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Effect of an improved cloud climatology on the total ozone mapping spectrometer total ozone retrieval

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Abstract. The 14.5 years of Nimbus 7 total ozone mapping spectrometer (TOMS) gridded data have been reprocessed using the Version 7 (V7) algorithm. Among a number of improvements made in the TOMS V7 algorithm, a new cloud top height climatology, based upon the International Satellite Cloud Climatology Project (ISCCP) data set, has been included to correct for the cloud height effect on total ozone. The new algorithm also contained an improved cloud model that used a modified Lambertian surface assumption in the partially clouded scenes. As a result, reductions in TOMS V7 total ozone, as compared to Version 6 data, could be more than 20 Dobson units over marine stratocumulus, while in high cloud regions the V7 measured total ozone amounts are generally higher than V6 values. The high correlation between TOMS V6 total ozone and reflectivity has been greatly reduced using the V7 data, particularly in the low cloud region of the tropical eastern Atlantic. Also, the land-ocean contrast in total ozone associated with the inadequate cloud height climatology and partial cloud model has diminished in the V7 data. The land-ocean contrast in total ozone due to the sensitivity of the lower tropospheric ozone to ground reflectivity, however, still remains.

1. Introduction

Variations of ozone in the troposphere have gained increasing attention over the past decade. Elevated levels of tropospheric ozone have been detected, from ground-based and airborne measurements, on regional as well as global scales [*Logan*, 1985; *Bojkov*, 1988; *Jiang and Yung*, 1996]. These measurements, however, are sporadic in both time and space, particularly in the tropics. Because of this, space-borne measurements of tropospheric ozone and its precursors are in demand to provide better understanding of the photochemistry and transport of tropospheric ozone.

Using the method of "tropospheric residual" obtained by differencing the total ozone mapping spectrometer (TOMS) and the Stratospheric Aerosol and Gas Experiment (SAGE) ozone data, *Fishman et al.* [1990] produced a global climatology of the ozone distribution in the troposphere. They showed relatively higher tropospheric ozone concentrations over the African continent and the southern tropical Atlantic Ocean during the dry season that appeared to be a result of in situ photochemical production related to biomass burning. They also found that the longitudinal distribution of stratospheric ozone from SAGE II measurements is quite flat at low latitudes and further proposed the use of TOMS total ozone as a proxy for tropospheric ozone in the tropics.

However, *Thompson et al.* [1993] and *Hudson et al.* [1995] cautioned that there is a high degree of statistical correlation between TOMS Version 6 (V6) total ozone and reflectivity in the regions of marine stratocumulus clouds. Since TOMS only measures the ozone amounts above clouds, the total ozone values are obtained by the sum of an estimated climatological ozone amount below clouds and the TOMS determined ozone above clouds. Therefore the assumption of the cloud top height used in the algorithm could have a direct impact on the retrieved total ozone amount by TOMS.

In an attempt to correct the artifact due to the inappropriate cloud height assumption, a new cloud height climatology based on the International Satellite Cloud Climatology Project (ISCCP) data set is now being used in the TOMS Version 7 (V7) algorithm. In this paper, we examine the impact of this new cloud height climatology and an improved partial cloud scheme on the TOMS total ozone retrieval. The improvements of the TOMS V7 ozone retrieval algorithm and instrument calibration will be described briefly in section 2. Section 3 focuses on the resulting changes in the local ozone maxima on the daily map in the tropics associated with the TOMS V7 new cloud treatment. The differences in the monthly averaged ozone between V6 and V7 are discussed in section 4. In section 5 the changes in the longitudinal variation and ocean-land contrast in total ozone in V7 data as a result of the new cloud treatment are examined.

2. Data Description

The 14.5 years of Nimbus 7 TOMS gridded data (November 1978 to May 1993) were recently reprocessed using the V7 algorithm. A number of modifications have been made in the TOMS V7 reprocessing, both in the instrument calibration and in the retrieval algorithm (for details of the algorithm and calibration changes made in V7, see the TOMS V7 user's manual [*McPeters et al.*, 1996]). For instance, a wavelength error of approximately 0.17 nm was corrected in the V7 calibration. This resulted in a generally 2–4% reduction in measured total ozone, which partially corrects a 4% persistent offset relative to Dobson using the V6 data [*McPeters and Komhyr*, 1991].

Two other major changes concern how the algorithm re-

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trieves ozone when there are clouds in the scene. The first change involved an improved model which was used to better interpret measurements over partially clouded scenes. Version 6 of the algorithm assumed that a given scene could be approximated by a single Lambertian reflecting surface with an effective scene reflectivity determined from an assumed surface pressure. For partially cloudy fields of view this model leads to a reflectivity dependence on wavelength which, in turn, results in an underestimation of total ozone [*Seftor et al.*, 1994]. In the V7 algorithm, two Lambertian reflecting surfaces are used, one for the ground (with an assumed reflectivity of 8%) and one for the cloud (with an assumed reflectivity of 80%). The assumed 8% (ground) and 80% (cloud) reflectivities were based on the TOMS reflectivity measurements of *Eck et al.* [1987]. An effective cloud fraction was calculated from the measured 380-nm radiance assuming these two Lambertian reflecting surfaces. The effective reflectivity can then be determined from the cloud fraction. For details of the partial-cloud algorithm, see *McPeters et al.* [1996]. The use of this algorithm reduced the wavelength dependence of the reflectivity over partially clouded scenes and therefore its effect on ozone retrieval when compared to the V6 model.

The second change involved the use of climatological monthly averages of the International Satellite Cloud Climatology Project (ISCCP) data from 1984 to 1990 [*Rossow and Schiffer*, 1991; *Rossow and Garder*, 1993; *Rossow et al.*, 1993] in order to better estimate cloud height pressure. In the V6 algorithm a simple latitude dependence was used to compute the typical cloud top pressure, that is,

$$P_{\text{cloud}}(\text{atm}) = 0.3 + 0.15 \times [1 - \cos(2 \times \text{lat})] \quad (1)$$

This climatology was based on averaging data from the temperature, humidity infrared radiometer (THIR) on board Nimbus 7 [*Stowe et al.*, 1988, 1989]. The resulting cloud height increases monotonously with latitude from 0.3 atm at the equator to 0.6 atm at the poles. In contrast, Plate 1 shows the global distribution of the cloud top pressure used in the TOMS V7 algorithm for the month of October based on the ISCCP cloud climatology. It appears that the cloud heights over the continents are systematically higher than those over the oceans. This may be due to the fact that the high-altitude cumulus generated by deep convection occurs more frequently over the land than over the ocean, while the low-altitude stratus or stratocumulus is seen more often over the ocean [*Warren et al.*, 1988; *Hwang et al.*, 1988]. These low clouds were also found to be persistent features in the tropical eastern Atlantic and in the tropical eastern Pacific throughout the year [*Coulmann et al.*, 1986], while the cloud heights in most parts of the world are highly variable. When compared to V6 climatology, differences between V6 and V7 cloud pressure are as large as 0.45 atm, particularly in the marine stratocumulus region. As will be shown in the next section, these changes in the cloud height climatology used in TOMS algorithm could have significant impacts in the local ozone maxima on the TOMS maps.

3. Changes on Daily TOMS Maps

Plate 2a shows the distribution of TOMS V6 total ozone in the vicinity of South America, Africa and the Atlantic for October 8, 1989. There are two regions of locally high ozone observed by TOMS in the tropical eastern Atlantic (one near 25°S, 3°W and the other extending from 15°S, 3°W to 22°S, 10°E). As seen from the TOMS reflectivity map shown in Plate

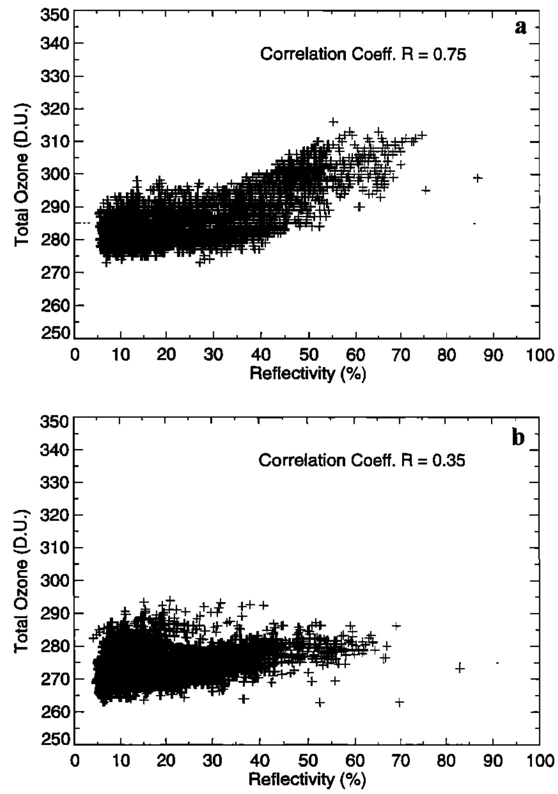

Figure 1. TOMS total ozone versus reflectivity over the eastern tropical Atlantic between 20°W and 15°E and 0° and 20°S for August 15, 1989, using (a) V6 data and (b) V7 data.

2b for the same day, these ozone anomalies occur at exactly the locations where clouds are present. With the new cloud climatology, these ozone maxima are virtually gone in the TOMS V7 total ozone map shown in Plate 2c. A reduction of more than 20 Dobson units was found in these local ozone maxima. In the absence of evidence that usually high concentrations of ozone accumulate over low cloud, the ozone derived in V7 appear much more reasonable. This indicates that these ozone anomalies are probably an artifact of the simple latitudinally dependent cloud height assumption used in the V6 algorithm.

The correlation between TOMS V6 total ozone and reflectivity in the eastern tropical Atlantic region between 20°W and 15°E and 0°–20°S was calculated for August 15, 1989. As shown in Figure 1a, a high total ozone-reflectivity correlation ($R = 0.75$) was obtained in the region of persistent marine stratus. Using TOMS V7 data, the correlation coefficient between total ozone and reflectivity dropped significantly down to 0.35 for the same region. As depicted in Figure 1b, the curve representing the relationship between total ozone and reflectivity has become flatter using the V7 data set.

In order to validate the V7 cloud height correction on ozone, V7 data was compared to the results obtained by *Thompson et al.* [1993]. *Thompson et al.* [1993] corrected TOMS V6 total ozone in the region of marine stratus by contrasting the retrieved Nimbus 7 SBUV total O_3 using (1) for cloud height with the retrieved total O_3 using the measured cloud height from THIR data. Figure 2 depicts the comparison of the ozone correction of *Thompson et al.* [1993] against the difference between TOMS V7 and V6 total ozone in the eastern Atlantic between 20°W and 15°E and 0°–20°S for October 14, 1989. It can be seen that after taking into account the -2% change in

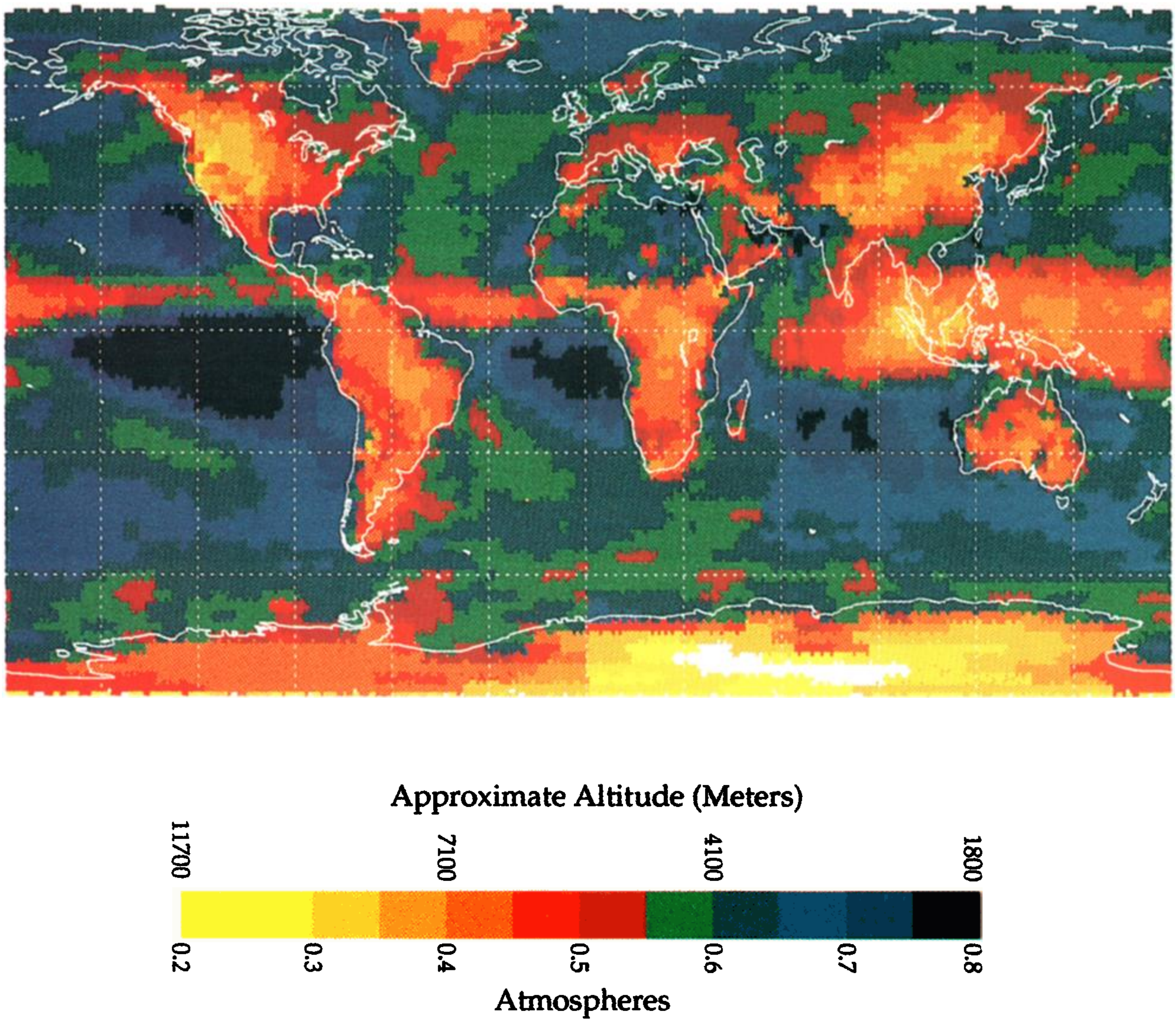

Plate 1. Distribution of the cloud top height pressure used in total ozone mapping spectrometer (TOMS) version 7 algorithm for the month of October, based on the ISCCP cloud climatology.

total ozone (~ −6 DU) due to the correction made in the V7 instrument calibration, the V7 cloud correction over marine stratocumulus is generally consistent with the cloud correction derived by *Thompson et al.* [1993] using the THIR data. On this day the reduction in total ozone was up to approximately 20 DU over the high-reflectivity area.

Because the partial cloud model used in V7 increases the retrieved total ozone in the cloudy scene, the cloud correction on the TOMS total ozone does not always result in negative ozone changes. Figure 3 illustrates the TOMS V7 and V6 total ozone differences in the southern Africa continent between 10°E and 40°E and 0°–33°S for October 14, 1989. In order to separate the partial cloud correction from the cloud height correction used in V7, only those measurements with small difference in the assumed cloud height between TOMS V7 and V6 (delta <200 mbar) were included in the analysis in Figure 3. After accounting for the −2% difference due to the wavelength adjustment the resulting increase in total ozone amount due to the partial cloud correction peaks at a medium reflectivity near 40–50% and drops close to zero at low and high reflectivity. Therefore the net effect of the TOMS V7 cloud correction will be an ozone reduction in the stratus region (over ocean) and an ozone enhancement in the deep convection zone (over land).

4. Changes on Monthly Mean TOMS Maps

The example for October 8, 1989, as discussed in section 3, showed that the total ozone difference between TOMS V6 and V7 on a daily map could be as large as 20 DU in the marine stratus region. In order to demonstrate that this is not a single incident, the TOMS V7 total ozone was compared to the V6 data on a monthly average basis. Plate 3a shows the map of TOMS V6 monthly mean total ozone for October 1988. The level of tropical ozone is generally higher in the vicinity of the south Atlantic, Africa, and South America than in the Pacific and the eastern Indian Ocean. In addition, a prominent ozone anomaly is seen in the south Atlantic off the coast of Africa. This ozone maximum occurs in the region of marine stratus, as shown in Plate 1, where the actual cloud height is much lower

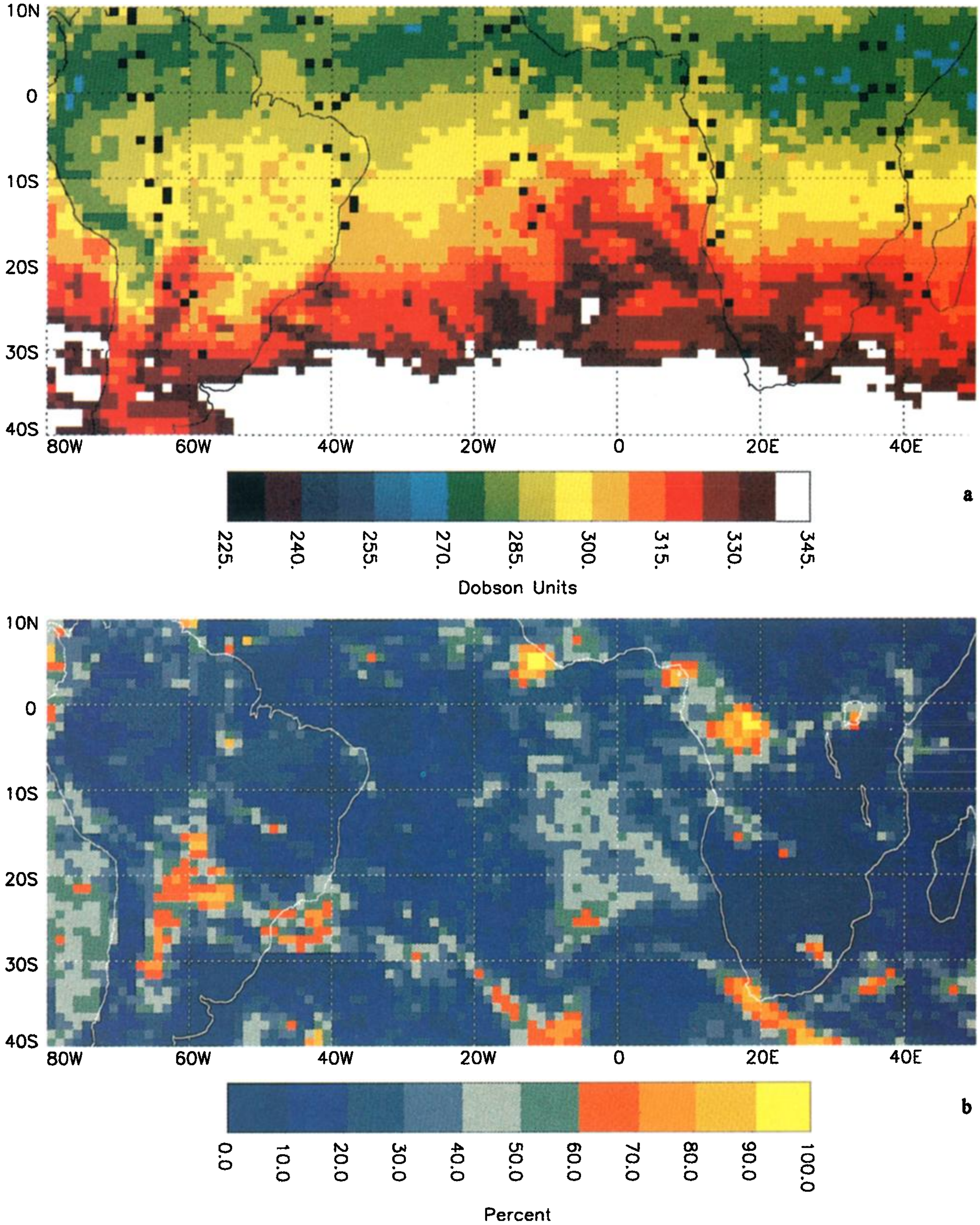

Plate 2. Maps of TOMS V6 and V7 data in the region of the Atlantic between 80°W and 50°E and 10°N–40°S. (a) TOMS V6 total ozone for October 8, 1989. (b) TOMS V7 reflectivity for October 8, 1989. (c) TOMS V7 total ozone for October 8, 1989. Note that the white color is for ozone values ≥337.5 DU and the black is for values less than 232.5 D.U. or no data.

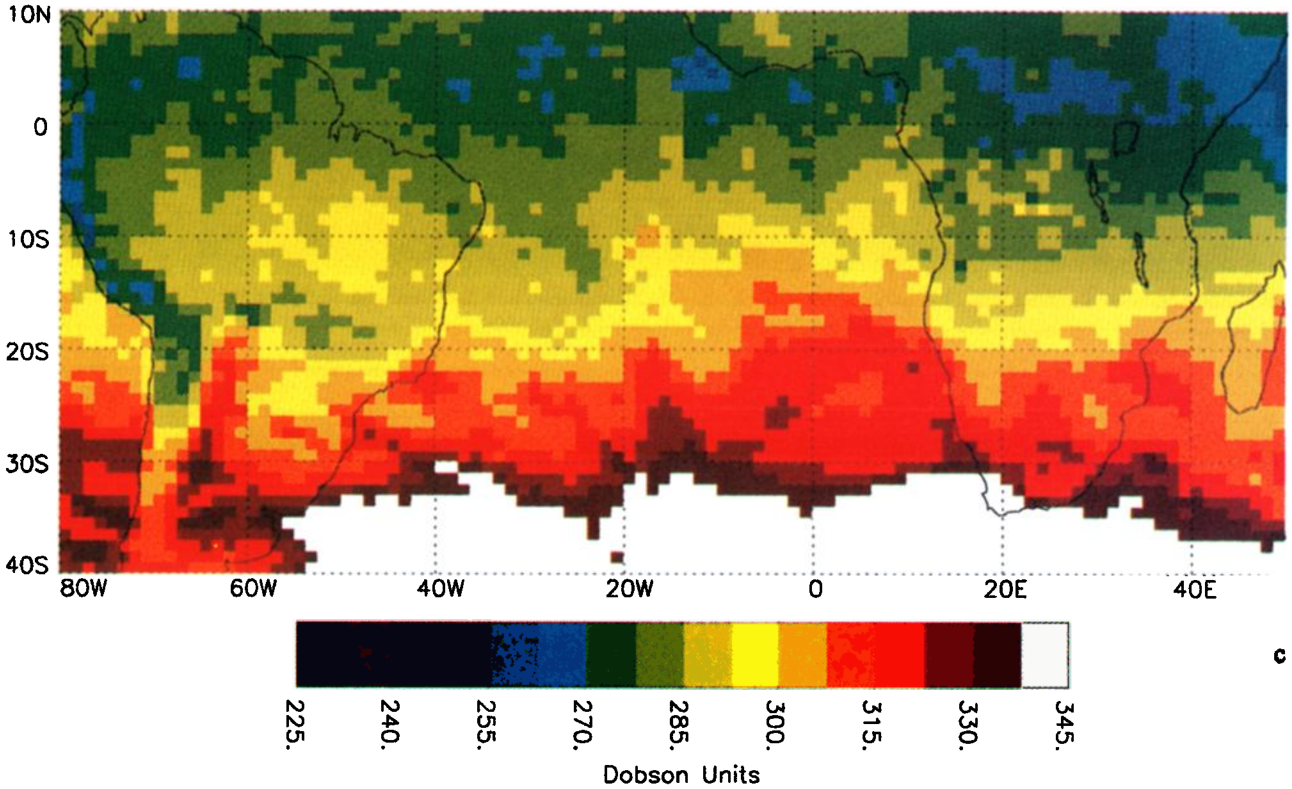

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Plate 2. (continued)

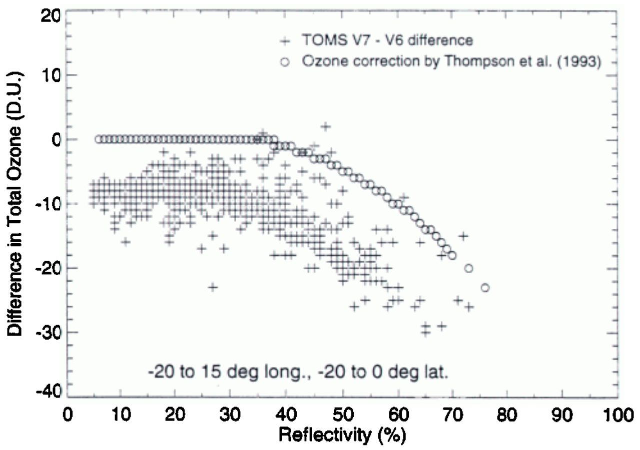

Figure 2. The comparison of the difference between TOMS V7 and V6 total ozone against the ozone correction of *Thompson et al.* [1993] in the eastern Atlantic between 20°W and 15°E and 0°–20°S for October 14, 1989. TOMS (V7-V6) ozone difference is generally consistent with the ozone correction by *Thompson et al.* [1993] over marine stratocumulus, after taking into account approximately −6 DU change in total ozone due to the correction in V7 instrument calibration.

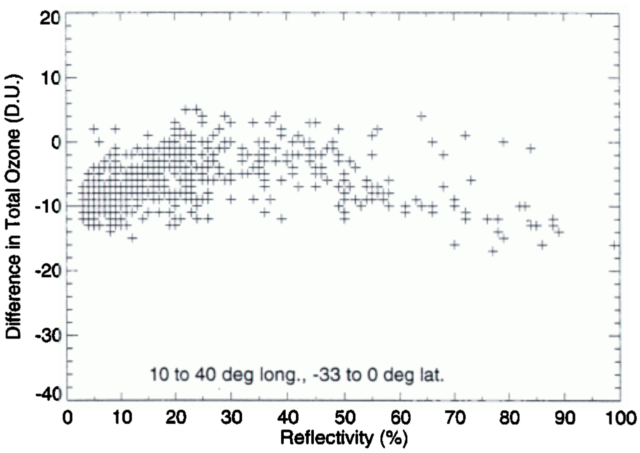

Figure 3. The difference of the TOMS V7 and V6 total ozone in southern Africa between 10°E and 40°E and 0°–33°S for October 14, 1989. In order to separate the partial cloud correction from the cloud height correction in V7, only those measurements with small difference in cloud height between TOMS V7 and V6 (delta <200 mbar) were included in the analysis.

than the value assumed in the V6 algorithm. Using the V7 data, as depicted in Plate 3b, this local ozone maximum disappears in the October monthly map, while an enhancement of ozone in the broader surrounding area of the south Atlantic still remains.

Likewise, the total ozone maxima are also reduced in V7 data in the regions west of South America and west of California where the stratus is frequently present. The ozone reduction due to the cloud correction in these cases, after taking into account the 5 DU reduction from the calibration correction, is generally 5–7 DU. In the ITCZ regime near the equator the partial cloud effect is nearly compensated for by the calibration correction so that the TOMS V7 measured ozone amounts are almost the same as, or even larger than, the V6 values in those regions.

Since the ISCCP data show that the frequency of marine stratocumulus in the regions indicated by the boxes in Plates 3a

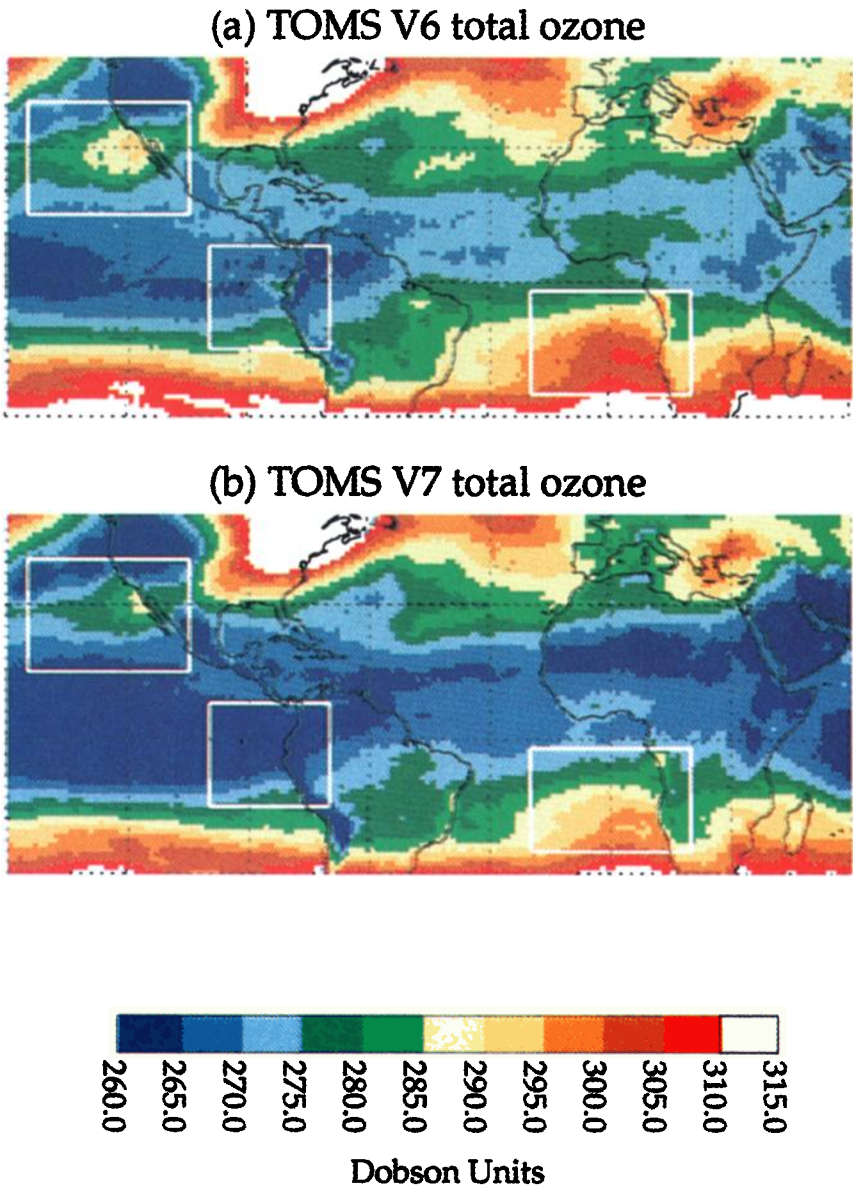

Plate 3. Maps of TOMS monthly mean total ozone for October 1988 derived from (a) V6 data and (b) V7 data. Note that the white color is for ozone values ≥310 DU and the dark blue is for values less than 265 DU.

and 3b is high (generally 60–75% every year from August to November) [*Thompson et al.*, 1993], the V7 cloud correction could also have a significant impact on the local maxima of the TOMS seasonally averaged O_3 maps.

5. Changes on the Longitudinal Variations of Monthly Mean Total Ozone

In order to study the impact of man-made activity on tropospheric ozone, the longitudinal variations of the TOMS total column ozone have been used as an index to reflect perturbations in tropospheric ozone at low latitudes [*Kim et al.*, 1996; *Hudson et al.*, 1995; *Fishman and Larsen*, 1987; *Fishman et al.*, 1986]. Figure 4a shows the longitudinal variation of the monthly averaged V7 total ozone versus V6 at 10.5°S for October 1989. Note that a wave one structure, relative to the zonal mean, is dominant in total ozone in both the V6 and V7 data. It has a peak centered in the Atlantic ocean near 0°–5°E longitude and a minimum in the vicinity of the Pacific Ocean. This wave feature in total ozone is believed to result from an elevated ozone concentration in the tropospheric component in the Atlantic, South America, and Africa continent, superimposed on a relatively flat stratospheric component of ozone [*Fishman and Larsen*, 1987; *Kim et al.*, 1996]. *Kim et al.* [1996] applied a cloud correction to tropical marine stratocumulus similar to the one used here but omitted other regions with reflectivity >0.15 from their analysis.

As shown in Figure 4a, the ozone level in V7 is generally lower than the V6 value, due to wavelength-dependent calibration correction. Also, the ocean-continent contrast (the Atlantic, Africa, and South America) in total ozone has been reduced in the V7 data by using the improved cloud height climatology and the V7 partial cloud model. Compared to aircraft ozone observations during TRACE-A, V6 TOMS gave rise to a too-large ocean-land ozone contrast [*Fishman et al.*, 1996]. This change in TOMS V7 ocean-land contrast is due to a combination of ozone enhancements over South America

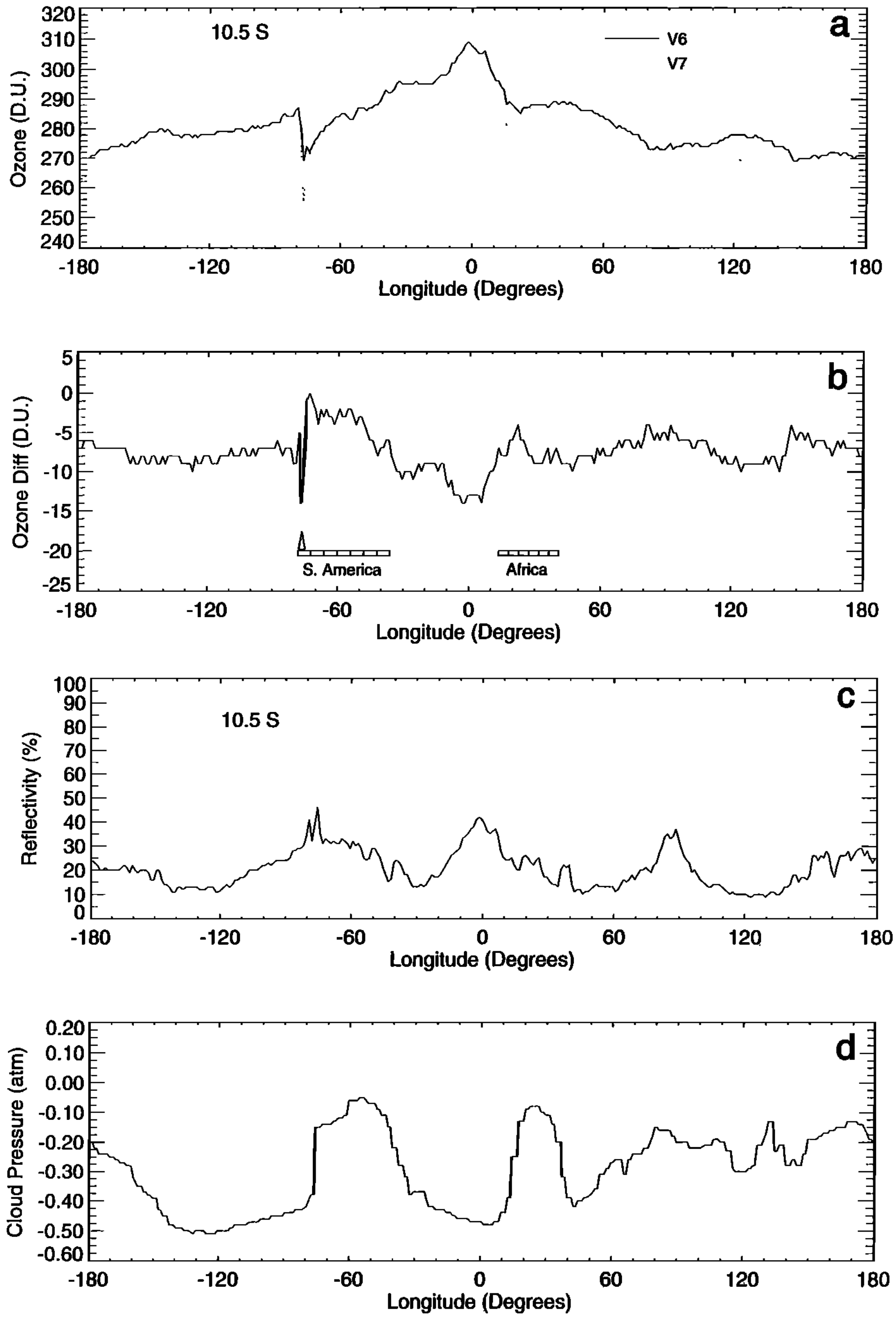

Figure 4. The longitudinal variations at 10.5°S for October 1989 of (a) the monthly averaged total ozone for V7 and V6; (b) the difference between V7 and V6 ozone shown in Figure 4a; (c) the monthly averaged TOMS reflectivity; and (d) the cloud height difference between TOMS V6 and V7.

and Africa continent, and an ozone reduction in the Atlantic, as depicted in Figure 4b. The elevated ozone value for the Atlantic maximum relative to the Pacific decreased in the V7 data from 40 DU to 34 DU, as compared to V6. The ozone slope on the west side of the Andes also became more continuous with that on the east side in V7.

The corresponding longitudinal variations of the monthly averaged TOMS V7 reflectivity and the cloud height pressure difference between V6 and V7 are shown in Figure 4c and 4d, respectively. At 10.5°S latitude there were three major regions where significant cloud coverage was present on a monthly mean basis. One was in the high cloud region (50°W–80°W) and is clearly attributable to the positive cloud correction for ozone over the South America continent. The other cloudy region was at around 15°W–10°E longitude in the Atlantic Ocean west of the African coast. The cloud height difference shown in Figure 4d indicates that the climatological cloud height is low in this region, resulting in an approximately 5 DU reduction relative to the zonal averaged ozone correction. The climatological cloud height in the region between 80°E and 90°E was medium to high, leading to a net positive cloud correction of roughly 5 DU in the V7 data. The combination of the ozone reduction in the Atlantic Ocean and the ozone increase over the Africa continent significantly reduces the ozone difference between the land and ocean in the vicinity of the west African coast.

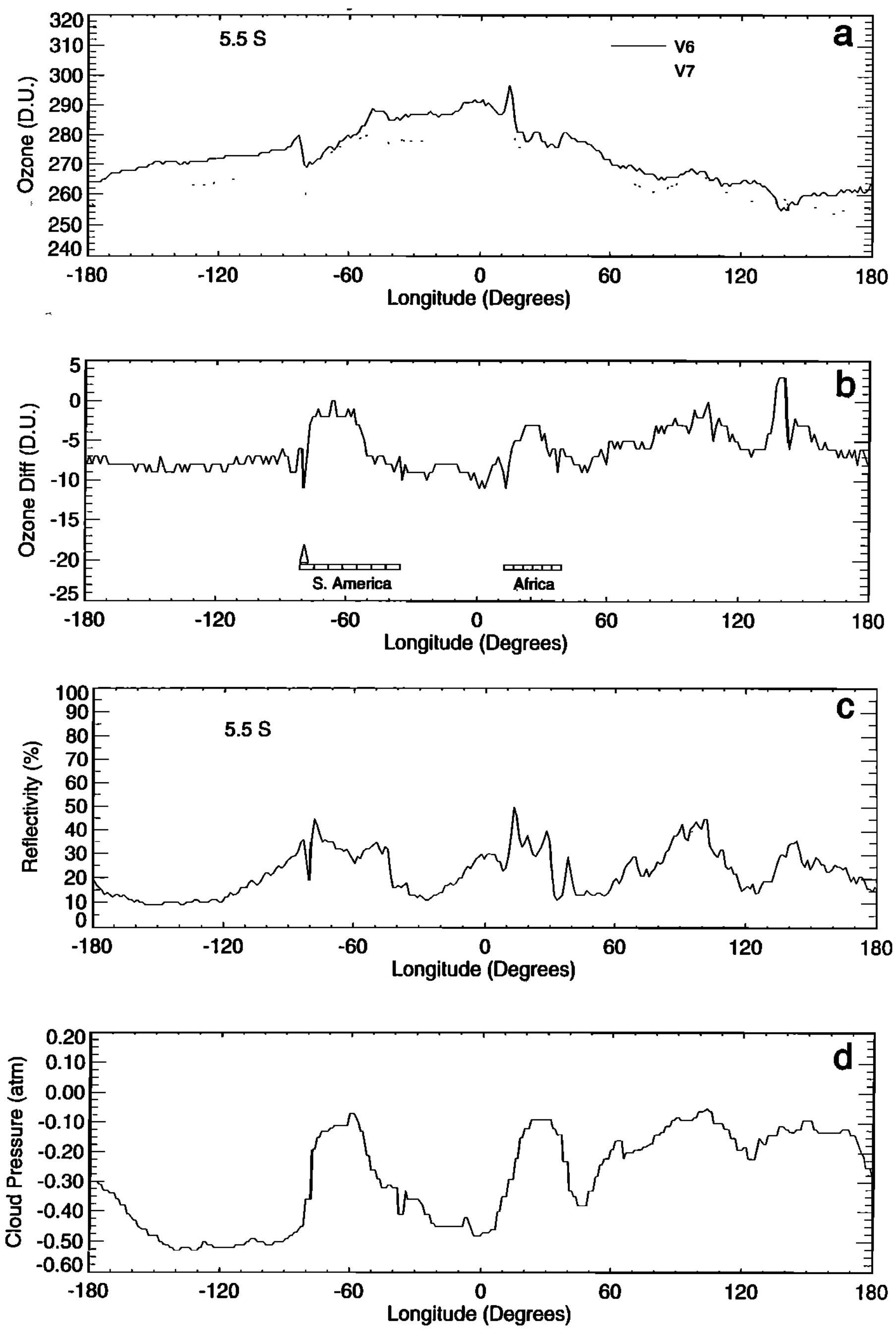

Figure 5. Same as Figure 4, except at 5.5°S.

It is noted that the ozone level dropped over the Andes in both V6 and V7 because, in the TOMS algorithm, the reported ozone amounts are values above the terrain surface, not above sea level. Since the coarse spatial resolution terrain height database used in V6 was replaced by a high resolution database in V7, significant differences in total ozone between V6 and V7 are observed in the regions where terrain height changes sharply.

As shown in Figure 5a and 5b, the impact of the new V7 cloud model on the longitudinal variation of ozone at 5.5°S is similar to the pattern observed at 10.5°S, except for a reduced cloud correction in the neighborhood of the Greenwich longitude due to less cloudiness in the Atlantic Ocean at this latitude in this time period. The amplitude of the zonal wave one in total ozone decreased slightly at this latitude from approximately 26 DU (in V6) to 24 DU (in V7). Once again, the contrast between land and ocean in total ozone amount has been significantly reduced in V7 over both continents. However, as depicted in Figure 5c and 5d, the ozone anomaly observed at around 12°E in V6 data appears to be closely tied to the presence of the marine stratocumulus. The magnitude of this local anomaly decreased in the V7 data, but it is still visible. This indicates that the actual cloud height could be even lower than the multi-year averaged climatology used in V7. Another sharp ozone change at around 140°E was a result of the improved terrain height information around Indonesia in V7.

Generally speaking, the zonal wave one structure in total ozone is still seen in the V7 data, only with a smaller magnitude. The land-ocean contrast associated with the use of the inadequate assumed cloud top height and partial cloud model has been reduced in the V7 data.

6. Summary and Conclusions

It is necessary for researchers to use the TOMS total ozone data judiciously for the studies of tropospheric ozone. *Klenk et al.* [1982] showed that TOMS underestimates the ozone amount below 5 km by as much as 40% for a low reflectivity surface. Therefore TOMS cannot efficiently detect elevated ozone resulting from in situ photochemical production related to biomass burning, until the ozone moves to higher altitudes. In southern hemisphere Africa, strong deep convection occurs frequently in October, transporting ozone generated in the surface layer into the upper troposphere. This may explain why the level of total ozone measured by TOMS in the African biomass burning region was usually much higher in October than in the months of July and August when the biomass burning is already in full scale.

Although the sensitivity to the variations of tropospheric ozone below 5 km is roughly the same in V7 as in V6, the effects of clouds on total ozone have been better taken into account in the new algorithm. The problem of underestimation of total ozone in the partial cloud region, due to the use of a single Lambertian surface, has been improved by using two reflecting surfaces in V7. Also, better cloud height climatology was obtained using ISCCP monthly averaged values. The net effect of these two cloud corrections results in ozone reductions over marine stratus and increases over deep convective cumulus. Thus the land-ocean contrast in total ozone, associated with the inadequate cloud height climatology and partial cloud model in V6, has been reduced in V7 data. However, the land-ocean contrast in total ozone due to the sensitivity of the lower tropospheric ozone to the ground reflectivity still remains in the TOMS V7 data.

The effect of high thin cirrus on the TOMS total ozone measurements could be significant at high solar zenith angles (Z. Ahmad, private communication, 1996). Also, in the Arctic and Antarctic polar region, the presence of polar stratospheric cloud (PSCs) above the ozone peak could result in an underestimation of total ozone [*Torres et al.*, 1992]. No corrections have been made in the TOMS V7 algorithm for these types of clouds.

The impact of the new cloud climatology employed in the V7 algorithm on total ozone is believed to be local and should not significantly alter the long term trend in total ozone (J. R. Herman, private communication, 1996). However, the effect on the TOMS ozone maxima could have important implication on the studies of tropospheric ozone variations in the tropics and their relationship to biomass burning.

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