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Estimates of Tropospheric Ozone from Nimbus 7 LIMS and TOMS Datasets

by

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Abstract. This work is a diagnostic study of distributions of tropical tropospheric column ozone (TRCO) based on subtracting Limb Infrared Monitor of the Stratosphere (LIMS) Version 6 (V6) Level 3 stratospheric column ozone (SCO) values from Total Ozone Mapping Spectrometer (TOMS) total ozone for several selected days of 1978-1979. The focus of this study is the low latitudes, where the tropopause is near 100 hPa and zonal wave activity is weak. TRCO exhibits a zonal wave-1 feature in the southern tropics with maximum values near 0° longitude during November 1978. Its zonal variation is 70 to 30 Dobson units (DU) and agrees with that of other similar analysis studies. V6 estimates of SCO and calculated TRCO are less reliable in March and May 1979 because those data are affected by temperature biases of order -1.0 to -2.0 K at 30 and 50 hPa; retrieved ozone at those levels may be too large by ~20% as a result. The LIMS Level 3 sequential estimation algorithm provides smoothed zonal wave ozone amplitudes and reduced zonal variations of SCO. The corresponding calculated TRCO amplitudes are enhanced and not quantitative in those instances. The findings herein should be helpful to others, as they analyze infrared limb measurements of ozone and subtract their stratospheric column amounts from coincident total ozone to obtain accurate zonal variations of tropospheric ozone.

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1 Introduction and Background

There have been numerous studies on observing and understanding the changes in tropospheric ozone both regionally and globally, as described recently in Gaudel et al. (2024). Those investigators use both satellite and balloon data to arrive at their findings. One possible opportunity to obtain early estimates of tropospheric ozone from satellite datasets comes from both the Limb Infrared Monitor of the Stratosphere (LIMS) and the Total Ozone Mapping Spectrometer (TOMS) instruments that operated from onboard the Nimbus 7 satellite. LIMS provided ozone profiles from the middle mesosphere to near the tropopause from October 25, 1978, to May 28, 1979, both day and night and with a duty cycle of about 6 days on followed by one day off. TOMS made measurements of ultraviolet (uv) molecular scattered and reflected radiation from the ground or cloud tops during daylight. Total ozone was determined from the TOMS measurements via the method of differential absorption at its uv wavelengths during daylight. TOMS provides good data coverage, although it also lacks observations for one orbit many days. This study reports on estimates of tropospheric column ozone (TRCO) obtained by subtracting LIMS stratospheric column ozone (SCO) from TOMS ozone. Initial estimates of layer ozone based on the LIMS Version 5 (V5), SBUV Version 5 data, and sonde profiles are noted, followed by earlier and current estimates of TRCO based on the archived LIMS Version 6 (V6) and TOMS Version 8 datasets.

Remsberg et al. (1984, their Fig. 15) compared V5 stratospheric ozone with correlative ozone measurements obtained by several independent methods, and they judged the V5 ozone as reasonably accurate, except at and below the 50 or 70-hPa level where ozone was biased high. Their calculations involved integrating a V5 profile from the lower mesosphere to the 50 or 70-hPa level and then adding its sum to column ozone from the ground to those same levels from coincident Brewer-Mast (BM) and Electrochemical Concentration Cell (ECC) sonde profiles. They reported that total ozone obtained in that way agreed with Dobson station measurements to within the combined uncertainties of the respective ozone measuring techniques.

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Remsberg and Wu (1989) compared LIMS V5 ozone with concurrent ozone distributions from the Solar Backscatter Ultraviolet (SBUV) and Stratospheric Aerosol and Gas Experiment (SAGE) satellite instruments. They obtained V5 stratospheric zonal mean ozone in terms of Umkehr layer amounts following a mapping of the V5 profiles. In general, their intercomparison results were also within the combined errors of the several techniques, except again in the lowermost stratosphere where the V5 ozone values were biased high. It was unclear at that time what were the cause(s) of bias(es) in V5 ozone in the lowermost stratosphere, although it was clear that there would be significant biases for calculated TRCO, as a result.

Fishman and Larsen (1987) made separate determinations of the zonal variations of TRCO by integrating Stratospheric Aerosol and Gas Experiment (SAGE) ozone profiles from 1 to 100 hPa and subtracting their SCO values from coincident TOMS measurements. They reported that the SAGE ozone profiles were accurate throughout the stratosphere for determining SCO and in turn the TRCO. In a more comprehensive study, Fishman et al. (1990) analyzed ozone profiles from the follow-on SAGE II instrument, and they found seasonal changes of TRCO and longitudinal excesses of TRCO at tropical latitudes. They reported indications of the production of ozone downwind of biomass burning regions. Ziemke et al. (1998) developed a convective cloud differential (CCD) algorithm for the determination of tropical TRCO directly from the TOMS data and over a span of many more years. They confirmed the initial conclusions of Fishman et al. (1990) in terms of longitudinal and seasonal increases in tropospheric ozone related to instances of biomass burning.

Remsberg et al. (2007) reported on a LIMS V6 Level 2 (or profile) ozone dataset using improved algorithms for the registration of the LIMS radiance profiles and improved line parameters for retrievals of both temperature and ozone. Based on those findings, Remsberg et al. (2013) added the V6 profiles to an assimilation model and found reasonable agreement for total ozone from the model analysis versus TOMS V8 ozone. The present study considers the use of the LIMS Level 3 (map) product for calculations of SCO and then subtracts that amount from TOMS data to obtain TRCO. Section 2 reviews the quality of the LIMS V6 ozone in the lower stratosphere. Section 3 reports on monthly zonal mean TRCO values based on LIMS and TOMS data. Section

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4 then shows the distributions of TRCO with longitude and latitude for several representative days of the LIMS V6 and TOMS data in November 1978 and in March and May 1979. Section 5 reports that daily V6 estimates of TRCO for November compare well with that of Fishman et al. (1990) and of Ziemke et al. (2006), specifically regarding its elevated ozone downwind of biomass burning regions in West Africa. Section 6 summarizes the findings and the details that are in the *Supplement*.

2 Quality of LIMS V6 Ozone in the Lower Stratosphere

Remsberg et al. (2007) compared V6 Level 2 zonal average ozone profiles with those from SBUV Version 8 (V8) for three specific days—8 November 1978, 15 March 1979, and 6 May 1979 (see their Figure 8). The V6 profiles have an effective vertical resolution of 3.7 km, not unlike those of SBUV. Figure 1 shows the results for V6 minus SBUV data of McPeters et al. (1984). There is a pattern to the differences in the upper stratosphere that is related to how well each measurement technique resolves the effects of the semi-annual oscillation (SAO) in ozone. V6 ozone is slightly smaller than SBUV ozone at tropical latitudes for levels from 10 to 50 hPa, below which there are only a limited number of V6 profiles, due to a screening for effects of emission/extinction from thin cirrus clouds. On the other hand, V6 ozone is larger than SBUV from 15°S to 40°S latitude all three months and from 15°N to 30°N in March and May between the 30 and 70-hPa levels.

Even though Remsberg et al. (2007) concluded that V6 ozone was improved over that of V5, estimates of V6 accuracy (from their Table 1) are still no better than 20 to 30% in the lowermost stratosphere. LIMS ozone has a large response at those levels to uncertainties in the associated, retrieved V6 temperatures (±1.2 K); a temperature bias of -1.2 K leads to an ozone bias of order +20% at 50 and 100 hPa. There are also potential ozone errors of 6% and 15% at 50 and 100 hPa, respectively, due to uncertainties in the V6 forward model for ozone.

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The archived V6 ozone profiles include a screening of first-order cloud contamination effects below the 45-hPa level and equatorward of ±30° latitude, as based on the changes with altitude for the retrieved ozone mixing ratio profile. That "V6 cloud detection" algorithm checks about the vertical gradient of ozone and assigns a cloud index, when ozone mixing ratio increases with decreasing altitude beyond a threshold amount (see Remsberg et al., 2007). The same detection algorithm was also applied at and below the 100-hPa level at higher latitudes, where there may also be false indications of cloud effects due to a vertical layering of the ozone profiles near the tropopause. Yet, one bias that was not characterized for V6 ozone is the likelihood of residual contamination effects in the tropics to subtropics from thin or subvisible cirrus just above the 100-hPa level or near the tropopause. An example of the presence of cirrus is in the *Supplement*. Climatological ozone values have been substituted at 68 hPa (±12° latitude) and at 100 hPa (±18° latitude) for calculations of SCO in the current study to avoid residual cirrus effects.

To check whether temperature errors are a significant source of bias for SCO, the V6 Level 2 temperature profiles are compared with those from MERRA in Figure 2 for one day, 26 January 1979, and for the latitude band of 20°S to 20°N. Note that their zonal standard deviations about the respective zonal means agree (top right), an indication that both data sets are equally responsive to zonal temperature waves. Their zonal averages (bottom left) show that the V6 temperatures have net positive biases from the middle stratosphere and into the mesosphere, or in a region where temperature tides are present and where the MERRA temperatures are not highly accurate due to the low vertical resolution of its operational stratospheric sounder unit (SSU) radiance data. Even so, a V6 temperature bias at those upper altitudes leads to only small errors in V6 ozone (and SCO). However, there are negative differences of nearly -1 K at about 30 and 50 hPa or where ozone partial pressure makes large contributions to SCO. At middle latitudes there are negative temperature differences for this day in the SH but not the NH (see details in the *Supplement*). There are rather large positive differences in Fig. 2 near the tropical tropopause, which leads to retrieved V6 ozone of near zero values at 68 and 100 hPa. But this region is also where the current study substitutes climatological ozone for calculations of tropical SCO to avoid effects of cirrus contamination.

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Temperature bias impacts retrievals of LIMS ozone in two ways. It affects (1) the registration of ozone radiance with pressure or the conversion of the observed radiance versus altitude onto a pressure-altitude grid prior to a retrieval of V6 ozone, and (2) the determination of ozone mixing ratios from the radiances, where the effect of temperature is accounted for via a forward calculation of Blackbody radiance in the ozone channel. Ozone radiance versus altitude profiles were registered in terms of radiance versus pressure both below and above the pressure versus relative altitude reference level of 20 hPa, and the small, net effect of (1) reflects the presence of any temperature biases. On the other hand, the relation of temperature to radiance from (2) is non-linear, such that where temperatures are biased cold (at 30 to 50 hPa) too little of the calculated (forward) radiance is due to temperature. As a result, accounting for the remaining radiance leads to retrieved V6 ozone mixing ratios and associated SCO values that are too large. As described in Remsberg et al. (2021), there are also ascending versus descending orbital differences in retrieved ozone that change sign between the SH and NH in the subtropics to middle latitudes. However, the combined orbital profiles are used for the present analysis.

3 Estimates of monthly, zonal mean TRCO

The results of Fig. 1 are also compared using monthly zonal mean TRCO values. TRCO versus latitude is determined by calculating LIMS monthly mean SCO down to near the tropopause and subtracting those values from monthly TOMS total ozone for the months of November 1978 through May 1979. The tropopause extends to about the 100-hPa level between ±30° latitude most months (Logan, 1999; Ziemke et al., 2006). Monthly LIMS data are from its Version 6 (V6) Level 3 product (Remsberg and Lingenfelser, 2010), as provided to the SPARC data initiative (or SPARC DI) (see *zenodo* archive in Hegglin et al., 2021). V6 tropical zonal mean ozone profiles are integrated from 0.7 to 100 hPa to give monthly zonal mean estimates of SCO versus latitude. Monthly TOMS data are from (https://data.gesdisc.earthdata.nasa.gov/data/Nimbus7_TOMS_Level3/TOMSN7L3ztoz.008/TOMSN7L3ztoz_19781101_19930506.tar.gz).

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Monthly TRCO results versus latitude are in Table 1. TRCO ranges from about 20 to 40 DU at equatorial latitudes, which agrees with TRCO estimates from more recent satellite data (Ziemke et al. 2006). There is a monthly progression toward higher values at 30N that is reflective of the seasonal changes of ozone at that latitude. Results are nearly steady in the tropics. Yet, there is also a progression toward zero and slightly negative TRCO values in the southern subtropics that is clearly unrealistic. It may be that the LIMS SCO values have positive biases in the SH, leading to TRCO values that are trending lower (c.f., Fig. 1). The results for March and May are discussed in the next section.

Are there any anomalous trends in the TOMS data of 1978-79? Herman et al. (1991) reported that the measured solar flux values from Nimbus 7 TOMS were affected by a degradation of the surface of and reflectivity from its diffusor plate during the first months of its operations. Diffusor plate degradation amounts to a spurious reduction in total column ozone, and they developed corrections for that and applied them to the TOMS V8.6 dataset from January 1979 onward. Herman et al. (1991, their Figure 4) also showed that there was a ~4% increase in the measured solar flux at the wavelength of 380 nm from late October 1978 to January 1979 due to the gain in the photomultiplier tube detector. That increase affects the measured reflected fluxes from the surface and cloud tops and translates to a decrease in inferred total ozone. Although they did not do so, a correction for that change would increase TOMS total ozone for January through May (in Table 1) by about 10 DU at all latitudes, not just in the SH subtropics.

Ziemke et al. (1998) and Ziemke et al. (2006) reported seasonal changes in both total ozone and tropospheric ozone at several SH tropical and subtropical stations. They found that tropical TRCO values decreased generally from about 45 DU in November to 25 DU in May or by about 20 DU, and they attributed most of those seasonal changes in total ozone to changes in the tropospheric column. TOMS ozone in 1978/1979 decreased by about 15 DU from 8 November to 6 May at Natal, Brazil. On the other hand, Dobson total ozone at Natal decreased by 35 DU from 19 November 1978 to 5 May 1979. Table 1 shows that the monthly zonal mean TRCO at 5°S (near Natal) decreased from 44 DU to 14 DU, or by 30 DU. Making the foregoing upward adjustment of 10 DU in TOMS ozone would lead to the same increase in TRCO and a change of

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only 20 DU from November to May. Nevertheless, such an adjustment does not account for the rather large decreases in TRCO in Table 1 for the SH subtropics. TOMS/Dobson ozone comparison checks at stations are provided in the next section, at least when Dobson station data are available.

4 Distributions of SCO and TRCO from TOMS and LIMS

a. 15 March 1979

As noted from Fig. 1, V6 ozone has rather large differences with SBUV ozone in the subtropical lowermost stratosphere for both 15 March and for 6 May. What is the nature of TRCO at those latitudes? Figure 3 shows the distribution of total ozone from a subset of daily gridded TOMS Version 8.6 ozone data for 15 March, where the original TOMS grid has a spatial resolution of 1° latitude x 1.25° longitude and was resampled (but not interpolated or smoothed) to match a 2° x 5° grid of the corresponding LIMS V6 ozone field. TOMS data are compared with the LIMS ozone from 84°N to 64°S for this study. The vertical white slice (near 20°W) is where TOMS made no observations that day.

The red dots from west to east longitude in Fig. 3 are the locations of six, low-to-middle latitude Dobson stations operating in 1978/79—Mauna Loa HI, Tallahassee FL, Natal Brazil, Poona India, Cairns Australia, and Invercargill New Zealand. Dobson/TOMS tropical total ozone values (in DU) are 290/300 (Mauna Loa, HI), 264/272 (Natal), 260/272 (Pune), and 233/256 (Cairns). Values at middle latitudes are 300/297 (Tallahassee) and 279/269 (Invercargill). On another day, 15 February, (not shown) the comparison results are—255/269 (Mauna Loa, HI), 261/258 (Natal), 256/266 (Pune), 254/255 (Cairns), 287/286 (Tallahassee). and 304/322 (Invercargill). There are no clear TOMS/Dobson biases from this set of station comparisons. However, it is also likely that their differing values are a result of the rather loose spatial coincidence criteria (1 day, 2° latitude x 5° longitude) and/or within the combined error estimates of the TOMS and Dobson data.

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Estimates of SCO are obtained by summing together V6 ozone amounts for the multiple layers from 0.68 hPa to 100 hPa, although fewer profiles extend to 68 and 100 hPa in the tropics. V6 Level 3 zonal Fourier coefficients are used for this study because they provide complete data coverage each day (Remsberg and Lingenfelser, 2010). To achieve estimates of SCO, ozone mixing ratios as a function of pressure-altitude are obtained at grid points every 2° latitude and 5° longitude from the V6 zonal mean and zonal wave coefficients. The zonal coefficients for 15 March are from an archived LIMS directory, day074, in its file named 'o3_comb_coef.txt', where the Level 3 pressures have a vertical spacing of six levels per decade of pressure-altitude. Ozone amounts (in DU) are obtained for each pressure layer in the manner of Ziemke et al. (2001, their Appendix B). At low latitudes many of the V6 zonal coefficients at 68 and 100 hPa are often zero for wavenumbers greater than three, indicating that some profile segments were contaminated by cirrus and that their zonal mean values may not be representative. At those levels and latitudes, the lower order wavenumber coefficients are also set to zero, and the zonal mean coefficients are replaced by monthly climatological values from Ziemke et al. (2021) as adjusted to November 1978 based on their Rotated Empirical Orthogonal Function (REOF) values. Figure 4 is a cylindrical map projection of SCO from 64°S to 84°N, generated in the foregoing manner. Largest values are at northern middle and high latitudes, and it is likely that some of that ozone extended southward toward the Equator during wintertime.

Figure 5 is the V6 TRCO distribution obtained by subtracting the above LIMS column ozone (middle) from TOMS ozone (top). The distribution of TRCO appears somewhat noisy, due to the higher resolution TOMS ozone fields. The three red dots denote Boulder (40°N, 105°W), Lhasa, Tibet (30°N, 91°E), and Santiago, Chile (33°S, 70°W) or where there are decreases in TRCO related, in part, to the effects of orography on TOMS ozone. TRCO in the tropics and southern hemisphere for 15 March is even smaller than the monthly zonal mean for March in Table 1. Notably, TRCO is negative at 70°W from 25°S to 50°S and clearly unphysical. That latitude zone is where V6 temperatures have a zonal mean bias versus MERRA of the order of -0.8 K at both 30 and 50 hPa, which translates to an excess of retrieved V6 ozone of ~14% or ~10 DU in SCO and amounts to an equivalent deficit in zonal mean TRCO. There is also a negative V6 temperature bias in the northern subtropics of order -0.6 K but only at 50 hPa, which amounts to

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biases in SCO and TRCO of no more than 5 DU. But what of the much larger negative TRCO biases at 35°S (70°W and 100°E) and at 40°S (160°W)?

To the extent that 100 hPa approximates the actual tropical tropopause level, one should be able to obtain reasonable estimates of TRCO versus both longitude and latitude—perhaps to latitudes of ±30 degrees. Figure 6 shows the distribution of geopotential height for 15 March at the 100-hPa level. Note that there is significant zonal wave activity in the subtropics, or where the SE algorithm used for the generation of Level 3 zonal ozone Fourier coefficients smooths the true amplitudes of the waves. As an example, the Level 3 ozone at 25°S and 46 hPa varies zonally from about 1.6 to 2.0 ppmv, but the RMS agreement between those Level 3 estimates and the co-located Level 2 profile points is no better than 0.3 to 0.4 ppmv. In other words, the maximum and minimum wave amplitudes are underestimated by up to 20%. That wave damping occurs near the peak of the ozone partial pressure profile and contributes significant local biases to SCO. If the zonal waves are nearly stationary, then the reduced wave amplitudes occur over a deeper region of the lower stratosphere, perhaps from 100 to 40 hPa. Reduced zonal wave amplitudes in SCO lead to enhanced zonal variations of TRCO. On the other hand, the effects are due to traveling waves, they are also smoothed because the SE algorithm has a memory of order ±3 days. As a result, the zonal variations of TRCO are qualitative at best, and the net effects of temperature bias, SE smoothing, and perhaps a small bias in the TOMS ozone can lead to significant errors in TRCO locally.

Figure 6 shows a weak zonal wave-5 pattern in geopotential at 30 to 40°S that is presumably due to upper tropospheric forcings in that latitude zone. As the tropopause descends to higher pressures at higher latitudes, one may also estimate V6 SCO by extending SCO to lower altitudes using the V6 coefficients for 147 hPa and even 215 hPa, keeping in mind that the accuracy of a V6 ozone profile degrades as its associated V6 temperature profile segment becomes less accurate and imparts a larger bias to retrieved ozone at those levels. For that reason, V6 estimates of SCO and associated TRCO distributions are evaluated further only for the tropics and subtropics.

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b. 6 May 1979

Figure 7 is the distribution of TOMS ozone for 6 May, and Figure 8 is the associated distribution of V6 SCO. Variations in SCO have a zonal wave-4 structure in the SH subtropics. Figure 9 is the distribution of TRCO, which varies from 0 to -20 DU in the tropics and from 20 to -40 DU in the SH subtropics. Zonal mean temperatures, V6 minus MERRA, are negative at 30 hPa by as much as -1.5 K at 40°S, falling to near zero from 30°S to 15°S, and then becoming positive in the tropics and northern subtropics. Temperature biases at 50 hPa are only slightly negative at SH middle latitudes, increasing to nearly -1.0 K from the SH subtropics to the northern middle latitudes. As for 15 March, temperature bias can explain an underestimate of ~10 DU in TRCO between ±30°. Again, the zonal variations of ozone are smoothed of the order of 20% by the SE algorithm, especially at the 46-hPa level, which affects the zonal amplitudes of SCO and causes the variations of TRCO to be larger than expected. Increasing the wave amplitudes of SCO at 30°S, for example, gives to a near uniform zonal distribution of TRCO.

c. 8 November 1978

Figure 10 is the distribution of TOMS ozone for 8 November 1978. Largest total ozone values occur in the southern hemisphere (SH) or in springtime just outside of the polar vortex region. The deep blue area at high latitudes of the northern hemisphere (NH) is in polar night or where TOMS did not observe. TOMS tropical ozone is of the order of 270 Dobson units (DU) and shows a weak wave-1 variation with longitude. Dobson/TOMS total ozone values (in DU) are 249/256 (Hawaii), 281/276 (Natal), 244/258 (Poona), and 260/276 (Cairns). Total ozone agreement at middle latitudes is 288/283 (Tallahassee) and 361/363 (Invercargill). Again, there are no clear indications of a bias in TOMS ozone on 8 November. Figure 11 shows the distribution of SCO, and its relative lack of zonal structure at low latitudes indicates that zonal ozone variations are weak at and above the 46-hPa level. As with the TOMS data, the largest SCO values occur at SH middle to high latitudes in November.

Figure 12 is the distribution of TRCO, and its minimum values are of the order of 20 to 35 DU, consistent with tropospheric values for November from satellite data (Fishman et al., 1990) and from balloon soundings of that era (Ziemke et al., 1998). Again, the red dots denote Boulder,

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Lhasa, and Santiago, where there may be decreases in TRCO related to the effects of orography in the TOMS data. More notably, there are excesses of TRCO at the latitude of 20°S and at about 0°, 40°E, and at 110°E longitude that may indicate transport of ozone from higher latitudes of the lower stratosphere to the uppermost subtropical troposphere. Figure 13 is the distribution of V6 zonal eddy geopotential height at 100 hPa. To a first approximation, wind vectors are oriented from west to east along the eddy contours at midlatitudes and follow cyclonic and anti-cyclonic curvatures that are in opposite directions around lows and highs in the northern and southern hemispheres. Based on the zonal variations in geopotential in Fig. 13, it appears that the relative maximums of TRCO at 0°, 40°E, and at 110°E in Fig. 12 could be due to equatorward transport of stratospheric ozone to below the 100-hPa level. As a check on that prospect, a new distribution of TRCO is calculated, but based on subtracting SCO from above the 147-hPa level rather than the 100-hPa level. The isolated feature of elevated ozone in Fig. 12 at 20°S and 0° longitude is nearly unchanged (see *Supplement*), indicating that it is not a result of equatorward transport in the layer from 100 to 147 hPa. A sequence of daily TRCO distributions is shown in the next section as a way of tracking that feature during November.

5 Tropospheric Ozone Distributions during November 1978

October and November are when the effects of biomass burning on ozone occur along the southwest coast of Africa (Fishman et al., 1990). Those months are also when temperature biases and SH medium scale wave activity are weaker in the lower stratosphere, such that the V6 TRCO values should be more representative of variations in tropospheric ozone. Is there any evidence in November 1978 that ozone was changing just west of 0° degrees longitude in the SH subtropics and tropics?

To check about that, SCO is integrated down to the 147-hPa level for eight November days (2, 4, 6, 8, 12, 15, 19, and 22). Those daily data are separated by three days on average; some days were skipped because they had one orbit of TOMS data missing. In addition, the results for each day of the sequence are nearly independent, as the memory of the V6 Level 3 SE mapping algorithm is of order three days. The associated TRCO results for each day are averaged over

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the southern tropics from 20°S to the Equator and then assembled as a Hovmöller diagram (longitude-time) in Figure 14. There is a general zonal wave-1 variation (max of ~70 DU near 0°, min of ~30 DU near 180°) in early November 1978 or like that in the monthly TRCO distributions of later decades (see Fishman et al., 1990; Ziemke et al., 1996). There is good continuity over time for the maximum around 0° longitude or southern Africa, and there is a decline from ~70 to only ~45 DU from 2 to 22 November. It is posited that the elevated feature indicates chemical production of ozone lower in the troposphere or downwind of biomass burning activities in Africa and that there was a dispersal of that ozone maximum during November. There is also an absolute minimum in the eastern Pacific and a secondary maximum of ~50 DU near 100°E around 8 November, the latter due perhaps to biomass burning activities in the Indonesia region.

6 Conclusions

The findings of this exploratory study indicate that estimates of the zonal variability of tropical to subtropical TRCO from LIMS/TOMS are reasonable for November 1978 but are not as reliable from January through May. V6 SCO values contain residual cirrus effects at times in the tropical lowermost stratosphere. To avoid those effects, climatological monthly zonal mean values were substituted at 68 and 100 hPa, prior to calculating SCO in the tropics. Forward model errors and net negative temperature biases of order -1 to -2 K give rise to V6 ozone values that are too large by ~20% at 30 and 50 hPa in the lower stratosphere, particularly in March and May. When considering the effects of the negative temperature biases, one should adjust SCO downward and TRCO upward by the same amount. The V6 mapping algorithm also smoothed ozone zonal wave amplitudes, leading to underestimates of those variations in SCO and overestimates of TRCO consequently.

Distributions of TRCO are generated for eight days in November 1978, spaced about three days apart. The daily TRCO distributions of the southern tropics are assembled as a Hovmöller diagram, showing elevated ozone (~70 DU) near 0° longitude that diminishes over time (~45 DU). Elevated ozone occurs in and just downwind of a region of seasonal biomass burning

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activity in West Africa. It is concluded that the subtraction of LIMS SCO values from TOMS total ozone provides reasonably accurate estimates of the spatial variations of tropical tropospheric ozone during November 1978.

Data Availability. LIMS V6, SBUV V8, and TOMS V8.6 data are from the NASA GES DISC data archive at https://disc.gsfc.nasa.gov/ . Dobson data are from the World Ozone and Ultraviolet Data Center (WOUDC) at https://woudc.org/data/explore.php .

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Table 1--Tropical Tropospheric Column Ozone (TRCO in Dobson units)

Latitude	Nov 78	Dec 78	Jan 79	Feb 79	Mar 79	Apr 79	May 79
30	28	33	44	69	76	76	69
25	26	27	25	48	18	57	53
20	24	20	17	35	19	45	42
15	24	18	15	26	21	35	33
10	27	20	17	21	20	28	28
5	29	25	21	18	22	24	23
0	30	30	27	21	24	22	20
-5	44	36	32	27	23	18	14
-10	44	41	34	30	24	10	8
-15	47	40	32	21	6	1	-3
-20	63	41	31	18	0	-2	-3
-25	66	45	31	20	2	1	-3
-30	73	50	28	16	8	1	1

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492 **Figures**

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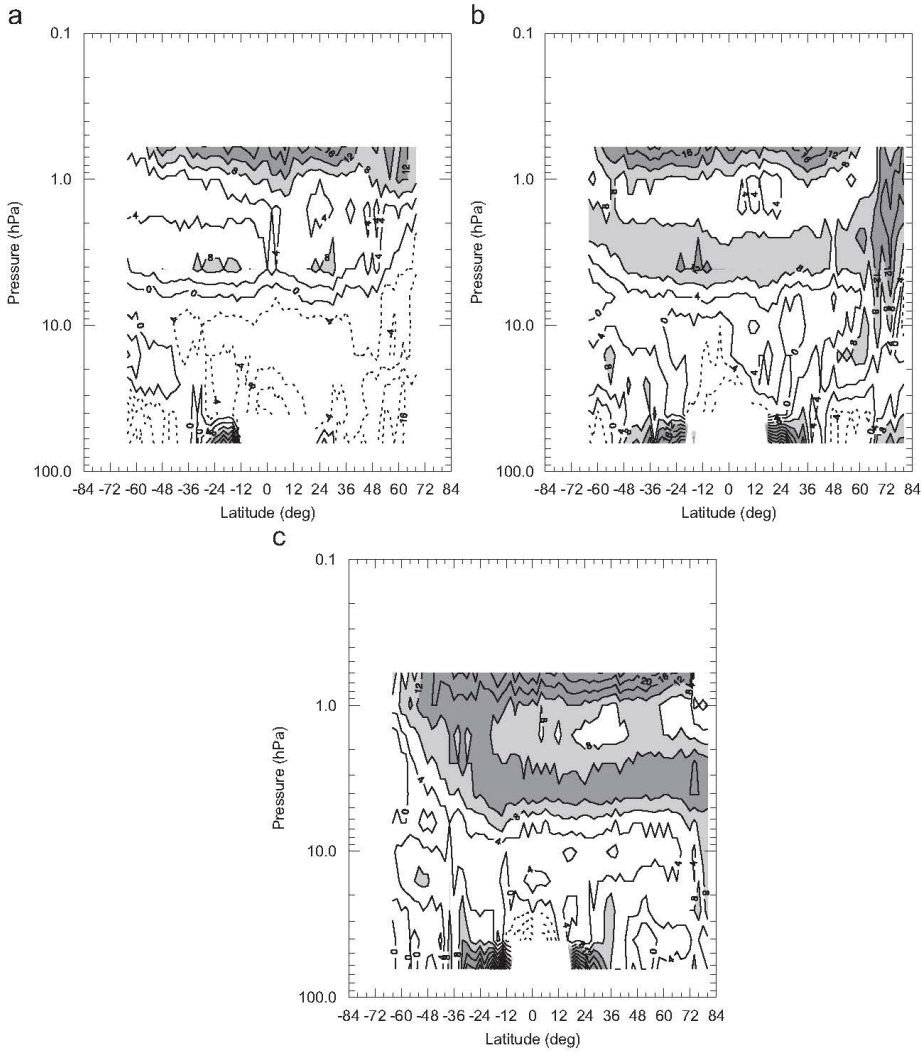

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495 Figure 1— Zonal mean cross section of LIMS V6 minus SBUV V8 ozone, divided by SBUV (in
496 %) for (left) 8 November 1978, for (right) 15 March 1979, and for (bottom) 6 May 1979.
497 Contour increment is 4%. Dashed contours are negative and the zero and positive contours are
498 solid. Values greater than +12% are shaded dark; values from +8% to +12% are shaded light.

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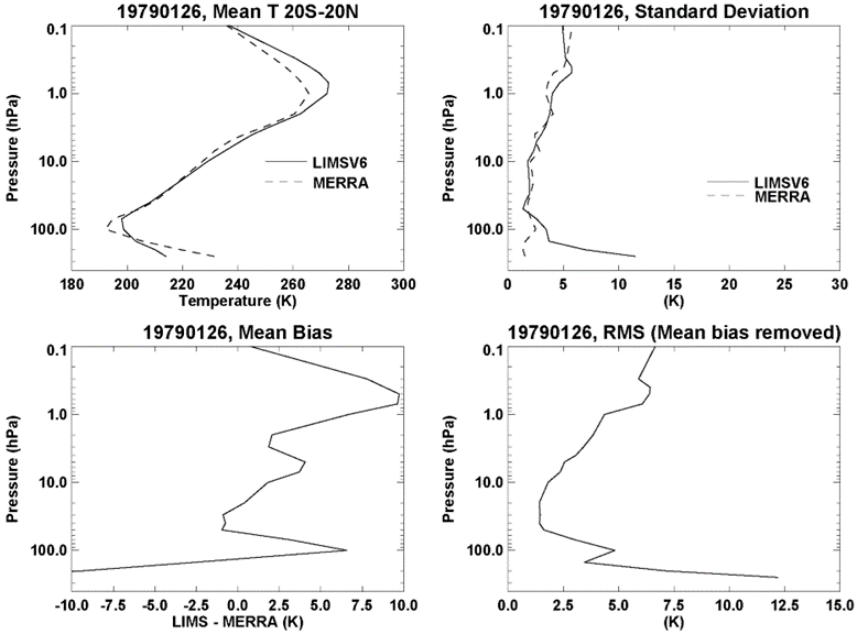

Figure 2—(top left) Zonal mean temperature profiles from LIMS V6 versus MERRA for the latitude band of 20°S to 20°N. (bottom left) Mean bias, V6 minus MERRA, for 26 January 1979. (top right) standard deviation about the zonal mean, and (bottom right) RMS deviation with mean bias removed.

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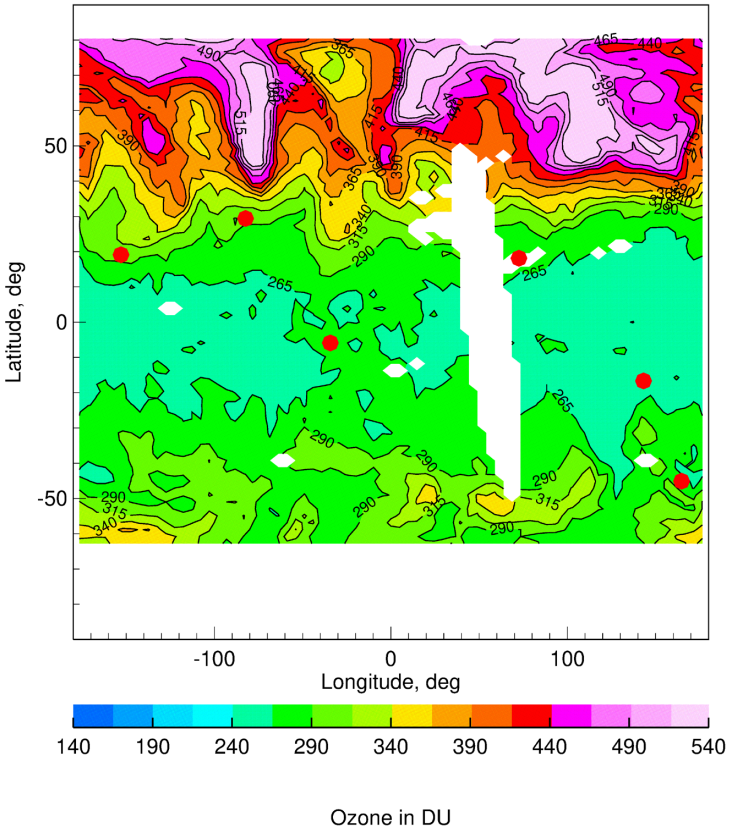

Figure 3—Total ozone distribution in Dobson units (DU) from TOMS data for 64°S to 84°N on 15 March 1979. West longitude is negative relative to Greenwich; east is positive. Contour spacing is 25 DU. The white vertical slice near 60°E and other sporadic locations are where TOMS did not operate that day. Red dots are station locations with concurrent Dobson total ozone data.

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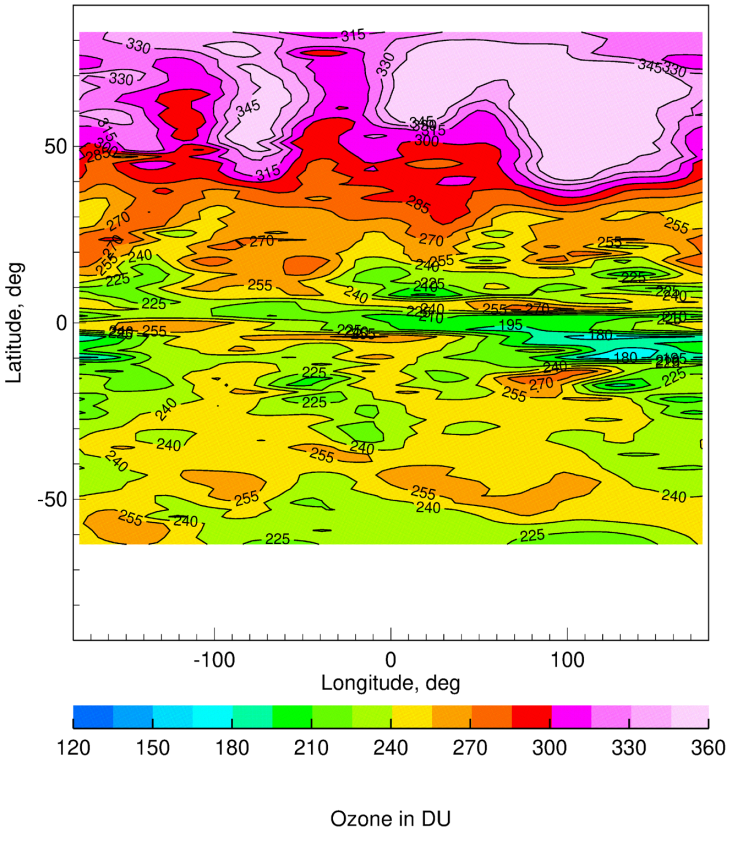

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528 Figure 4—Distribution of SCO (in DU) from LIMS V6 for 15 March; contour spacing is 15 DU.

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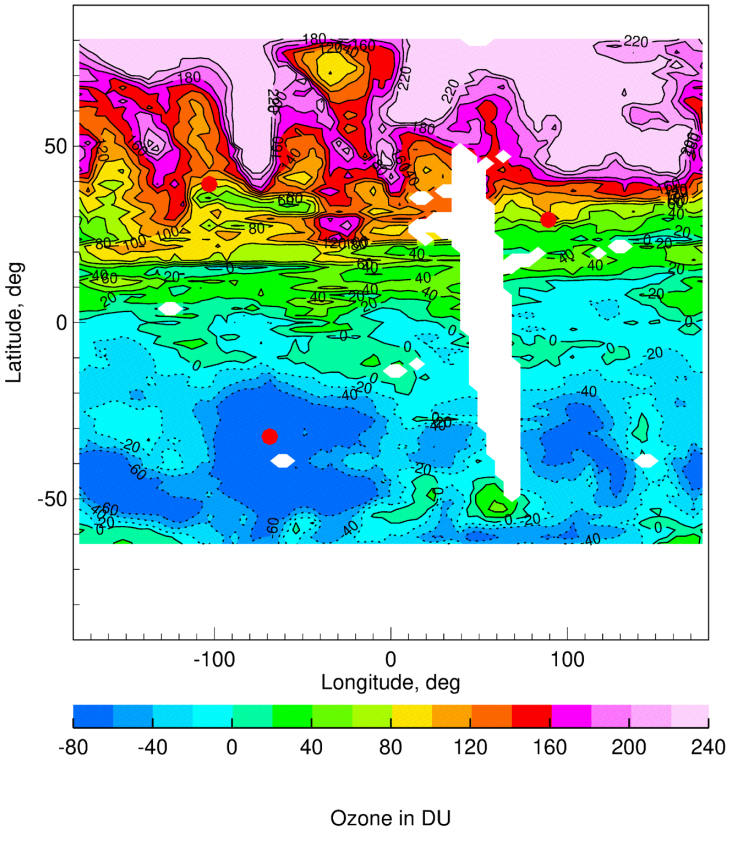

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537 Figure 5—Tropospheric column ozone (TRCO) for 15 March; contour spacing is 20 DU.

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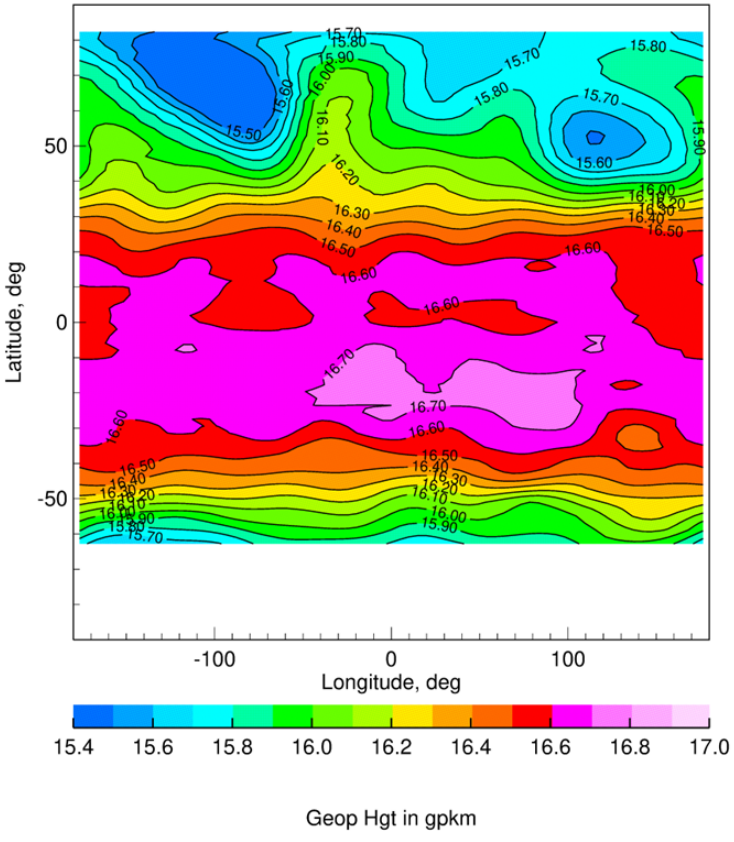

Figure 6— V6 geopotential height contours at 100 hPa for 15 March 1979. Isolines are spaced by 0.1 gpkm.

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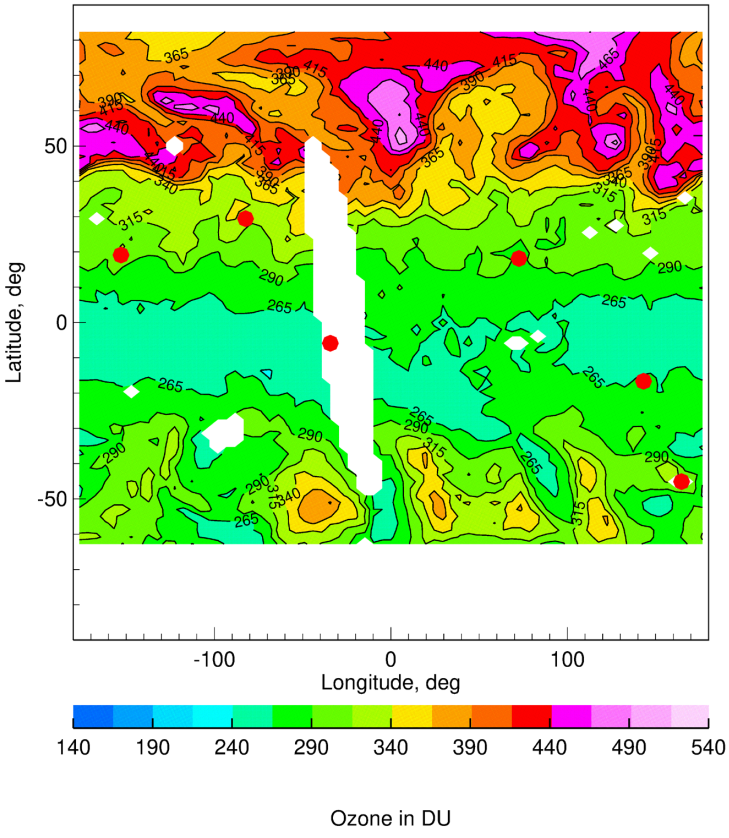

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555 Figure 7—As in Fig. 3, but TOMS data for 6 May 1979. The white vertical slice near 20°W and
556 the small area at 30°, 90°W is where TOMS made no observations that day.

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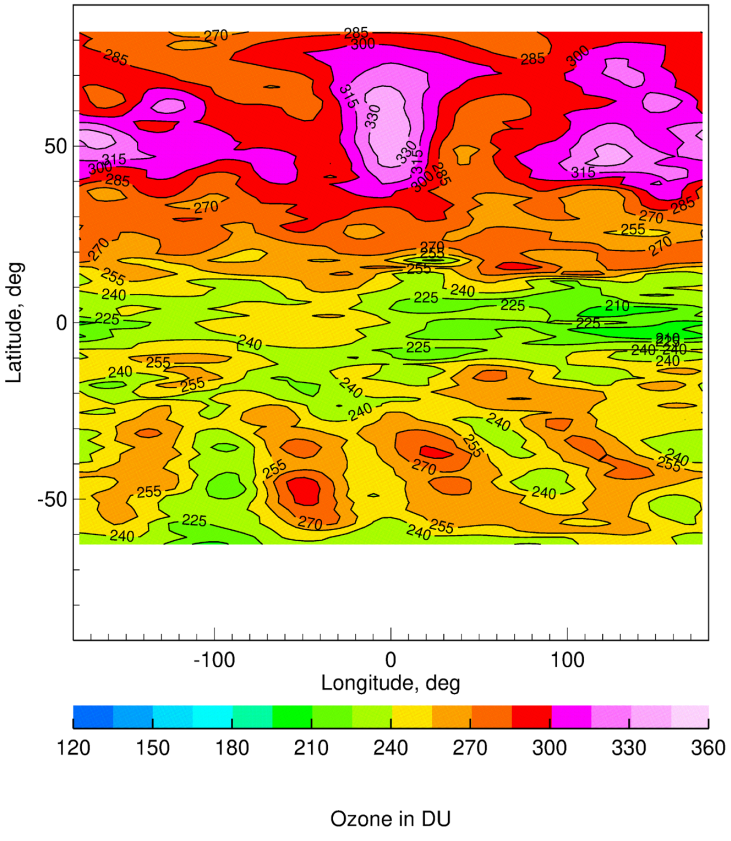

Figure 8—As in Fig. 4, but for SCO on 6 May 1979.

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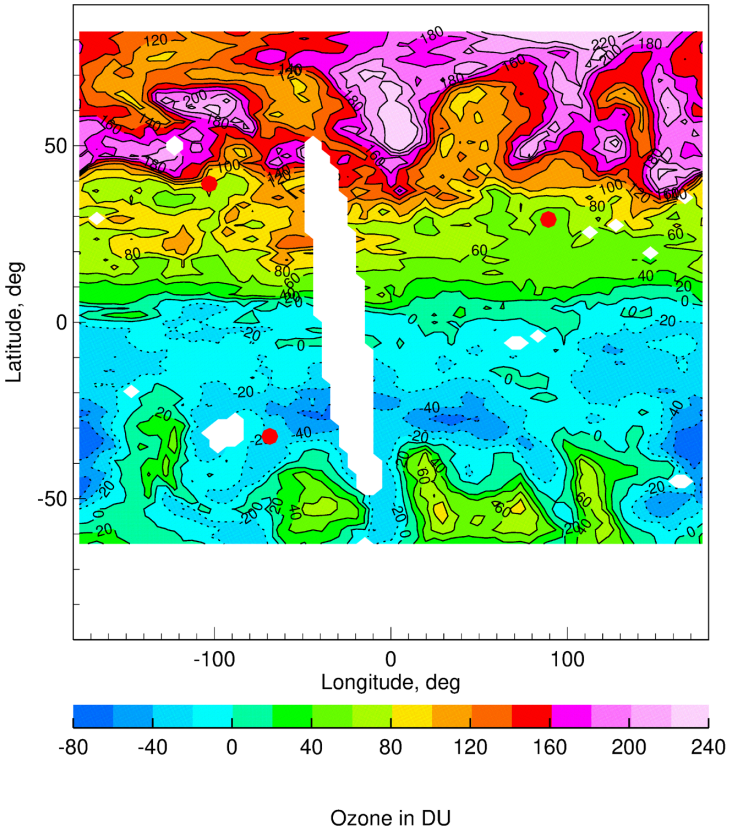

Figure 9—As in Fig. 5, but TRCO for 6 May 1979.

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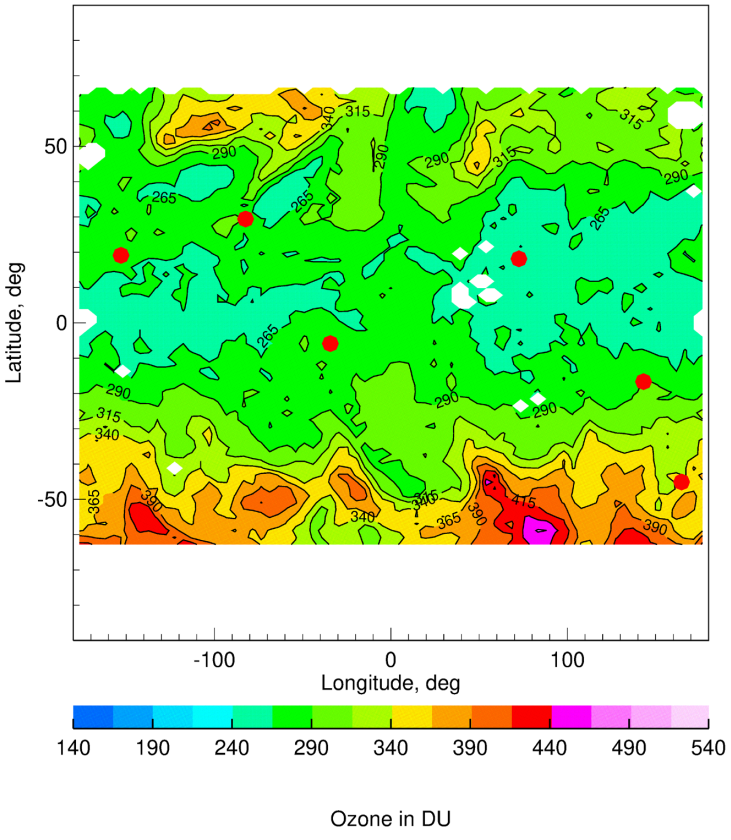

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590 Figure 10—As in Fig. 3, but for TOMS ozone on 8 November 1978.

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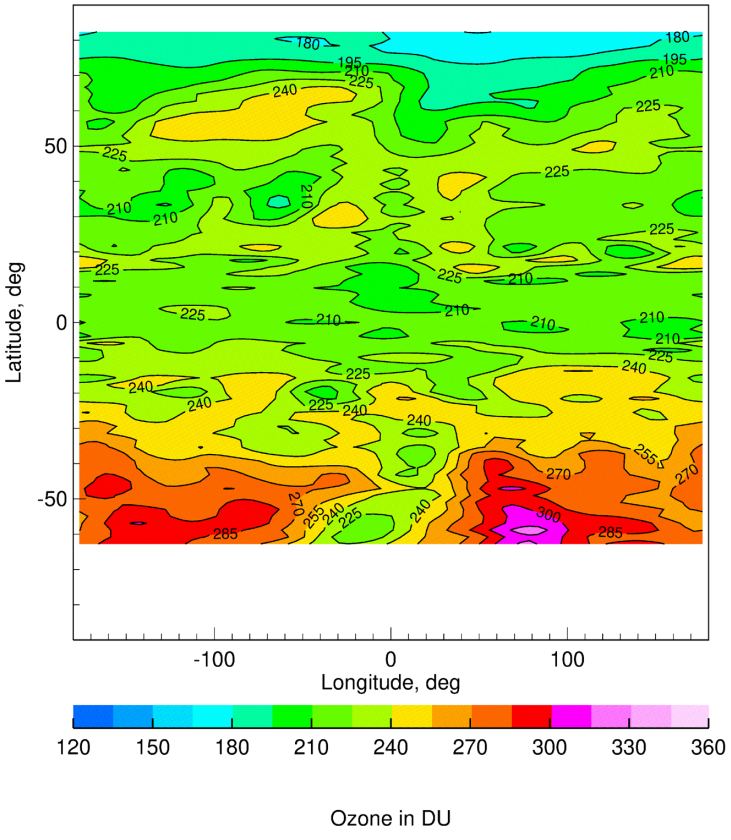

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602 Figure 11—As in Fig. 4, but for SCO on 8 November 1978.

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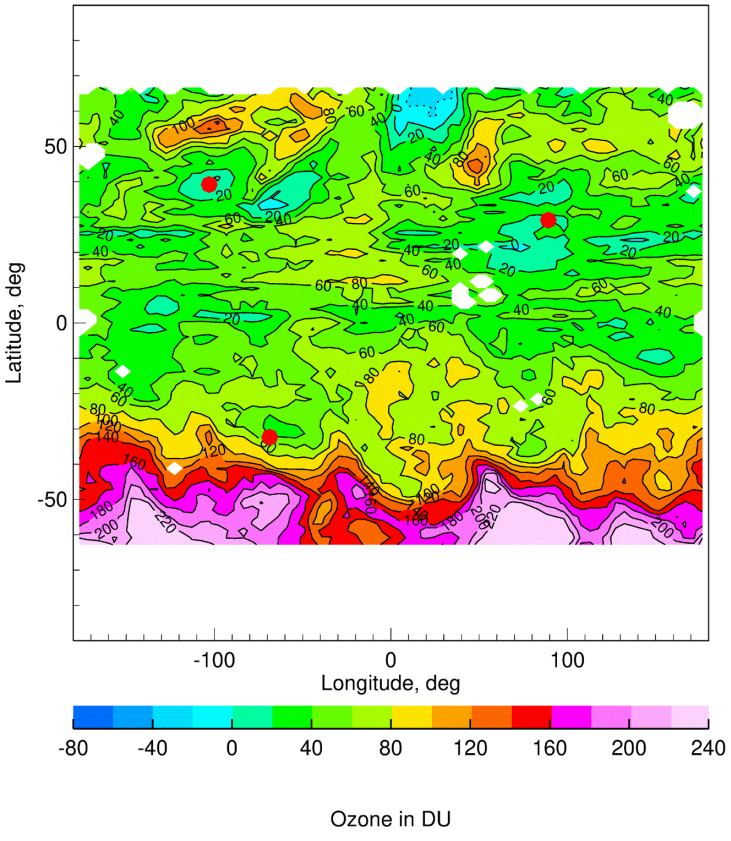

Figure 12—As in Fig. 5, but for TRCO on 8 November 1978.

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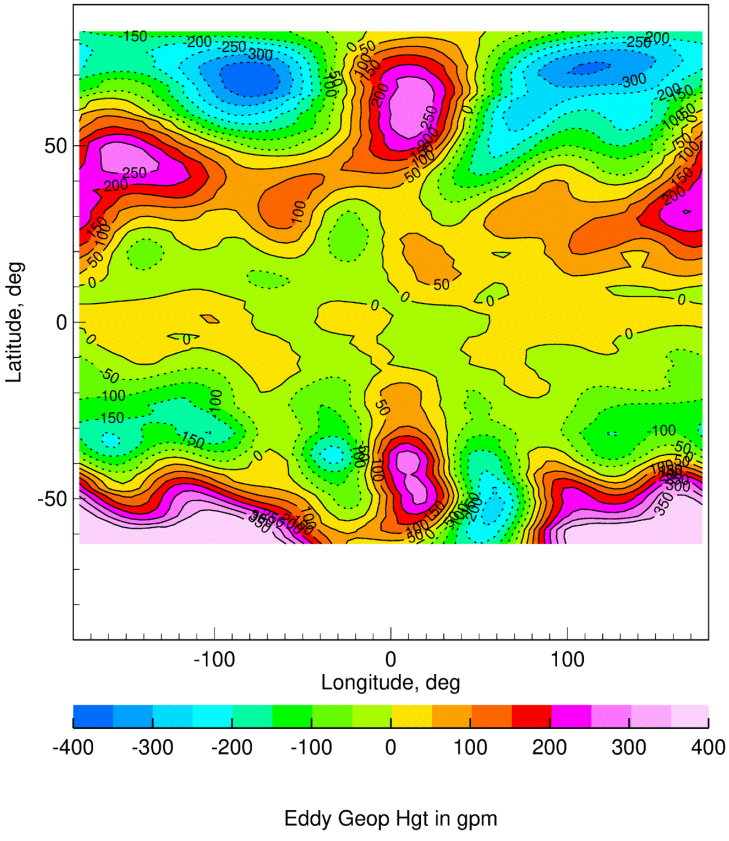

Figure 13—Distribution of zonal eddy geopotential height at 100 hPa on 8 November 1978; contour interval is 50 geopotential meters.

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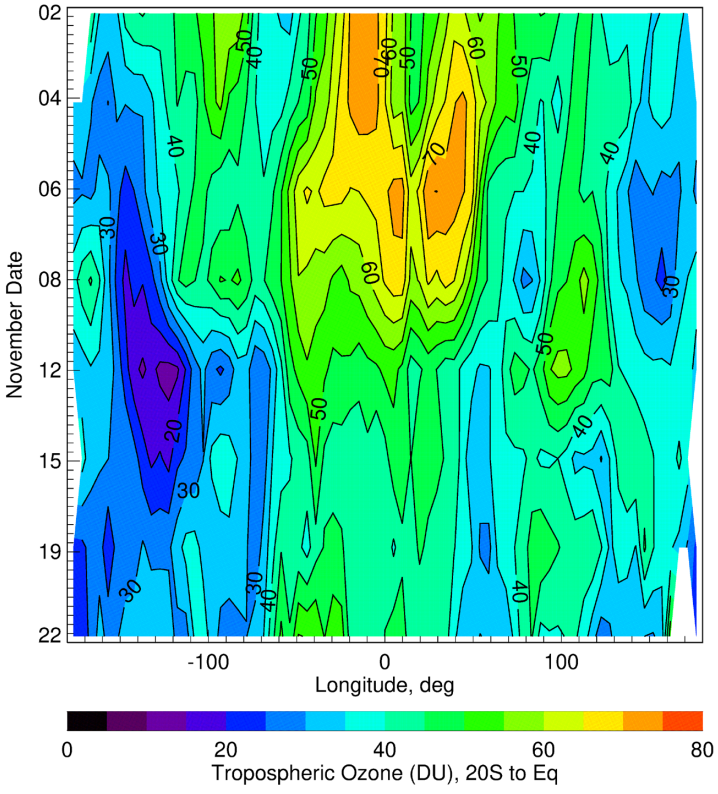

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637 Figure 14—Hovmöller diagram of TRCO results from 2 to 22 November as averaged from 20°S
638 to Equator. Contour interval is 5 DU, and white areas are where TOMS data are missing.

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