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Effects of the 2004 El Niño on tropospheric ozone and water vapor

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[1] The global effects of the 2004 El Niño on tropospheric ozone and H_2O based on Aura OMI and MLS measurements are analyzed. Although it was a weak El Niño from a historical perspective, it produced significant changes in these parameters in tropical latitudes. Tropospheric ozone increased by 10–20% over most of the western Pacific region and decreased by about the same amount over the eastern Pacific region. H_2O in the upper troposphere showed similar changes but with opposite sign. These zonal changes in tropospheric ozone and H_2O are caused by the eastward shift in the Walker circulation in the tropical pacific region during El Niño. During the 2004 El Niño, biomass burning did not have a significant effect on the ozone budget in the troposphere, unlike the 1997 El Niño. Zonally averaged tropospheric column ozone did not change significantly either globally or over tropical latitudes. **Citation:** Chandra, S., J. R. Ziemke, M. R. Schoeberl, L. Froidevaux, W. G. Read, P. F. Levelt, and P. K. Bhartia (2007), Effects of the 2004 El Niño on tropospheric ozone and water vapor, *Geophys. Res. Lett.*, *34*, L06802, doi:10.1029/2006GL028779.

1. Introduction

[2] *Ziemke and Chandra* [2003] have shown that El Niño and La Niña events are major sources of decadal variability in tropospheric O_3 in the tropical atmosphere. These events produce changes in the convection pattern and large-scale circulation in the tropical Pacific region causing tropospheric column ozone (TCO) to vary from the western to the eastern Pacific with a sign change near the dateline. During El Niño, TCO is enhanced over the Indonesian region and reduced over the eastern Pacific. La Niña generally produces the opposite effect. One of the most intense El Niño events on record occurred during 1997 which caused a major perturbation in the ocean-atmosphere system including a drought and large-scale forest fires in the Indonesian region. The effects of the 1997 El Niño on tropospheric O_3 in the tropics have been extensively studied from both satellite and ground based measurements [e.g., *Chandra et al.*, 1998, 2002; *Fujiwara et al.*, 1999; *Thompson et al.*, 2001] and are, generally, well simulated by global models of atmospheric chemistry and transport [e.g., *Sudo and Takahashi*, 2001; *Chandra et al.*, 2002; *Peters et al.*, 2001, *Zeng and Pyle*, 2005, *Doherty et al.*, 2006]. The study of El Niño and La Niña related changes in tropospheric O_3 has been generally limited to the tropical region because global measurements of tropospheric O_3 outside the tropics were not available. A number of studies have suggested that El Niño has significant influence on the inter-annual variation of stratosphere-troposphere exchange (STE) which affects tropospheric O_3 outside the tropics [*Langford et al.*, 1998; *James et al.*, 2003; *Zeng and Pyle*, 2005].

[3] Recently, *Ziemke et al.* [2006] produced global maps of TCO from the Aura Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS) measurements beginning August 2004. TCO is determined using the tropospheric O_3 residual method which involves subtracting stratospheric column ozone (SCO) from total column ozone measured from MLS and OMI instruments. There was an El Niño event during the latter part of 2004. Even though this event was weak by historical standards, it provides an opportunity to study the possible effects of El Niño on tropospheric O_3 outside the tropical region. The purpose of this paper is to study global effects of the 2004 El Niño on tropospheric O_3 derived from the OMI/MLS instruments on the Aura Satellite. This study combines tropospheric O_3 measurements with H_2O measurements from the MLS instrument on the same satellite. Like O_3, H_2O is affected by deep tropical convection and large-scale transport processes. During 1997, El Niño-related changes in tropospheric O_3 and upper troposphere (UT) H_2O were anti-correlated over most of the tropical region [*Chandra et al.*, 1998].

2. The 2004 El Niño Event

[4] According to the World Meteorological Organization (WMO) criterion (available at http://www.nws.noaa.gov/ost/climate/STIP/ElNinoDef.htm), an El Niño event occurs when the sea surface temperature (SST) in the Niño 3.4 region (a rectangular region covering longitudes 120°W–170°W and latitudes 5°S–5°N) is at least 0.5°C above normal when averaged over three consecutive months. Using this criterion, the last six months of 2004 may be categorized as El Niño months. The mean values of SST in these months were 0.7°C to 0.9°C higher with respect to 1971–2000 base periods (available at http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). The SST values are lower compared to the 2002 El Niño and significantly lower compared to the 1997 El Niño. For example, the mean SST anomalies (ΔSST) for November and December 2004 were respectively 0.9°C and 0.8°C. For the same two months, ΔSST were 1.5°C for the 2002 El Niño, and 2.5°C for the 1997 El Niño. In all cases, the mean represents a three-month

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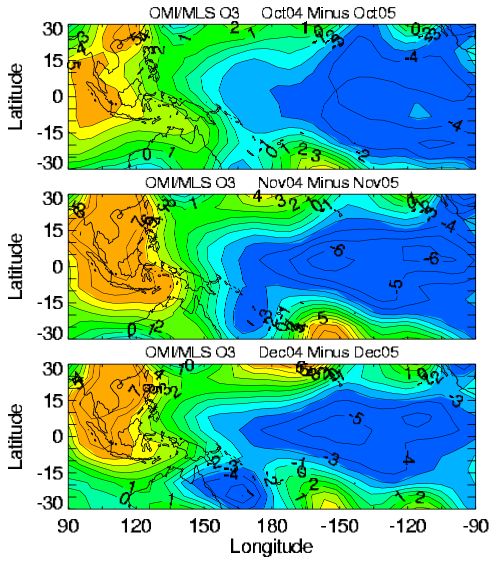

Figure 1. El Niño related changes in tropospheric O_3-AVMR over the Pacific region (90°W to 90°E) covering the latitude range ±30°. Relative changes in (top) October, (middle) November, and (bottom) December months in 2004 with respect to corresponding months in 2005 (a non-El Niño year). The contour lines are in ppbv. The colors are used to highlight main features.

average which includes the preceding and following months. In order to study the El Niño-related changes in the atmosphere, it is important to establish a base reference. Ideally the base reference should include several years of measurements to estimate climatological means. With only about 2 years of satellite measurements for this study, we have chosen the corresponding months in 2005 as reference (i.e., non-El Niño) months. For October, November, and December 2004, ΔSST with respect to the corresponding months in 2005 (i.e., year 2004 minus 2005) were respectively 1.1°C, 1.3°C, and 1.5°C. A similar approach was adopted by *Chandra et al.* [1998] in their study of the 1997 El Niño.

3. Satellite Data

[5] The OMI and MLS instruments on board the Aura spacecraft [*Schoeberl et al.*, 2004] have been providing daily O_3 measurements in the troposphere and stratosphere soon after launch in July 2004. The Dutch-Finnish OMI instrument is a UV/VIS nadir solar backscatter spectrometer which provides near global coverage of total O_3 column each day with a spatial resolution of 13 km × 24 km [*Levelt et al.*, 2006]. The Aura MLS limb sounding instrument measures the microwave emission lines in the frequency range 118 GHz – 2.5 THz for several trace gases in the upper troposphere and middle atmosphere. These measurements are reported every 1.5 degrees of latitude along the satellite orbital track [*Waters et al.*, 2006; *Froidevaux et al.*, 2006]. We have used MLS SCO data as in the work of *Ziemke et al.* [2006] and MLS H_2O data at two pressure levels, 215 hPa and 316 hPa. *Su et al.* [2006] have studied some of the characteristics of H_2O data related to tropical convection.

[6] Nearly two continuous years of daily O_3 and H_2O data are now available for studying inter-annual changes including a recent El Niño event in mid-2004 and early 2005. TCO is derived using the residual method of *Fishman et al.* [1990]. MLS SCO is subtracted from OMI total column ozone after adjusting MLS SCO relative to OMI SCO using the Convective Cloud Differential (CCD) method of *Ziemke et al.* [1998]. We have chosen to express TCO in terms of O_3 average volume mixing ratio (O_3-AVMR) instead of TCO. They are related by the following expression [*Ziemke et al.*, 2006: $O_3\text{-AVMR} = 1.27\ \text{TCO}/(P_{surface} - P_{tropopause})$ where O_3-AVMR is in parts per million by volume (ppmv), TCO is in Dobson Units (DU, 1 DU = 2.69×10^{20} molecules m^{-2}), and $P_{surface}$ and $P_{tropopause}$ are surface and tropopause pressure in hPa. As shown by *Ziemke et al.* [2006], TCO and O_3-AVMR have similar spatial patterns except in regions where changes in tropopause and terrain pressures are significant. On average, 1 DU in TCO corresponds to about 1.5 ppbv in O_3-AVMR in the tropics and about 1.7 ppbv in middle and high latitudes.

4. El Niño Related Changes in Ozone and Water Vapor

[7] Figure 1 shows zonal changes in O_3-AVMR in the Pacific region (90°W–90°E) between 30°S and 30°N for three El Niño months (October, November and December) in 2004. These changes are with respect to corresponding months in 2005 which are taken as reference months for a non-El Niño condition. Figure 2 is similar to Figure 1 but for H_2O volume mixing ratio at 215 hPa. It is pre-filtered for NCEP tropopause (using WMO 2K-km^{-1} definition) to ensure that the air mass origin for all H_2O is in the troposphere. All O_3-AVMR and H_2O data fields were spatially smoothed using a three point running average in latitude and longitude to highlight planetary-scale features. Figure 1 shows an El Niño signature in O_3-AVMR with a positive anomaly in the western Pacific and a negative anomaly in the eastern Pacific in all three months. The

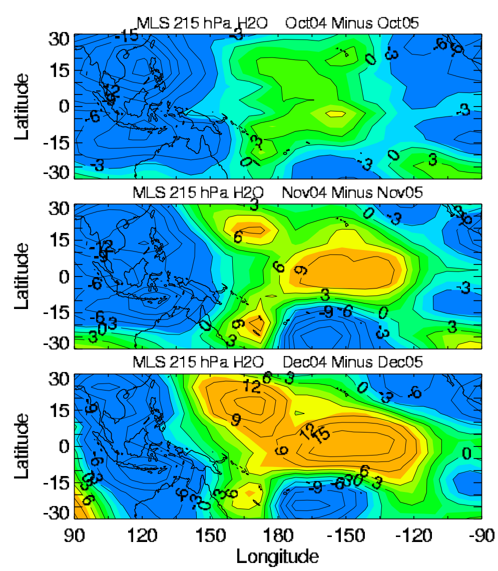

Figure 2. Same as Figure 1 but for H_2O at 215 hPa. The contour lines are in ppmv.

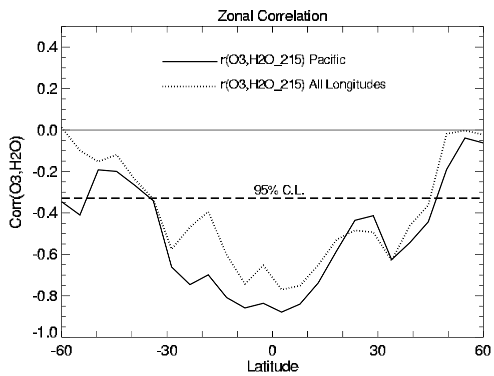

Figure 3. Correlation coefficient of El Niño related changes in O_3-AVMR and 215 hPa H_2O mixing ratio. The dotted line includes all data between longitudes ±180°. The solid line includes only the Pacific data (90°W–90°E) as in Figures 1 and 2. The dashed line represents the 95% confidence level.

peak values of these anomalies are about 5–7 ppbv and represent 15–20% changes over mean values of 30–35 ppbv in this region. However, the regions of negative anomaly extend over a larger area in the zonal direction compared to the positive anomaly. The O_3 field thus appears like an asymmetrical dipole. The H_2O field at 215 hPa in Figure 2 shows a similar zonal pattern, but with an opposite sign, i.e., a negative anomaly over the western Pacific and a positive anomaly over most of the eastern Pacific region. The peak values of H_2O anomaly are in the range of 10–20 ppmv and represent a change of 30–40% over the non El Niño months. The zonal anomalies in O_3 and H_2O shown in Figures 1 and 2 persist for several months in 2005. In all these cases, the anomalies are calculated with respect to the corresponding months in 2006 when ΔSST > 0.5°C.

[8] The out of phase relation between O_3 and H_2O fields seen in Figures 1 and 2 does not hold at middle and high latitudes. Even in tropical latitudes this relation is not robust outside the Pacific region. This is apparent in Figure 3 which shows the correlation between El Niño related changes in O_3 and H_2O as a function of latitude. The solid line in Figure 3 contains data only from the Pacific region as in Figures 1 and 2. The dotted line includes all data between longitudes ±180°. In both cases the correlation coefficient is the average of three months (October, November, and December).

[9] The latitudinal characteristics of the two curves in Figure 3 are similar. They both show significantly high negative correlation between ±20° which decreases rapidly towards higher latitudes. Figure 3 further suggests that the Pacific region mostly contributes to the high negative correlation between O_3 and H_2O. The inclusion of the non-Pacific data tends to reduce the correlation. The correlation coefficient, nevertheless, is significant over the tropical and subtropical latitudes even in this case.

[10] The phase relations between O_3-AVMR and H_2O mixing ratio at 215 hPa shown in Figure 3 do not change substantially if one uses H_2O mixing ratio at 316 hPa. In principle, the use of the 316 hPa level has some advantage since it is lower in the troposphere compared to 215 hPa. Outside ±30° the air mass at 316 hPa is a better representative of the tropospheric air mass condition than at 215 hPa.

5. Comparison With the 1997 El Niño

[11] As noted in the Introduction, one of the most intense El Niño events in recent years occurred during 1997 which caused major perturbations in the ocean-atmosphere system including a drought and large-scale forest fires in the Indonesian region. By comparison, the 2004 El Niño was a weak event. Figure 4 compares the similarities and differences of the two events with respect to changes in O_3-AVMR at tropical latitudes. The O_3-AVMR changes are averaged over ±15° latitude to include most of the tropical region. The reference (non-El Niño) years for calculating these changes are 1996 for the 1997 El Niño as in the work of *Chandra et al.* [1998] and 2005 for the 2004 El Niño as in Figures 1 and 2. Both events (Figure 4) show similar zonal patterns in tropospheric O_3, i.e., an asymmetrical dipole with positive anomaly in the western Pacific and negative anomaly in the eastern Pacific. Their relative values are however significantly different, particularly in October and November months (Figure 4, top and middle). For example, the El Niño related increase in O_3-AVMR in the western Pacific in these months is about 15–20 ppbv in 1997 compared to 4–5 ppbv in 2004. Model studies [*Sudo and Takahashi*, 2001; *Chandra et al.*, 2002; *Doherty et al.*, 2006] suggest that in 1997 both biomass burning and meteorological factors contributed to observed enhancements in O_3-AVMR in the western pacific region. Meteorological factors are related to changes in SST which cause an eastward shift in the large-scale Walker circulation.

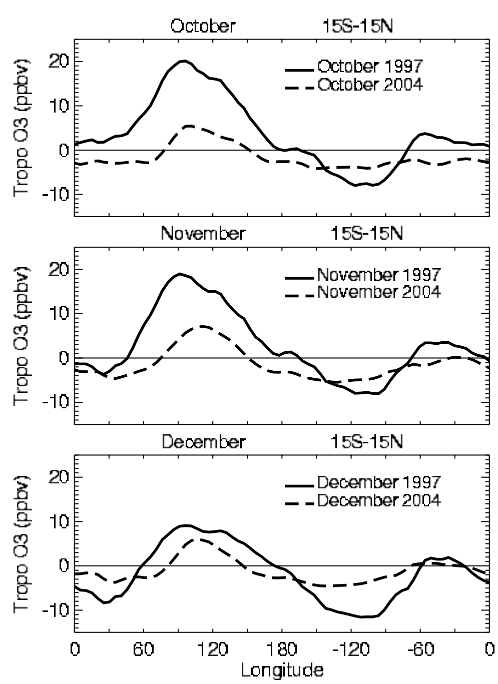

Figure 4. Comparison of relative changes in O_3-AVMR for the 1997 and 2004 El Niño events. The 1997 values are derived from the version 8 total column ozone data using the Convective Cloud Differential (CCD) method [*Ziemke et al.*, 1998].

Table 1. O_3 Mass Abundance in the Troposphere Averaged Over Three Months in 2004 and 2005[a]

Year	15S–15N	30S–30N	60S–60N
2004	79.2 (1.7)	168.2 (2.3)	281.2 (4.3)
2005	82.2 (1.7)	170.8 (2.2)	286.8 (4.1)

[a]O_3 mass abundance (in Tg) averaged during October, November, and December months in 2004 and 2005. Numbers in parentheses denote calculated 2σ uncertainties.

Atmospheric changes produced by this shift are (1) downward (upward) motion, (2) suppressed (enhanced) convection and (3) decrease (increase) in specific humidity in the western (eastern) pacific region. Downward motion and suppressed convection bring ozone produced in the upper troposphere down to the middle and lower troposphere causing ozone increase in this region. The decrease in specific humidity also contributes to ozone increase since H_2O is the sink for ozone in the troposphere [*Kley et al.*, 1996]. In the eastern Pacific region where these processes are reversed, upward motion and enhanced convection transport low ozone and high H_2O from the boundary layer to the middle and upper troposphere causing a decrease in O_3 and increase in H_2O.

[12] These model studies also suggest that the positive and negative anomalies in O_3 are nearly equal in magnitude when only meteorological processes are considered. However, they are not necessarily zonally symmetrical with respect to the date line or any other reference line as seen in Figures 1 and 2. In 2004, both these anomalies in O_3-AVMR are nearly of equal magnitude in all three months but asymmetrical with respect to the dateline. It is reasonable to conclude that they are primarily of dynamical origin. A similar inference can also be made for the O_3-AVMR anomaly in December 1997 (Figure 4, bottom). A nearly equal magnitude of O_3 anomaly in December 1997 is consistent with the model prediction since biomass burning in the Indonesian region decreased significantly in December 1997.

6. Global Implications of the 2004 El Niño on Tropospheric Ozone

[13] During September–November 1997, TCO integrated over the tropical region between 15°N and 15°S increased by about 6–8 teragram (Tg; 1 Tg $\equiv 10^{12}$ g) over the annual mean climatological value of 77 Tg [*Chandra et al.*, 2002]. This increase was attributed to biomass burning since dynamically induced dipole changes in tropospheric O_3 in the tropical region tend to cancel out. We have carried out a similar analysis for the 2004 El Niño for both tropical and extra-tropical regions. Table 1 summarizes the results of this analysis.

[14] Table 1 suggests that the O_3 burden in 2004 was generally less than in 2005 both inside and outside the tropics, but these differences are not statistically significant according to the 2σ uncertainty values shown in the table. This implies that biomass burning and other sources of O_3 production (e.g., lightning NO_X, stratospheric O_3 influx) did not play significant roles during the 2004 El Niño period in affecting global tropospheric O_3. This does not rule out the possibility of delayed response of some of these processes as discussed in recent modeling studies [e.g., *Zeng and Pyle*, 2005; *Doherty et al.*, 2006].

7. Summary and Conclusions

[15] In this paper we have studied the effects of the 2004 El Niño on tropospheric O_3 and H_2O based on Aura OMI and MLS measurements. Even though this was a weak El Niño from a historical perspective, the availability of global data for this event has enabled us to study its effects both inside and outside the tropical region. The zonal characteristics of El Niño-related changes in O_3 and H_2O in 2004 are similar to the 1997 El Niño in tropical latitudes between ±15°. Both events showed an increase (decrease) of O_3 (H_2O) in the western Pacific and decrease (increase) of O_3 (H_2O) in the eastern Pacific. However, the magnitude of the change was very different. For example, the 2004 El Niño produced an increase of 10–15% in O_3 in the tropical western pacific region. The corresponding increase in O_3 during the 1997 El Niño was about 40–50%. About half of the increase in 1997 was due to biomass burning and the other half due to dynamical effects. After accounting for biomass burning, the zonal anomalies in tropospheric O_3 during 1997 are similar to 2004 over tropical latitudes. They are both anti-correlated with upper troposphere H_2O. For the 2004 El Niño, the strong negative correlation between O_3 and H_2O seen in tropical latitudes decreases rapidly towards higher latitudes. This suggests that the convective processes affecting the distribution of O_3 and H_2O during an El Niño event are important mostly in tropical latitudes. The observed changes in tropospheric O_3 and H_2O during a weak El Niño like in 2004 suggest that the atmosphere is very sensitive to small perturbations in SST.

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References

Chandra, S., J. R. Ziemke, W. Min, and W. G. Read (1998), Effects of 1997–1998 El Niño on tropospheric ozone and water vapor, *Geophys. Res. Lett.*, *25*, 3867–3870.

Chandra, S., J. R. Ziemke, P. K. Bhartia, and R. V. Martin (2002), Tropical tropospheric ozone: Implications for dynamics and biomass burning, *J. Geophys. Res.*, *107*(D14), 4188, doi:10.1029/2001JD000447.

Doherty, R. M., D. S. Stevenson, C. E. Johnson, W. J. Collins, and M. J. Sanderson (2006), Tropospheric ozone and El Niño-Southern Oscillation: Influence of atmospheric dynamics, biomass burning emissions, and future climate change, *J. Geophys. Res.*, *111*, D19304, doi:10.1029/2005JD006849.

Fishman, J., C. E. Watson, J. C. Larsen, and J. A. Logan (1990), Distribution of tropospheric ozone determined from satellite data, *J. Geophys. Res.*, *95*, 3599–3617.

Froidevaux, L., et al. (2006), Early validation analyses of atmospheric profiles from EOS MLS on the Aura satellite, *IEEE Trans. Geosci. Remote Sens.*, *44*(5), 1106–1121.

Fujiwara, M., et al. (1999), Tropospheric ozone enhancements during the Indonesian forest fire events in 1994 and in 1997 as revealed by ground-based observations, *Geophys. Res. Lett.*, *26*, 2417–2420.

James, P., A. Stohl, C. Forster, S. Eckhardt, P. Seibert, and A. Frank (2003), A 15-year climatology of stratosphere-troposphere exchange with a Lagrangian particle dispersion model: 2. Mean climate and seasonal variability, *J. Geophys. Res.*, *108*(D12), 8522, doi:10.1029/2002JD002639.

Kley, D., et al. (1996), Observations of near-zero ozone concentrations over the convective Pacific: Effects on air chemistry, *Science*, *274*, 230–232.

Langford, A. O., T. J. O'Leary, C. D. Masters, K. C. Aikin, and M. H. Proffitt (1998), Modulation of middle and upper tropospheric ozone at

Northern midlatitudes by the El Niño/Southern Oscillation, *Geophys. Res. Lett.*, *25*, 2667–2670.
Levelt, P. F., et al. (2006), The Ozone Monitoring Instrument, *IEEE Trans. Geosci. Remote Sens.*, *44*(5), 1199–1208.
Peters, W., M. Krol, F. Dentener, and J. Lelieveld (2001), Identification of an El Niño Southern Oscillation signal in a multiyear global simulation of tropospheric ozone, *J. Geophys. Res.*, *106*, 10,389–10,402.
Schoeberl, M. R., et al. (2004), Earth observing systems benefit atmospheric research, *Eos Tran. AGU*, *85*, 177–178.
Su, H., W. G. Read, J. H. Jiang, J. W. Waters, D. L. Wu, and E. J. Fetzer (2006), Enhanced positive water vapor feedback associated with tropical deep convection: New evidence from Aura MLS, *Geophys. Res. Lett.*, *33*, L05709, doi:10.1029/2005GL025505.
Sudo, K., and M. Takahashi (2001), Simulation of tropospheric ozone changes during 1997–1998 El Niño: Meteorological impact on tropospheric photochemistry, *Geophys. Res. Lett.*, *28*, 4091–4094.
Thompson, A. M., et al. (2001), Tropical tropospheric ozone and biomass burning, *Science*, *291*, 2128–2132.
Waters, J. W., et al. (2006), The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite, *IEEE Trans. Geosci. Remote Sens.*, *44*(5), 1075–1092.
Zeng, G., and J. A. Pyle (2005), Influence of El Niño Southern Oscillation on stratosphere/troposphere exchange and the global tropospheric ozone budget, *Geophys. Res. Lett.*, *32*, L01814, doi:10.1029/2004GL021353.
Ziemke, J. R., and S. Chandra (2003), La Niña and El Niño-induced variabilities of ozone in the tropical lower atmosphere during 1970–2001, *Geophys. Res. Lett.*, *30*(3), 1142, doi:10.1029/2002GL016387.
Ziemke, J. R., S. Chandra, and P. K. Bhartia (1998), Two new methods for deriving tropospheric column ozone from TOMS measurements: The assimilated UARS MLS/HALOE and convective-cloud differential techniques, *J. Geophys. Res.*, *103*, 22,115–22,127.
Ziemke, J. R., S. Chandra, B. N. Duncan, L. Froidevaux, P. K. Bhartia, P. F. Levelt, and J. W. Waters (2006), Tropospheric ozone determined from Aura OMI and MLS: Evaluation of measurements and comparison with the Global Modeling Initiative's Chemical Transport Model, *J. Geophys. Res.*, *111*, D19303, doi:10.1029/2006JD007089.

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