Distribution of Tropical Tropospheric Ozone Determined by the Scan-Angle Method Applied to TOMS Measurements

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ABSTRACT

This work describes the first method to determine the tropical tropospheric ozone column directly from the Total Ozone Mapping Spectrometer (TOMS) space-borne instrument based on the physical differences in ozone-column detection as a function of its scan-angle geometry. Comparisons to tropical ozonesonde observations suggest the accuracy of these retrievals is $\pm 20\%$. Tropospheric ozone derived from this scan-angle method (SAM) exhibits a broad enhancement over South America, the southern Atlantic Ocean, and western South Africa and a minimum over the central Pacific Ocean in September–October. An ozone enhancement in equatorial North Africa is seen in March, the northern burning season. This ozone abundance is not detected by other retrieval methods. The magnitude of the ozone enhancement south of the equator is greater than the enhancement north of the equator. Abnormally high tropospheric ozone occurs over the western Pacific Ocean during the El Niño season when the ozone amounts are as high as those over Africa.

1. Introduction

Initial studies used a satellite technique for indirectly measuring tropospheric column ozone climatology by subtracting the average stratospheric-column ozone measured by the Stratospheric Aerosol and Gas Experiment (SAGE) from the total-column ozone climatology obtained from the Total Ozone Mapping Spectrometer (TOMS) (Fishman and Brackett 1997; Fishman and Larsen 1987). This technique is called the Tropospheric Ozone Residual (TOR) method. Two later studies used Microwave Limb Sounder observations in conjunction with Halogen Occultation Experiment measurements to determine the stratospheric ozone field in the Tropics (Ziemke et al. 1998; Ziemke et al. 1996). This technique is called the Tropospheric Ozone Residual (TOR) method. Two later studies used Microwave Limb Sounder observations in conjunction with Halogen Occultation Experiment measurements to determine the stratospheric ozone field in the Tropics (Ziemke et al. 1998; Ziemke et al. 1996). Both techniques indicated that the zonal distribution of TOMS total ozone in the Tropics follows a zonal wavenumber 1 pattern with a maximum over the Atlantic and a minimum over the western Pacific Ocean, while the zonal variation of stratospheric ozone appeared to be relatively low. Stratospheric ozone derived from the convective cloud differential (CCD) method (Ziemke and Chandra 1999; Ziemke et al. 1998) and assumed in the modified residual method (Hudson and Thompson 1998) was considered to be zonally invariant. As a result, these studies concluded the zonal distribution of tropospheric ozone is determined primarily by the zonal distribution of total ozone in the Tropics.

However, another study that derived tropospheric ozone from TOMS data suggested that the zonal wave-number 1 pattern in TOMS total ozone is due not only to tropospheric ozone but also to stratospheric ozone (Kim et al. 1996). Because of inaccuracies in the lower-stratospheric SAGE data (Cunnold et al. 2000; Harris et al. 1998) used in the TOR studies, the characteristics of the zonal distribution of stratospheric ozone are still open to question. Therefore, this study presents an in-
dependent method to examine the characteristics of the tropospheric ozone field in the Tropics.

This paper introduces the first method for determining the distribution of tropical tropospheric ozone directly from TOMS data based on the physical differences in ozone-column detection from TOMS as a function of its scan-angle geometry. This paper discusses the distribution of tropospheric ozone resulting from this new method for dry and wet seasons, and for El Niño and non–El Niño years.

2. Method

The TOMS instrument on board a sun-synchronous satellite measures UV radiances backscattered by the underlying atmosphere and earth’s surface or clouds (McPeters et al. 1996). TOMS scans its field of view (FOV) using a mirror perpendicular to the orbital track at 35 sample positions with 3° intervals. Scan positions 1, 18, and 35 correspond to the highest scan position to the right, nadir, and the highest scan position to the left, respectively. Hereafter, scan positions of 1, 2, 3, 33, 34, and 35 are defined as the high scan position, and scan positions of 16, 17, 18, 19, and 20 as the nadir scan position. The measured radiances are a function of total-column ozone, the vertical distribution of that column, solar-zenith angle, satellite-zenith angle (azimuthal angle and scan angle), and the pressure level and reflectivity of the lower boundary. All parameters except total ozone can be determined from satellite position, International Satellite Cloud Climatology Project cloud data, and the radiance measured at the wavelength of 360 nm (380 nm for Nimbus-7 TOMS) where ozone absorption is negligible. The TOMS algorithm then determines total ozone by comparing the measured radiances with calculated radiances at the determined parameters from a radiative transfer code by varying the total amount of ozone, almost entirely in the stratosphere, with an assumed profile shape (McPeters et al. 1996).

Because for clear-sky conditions the contribution of backscattered radiation from the atmosphere dominates over the reflected radiation from earth’s surface, the effective scattering surface for the backscattered UV radiation to the TOMS instrument is at the middle to upper troposphere (Hudson et al. 1995; Klenk et al. 1982). For ozone above the middle to upper troposphere, the TOMS algorithm can retrieve the actual amount of ozone above the effective scattering surface with little error. However, if the assumed ozone profile below the effective scattering surface is different from the actual ozone profile, the retrieval will sense less than the actual deviation because some of the backscattered radiation will not have passed through the middle and lower troposphere. Then, the retrieved total ozone is either over-estimated or underestimated depending on whether the assumed ozone amount below the effective scattering surface is less than or greater than the actual ozone amount.

In order to analyze this error Hudson et al. (1995) introduced a tropospheric ozone retrieval efficiency factor (TORE) relative to stratospheric ozone. Here, TORE is defined as the ratio of the calculated increase in N value by adding 10 Dobson Units (DU) to the troposphere to the increase in N value by adding 10 DU to the lower stratosphere. Here \( N = -100 \log_{10}(A) \), where A is earth’s albedo at a given wavelength. Figure 1 shows the TORE as functions of solar zenith angle and satellite scan angle for fixed azimuth angle and surface conditions.
Fig. 2. Six different tropospheric ozone profiles used to calculate the TOMS sensitivity to varying ozone amounts. The 275-DU ozone profile is the standard tropical profile used by the TOMS algorithm. The 265- and 245-DU ozone profiles are 10 and 30 DU less, respectively, than the standard profile, while the 285 and 305 (A and B) DU profiles are 10 and 30 DU more, respectively, than the standard profile. The limiting case 245-DU profile contains no tropospheric ozone.

Fig. 3. Total retrieved ozone as a function of scan angle using the TOMS algorithm operating on synthetic radiances assuming that the actual tropospheric ozone profiles are the 245, 265, 285, and 305-A profiles shown in Fig. 2.

reflectivity. This figure shows that when the reflectivity is low, such as over clear-sky conditions, the TORE is always less than 1.0. The TORE depends weakly on azimuth angle, but it depends strongly on solar-zenith angle for values greater than 30° and on satellite scan angle because the effective scattering surface depends on the photon pathlength, which is a strong function of these two factors. When the solar-zenith angle is large, fewer photons penetrate into the lower troposphere and scatter back to the satellite. In this case, the backscattered photons contain less information about tropospheric ozone. Furthermore, at all given solar zenith angles, the TORE is smaller at the TOMS high scan positions than at the nadir scan position. How does this efficiency affect total ozone retrieved by the TOMS algorithm? For a difference between actual and assumed ozone profile in the troposphere used by the TOMS algorithm, an error is introduced in retrieved total ozone whose magnitude depends strongly on scan angle and solar-zenith angle. Figure 1 shows that the retrieved total ozone at the nadir position is always closer to truth relative to the ozone at the high scan position because the TORE is higher at nadir than at the high scan position. If the actual tropospheric ozone is less than the TOMS assumption, then the total ozone retrieved at the high scan positions will be greater than the ozone retrieved at the nadir position (i.e., the algorithm will not sense all of the negative deviation from the assumed amount). On the other hand, if the actual tropospheric ozone is greater than the TOMS assumption, then the retrieval at the high scan positions will be less than at the nadir retrieval (i.e., the algorithm will not sense all of the positive deviation from the assumed profile).

In order to estimate the TOMS retrieval error associated with TORE as a function of scan angle, this study uses six tropospheric ozone profiles, as shown in Fig. 2. Synthetic radiances are calculated using the TOMS algorithm operating on synthetic radiances assuming that the actual tropospheric ozone profiles are the 245, 265, 285, and 305-A profiles shown in Fig. 2.
radiative transfer code with the standard ozone profile of 275 DU and also with the other five profiles, two with less tropospheric ozone and three with more. Figure 3 shows total ozone retrieved using the TOMS algorithm operating on four of these synthetic radiances. Retrieved total ozone with a 265-DU ozone profile (10 DU less than the standard 275 DU) is overestimated with a minimum of about 3 DU at nadir and a maximum of about 5 DU at 63°, corresponding to scan positions 1 and 35 (Fig. 3a). The magnitude of this error is affected little by variation in the azimuth angle or by variation in solar-zenith angle between 0° and 30°. The same procedure is used to retrieve total ozone from a 245-DU ozone profile, which has no ozone in the troposphere. As expected, the error is larger with overestimation of about 7 DU at nadir and about 13 DU at the high scan position (Fig. 3b). Figure 3c shows derived total ozone with an ozone profile of 285 DU, which has 10 DU more than the standard tropospheric column ozone in the TOMS algorithm. Analogous to the inverse case with 10 DU less than the standard profile, this case underestimates total ozone by about 2 DU at nadir and about 4 DU at the 63° position. Figure 3d shows derived total ozone with the ozone profile of 305-A DU, which has twice the tropospheric column ozone as the TOMS standard assumption. Retrieved total ozone is underestimated by about 5 DU at nadir and about 11 DU at 63°. The 305-B profile has the same amount of tropospheric as the 305-A profile, but it is distributed with more ozone in the lower troposphere and less in the upper troposphere. The nadir values (not shown) are underestimated by 3 DU and the high-scan position is underestimated by about 13 DU, as expected from the ozone profile dependence of the retrieval efficiency. However, the difference between the nadir-position underestimate and high-scan-position underestimate is approximately the same for both 305-A and 305-B profiles (about 6 DU).

Figure 4 shows the calculated, normalized difference of TORE between that at nadir and high scan positions as a function of altitude. The curves in this figure are the averaging kernels (Rodgers 1990) that result from a numerical simulation of 5-DU δ-function responses. This averaging kernel shows a broad response with its peak centered at 5-km altitude. This response suggests that the difference of retrieved total ozone between nadir and high scan positions can be used to detect the signal from tropospheric ozone.

Table 1 shows the differences between retrieved total ozone averaged over the high scan positions and averaged over the nadir scan positions (hereafter ΔO₃) as a function of solar-zenith angle for the ozone profiles shown in Fig. 2. The values in Table 1 assume that solar-zenith angle is the same between the nadir positions and the high scan positions. However, ΔO₃ will actually slightly increase (or decrease) if the solar-zenith angle at the high scan position is larger than (or smaller than) that at the nadir position. Because the solar-zenith angle at both scan positions averaged over a month is small (about 10°–20°) in March and September, corresponding to equinox conditions, the ΔO₃ values for these months are not significantly affected by this approximation. Because the TORE is a function of both the tropospheric ozone amount and its vertical distribution, ΔO₃ also depends on the tropospheric ozone amount and profile shape. As the difference between the assumed and the actual ozone profile becomes larger, ΔO₃ also becomes larger. However, the total tropospheric deviation from the TOMS climatology is more important than the deviation of the profile shape, as evidenced by the similar values for the 305-A and 305-B profiles in Table 1.

Because the magnitude and sign of ΔO₃ depend on the difference between the actual and the assumed tropo-

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TABLE 1. Retrieved total ozone difference between the nadir positions (16–20) and high scan positions (1–3 and 33–35) at solar-zenith angle from 0° to 30° and at azimuth angle of 135° with the five nonstandard ozone profiles in Fig. 2. These values have not been multiplied by the retrieval efficiency factor, and therefore do not represent true ozone amounts.

<table>
<thead>
<tr>
<th>SZA</th>
<th>ΔO₃ (265) DU</th>
<th>ΔO₃ (245) DU</th>
<th>ΔO₃ (285) DU</th>
<th>ΔO₃ (305-A) DU</th>
<th>ΔO₃ (305-B) DU</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>1.1</td>
<td>1.3</td>
<td>1.5</td>
<td>1.6</td>
<td>2.1</td>
</tr>
<tr>
<td>15°</td>
<td>1.3</td>
<td>1.1</td>
<td>1.5</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>30°</td>
<td>1.1</td>
<td>1.3</td>
<td>1.5</td>
<td>1.6</td>
<td>1.3</td>
</tr>
</tbody>
</table>

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Fig. 4. The difference in tropospheric ozone retrieval efficiency between nadir observation positions and high scan positions normalized to the peak difference at solar zenith angle of 30°. Reflectivity and azimuth angle are 10% and 135°, respectively. These curves are the averaging kernels of the scan-angle technique.
pospheric ozone column, this distribution of tropospheric ozone can be determined directly from the difference between total ozone measurements at the nadir and at the high scan positions. However, this method cannot be directly applicable because the current TOMS instruments do not measure simultaneously at both nadir and high scan positions. A future instrument could be designed to observe both high and nadir scan angles nearly simultaneously, providing a powerful observation technique for tropospheric ozone. One can apply this method to current TOMS data by carefully analyzing the scanning geometry and the satellite orbit. One scan of the Earth Probe TOMS instrument covers about 12° longitude at the equator before December 1997 when the satellite altitude was about 500 km and it covers 18° at the current altitude of about 740 km. The orbital track of this sun-synchronous satellite drifts eastward in longitude by about 5° or 10° day^{-1} depending on the satellite altitude. This drift will cause the FOV at the 18th scan position (nadir) to closely overlap with the FOV at the first scan position over the same location about 1 or 2 days later. However, if stratospheric ozone undergoes significant variation on a 1- or 2-day timescale, the magnitude and sign of ΔO_3 will be significantly influenced by this variation. If the variation is moderate and smooth, the contribution of this variation to monthly averaged ΔO_3 will be filtered out because stratospheric ozone retrieval is not affected by the scan position. Unfortunately, due to a lack of data, no study has examined daily variation of stratospheric column ozone, especially in the Tropics.

One way to assess the validity of this assumption is to examine the variation of ΔO_3. Because the tropospheric ozone climatology is observed to be greater than 0 DU and less than 60 DU, the values of ΔO_3 should be within ±5 DU based on the retrieval efficiency of the synthetic radiances as discussed above. However, if the daily variation of stratospheric ozone is neither moderate nor smooth, one should see the value of ΔO_3 beyond this range. For the calculation of monthly averaged ΔO_3, this study selects 2° lat × 10° long boxes, which are large enough to obtain many TOMS measurements at nadir and at high scan positions, and small enough to remove latitudinal and longitudinal total ozone variation within a selected grid box. We calculate monthly averaged ΔO_3 for boxes containing at least five daily measurements at both nadir and high positions when the time interval between the first and last measurement is longer than 15 days to ensure a reasonable temporal distribution. Version-7 TOMS total ozone suffers from other errors associated with aerosols and sea-glint effects, which also depend on scan angle. The sea-glint effect introduces an error that underestimates total ozone at nadir scan position compared to high scan position (McPeters et al. 1996). To remove these errors, the pseudo-version-7.5 TOMS algorithm [courtesy of the National Aeronautics and Space Administration (NASA) Ozone Processing Team] is applied to level-2 TOMS data with reflectivities less than 20% corresponding roughly to clear-sky conditions. The data in Fig. 5 show that the absolute value of ΔO_3 increases as latitude increases. Because daily stratospheric ozone variation is larger as latitude increases, the latitudinal dependence of ΔO_3 comes from the contribution of dynamical activity in the stratosphere that depends on latitude and season. The values of ΔO_3, corrected for aerosol and sea-glint effects (blue points in Fig. 5), average ~2 DU for latitude of ±20°. Therefore, we limit this method of retrieving tropospheric ozone distribution to the ±20° lat band. The corrections for aerosol and sea-glint effects increase the negative values of ΔO_3 by ~2 DU between ±20° latitude, as seen in Fig. 5 (uncorrected values in red, corrected values in blue). Even after these corrections, the minimum ΔO_3 value (~6 DU) is somewhat lower than the authors’ theoretical prediction of ~5 DU. Note that all values less than ~5 DU occur over oceans, and no values greater that ~5 DU occur between ±20° latitude. These results suggest that some residual sea-glint effect remains in the corrected data. Therefore, the sea-glint problem may cause significant errors in derived tropospheric ozone, but the effect is localized. The results shown in Fig. 1 indicate that the physics controlling the TOMS sensitivity to tropospheric ozone does not vary much for solar zenith angles less than 30°. Therefore, to ensure that the solar zenith angle remains less than 30° during 1-month averaging periods, the authors further restrict this study to ±15° latitude.

3. Results

The ΔO_3 values in Table 1 are related to the true changes in tropospheric ozone through the TORE, which itself is a function of viewing geometry and tropospheric ozone amount. The scaling factor can be determined directly from the ΔO_3 values resulting from specified deviations from the TOMS tropospheric climatology. The relationship is as follows: true ozone amount – TOMS climatology = efficiency scale factor × ΔO_3. The magnitude of that scale factor varies from approximately 5 to 8 and averages 6.7 for the ozone
profiles reported here recognizing that the TOMS tropical tropospheric ozone climatology is about 32 DU. Because this study uses the average factor for all cases, some variance remains in the tropospheric ozone results due to the variation in this factor over the conditions studied. Furthermore, some of the scaled tropospheric ozone column is less than 5 DU, and very rarely it is negative. The plates below identify these few results as omitted values.

In order to validate the tropospheric ozone column derived from the scan-angle method (hereafter SAM), we use Southern Hemisphere Additional Ozonesondes (SHADOZ) measurements at Ascension Island (8°S, 14°W), San Cristobal (1°S, 90°W), Nairobi (1°S, 37°E),

Table 2. Rms difference at six stations and an average rms difference [ozonesonde − (SAM)/ozonesonde]. The values in parentheses are the rms differences derived at satellite locations east of the stations given in Fig. 6. The average rms difference across all six stations is 20%. When data at satellite locations east of Ascension and San Cristobal are used, the average rms difference is 17%.

<table>
<thead>
<tr>
<th>Station</th>
<th>Ascension</th>
<th>San Cristobal</th>
<th>Natal</th>
<th>Nairobi</th>
<th>Java</th>
<th>Samoa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rms difference (%)</td>
<td>18 (19)</td>
<td>35 (17)</td>
<td>26</td>
<td>16</td>
<td>11</td>
<td>18</td>
</tr>
</tbody>
</table>
Figure 7 shows the distribution of tropical tropospheric ozone in September 1996 derived by this scan-angle technique. The distribution in this particular year is somewhat different from the climatological TOR results of Fishman and Brackett (1997) and the September 1997 CCD results of Ziemke et al. (1998), both of which show a broad maximum extending from South America over the southern Atlantic Ocean to the eastern coast of southern Africa. The scan-angle results in Fig. 7a are similar in extent and maximum value (~50 DU), except for a noticeable minimum between the South American maximum and the African maximum, which is also seen in a study by Thompson and Hudson (1999), but with somewhat higher values. This distribution is consistent with the finding of significant spatial gradients influencing the differences between SAM areal averages and sounding point measurements. Except for noticeable excursions in January and April, the SAM retrievals over Natal follow the ozone-sounding measurements at Natal for the year of 1999 showing a broad maximum in austral spring and minimum in austral autumn. The sounding and SAM measurements at Nairobi do not show any significant seasonality, although a small difference between two measurements occurs. Exceptionally good agreement between two measurements is observed at Java and Samoa. Table 2 shows an rms difference that gives a quantitative measure of the accuracy of the SAM measurements relative to ozone-sounding measurements at these six stations. Overall rms difference is about 20%. We conclude therefore that SAM is a reasonable method for determining tropical tropospheric ozone column.

Ozone-sounding measurements over Ascension Island show a maximum in the September–November period resulting from the well-known enhancement due to biomass burning over southern Africa near this period. The global fire count data from the ATSR World Fire Atlas (available online at http://shark1.esrin.esa.int/ionia/FIRE/AF/ATSR/) shows that strong biomass burning generally occurs a month or two earlier, in August–September period, consistent with the seasonality of the SAM measurements. This discrepancy between the point measurements and the areal average satellite measurements results from the significant spatial gradients in tropospheric ozone seen below. The SAM ozone values are generally less than or equal to the sounding measurements at Ascension Island and San Cristobal. However, the SAM measurements located directly east of Ascension Island (5°–11°S, 0°–15°E) and east of San Cristobal (4°S–2°N, 70°–85°W) (open circles in Fig. 6), which are closer to the tropospheric ozone source regions, reduce or even reverse the difference. The measurements show remarkably good agreement with ozone-sounding measurements at San Cristobal consistent with the finding of significant spatial gradients influencing the differences between SAM areal averages and sounding point measurements. Except for noticeable excursions in January and April, the SAM retrievals over Natal follow the ozone-sounding measurements at Natal for the year of 1999 showing a broad maximum in austral spring and minimum in austral autumn. The sounding and SAM measurements at Nairobi do not show any significant seasonality, although a small difference between two measurements occurs. Exceptionally good agreement between two measurements is observed at Java and Samoa. Table 2 shows an rms difference that gives a quantitative measure of the accuracy of the SAM measurements relative to ozone-sounding measurements at these six stations. Overall rms difference is about 20%. We conclude therefore that SAM is a reasonable method for determining tropical tropospheric ozone column.
with the distribution of biomass burning activities and lidar measurements that have observed tropospheric column ozone of 45–55 DU over the African continent (Browell et al. 1996). These distributions are consistent with the distribution of biomass-burning activity and atmospheric circulation in September, which corresponds to the dry season south of the equator. The actual value in the western southern Atlantic Ocean cannot be distinguished independently. The lowest tropospheric ozone is observed over the central Pacific Ocean with values ≤10 DU. Elevated ozone over the Indochina peninsula and enhanced ozone over northern Australia agree well with the CCD results. The tropospheric ozone amounts over the Indian Ocean are somewhat higher than the amounts over the Pacific Ocean. Locations with values less than 5 DU, which appear to be related to the sea-glint effect, are all located over the ocean and localized.

Figure 7b shows the distribution in September 1997, corresponding to an El Niño season. Comparison between September 1996 and September 1997 shows that the ozone amounts are significantly reduced from South America to the Atlantic and somewhat reduced over the African continent. A significant decrease of ozone occurs in September 1997 north of equatorial South America compared with measurements in September 1996. This variation is likely a result of the movement of convective activity regions associated with El Niño events (e.g., Chandra et al. 1998). The tropospheric column ozone over the eastern Pacific Ocean is significantly reduced as well. A noticeable increase of very high column ozone occurs over the intense biomass burning in New Guinea. It is interesting that the variation of tropospheric ozone over the eastern Pacific Ocean appears to be positively correlated with the variation of ozone amounts from South America, across the Atlantic, to the African continent (cf. Figs. 7a,b). This coherence suggests that a significant amount of tropospheric ozone has been transported from South America to the eastern Pacific Ocean. This result is consistent with the observation of elevated tropospheric ozone in the lower troposphere over the western coast of South America (Jiang and Yung 1996; Kim and Newchurch 1996).

Over the period of a month, the solar-zenith angle during TOMS observations changes at a given latitude. In March and September, the sun’s location is near the equator, resulting in insignificant effects from the solar-zenith angle variation over a month. However, in October, the sun is south of the equator, resulting in a noticeable difference between the solar-zenith angle north of the equator (~25°) compared to the lower solar-zenith angles south of the equator (~10°). This difference results in overestimating ozone north of the equator relative to that in the south by about 2 or 3 DU. Zonal variation, however, does not occur because the solar-zenith angle is constant at a given latitude.

A dramatic increase in ozone appears in the Tropics over Malaysia, Indonesia, Borneo, and New Guinea in October 1997, as seen in Fig. 7c. This increase is consistent with observations that show a significant increase of tropospheric column ozone from 20–40 DU in October 1994 to 20–55 DU in October 1997, corresponding to an El Niño year (Fujiwara et al. 1999; Nakajima et al. 1999; Sawa et al. 1999). In a 1999 study, Fujiwara et al. suggested that forest fires trigger enhancement of the photochemical production rate of tropospheric ozone due to the precursors emitted from the fires. Ozone over the south Atlantic results from less African continental ozone outflow.

The distribution of enhanced ozone over northern equatorial Africa in March 1997 (Fig. 7d) is well correlated with the dry season north of the equator and with the wet season over the south, strongly influencing biomass-burning activity. The enhanced ozone band migrates from the south of equatorial Africa to the north from September–October to March (Figs. 7b, c, and d). This movement agrees well with shifting from the southern biomass-burning season corresponding to the July–October period over the south to the northern burning season corresponding to the December–March period over the north (Nganga et al. 1996). Very clean air is observed south of equatorial South America. This African distribution is different from the CCD results reported by Ziemke et al. (available online at http://hyperion.gsfc.nasa.gov/Data_services/cloud_slice/gif/1997asi.gif and at the Thompson and Hudson Web site http://metosrv2.umd.edu/~tropo). Because the CCD and modified residual methods rely heavily on the total ozone distribution, which as seen in Fig. 7e, maximizes south of the equator in Africa, those methods do not retrieve the enhanced tropospheric ozone in northern equatorial Africa seen by SAM in Fig. 7d. By inspecting the gradients in total ozone, which are very similar both before (not shown) and after correction for aerosols and sea glint (seen in Fig. 7e), one can determine that the tropospheric information is not directly evident in the total-column measurements. A powerful strength of the SAM is the fact that its results are independent of the total ozone-column amounts. As a result, this method is able to derive the actual tropospheric enhancement in northern equatorial Africa in March 1997.

The amount of ozone over India and Southeast Asia as well as over Borneo and New Guinea increases as the season changes from September to March. The regions with low ozone extend from the central Pacific to the eastern Pacific Ocean, where the scan-angle values are comparable to the values of ~10 DU measured during the Central Equatorial Pacific Experiment (CEPEX) campaign in March 1993. The amount of ozone south of the equatorial Indian Ocean is also lower in March than in September.
The tropospheric ozone values averaged over the entire latitude and longitude region in Figs. 7a–d are 26 DU for September 1996, 22 DU for September 1997, 23 DU for October 1997, and 20 DU for March 1997. The amount of ozone for the dry season south of the equator is greater than for the dry season north of the equator. The amount of ozone is greater in September 1996, a non-El Niño year, compared to March, September, and October 1997, during an El Niño year. These differences suggest that even though tropospheric ozone is significantly increased over the western Pacific regions, overall, tropical ozone is significantly decreased due to the decrease of ozone production over the South American and African regions during an El Niño year.

4. Conclusions and discussion

Because TOMS retrieves tropospheric ozone with less than perfect efficiency, it will overestimate clear-sky tropospheric ozone amounts in areas with particularly low ozone and underestimate amounts in areas with high ozone. This study takes advantage of this physical retrieval efficiency aspect to obtain tropospheric ozone from TOMS column measurements. The results of this first method to directly determine the tropospheric ozone column from the TOMS instrument are consistent with the morphology of biomass-influenced ozone production following the change from the wet to the dry season in Africa and also consistent with rainfall changes associated with El Niño. These results agree, in general, with previous indirect residual methods over the southern Tropics during the burning season there, but present significantly higher values over the northern Tropics in Africa more consistent with the burning season in that region. Minimum values agree in general with the location in the western Pacific but indicate somewhat lower magnitudes consistent with ozonesonde measurements. Comparisons to six tropical sonde stations indicate that the scan-angle method retrieves tropospheric ozone to an accuracy of ~20%. These data and results are available at http://vortex.nsstc.uah.edu/atmchem. An instrument similar to TOMS that scans both nadir and high scan angles nearly simultaneously could be designed to provide a powerful technique for observing tropospheric ozone globally.

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