Zonal wave-1 structure in TOMS tropical stratospheric ozone

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Abstract. Using measurements of the stratospheric ozone column observed by NIMBUS-7 TOMS above high-altitude clouds observed by the collocated Temperature Humidity InfraRed (THIR) sensor, we analyze the stratospheric ozone column zonal wave structure in the tropics. A zonal wave-1 structure occurs roughly longitudinally coincident with the total-ozone wave with its peak near the prime meridian and trough near the central Pacific Ocean. The monthly average stratospheric ozone exhibits a wave-1 pattern with amplitude of ~4 DU and a maximum peak-to-trough difference of ~13 DU in the 1979-1984 time period. This stratospheric amplitude represents about one half of the ~7 DU amplitude in total column ozone. This partitioning of some of the total ozone column wave into the stratosphere affects the tropospheric ozone component of derivations that assume stratospheric zonal invariance.

Introduction

Tropical total ozone columns observed from TOMS typically exhibit a zonal wave-one feature with the peak near the Atlantic Ocean and the minimum in the Pacific Ocean. Fishman and Larsen [1987] and Shiotani and Hasebe [1994] analyzed the Stratospheric Aerosol and Gas Experiment (SAGE) stratospheric ozone column to understand the characteristics of the zonal structure and found that generally the zonal stratospheric ozone is relatively invariant. Therefore, they concluded that tropospheric ozone is responsible for the TOMS zonal structure. HALOE data in conjunction with MLS data also showed the same zonal invariance in stratospheric ozone [Ziemke et al., 1998]. Hudson and Thompson [1998] and Thompson and Hudson [1999] also assume a zonally invariant stratospheric ozone field. However, Kim et al. [1996] first suggested that both tropospheric and stratospheric ozone column variations are responsible for the zonal structure of TOMS total ozone. Using TOMS total ozone column measurements, Ziemke and Stanford [1994] presented evidence of eastward-propagating zonal waves 1 and 2 with periods of ~5-15 days and amplitudes ~3-5 Dobson Units. They suggested the primary source of this perturbation was in the lower-to-middle stratosphere. Other works (e.g., Stanford and Ziemke [1993], Randel [1990] and references therein) have identified Rossby, Gravity, and Kelvin waves in the equatorial stratosphere. In this paper, we demonstrate that the monthly average stratospheric ozone structure also includes a standing wave with an amplitude of ~4 DU in a wave-1 feature.

Accurate tropical tropospheric ozone columns are useful for addressing climatology studies [Logan, 1999], process studies [Thompson et al., 1996; Ziemke et al., 1996], and trend studies [Kim and Newchurch, 1996, 1998; Logan et al., 1999].

Stratospheric Ozone from TOMS and THIR

The TOMS algorithm derives the total ozone column above Earth’s surface in clear areas or above the cloud top in cloudy areas. The reported TOMS total ozone at cloudy points includes the ozone column above the cloud top (derived directly from the TOMS measurements) and also the ozone column below the clouds (estimated from tropospheric ozone column climatology). In the presence of high-altitude, highly reflecting clouds, the measured column will represent the stratospheric ozone column. Ozone retrieval errors due to sun glint [McPeters et al., 1996] and tropospheric aerosols [Torres and Bhartia, 1999] were corrected using the Dave reflectivity code [C. G. Wellemeyer, Personal communication, 1999]. By using the infrared temperatures measured by the Temperature Humidity InfraRed (THIR) sensor, collocated with the TOMS on NIMBUS-7, and the 380-nanometer reflectivity measured by TOMS, we identify those measurements of the stratospheric ozone column. Our study focuses on the Inter-Tropical Convergence Zone (ITCZ) between 0° and 10°N, an area with a significant number of convective clouds.

Currently archived THIR data often report cloud-top pressures between 60-80 mb and sometimes lower. These pressures correspond to altitudes significantly higher than the typical tropical tropopause pressure of ~100 mb. Comparing these values to the only available two months of revisited THIR pressures reveals that the archived values for pressures less than 200 mb are always too low as seen in Figure 1. In order to use the six years of archived THIR data (1979-1984), we scaled the archived values according to the relationship shown in Figure 1. The resulting high-altitude clouds are then identified as those with reflectivity greater than 85% and scaled THIR cloud-top pressures be-
tween 145-165 mb. For the purposes of determining the wave-1 structure in the stratosphere, the critical aspects are 1) the cloud-top heights are near the tropopause, and 2) the measurements are consistent as a function of longitude. The first criterion is satisfied by virtue of the fact that we are using only the highest altitude clouds (we quantify the uncertainty in this criterion below) and the second is satisfied by virtue of the fact that the instrument has no intrinsic longitudinal dependence.

Figure 2(a) shows the derived stratospheric ozone column relative to its zonal median value between 0~10°N averaged over 1979-1984 (excluding April 1982 to March 1983, the year following the El Chichon eruption). The standard deviation at each location over the 6-year period appears in Figure 2(b). These standard deviations vary from 2 to 5 and average 4 DU. The amplitudes resulting from a sine fit to the northern region zonal values in Figure 2a and one half of the absolute peak-to-trough differences appear in Table 1. Although the standard deviations are relatively uniformly distributed, inspection of the latitudinal distribution of the cloudy data reveals that during the northern dry season (December to March) most points are near the equator and few points occur north of 5°N. Therefore, the 0-10°N average is disproportionately influenced by more equatorial values. During the wet season, however, the data points are much more uniformly distributed.

In northern equatorial regions, the stratospheric ozone column exhibits a wave-1 structure with a peak near the prime meridian and a trough in the central Pacific Ocean. The amplitude of this wave varies seasonally from 2 to 6 DU as characterized by the sine fit in Table 1, or 4 to 8 in absolute magnitude seen in Figure 2a. Months from April to September also show higher-number (2 and 3) wave features. These features are roughly comparable to their associated standard deviations, except for the January-March wave, which is significantly larger than its standard deviation. Also, the coherent structure of the six-year average wave structure lends credence to the presence of this wave.

Because our upper pressure limit for cloud tops is actually below the tropopause, one could question the influence of ozone between 165 mb and the tropopause on our stratospheric ozone columns. Figure 3 shows the zonal structure of the ozone column between 100~165mb derived from SHADOZ ozonesonde observations over 1998-2000 [Thompson and Witte, 1999]. Because the SHADOZ ozonesonde observations display site-to-site offsets with respect to collocated TOMS total ozone, we scaled the SHADOZ total
Table 1. The monthly average zonal amplitude from a sine fit and from 1/2 peak-to-trough differences of stratospheric ozone derived from TOMS between 0°-10° N latitude from 1979 to 1984 excluding one year following the El Chichon eruption in April, 1982.

<table>
<thead>
<tr>
<th>Month</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>mean</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Amp (DU)</em></td>
<td>4.8</td>
<td>5.0</td>
<td>6.3</td>
<td>5.0</td>
<td>2.4</td>
<td>3.2</td>
<td>4.8</td>
<td>4.1</td>
<td>3.3</td>
<td>4.3</td>
<td>4.0</td>
<td>3.7</td>
<td>4.2</td>
</tr>
<tr>
<td>1/2 PTT (DU)</td>
<td>4.7</td>
<td>4.9</td>
<td>6.2</td>
<td>5.0</td>
<td>2.4</td>
<td>3.2</td>
<td>4.5</td>
<td>4.0</td>
<td>3.3</td>
<td>4.3</td>
<td>3.9</td>
<td>3.7</td>
<td>4.1</td>
</tr>
</tbody>
</table>

*One half the peak-to-trough difference.

ozone to ensure site-to-site consistency with TOMS total ozone. We can see the sondes measurements show a weak zonal wave structure with amplitudes less than 1 DU in all seasons, this 1 DU amplitude may be included in the 4 DU amplitude of stratospheric ozone wave-1. The cloud-slicing method [Chandra, Personal communication, 2000] also shows that the upper-tropospheric ozone column between 100~165 mb is almost zonal flat, so it will not significantly influence the zonal structure of stratospheric ozone column derived here.

The wave-1 structure in total ozone is evident in Figure 2(c), with amplitudes from 5 to 9 DU. The total column shows little variation in the longitude of the peak and little evidence of higher number wave features. Because the amplitude of the stratospheric wave in the largest fraction of the total amplitude in January-March (Boreal winter-spring planetary wave activity), during these months the neglect of the partitioning of a significant fraction of the total amplitude into the stratosphere will significantly affect the derived tropospheric values. The 6-year average tropospheric ozone resulting from the difference between total ozone columns and stratospheric columns appears in Figure 2(d). In most seasons, the peak of this distribution occurs in western equatorial Africa (recall this analysis occurs between 0-10 degrees north latitude).

Because the maximum amplitude in stratospheric wave structure occurs near March and the maximum in total ozone amplitude occurs in September, we display these two months for both southern (0°-10°S) and northern (0°-10°N) equatorial regions relative to their respective medians averaged from 1979-1984 (excluding April 1982 to March 1983, the year following the El Chichon eruption) in Figure 4. In March, for both the southern and northern regions, we see that most of the amplitude in the total column is accounted for by the stratospheric variation. In September, roughly half of the total amplitude occurs in the stratosphere and half in the troposphere in the northern region. Although the frequency of high-altitude clouds in the southern region is inadequate to determine stratospheric ozone for the dry season (June to October), the available data present no evidence contrary to the results from the northern region.

Discussion

MLS and HALOE measurements suggest that the ozone wave in total-column ozone is attributed entirely to tropospheric ozone [Ziemke et al., 1998]. Shiotani and Hasebe [1994] analyzed the Stratospheric Aerosol and Gas Experiment data and showed that the tropical stratospheric ozone wave can be neglected. However, SAGE profiles contain at least 10% uncertainty, increasing in the lower stratosphere, and MLS contains ≥40% uncertain below 68 mb [Cunnold et al., 2000]. The limb-scanning satellite observations also have poor sampling in the tropics, a few days per month. There-
fore, if the column variance is controlled by the lower part of the stratosphere, SAGE observations or MLS and HALOE observations will be unable to detect a stratospheric ozone wave feature with amplitude of 4–5 DU as we deduce in this paper using TOMS with accuracy of ozone measured above earth surface or cloud top of 2–3% [McPeters et al., 1996], much higher than that of SAGE or MLS for the integrated ozone column above clouds.

The presence of a significant stratospheric wave structure in column ozone will affect the magnitude of tropospheric ozone derived from residual techniques that assume a zonally invariant stratosphere. The effect will be to reduce the magnitude of the derived tropospheric column in the longitudes of the peak and increase ozone in the area of the trough of the stratospheric wave. However, due to less than perfect retrieval efficiency, TOMS measurements of tropospheric ozone are underestimated in areas where the true tropospheric ozone is higher than the climatology and overestimated in areas where the ozone is lower than the climatology [Kim et al., 1996]. The climatology in the area of the peak is roughly correct, but the values in the Pacific trough region are typically too high. Therefore in the Pacific, the effects of the stratospheric-wave trough and the detection efficiency considerations are of opposite sign and similar magnitude. In the Atlantic peak region, the wave effect is significant, but the efficiency consideration is small because the climatology is nearly correct. The result is that the zonal amplitude of the tropospheric wave is reduced by an amount somewhat less than the magnitude of the stratospheric-wave. The phase is little affected.

Conclusion

Analysis of TOMS ozone observations over high-altitude clouds in the tropics of stratospheric ozone indicate that the tropical monthly average stratospheric ozone field is not zonally invariant. It exhibits, on average, a wave-one amplitude of 4 DU. This characteristic peak-to-trough difference of 8 DU exceeds 12 DU in the extreme. Although the amplitude and spatial distribution of this wave structure exhibits significant seasonal variance, the longitude of the wave peak is generally near the prime meridian, roughly coincident with the peak of the total-ozone zonal wave. Accounting for the fraction of the total-ozone zonal amplitude that is in the stratosphere will reduce by ~8 DU the tropospheric component over the Atlantic Ocean relative to Pacific-Ocean values derived from differences in TOMS measurements over clear and high-altitude cloud regions and from methods that assume stratospheric zonal invariance in the ozone field.

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References


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