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Comparison of satellite total ozone measurements with the distribution of tropospheric ozone obtained by an airborne UV-DIAL system over the Amazon Basin

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ABSTRACT

During July and August 1985, an extensive field program was conducted throughout the Amazon Basin in Brazil to characterize the chemical composition of the atmosphere in this region of the world. Using the NASA Electra aircraft, a comprehensive picture of the distribution of tropospheric ozone was obtained during this 3-week experiment. The data indicate that substantial gradients of tropospheric ozone can be present on a horizontal scale of 100 km and a vertical scale of less than 1 km. Throughout this period, the integrated amount of ozone in the lowest 3–4 km of the atmosphere more than doubled because of the photochemical reactions associated with the polutants emitted to the atmosphere as a result of widespread biomass burning that was present during the latter portions of the field experiment. This study compares this comprehensive tropospheric ozone data set with a set of satellite total ozone measurements. These comparisons indicate that the spatial and temporal variability in the total ozone satellite data is closely related to the variability in the observed distributions of tropospheric ozone, even though the troposphere contains less than 15% of the total ozone in the atmosphere. Additional data obtained from a series of ozonesonde launches and other satellite measurements confirm that the increase in total ozone amounts over this period was a result of ozone increases in the troposphere.

1. Introduction

Tropical biomass burning has been hypothesized to be one of the largest sources, if not the largest source, of several trace gases released to the atmosphere (Crutzen et al., 1979). Significant quantities of nonmethane hydrocarbons (Greenberg et al., 1984), carbon monoxide (Logan et al., 1981) and oxides of nitrogen (Enhalt and Drummond, 1982) can react photochemically in the tropical troposphere to produce substantial amounts of ozone which can be important for the global budget of tropospheric ozone (Crutzen et al., 1985; Fishman, 1985; Logan and Kirchhoff, 1986). Aircraft measurements (e.g., Delany et al., 1985; Gregory et al., 1988; Browell et al., 1988) indeed confirm that ozone production does take place in conjunction with biomass burning in Brazil. Since all of these measurements capture only a glimpse of the atmosphere at the sporadic times during which their airborne platforms were operating, it is difficult to extrapolate these relatively localized sets of measurements to assess the impact of biomass burning on the global tropospheric ozone cycle. Fishman (1988) has suggested, however, that the amount of tropospheric ozone produced photochemically by biomass burning in the Tropics is comparable to the amount of ozone produced by industrialized pollution at northern temperate latitudes. Such a comparison is not surprising if the magnitudes of these two anthropogenic sources of the precursors to photochemically generated tropospheric ozone are comparable.

Several recent studies (Fishman et al., 1986; Fishman and Larsen, 1987; Fishman, 1988) have shown that the production of tropospheric ozone

at low latitudes can be observed from satellite measurements of the total column abundance of ozone (i.e., the sum of the amount of ozone in both the troposphere and the stratosphere) even though most of the total ozone (85–95%) is located in the stratosphere. In Fishman et al. (1986), it was shown that enhanced qualities of total ozone in the Amazon Basin of Brazil appeared to be associated with the presence of biomass burning that was identifiable from visible and infrared GOES (Geostationary Operational Environmental Satellite) imagery. Analysis of satellite total ozone data for an entire year likewise indicates that relatively higher amounts of total ozone are present over this region during the dry season (generally August through October) when most of the widespread biomass burning occurs (Fishman and Larsen, 1987). An analysis of ozonesonde measurements from Natal, on the east coast of Brazil (Logan and Kirchhoff, 1986), concludes that most of the increase in total ozone during the dry season results from larger ozone concentrations in the troposphere rather than in the stratosphere. Logan and Kirchhoff speculate that these higher concentrations of tropospheric ozone exist because of the increased amount of biomass burning during this time of the year.

In another study, Fishman et al. (1987b) have shown that the distribution of ozone at the surface can be identified from satellite total ozone observations at northern mid-latitudes during a widespread air pollution episode if meteorological conditions are favorable. In turn, Vukovich et al. (1985) have shown that the distribution of surface ozone on the synoptic scale (a spatial domain on the order of 1000 km) does fairly accurately describe the distribution of ozone throughout the lower troposphere. From these studies, we can infer that the distribution of ozone in the lower troposphere can be captured by satellite total ozone measurements under certain conditions. Interestingly, Fishman et al. (1987b) state that during the time of their case study in which they related the synoptic distribution of surface ozone to gradients observed in the total ozone distribution, the structure of the atmosphere resembled one with tropical characteristics (with respect to temperature and tropopause height), even though their study region was the eastern United States.

The purpose of this study is to present a direct comparison of the distribution of ozone in the lower troposphere obtained from a set of ozone measurements obtained on an airborne platform with the distribution of total ozone which had been obtained from a satellite platform. If we can conclude that satellite total ozone measurements can be used to provide some provisional insight into the distribution of tropospheric ozone, then these satellite measurements will give us a new understanding of the distribution of tropospheric ozone over many regions of the world that otherwise would be extremely difficult to obtain. The knowledge of the distribution of ozone in the tropical troposphere is crucial if we are to understand the global distribution of the hydroxyl (OH) radical, the critical component of global tropospheric chemistry.

2. UV-DIAL ozone measurement technique

The remote measurement of the vertical distribution of ozone (and aerosols) along an aircraft ground track can be made by the NASA airborne differential absorption lidar (DIAL) system (Browell et al., 1983). This lidar system provides ozone profiles along its line-of-sight, and when operated in a nadir mode from an aircraft, ozone mixing ratios can be measured over a 5-km altitude with an accuracy of better than 10% and a vertical and horizontal resolution of 210 m and 6 km (300 laser shots), respectively (Browell, 1983; Browell et al., 1983, 1985a). The system has been used in numerous studies of tropospheric ozone (Browell et al., 1985b, 1987, 1988; Fishman et al., 1985; Vukovich et al., 1985; Ching et al., 1988). To measure ozone, two independent laser pulses are simultaneously emitted; one pulse is set to a wavelength that is strongly absorbed by ozone (286 nm) and the other is set to a wavelength that is only slightly absorbed by ozone (300 nm). These simultaneous output pulses are transmitted in a traditional lidar mode to obtain range-dependent information at these two wavelengths. The relative difference between the two return lidar signals is predominantly due to the absorption of the amount of ozone present, which can be related to the concentration of ozone along the path of the laser. An ozone profile can then be derived by calculating the

absorption over 210-m range intervals along the UV lidar returns. Additional details on the airborne UV-DIAL system and the techniques used in the DIAL ozone data reduction are discussed in Browell et al. (1983, 1985a). In the measurements utilized for the present study, airborne lidar data were obtained at a 5 Hz rate with each lidar profile having a vertical and horizontal spacing of 15 and 20 m, respectively. The¡ data were averaged vertically and horizontally to improve the DIAL measurement statistics.

3. UV-DIAL data used in this study

In July and August 1985, a series of 15 flights were conducted over the Amazon Basin to characterize the chemistry and dynamics over this region during the early part of the dry season. Collectively, these flights, in conjunction with other ground-based and balloon-borne instrumentation, were part of the Amazon Boundary Layer Experiment (ABLE-2A); an overview of this field experiment is given in Harriss et al. (1988). A summary of the various flight scenarios is shown in Fig. 1. The data discussed in this study are from the four survey flights between Manaus and Belem.

The first two flights took place on 23–24 July, just as the dry season began to establish itself. The week of 11–17 July was characterized by frequent, widespread convective showers over the Amazon Basin, conditions typical of the late wet season. Beginning 17–18 July, the region from Manaus to Belem and south of the Solimoes and Amazon Rivers was progressively influenced by the presence of a subtropical anticyclone which gradually migrated north. By the time of the first survey flight from Manaus to Belem on the 23rd, meteorological conditions were relatively dry,

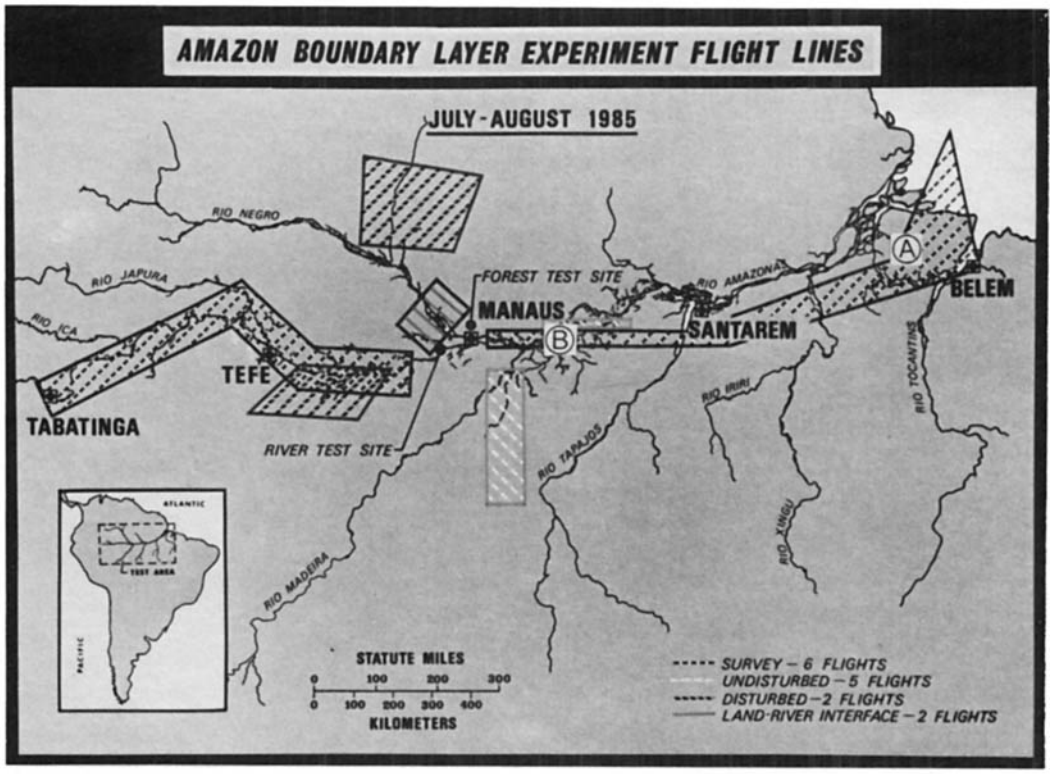

Fig. 1. Map of the Amazon Basin region of Brazil showing the locations of ABLE-2A studies (from Harriss et al. (1988)). The circled letters "A" and "B" illustrate the approximate locations of the profiles that are discussed in Figs. 5, 6.

although high soil moisture inhibited widespread biomass burning in the vicinity of the Amazon Basin. Similar conditions were present for the westbound (return) flight on the 24th (Harriss et al., 1988).

The ozone distribution between Belem and Manuas for these two survey flights is shown in Fig. 2. It should be noted that some of the UV-DIAL measurements were supplemented by in situ ozone measurements obtained during profile maneuvers on these survey flights (Browell et al., 1988). These additional measurements agreed very well with the UV-DIAL data during these flights and added an additional measure of continuity along the flight paths on these days.

Fig. 3 depicts the observed ozone distribution along approximately the identical flight path for the period of 8–9 August. Comparing Figs. 2 and 3, it is particularly noteworthy that ozone concentrations have generally increased substantially between the times of these pairs of survey flights. Whereas only a small percentage of the measurements exceeded 30 ppbv below 3.5 km on 23–24 July, more than half of the spatial domain of the survey flights contained concentrations that were greater than 30 ppbv by the time of the August flights. Integrated throughout the entire measurement domain, the amount of ozone more than doubled during this 17-day period. The presence of elevated concentrations of other trace gases and aerosols in conjunction with the relatively high ozone concentrations leaves little doubt that this enhancement of tropospheric ozone is a direct result of the presence of widespread biomass burning during this time (Andreae et al., 1988; Browell et al., 1988; Sachse et al., 1988).

An examination of GOES satellite imagery (see Fig. 4) shows that the most intense burning was located several hundred km south of the flight track on 8–9 August. Trace gas emissions from these figures were advected to the west and northwest by the prevailing boundary-layer trade winds and intercepted the western portion of the flight path. For example, Sachse et al. (1988) show an increase in carbon monoxide (CO) concentrations from 100–120 ppbv in the early sur-

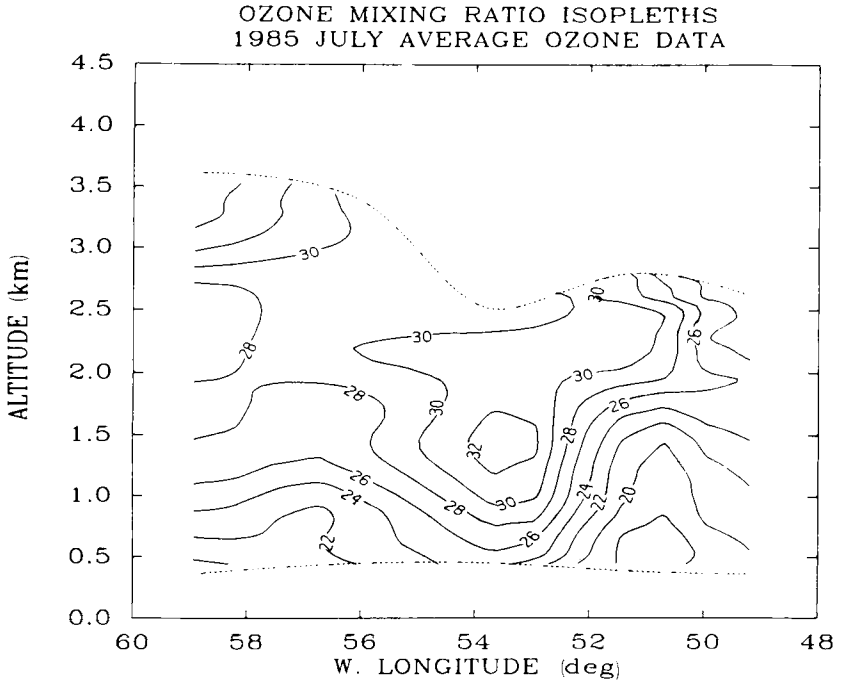

Fig. 2. Isopleths of ozone mixing ratios (ppbv) between Manaus and Belem for the survey flights of 23–24 July. The dotted lines indicate the altitude range of the measurements for these flights (from Browell et al. (1988)).

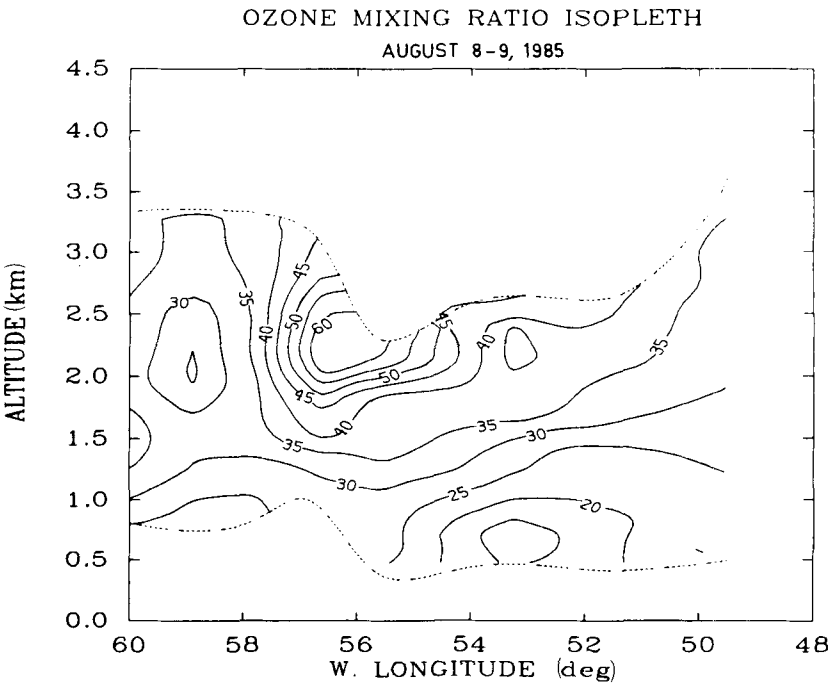

Fig. 3. Same as Fig. 2, except for the flights on 8–9 August (from Browell et al. (1988)).

vey flights west of 55°W to more than 215 ppbv on 8 and 9 August at the same location. It should be noted that the highest ozone concentrations shown in Fig. 3 were associated with the very high CO concentrations.

In Fig. 5, we show a set of vertical profiles of temperature, dew-point temperature, ozone, and carbon monoxide that were obtained 150–200 km east of Belem (refer to circled letter "A" in Fig. 1). Fig. 5a was obtained from a set of measurements on 24 July, whereas Fig. 5b depicts observations from 9 August. The wind speeds and directions are plotted on the right margin of the figures at each 500-m interval. For both profiles, the winds are quite similar and have an easterly component to them throughout both days. In the lower portions of the profiles, the winds are generally from the northeast and turn more southerly with increasing altitude. Near 200 m in both profiles, the winds are from the due east and the flight path of the airplane intercepts the plume emanating from the city of Belem at this level. In both figures, an inversion can be seen near 3000 m. Just below this inversion, the winds are from the southeast; above it, the winds have a northerly component. The wind speeds remain relatively constant. In these figures (and in Figs. 6a, b), a long wind barb represents 5 m s^{-1}; a short barb, 2.5 m s^{-1}.

Although burning is quite prevalent on 9 August (Fig. 5b), the trace gas profiles do not appear to be contaminated directly by the plumes from these fires. This finding is substantiated by the trajectory analyses discussed in Andreae et al. (1988). The average CO concentration increases from 82 to 88 ppbv between 24 July and 9 August, whereas the average ozone concentration increases from 23 to 30 ppbv during this same time. Within the Belem plume, the highest concentration measured on the 24th is 122 ppbv and 39 ppbv for CO and ozone, respectively; on the 9th, these maximum values are 132 and 45 ppbv. Thus, the Belem plume intercepted near 2000 m contains elevated CO concentrations of 40–45 ppbv and enhanced ozone concentrations of 10–15 ppbv. Because these plumes are the dominant features on these profiles, O_3 and CO are positively correlated with values of 0.81 and

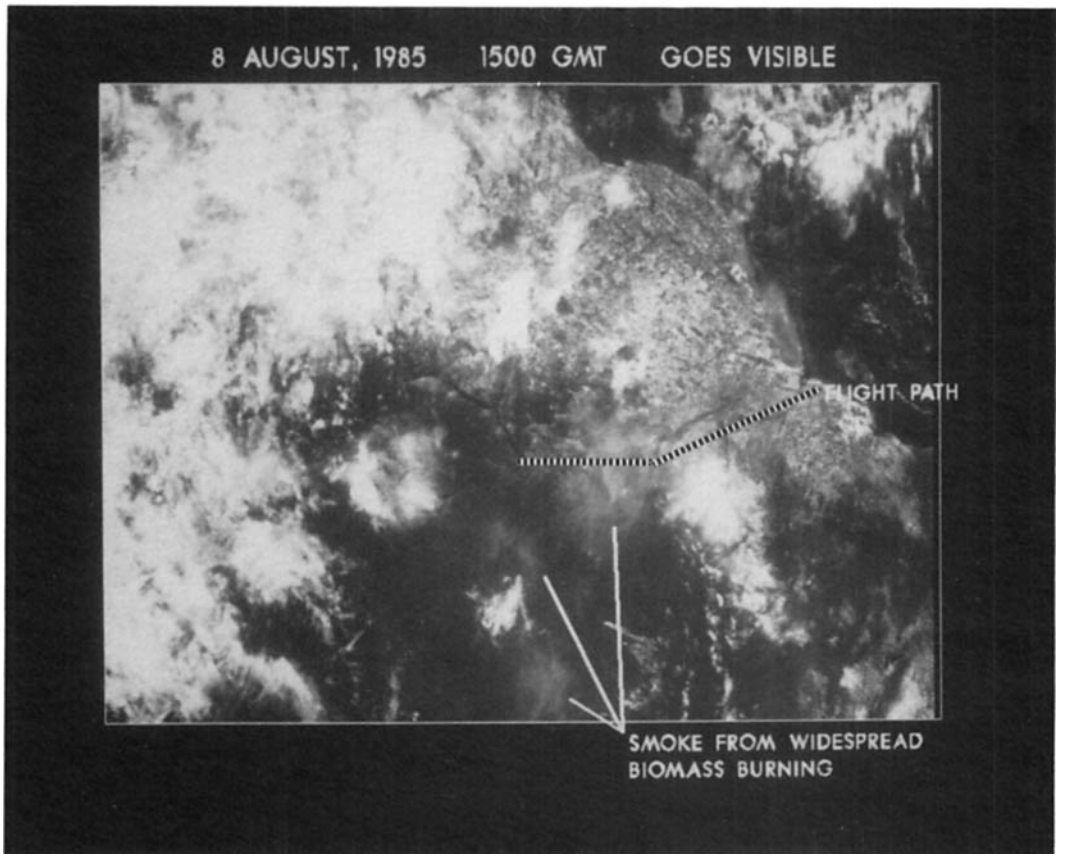

Fig. 4. GOES visible image of northern South America for 1500 GMT on 8 August 1985. The ground track of the aircraft survey flights between Manaus and Belem is depicted by the heavy dashed line. This box is approximately bounded by 7°N, 15°S, 75°W and 40°W.

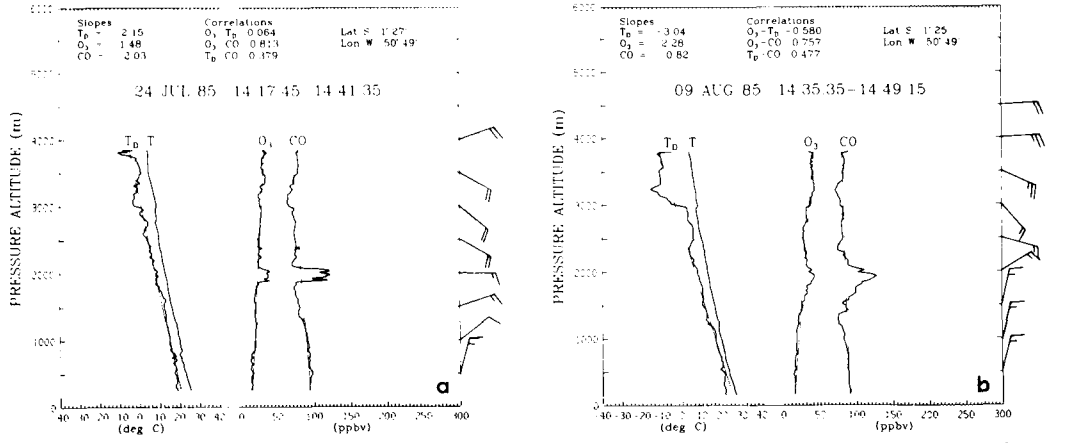

Fig. 5. (a) Vertical profiles obtained on 24 July 1985, near 1°S and 51°W. Wind speed and directions at 500-m increments are displayed on the right border of this figure. The longer wind barbs indicate wind speeds between 4 and 6 m s^{-1}, whereas the shorter wind barbs depict wind speeds between 2 and 3 m^{-1}. (b) Same as (a) except for 9 August 1985.

0.76 (computed from the method described in Fishman and Seiler, 1983; Fishman et al., 1987a) on these two days.

In contrast to the relatively small influence of biomass burning on these profiles near Belem, the measurements depicted in Fig. 6 show extreme differences. These profiles likewise were obtained on 24 July (Fig. 6a) and 9 August (Fig. 6b) near a point (the circled letter "B" in Fig. 1) 200–250 km west of Manaus during the latter portions of the survey flights during these two days. The wind direction throughout both sets of profiles is easterly. On the 24th, the wind is generally east-northeast except for a small layer between 1000 and 1500 m where the winds are east-southeast. On the 9th, most of the winds have a southerly component; only the winds up to 1000 m are east-northeasterly, whereas the winds above 1000 m are from the east-southeast. This observation is consistent with the trajectory analyses in Andreae et al. (1988) and support their finding that the origin of the high CO and O_3 concentrations measured in these profiles and the accompanying haze layers on the 9th is the fires observed by satellite 500–800 km southeast of the location of these measurements.

Between 24 July and 9 August, CO concentrations have increased from approximately 100 ppbv to 180 ppbv in the lowest 3500 m. Ozone has increased from an average concentration of 24 ppbv to 36 ppbv. The CO and O_3 profiles shown in these sets of figures illustrate qualitatively the magnitude of the source of widespread biomass burning in the Tropics. For comparison, the profiles in Figs. 5a, b show the enhancement of pollutant concentrations from a city of approximately 1 million people sampled 150–200 km downwind from the source. On the other hand, the integrated burdens of both CO and ozone have been increased considerably more by emissions from fires that are more than 500 km away. Because of the complex nature of these measurements and the prevailing meteorological situation, (as can be seen from the detailed vertical structure of the wind in Figs. 5 and 6) and the paucity of standard upper-air stations in South America, no attempt to quantify the impact of biomass burning will be presented. On the other hand, it is safe to conclude that the impact of biomass burning on the regional budgets of many trace gases in the ABLE-2A region is considerable. A more detailed analysis and discussion are presented in Andreae et al. (1988).

4. TOMS total ozone measurements

Total ozone amounts have been measured globally on a daily basis since 1978 by the total ozone mapping spectrometer (TOMS) instrument aboard the polar-orbiting Nimbus 7 satellite.

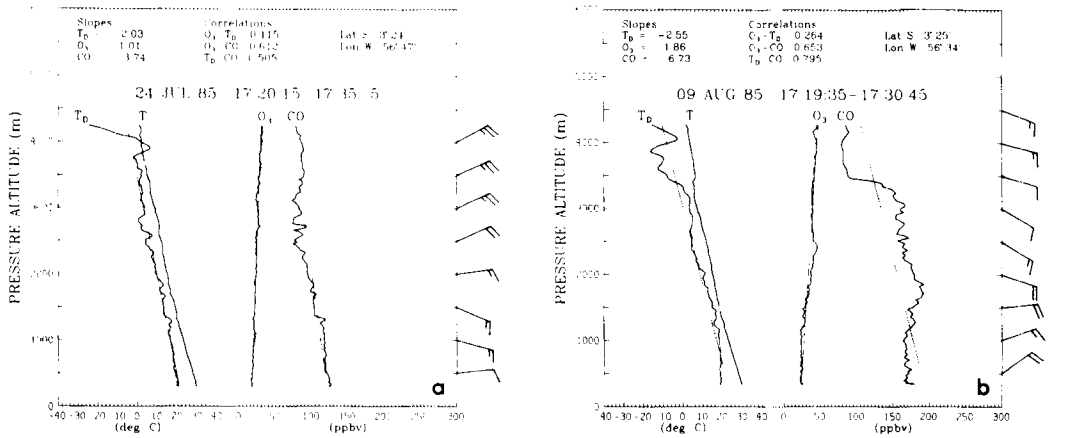

Fig. 6. (a) Vertical profiles obtained on 24 July 1985, near 3°S and 57°W. Note the apparent malfunction of the dew-point sensor above 3800 m as the airplane ascended through a small cloud. (b) Same as (a) except for 9 August 1985.

TOMS works on the principle of backscattered ultraviolet radiation (see Heath et al. (1975) for details) and can obtain a horizontal resolution of approximately 80 km. The distributions of total ozone over northern South America for 23–24 July and 8–9 August are shown in Figs. 7, 8, respectively. These distributions have been obtained from TOMS data tapes which provide gridded total ozone analyses with a resolution of 1° latitude by 1.25° longitude in the Tropics. The location of the flight paths on these two pairs of flights is shown by the heavy dashed line.

For the time period of the first two flights, 23–24 July, very little structure in the total ozone field is noted along the flight path. A relatively small gradient is observed in the total ozone field as values decrease from 275 D.U. (Dobson Unit; 1 D.U. = 2.69×10^{16} molecules of ozone cm^{-2}) near Manaus, to 271 D.U. near Belem. Somewhat more structure is seen for the total ozone fields on 8–9 August (Fig. 8), where a relative maximum of 287 D.U. is found along the flight track near 56°W. The total ozone amount is 284 D.U. near Manaus and is lowest near Belem with a value of 281 D.U.

It is also important to note that the area in which the Electra flights took place was generally cloud-free. The GOES visible and infrared satellite imagery show some cumulus clouds located north-northeast of Manaus near 3°N, 65°W, and some smaller well-developed cumulus clouds south of the flight path near 5°S, 54°W and several hundred km to the southwest of the flight track (near 6°S, 63°W) on 8–9 August. A careful examination of the TOMS data suggests that the total ozone amounts at these locations may have been underestimated by several Dobson Units since TOMS cannot sense ozone below cloud tops. It is likely that the data-reduction algorithm used to compensate for the presence of clouds slightly underestimated the amount of ozone present on these days (Bhartia, personal com-

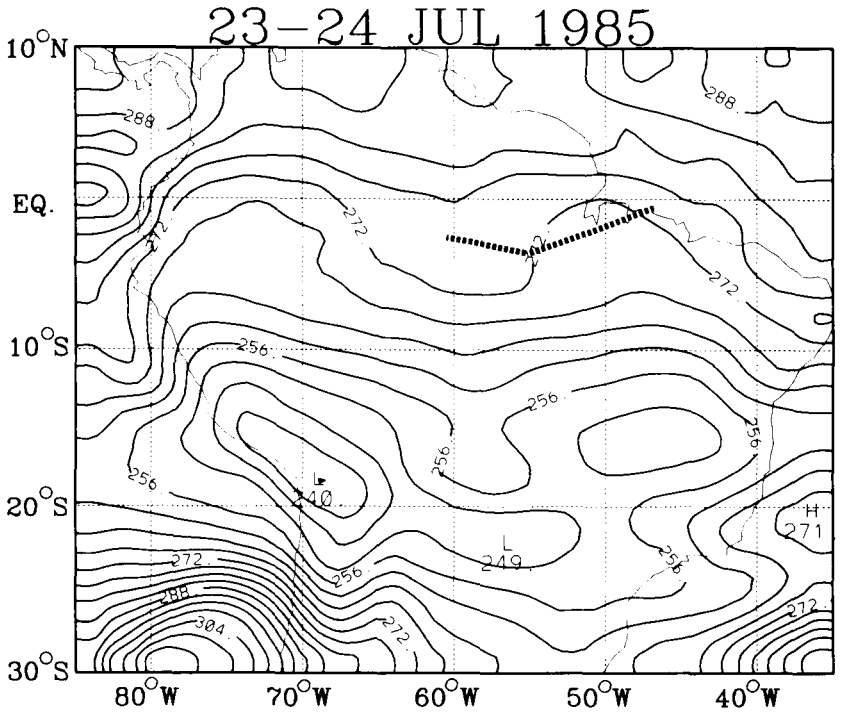

Fig. 7. The distribution of the total ozone field derived from gridded TOMS data is shown for 23–24 July 1985. The contours are in Dobson Units (D.U.) with a grid interval of 4 D.U. The average total ozone values for the 2 days is used in this depiction. The heavy dashed line indicates the flight path of the airplane during these days.

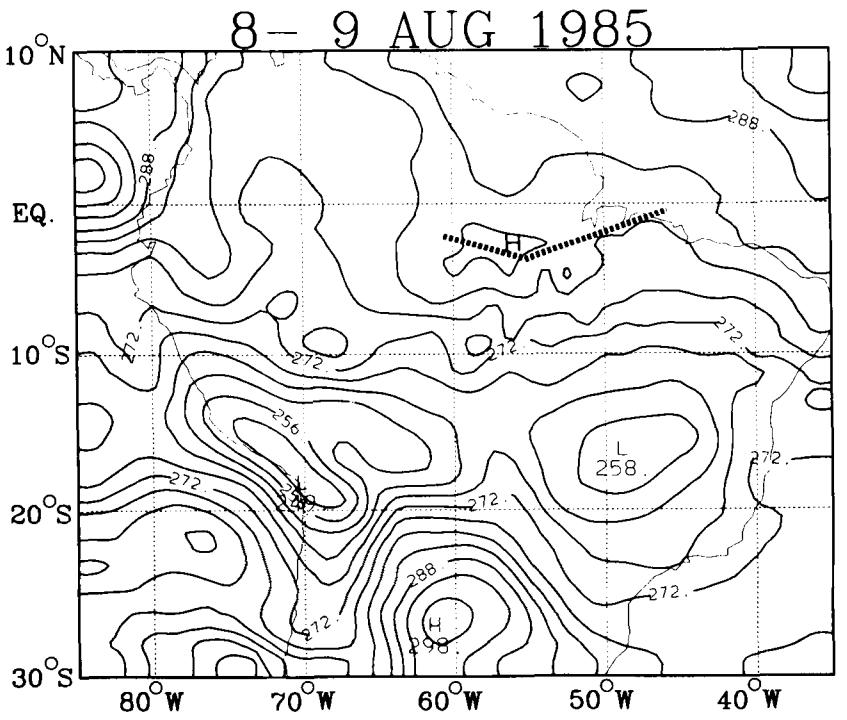

Fig. 8. Same as Fig. 7, except for the flights on 8–9 August.

munication). Such an underestimation is not surprising in light of the relatively high concentrations of ozone measured by the UV-DIAL; such concentrations are significantly higher than the climatological values that would have been substituted in the regions where clouds were present. Again, however, it is important to emphasize that clouds were very sparse in the region of the airplane flights, and that the data discussed in the following section were obtained in regions that were virtually cloudless.

5. Discussion

In Fig. 9, the integrated amounts of ozone derived from the two pairs of survey flights between Manaus and Belem are compared with the measured total ozone amounts measured by TOMS along these flight paths. For both the TOMS and the UV-DIAL data, the amount of ozone measured by both is greater on 8–9 August than on 23–24 July and the relative trends between Belem and Manaus are similar. The difference in the UV-DIAL depictions ranges between 1 and 6 D.U., whereas the difference in the TOMS measurements ranges between 9 and 13 D.U. The average increase along the flight path is 3 D.U. for the UV-DIAL data and 10 D.U. for the TOMS data. If the increase in the TOMS were due to higher levels exclusively in the troposphere, it is not surprising that the difference observed by the UV-DIAL measurements is considerably lower than the difference throughout the entire troposphere since the UV-DIAL is measuring primarily below 3.5 km in the lower troposphere. The ozone profiles reported by Delany et al. (1985) suggest higher concentrations up to 10 km (the highest altitude of their measurements) as a result of biomass burning. Comparing ozonesonde profiles obtained from Manaus during ABLE-2A shows a tropospheric (up to 100 mb) increase of 10 D.U. between 23–24 July and 3 August (Kirchhoff et al., 1988), the day of the last ozonesonde launch during this time period. The TOMS data show an 8-D.U. increase from 275 D.U. to 283 D.U. over Manaus during this time period.

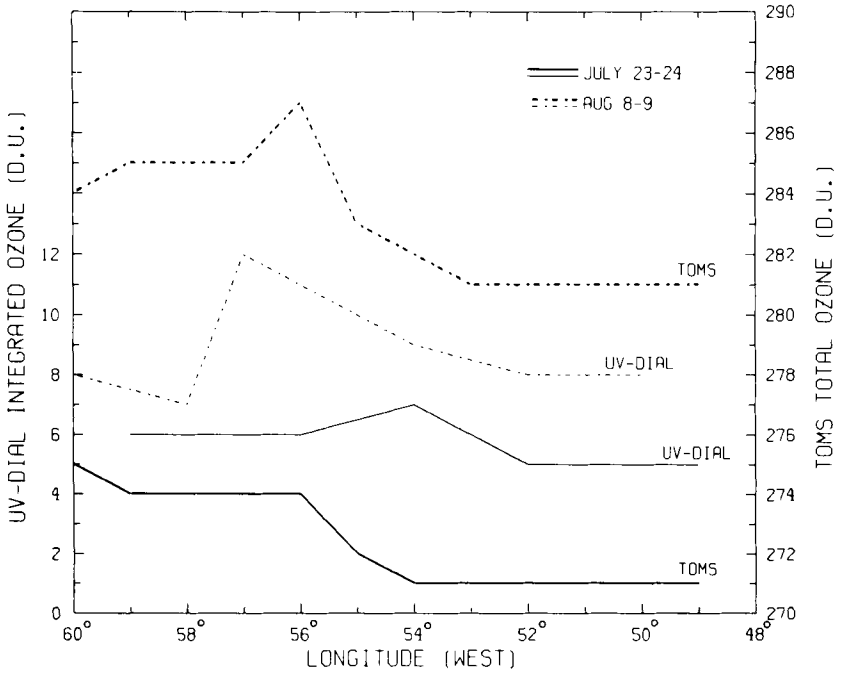

Fig. 9. The integrated total ozone from TOMS along the flight track is shown for the two pairs of survey flights as a function of longitude. For comparison, the integrated ozone amounts from the airborne data shown in Figs. 2, 3 are also depicted as a function of longitude between Manaus and Belem.

Also noteworthy is the fact that both the TOMS and UV-DIAL measurements depict similar spatial gradients for both pairs of flights. Both data sets exhibit a very small horizontal (longitudinal) gradient for 23–24 July and a considerably more pronounced gradient for the 8–9 August flights. Whereas the UV-DIAL measurements maximize near 57°W, the TOMS total ozone data are largest at 56°W. Such agreement is quite good in light of the fact that the measurements are not completely synchronous (due to the aircraft requiring several hours to travel along the Amazon, whereas the satellite obtained its information within a few seconds during one or two passes close to local noon) and the fact that the distribution in the middle of an upper troposphere may be somewhat different from what was observed by the UV-DIAL. It was fortuitous that a significant increase of ozone occurred between the times of these pairs of flights. Fig. 10 shows the daily total ozone amounts (plotted with a 5-day running average) over the region bounded by 3°N, 7°S, 50°W, and 70°W, an area of approximately 2 million km^2 incorporating the Amazon River. Consistent with our findings in previous studies (Fishman et al., 1986; Fishman and Larsen, 1987), total ozone values in 1985 maximized over this region in August and September. The arrows on this figure indicate the times of the survey flights. As can be seen from this depiction, a very sharp increase takes place over the entire region between the end of July and the early part of August. The total ozone behavior for 1980 exhibits a similar rapid increase over this region, but shifted by about 2 weeks, with low values ending by 8 July. Thus, Fig. 10 illustrates two important points; first, the increase obtained along the flight paths during these two times is not a phenomenon isolated to a relatively localized region, but rather to the entire Amazon Basin; and second, the 17-day interval between the sets of survey flights captured one of the most significant increases, if not the largest increase, that could have been seen during 1985 over such a time period.

Also plotted on this figure is a set of ozonesonde data that was obtained from a special series of ozonesonde launches near Manaus dur-

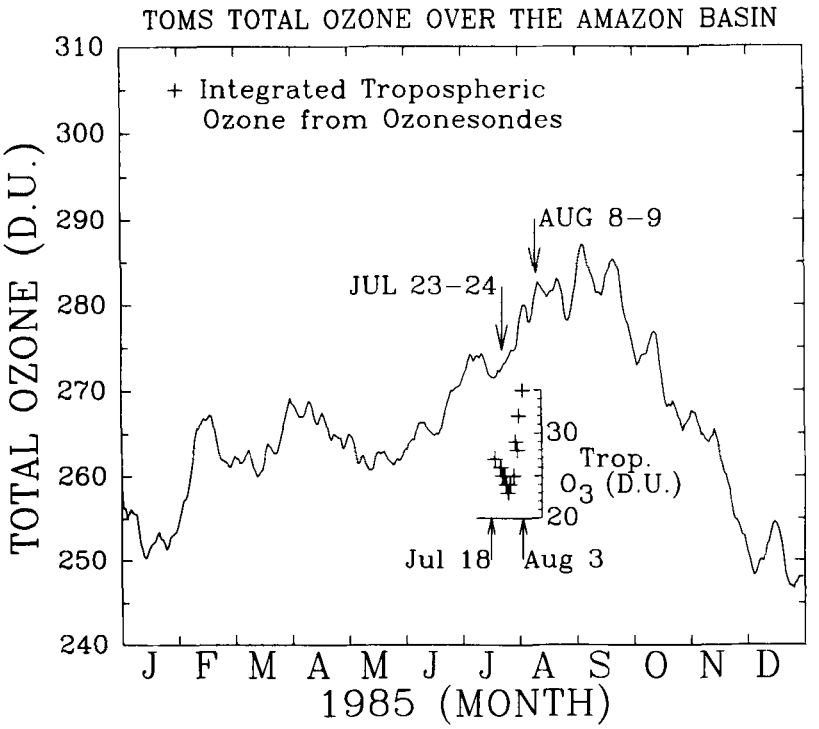

Fig. 10. The daily average of the total ozone amounts from TOMS over the Amazon Basin (a region bounded by 3°N, 7°S, 50°W, and 70°W) during 1985 is plotted as a function of day. The days of the two survey flights are shown by the larger arrows. The crosses indicate the integrated tropospheric ozone amounts (between the surface and 100 mb) obtained from a series of ozonesonde launches from Manaus between 18 July and 3 August.

ing ABLE-2A between 18 July and 3 August (Kirchhoff et al., 1988). On the 18th, the integrated ozone below 100 mb was 27 D.U. By the 23rd, tropospheric ozone decreased to 25 D.U. and reached a minimum of 23 D.U. on the 26th. Tropospheric ozone concentrations then increased with the last two ozonesondes indicating integrated tropospheric ozone amounts of 32 D.U. and 35 D.U. on 1 and 3 August, respectively. The stratospheric component of the ozonesonde data does not show a systematic increase during this time period. It should be noted, however, that these upper atmospheric measurements exhibit a much wider range of diel variability than the tropospheric portions of the soundings. None of the ozonesonde data discussed here have been normalized by ground-based spectroscopic total ozone measurements. Therefore, it is likely that some of the day-to-day variability observed by Kirchhoff et al. (1988) in the stratosphere may be due to variable pump efficiency and/or sensor performance when the balloons reach higher altitudes (e.g., see discussion by Hilsenrath et al. (1986)). Thus, despite some of the limitations of the stratospheric ozonesonde measurements, we conclude that most of the increase observed by TOMS during this period is a result of the increase in ozone concentrations below 100 mb.

In Fishman and Larsen (1987) and Fishman (1988), the climatologies of total ozone, integrated stratospheric ozone profiles above 100 mb (computed from SAGE I [1979–1981] vertical profiles), and the inferred integrated tropospheric ozone (i.e., residual) amount in the Tropics were presented. Consistent with the methodologies described in those studies, Table 1 summarizes the SAGE II (operating since 1984) measurements during 1985 that were located near the Amazon Basin (the same area described for the TOMS

measurements discussed in Fig. 10). During 1985, 24 SAGE II profiles were obtained within the box defined by 7°S, 3°N, 50°W and 70°W. Fourteen measurements were before 21 July; ten were after 18 August. The location of each of these profiles is summarized in Table 1. The temporal variability of the integrated amount of ozone above 100 mb for these 24 profiles is very small. The average stratospheric amount of ozone (under the SAGE column) is 248 D.U. for the first 14 profiles through July, and 246 D.U. for the last 10 after 18 August. On the other hand, the coincident amount of total ozone for the 24 times when SAGE II profiles were taken vary considerably between the first 14 and the latter 10 observations. This finding is consistent with the annual cycle depicted in Fig. 10. The average TOMS total ozone for these particular times is 263 D.U. before 21 July, and 277 D.U. after 18 August. The value in parentheses under the "TOMS" column in Table 1 refers to the average value throughout the entire region whereas the

Table 1. *SAGE (Stratospheric Aerosol and Gas Experiment) II profiles obtained in 1985 located in the region bounded by 3° N, 7° S, 50° W and 70° W*

Date	Lat.	Long.	TOMS (D.U.)	SAGE (D.U.)	Tropospheric residual
Jan. 12	4 S	69 W	249 (251)	236	13
Jan. 13	1 N	50 W	249 (250)	247	2
Jan. 20	0	66 W	252 (253)	236	16
Feb. 16	1 N	56 W	271 (267)	252	19
Feb. 26	1 S	62 W	255 (261)	246	9
Mar. 25	3 S	50 W	265 (263)	259	6
Apr. 5	1 S	56 W	275 (267)	250	25
May 3	4 S	52 W	274 (265)	244	29
May 9	7 S	63 W	251 (262)	243	8
May 10	1 S	68 W	258 (262)	248	10
Jul. 14	1 N	51 W	277 (273)	258	19
Jul. 15	4 S	56 W	271 (273)	261	10
Jul. 20	7 S	62 W	261 (272)	242	19
Jul. 21	2 S	68 W	272 (272)	250	22
Jan.–Jul. average (14 obs.)			263 (263)	248	15
Aug. 18	3 N	61 W	281 (282)	255	26
Aug. 29	1 S	68 W	295 (280)	252	43
Sep. 24	3 N	57 W	282 (282)	255	27
Sep. 25	6 S	60 W	281 (280)	248	33
Oct. 4	7 S	61 W	267 (273)	243	24
Oct. 5	2 N	63 W	287 (274)	252	35
Oct. 31	7 S	50 W	276 (267)	241	35
Nov. 1	1 S	54 W	276 (268)	243	33
Nov. 9	1 N	50 W	266 (264)	242	24
Nov. 10	5 S	55 W	264 (265)	239	25
Aug.–Nov. average (10 obs.)			277 (274)	246	31

The total ozone from TOMS obtained at the same date and location is given; for comparison, the average amount over the entire region is also given in that column in parentheses. The integrated ozone above 100 mb from the SAGE II profiles is given in the next-to-last column. The difference between these integrated ozone amounts (i.e., the tropospheric residual) is given in the last column. The table is divided into two parts: the top half summarizing the observations between 12 January and 21 July, when biomass burning was relatively less prevalent; the second half summarizes the profiles between 18 August and 10 November (the last 1985 SAGE II profile in this region) when biomass burning was considerably more abundant. All entries are in Dobson Units (D.U.).

first value in this column is the gridded TOMS total ozone value closest to the location of the SAGE II profile.

For the most part, the two values in this column agree to within a few D.U., except for three entries where these two numbers differ by more than 10 D.U. On 20 July, there is a relatively large north-south gradient with higher total ozone amounts to the north. The location of the 20 July profile is on the southern edge of the box, and therefore, 11 D.U. lower than the average within the box. On 29 August, there is a significant "hot spot" on the western edge of the box; the location of this profile captures this anomaly. On 5 October, there is likewise a "hot spot" (not as anomalous as the one on 29 August) at this particular location as well as a north-south gradient again with higher values to the north. These two factors contribute to the 13-D.U. difference between the two values in this column.

Perhaps the most significant column in this table is the last one in which the "tropospheric residual" values for the 24 observations are summarized. Before 21 July, the average tropospheric residual is 15 D.U. whereas it more than doubles to 31 D.U. after 18 August. On 20, 21 July, the tropospheric residual is 21 D.U. for two SAGE II profiles located approximately 500 km south of Manaus on the 20th and approximately 600 km west of Manaus on the 21st. The ozonesondes launched from Manaus on both sides of these two days between 18 July and 24 July measured an average of 25 D.U. in the troposphere with a range between 24 and 26 D.U. We consider this agreement to within 20% to be very good in light of the many uncertainties involved in this analysis. Furthermore, the integrated tropospheric residual on the 20th was at a location on the southern edge of the box where, as stated previously, the TOMS measured relatively lower total ozone amounts on that particular day. In summary, this independent analysis incorporating additional satellite measurements from the SAGE II data base lends credence to the hypothesis that TOMS total ozone measurements can be used to study the distribution and behavior of tropospheric ozone in the Tropics and supports the rationale behind the methodology described in Fishman (1988) that a useful quantitative data base might be attainable from the concurrent use of TOMS and SAGE measurements.

6. Summary and conclusions

Ozone measurements from the Amazon Boundary Layer Experiment (ABLE-2A) during July and August 1985 have been compared with a set of satellite total ozone observations from the TOMS instrument aboard Nimbus 7. Until a field program is designed to verify explicitly the utility of the TOMS for tropospheric ozone studies, this data set is the most comprehensive one available in the Tropics to which the TOMS observations can be compared.

The ABLE-2A data indicate that ozone concentrations increased considerably during the 17-day period between the pairs of survey flights that were used in this study. Visual observations, other trace gas and aerosol measurements, and GOES satellite imagery confirm that the enhanced ozone was a result of widespread biomass burning which increased significantly with the onset of the dry season in late July.

During this time period, TOMS total ozone amounts also increased throughout the Amazon Basin. In general, TOMS measured an integrated ozone increase that was approximately three times greater than the increase derived from the UV-DIAL measurements. This finding is not surprising since the vertical range of the UV-DIAL observations was generally limited to the planetary boundary layer. The spatial gradients of the total ozone fields likewise captured the relative spatial gradients observed during the survey flights between Manaus and Belem reasonably well.

An analysis of a special set of ozonesonde measurements obtained near Manaus for the ABLE-2A experiment indicates that tropospheric ozone increased by approximately 50% between 26 July and 3 August (from 23 D.U. to 35 D.U.). This 12-D.U. increase in the troposphere over the Manaus site was observed by TOMS as a total-ozone increase of 13 D.U. Throughout the entire region, TOMS data (see Fig. 10) indicate an increase of 10 D.U. Between 18 July and 26 July, the ozonesondes indicated a tropospheric decrease of 4 D.U. whereas the TOMS data show a decrease in total ozone of 3 D.U. over Manaus. On the other hand, the TOMS data indicate an increase of 2 D.U. over the entire region.

In conclusion, it appears that most of the temporal and spatial behaviors of the total ozone fields depicted by the TOMS instrument are in

good agreement with the aircraft and balloon-borne measurements obtained in the troposphere during ABLE-2A. Ideally, the aircraft measurements would have extended throughout a larger portion of the troposphere to verify this finding, but the fact that the UV-DIAL instrument consistently underestimated the spatial variability by a factor of 2–3 is reasonable in light of the limited altitude range of its measurements. Thus, the analyses presented in this study strengthen our premise that TOMS total ozone information can be utilized to investigate photochemical and possibly dynamical processes that impact the distribution of tropospheric ozone and its global budget.

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