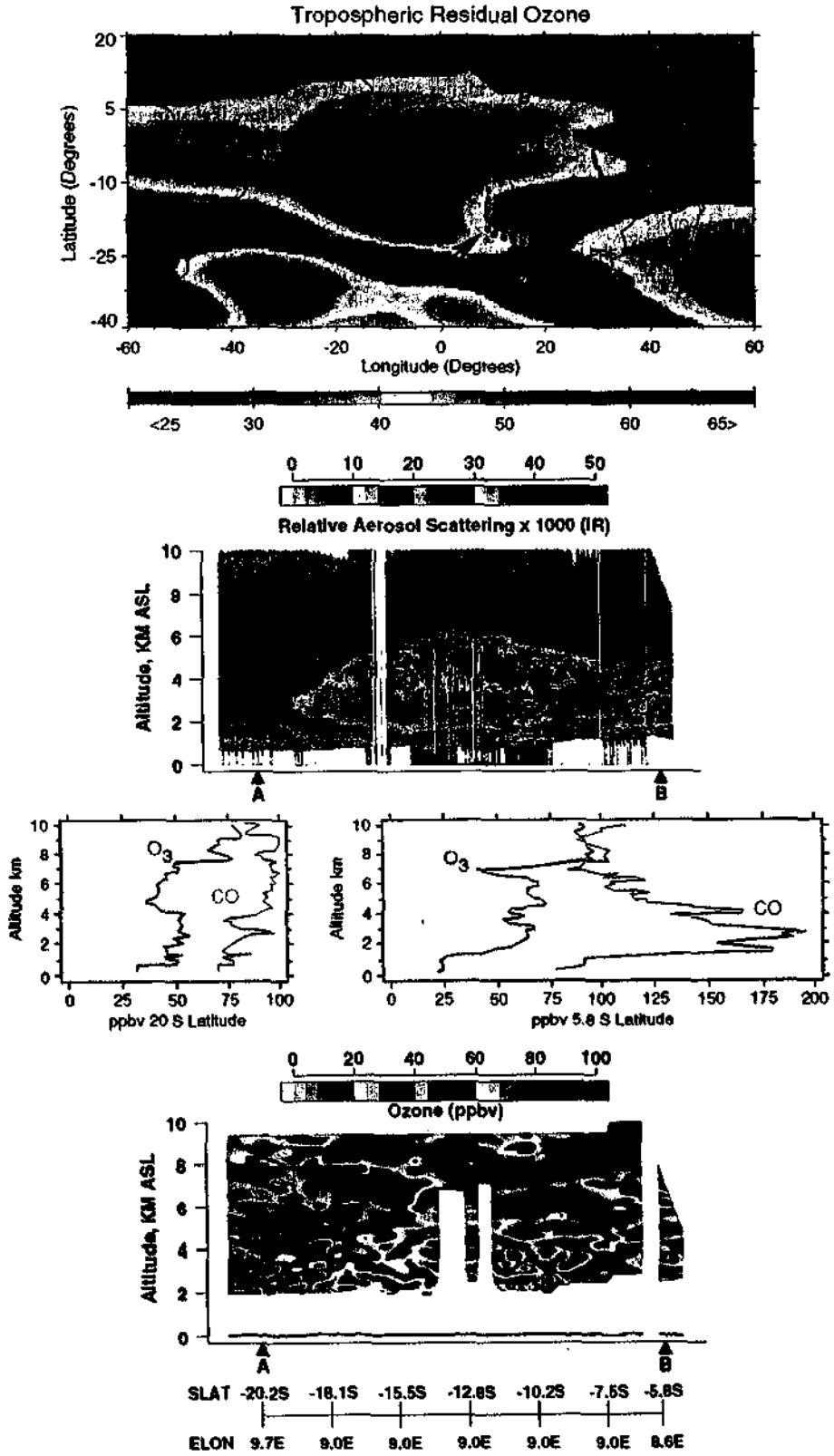

Plate 4. Composite of TRACE A data illustrating the outflow from Africa; specific example is for October 14, 1992. (top) Satellite measurements with DC-8 track superimposed; second panel from top shows UV-DIAL aerosol depiction along flight path with profiles for CO and ozone shown for points A and B depicted in panels below; (bottom) ozone cross section from the UV-DIAL.

southern Africa. A study performed by *Fuelberg et al.* [this issue (a)] shows that the specific lamina within this polluted outflow can be traced back to subtle changes in the thermal structure of the air over the continent. As the DC-8 flew northward at higher altiudes, dropwinsondes were released every 20 min providing information about the temperature, humidity, and wind structure coincident with these distributions of aerosols and ozone. Flying north from Windhoek, an increase in aerosols at ~3 km is noted just south of the Angola-Namibia border. Eventually the vertical extent of the plume thickens to ~5 km in a region between 11°S and 15°S although the heaviest loading is situated somewhat north near 9°S at an altitude of ~3 km. As the DC-8 reaches its northernmost location at a point due west of the Congo-Zaire border (~5.5°S), the vertical extent and density of the aerosols has decreased considerably. This high-resolution depiction of the aerosol structure over such a wide spatial domain off the coast has provided a unique opportunity to examine how well these motions can be simulated with a meteorological model capable of reproducing such fine-scale structure [*Krishnamurti et al.*, this issue]. Results from these model runs show that high concentrations of ozone and aerosols in the lower troposphere could not be reproduced without input from the African source regions, being the dominant source of this material.

The ozone depiction, shown in the bottom half of this figure, is considerably more difficult to interpret. Perhaps the most noteworthy feature is that there is not a strong correlation between the location of the high amount of aerosols and the location of the very high ozone values. The lowest ozone mixing ratios in the 30–40 ppbv range are seen in a layer at an altitude of ~5 km located south of the aerosol plume. Although ozone mixing ratios in the plume are generally higher than those outside the plume at altitudes between 2 and 6 km, highest ozone mixing ratios are found at altitudes above the layer of intense aerosols. On the return flight, a transect was made through a dense aerosol layer near 3.9 km between 7° and 12°S and through a layer of high ozone mixing ratio above the aerosol plume near 7.4 km between 13°and 17°S. In the coincident layer of high ozone and aerosols the dropwinsonde winds (Figure 3) show a significant wind shift at the top of the aerosol layer indicating that this pollution plume probably was coming directly from a region of widespread burning [*Bachmeier and Fuelberg*, this issue]. The burning pattern during the entire TRACE A period over southern Africa is

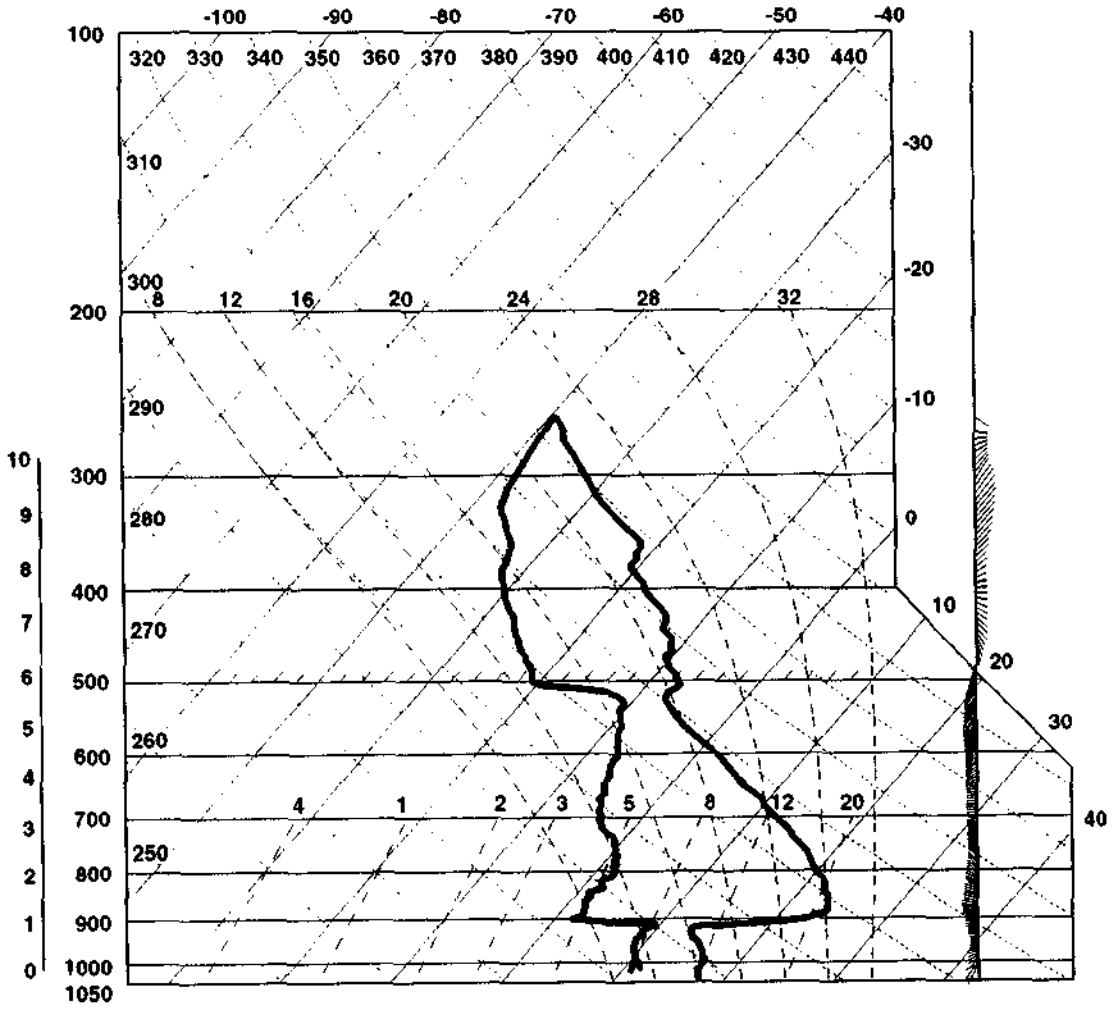

Figure 3. Dropwinsonde profile off west coast of southern Africa during flight 13 showing temperature, dew point, and winds. Note that wind barbs indicate speed and direction to which the wind is blowing (i.e., generally from Africa at lower altitudes and to Africa at higher altitudes). The length of the wind barbs indicate speed. Vertical scale on the far left is approximate altitude in km; primary vertical scale is pressure in hPa.

depicted in Plate 5 [*Kendall et al.*, 1995]. The dropwinsonde also shows the presence of a fairly strong secondary subsidence inversion at the top of the aerosol layer. The highest ozone mixing ratios sit above the aerosol layer where westerly winds prevail.

Figure 3 and Plate 6, on the other hand, illustrate the type of measurements found over a region far removed from recent continental influence. Even in this region near Ascension Island, the CO and C_2H_2 (acetylene) measurements confirm that relatively higher ozone at all altitudes are accompanied by well-defined enhancements of combustion products. The flow patterns in Figure 4 show that the meteorology is complex and often nebulous. High or low mixing ratios of ozone and ozone precursors are highly sensitive to the position of the quasi-permanent high-pressure center that migrates aimlessly in the tropical South Atlantic. The particular example during this mission on October 22 shows higher ozone north of Ascension Island, which is also considerably farther north than the climatological maximum described by *Fishman et al.* [1990]. However, the daily depiction of tropospheric ozone determined from the satellite-derived tropospheric ozone residual method (top part of Plate 7) also showed the ozone maximum north of Ascension Island [*Fishman et al.*, this issue].

During the transit flight between Windhoek and Ascension Island on October 20 the tropospheric ozone maximum was southeast of Ascension Island (consistent with the climatological position of the ozone maximum) and this flight provided an excellent opportunity to attempt to transect the climatological ozone maximum observed by the TOMS west of Angola (bottom part of Plate 7). The combination of the UV-DIAL measurements [*Browell et al.*, this issue] and the in situ ozone measurements aboard the DC-8 [*Gregory et al.*, this issue] provided an unprecedented opportunity to determine the utility and possible shortcomings of the satellite-derived tropospheric ozone distribution [*Fishman et al.*, this issue].

Transit Flights

Although the primary purpose of a transit flight is to move the operation of the mission from one location to another, each was designed to enhance the likelihood of producing scientifically useful data. In particular, the transit between Rio and Johannesburg provided an unusual opportunity to intercept the trace gas signature of a trough of low pressure at 38°S. Such meteorological features are often indicative of the presence of a tropopause fold [*Loring et al.*, this issue]. For a substantial portion of this flight the plane flew well above the tropopause, allowing the downward looking UV-DIAL to obtain a detailed depiction of the mesoscale structure of particles and ozone within a region of stratosphere-troposphere exchange. The transit flight between Windhoek and Ascension Island provided the opportunity to intercept the ozone maximum at a position close to its climatological location over the tropical South Atlantic Ocean (see bottom panel in Plate 7). Toward the end of the TRACE A mission the transit flight between Ascension Island and San Juan provided a set of measurements in the upper tropical troposphere showing generally much cleaner air in the northern hemisphere as the DC-8 transected the Intertropical Convergence Zone [*Fishman et al.*, this issue].

Studies of Atmospheric Photochemistry

To answer the overriding question of how much of the ozone enhancement is a result of in situ generation, photochemical calculations were performed using the in situ DC-8 measurements as input. Calculations near the source regions indicate that photochemical generation of ozone in the lower atmosphere on the regional scale (100–1000 km) near sources of biomass burning are comparable to the amount of regionally generated ozone over industrialized regions at temperate middle latitudes during summertime [*Fishman et al.*, 1985; *Jacob et al.*, this issue]. Perhaps the most important finding is the ubiquitous nature of ozone generation in the upper tropical troposphere where integrated ozone production is calculated to be $>1 \times 10^{11}$ mol cm^{-2} s^{-1} between 8 and 12 km. This large net photochemical production in the upper troposphere offsets the photochemical destruction of ozone within the tropical marine boundary layer [e.g., *Carney and Fishman*, 1986; *Jacob et al.*, this issue]. Correlation of NO_y with CO suggests that biomass burning was an important source of

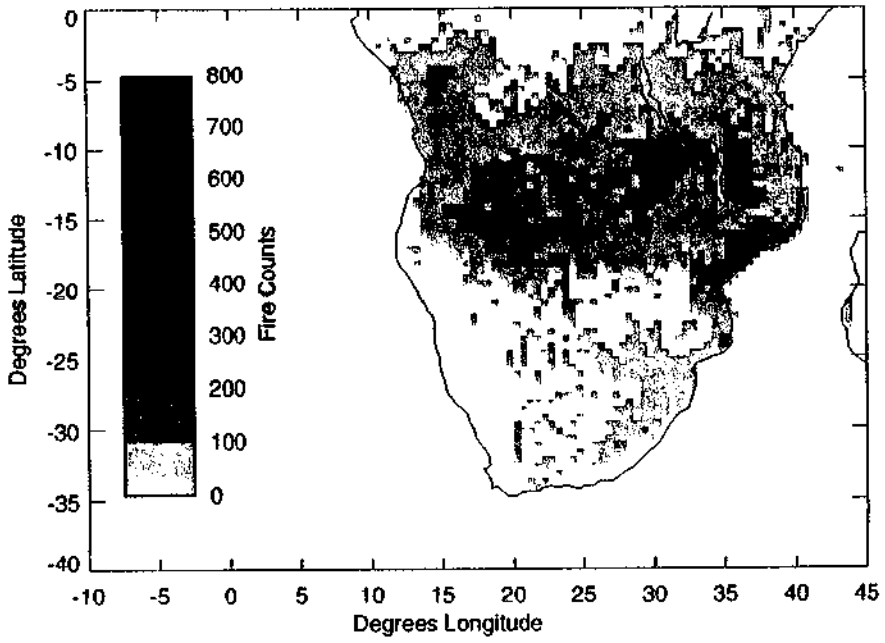

Plate 5. AVHRR depiction of fires over southern Africa for September-October (figure courtesy of J. Kendall).

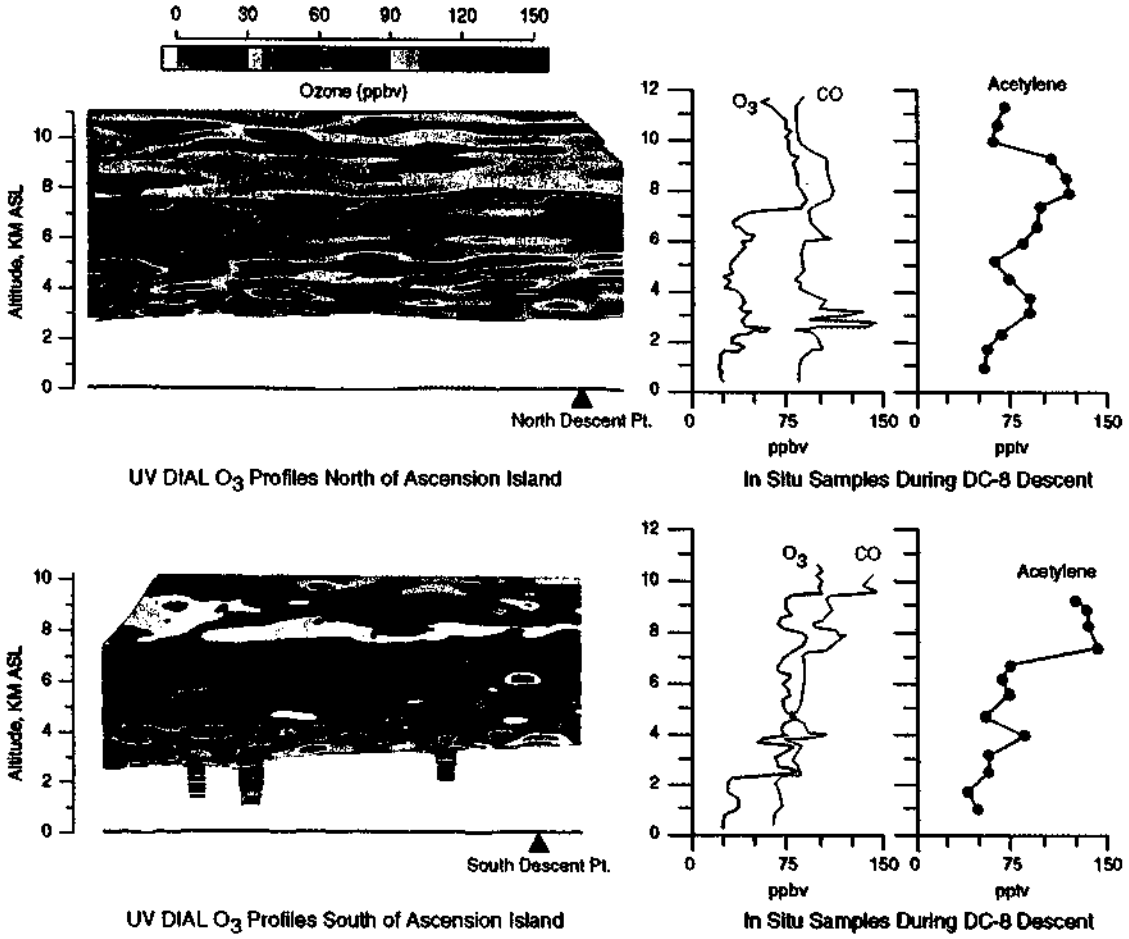

Plate 6. Cross sections of ozone at northern and southern ends of flight track for flight 17. Vertical profiles of CO, O_3, and acetylene at the northern and southern descent points are also shown.

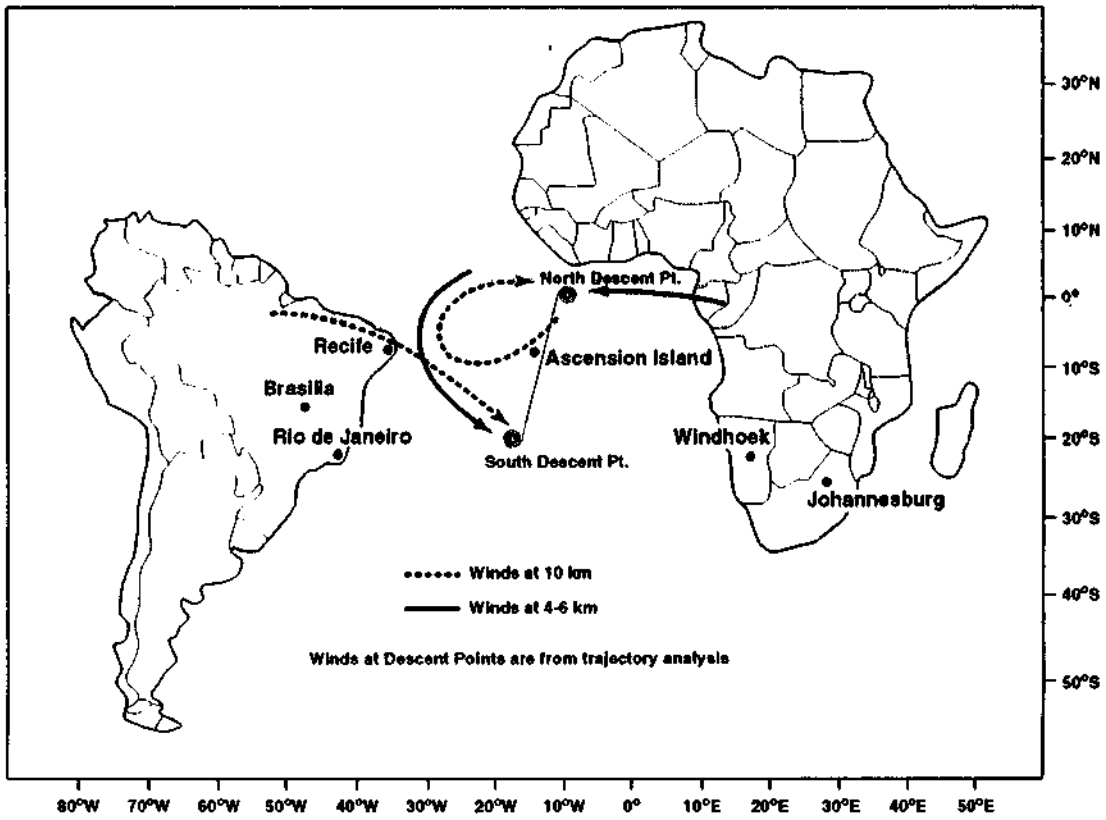

Figure 4. Wind depiction over tropical ocean during flight 17, October 22, is shown. Arrows indicate mean flow patterns in middle (4–6 km) and upper (~10 km) troposphere.

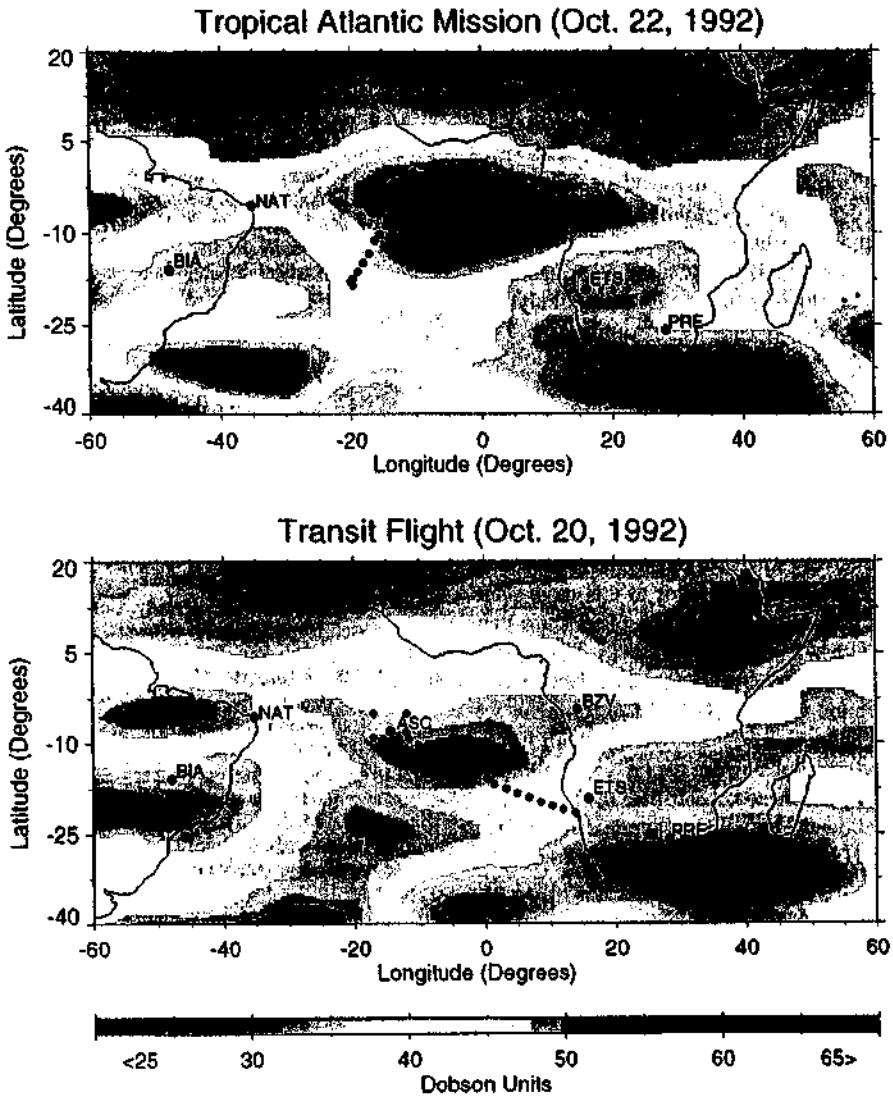

Plate 7. Satellite-derived tropospheric ozone distribution is shown for October 22, 1992, where dots represent flight path during mission 17 (top) and for October 20, 1992, mission 16 (bottom).

NO_x at all altitudes during TRACE A. There is also evidence that NO_x throughout the TRACE A region was recycled from its oxidation products rather than directly transported from its primary sources. The low HNO_3 mixing ratios observed above 8 km suggest a rapid mechanism of HNO_3 to NO_x conversion, not currently considered in current models [*Jacob et al.*, this issue]. Mixing ratios of peroxides and formaldehydes (by-products of hydrocarbon oxidation and indicators of the oxidizing capacity of the troposphere) were fairly well simulated by the photochemical calculations. Discrepancies between the calculated mixing ratios and the ratios among the species point to possible deficiencies in our understanding of the chemical mechanisms by which these compounds are generated in the atmosphere. Additional details are provided in the *Jacob et al.* paper.

Trajectory Studies

In many previous atmospheric chemistry field experiments, trajectory analysis was used in conjunction with the composition of the air to provide insight into the origin of air parcels being sampled. In TRACE A a concerted effort was conducted to examine the utility and potential deficiencies of various trajectory methods. Because of the general dearth of meteorological observations in the region of the experiment, comparisons of trajectories were made on both the types of analyses used for the trajectories (i.e., National Meteorological Center versus European Center) and the trajectory methods (i.e., isentropic versus kinematic). These results are summarized by *Pickering et al.* [this issue (a)] and *Fuelberg et al.* [this issue (b)]. One of the important points illustrated by these studies is the advantage gained by the use of cluster analysis of trajectories (i.e., many trajectory calculations in the vicinity of a particular region of interest) rather than stringent reliance of a calculated trajectory for a specific location. Use of clusters of trajectories about the points of interest aid in the assessment of uncertainty in the regions of wind shear.

Summary

The TRACE A mission has provided the opportunity to examine a fascinating region of the world, both from an atmospheric chemistry point of view and from a meteorological perspective.

From the in situ and remotely sensed data obtained from the DC-8 and from the analysis of several satellite data sets [*Kendall et al.*, 1995; *Fishman et al.*, this issue], the explanation for the existence of the feature originally identified by *Fishman et al.* [1990] can now be much better elucidated. The findings suggest that the presence of widespread biomass burning in both South America and southern Africa is a primary driver that leads to the "global smog" phenomenon described in many of the earlier measurements in the southern tropics [*Kirchhoff*, 1984; *Logan and Kirchhoff*, 1986; *Cros et al.*, 1988]. On the other hand, the presence of biomass burning, by itself, is most likely not sufficient to generate the observed ozone maximum found far away from these trace gas sources. A combination of meteorological processes occurring on various scales of motion interact uniquely to yield the ozone enhancement initially detected by the satellite analysis. From our findings, it appears that the photochemistry taking place in the upper troposphere, where lightning may provide an important source for ozone precursors [*Smyth et al.*, this issue], is an important ubiquitous generator of ozone. It is likely that relatively small-scale convective processes collectively become an important contributor to this large-scale phenomenon and our findings in the upper troposphere show that emissions from both South America and southern Africa contribute to the enhancement of ozone over the South Atlantic basin.

Through our collaboration with the SAFARI experiment, we understand more clearly how the emissions over southern Africa may go through contorted gyrations before they either waft or are efficiently ejected from the continent to contribute the high ozone mixing ratios found over both the adjacent Atlantic and the Indian Oceans [*Garstang et al.*, 1995; *Thompson et al.*, this issue]. In addition, we also realize that the large-scale subsidence over the tropical South Atlantic Ocean is a consequence of the overall general circulation of the atmosphere [*Krishnamurti et al.*, 1993] and that these global-scale circulation patterns also play an important role in the accumulation of large amounts of ozone in the South Atlantic.

Thus the mechanism for the ozone formation is indeed a complex synthesis of sophisticated mechanisms that determine the transport and atmospheric chemistry in this intriguing region of the world. Although the TRACE A measurements have given us unprecedented insight into many of these mechanisms, the results discussed in the following papers also pose additional questions that need to be addressed in future field programs.

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