

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

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Abstract. The global effects of the 2004 El Nino on tropospheric ozone and H₂O based on Aura OMI and MLS measurements are analyzed. Although it was a weak El Nino 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. H₂O in the upper troposphere showed similar changes but with opposite sign. These zonal changes in tropospheric ozone and H₂O are caused by the eastward shift in the Walker circulation in the tropical pacific region during El Nino. For the 2004 El Nino, biomass burning did not have a significant effect on the ozone budget in the troposphere unlike the 1997 El Nino. Zonally averaged tropospheric column ozone did not change significantly either globally or over the tropical and subtropical latitudes.

1. Introduction.

Ziemke and Chandra [2003] have shown that El Nino and La Nina events are major sources of decadal variability in tropospheric O₃ in the tropical atmosphere. These events produce changes in the convection pattern and large-scale circulation in the tropical Pacific region which cause tropospheric column ozone (TCO) to vary from the western to the eastern Pacific with a sign change near the date line. During El Nino, TCO is enhanced over the Indonesian region and reduced over the eastern Pacific. La Nina generally produces the opposite effect. One of the most intense El Nino 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 Nino on tropospheric O₃ 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.*, 2003, *Zeng and Pyle*, 2005, *Doherty et al.*, 2006]. The study of El Nino and La Nina related changes in tropospheric O₃ has been generally limited to the tropical region because global measurements of tropospheric O₃ outside the tropics were not available. A number of studies have suggested that El Nino has significant influence on the inter-annual variation of stratosphere-troposphere exchange (STE) which affects tropospheric O₃ outside the tropics [*Langford et al.*, 1998; *James et al.*, 2003; *Zeng and Pyle*, 2005].

Recently, *Ziemke et al.* [2006] produced global maps of TCO from Aura Ozone Monitoring Instrument (OMI) and Microwave Limb Sounder (MLS) measurements beginning August 2004. TCO is determined using the tropospheric O₃ residual method which involves subtracting stratospheric column ozone (SCO) from total column ozone measured from MLS and OMI instruments. There was an El Nino 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 Nino on tropospheric O₃ outside the tropical region. The purpose of this paper is to study global effects of the 2004 El Nino

on tropospheric O₃ derived from the OMI/MLS instruments on Aura Satellite. This study combines tropospheric O₃ measurements with H₂O measurements from the MLS instrument on the same satellite. Like O₃, H₂O is affected by deep tropical convection and large-scale transport processes. During 1997, El Nino-related changes in tropospheric O₃ and upper troposphere (UT) H₂O were anti-correlated over most of the tropical region [*Chandra et al.*, 1998].

2. The 2004 El Nino Event.

According to the World Meteorological Organization (WMO) criterion [<http://www.nws.noaa.gov/ost/climate/STIP/ElNinoDef.htm>], an El Nino event occurs when the sea surface temperature (SST) in the Nino 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 Nino 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 (http://www.cpc.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). The SST values are lower compared to the 2002 El Nino and significantly lower compared to the 1997 El Nino. For example, the mean SST anomalies (Δ SST) for November and December 2004 were respectively 0.9°C and 0.8°C. For the same two months, Δ SST were 1.5°C for the 2002 El Nino, and 2.5°C for the 1997 El Nino. In all cases, the mean represents a three-month average which includes the preceding and following months. In order to study the El Nino-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 Nino) months. For October, November, and December 2004, Δ SST 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 Nino.

3. Satellite Data.

The OMI and MLS instruments on board the Aura spacecraft [Schoeberl, *et al.*, 2004] have been providing daily O₃ 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 O₃ 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 Ziemke *et al.* [2006] and MLS H₂O data at two pressure levels, 215 hPa and 316 hPa. Su *et al.* [2006] have studied some of the characteristics of H₂O data related to tropical convection.

Nearly two continuous years of daily O₃ and H₂O data are now available for studying inter-annual changes including a recent El Nino 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 O₃ average volume mixing ratio (O₃-AVMR) instead of TCO. They are related by the following expression [Ziemke *et al.* 2002]: $O_3\text{-AVMR} = 1.27 \text{ TCO} / (P_{\text{surface}} - P_{\text{tropopause}})$ where O₃-AVMR is in parts per million by volume (ppmv), TCO is in Dobson Units (DU, 1 DU = 2.69 × 10²⁰ molecules m⁻²), and P_{surface} and P_{tropopause} are surface and tropopause pressure in hPa. As shown in Ziemke *et al.* [2006], TCO and O₃-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 O₃-AVMR in the tropics and about 1.7 ppbv in middle and high latitudes.

4. El Nino Related Changes in Ozone and Water Vapor.

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 Nino 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 Nino 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 Nino 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 peak values of these anomalies are about 5-7 ppbv and represent 10-15% changes over mean values of 30-35 ppbv in this region. However, the regions of negative anomaly extend over a larger area 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 Nino 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 $\Delta\text{SST} > 0.5^\circ\text{C}$.

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 Nino related changes in O_3 and H_2O as a function of latitude. The solid line in Figure 3 contains data from the Pacific region only as in Figures 1 and 2. The dotted line includes all data between longitudes $\pm 180^\circ$. In both cases the correlation coefficient is the average of three months (October, November and December).

The latitudinal characteristics of the two curves in Figure 3 are similar. They both show significantly high negative correlation between $\pm 20^\circ$ 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.

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 deeper in the troposphere. Outside $\pm 30^\circ$ 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 Nino.

As noted in the Introduction, one of the most intense El Nino 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 Nino 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 $\pm 15^\circ$ latitude to include most of the tropical region. The reference (non-El Nino) years for calculating these changes are 1996 for the 1997 El Nino as in *Chandra et al.* [1998] and 2005 for the 2004 El Nino 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 (upper and middle panels). For example, the El Nino 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 sea surface temperature which cause an eastward shift in the large-scale Walker circulation. 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 H₂O 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 H₂O from the boundary layer to the middle and upper troposphere causing a decrease in O₃ and increase in H₂O.

These model studies also suggest that the positive and negative anomalies in O₃ are nearly equal in magnitude when only meteorological processes are considered. In 2004, both these anomalies in O₃-AVMR are nearly of equal magnitude in all three months. It is reasonable to conclude that they are primarily of dynamical origin. A similar inference can also be made for the O₃-AVMR anomaly in December 1997 (Figure 4, lower panel). A nearly equal magnitude of O₃ 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 Nino on Tropospheric Ozone.

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 10¹² 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 O₃ in the tropical region tend to cancel out. We have carried out a similar analysis for the 2004 El Nino for both tropical and extra-tropical regions. Table 1 summarizes the results of this analysis.

Table 1. O₃ mass abundance (in Tg) in the troposphere averaged over three months (October, November and December) in 2004 and 2005. Numbers in parentheses denote calculated 2 σ uncertainties.

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)

Table 1 suggests that the O₃ 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 2 σ uncertainty values shown in the table. This implies that biomass burning and other sources of O₃ production (e.g. lightning NO_x, stratospheric O₃ influx) did not play significant roles during the 2004 El Nino period in affecting global tropospheric O₃. 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.

In this paper we have studied the effects of the 2004 El Nino on tropospheric O₃ and H₂O based on Aura OMI and MLS measurements. Even though this was a weak El Nino 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 Nino-related changes in O₃ and H₂O in 2004 are similar to the 1997 El Nino in tropical latitudes between $\pm 15^\circ$. Both events showed an increase (decrease) of O₃ (H₂O) in the western Pacific and decrease (increase) of O₃ (H₂O) in the eastern Pacific. However, the magnitude of the change was very different. For example, the 2004 El Nino produced an increase of 10-15% in O₃ in the tropical western pacific region. The corresponding increase in O₃ during the 1997 El Nino 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 O₃ during 1997 are similar to 2004 over tropical latitudes. They are both anti-correlated with upper

troposphere H₂O. For the 2004 El Nino, the strong negative correlation between O₃ and H₂O seen in tropical latitudes decreases rapidly towards higher latitudes. This suggests that the convective processes affecting the distribution of O₃ and H₂O during an El Nino event are important mostly in tropical latitudes. The observed changes in tropospheric O₃ and H₂O during a weak El Nino like in 2004 suggest that the atmosphere is very sensitive to small perturbations in sea surface temperature.

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References.

- Chandra, S., J. R. Ziemke, W. Min, and W. G. Read, Effects of 1997-1998 El Nino on tropospheric ozone and water vapor, *Geophys. Res. Lett.*, 25, 3867-3870, 1998.
- Chandra, S., J. R. Ziemke, P. K. Bhartia, and R. V. Martin, Tropical tropospheric ozone: Implications for dynamics and biomass burning, *J. Geophys. Res.*, 107(D14), doi:10.1029/2001JD000447, 2002.
- Doherty, R. M., D. S. Stevenson, C.E. Johnson, W. J. Collins, and M. J. Sanderson, Tropospheric Ozone and El Nino-Southern Oscillation: Influence of atmospheric dynamics, biomass burning emissions, and future climate change, *J. Geophys. Res.*, 111, D19304, doi:10.1209/2005JD006849, 2006.
- Fishman, J., C. E. Watson, J. C. Larsen, and J. A. Logan, Distribution of tropospheric ozone determined from satellite data, *J. Geophys. Res.*, 95(D4), 3599-3617, 1990.
- Froidevaux, L., et al., Early validation analyses of atmospheric profiles from EOS MLS on the Aura satellite, *IEEE Trans. Geophys. Rem. Sens.*, 44, no. 5, 1075-1092, 2006.
- Fujiwara, M., et al., 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, 1999.
- James, et al., A 15-year climatology of stratosphere-troposphere exchange with a Lagrangian particle dispersion model 2. Mean climate and seasonal variability, *J. Geophys. Res.*, 108, 8522, doi:10.1029/2002JD002639, 2003.

- Kley, D., et al., Observations of near-zero ozone concentrations over the convective Pacific: Effects on air chemistry, *Science*, 274, 230-232, 1996.
- Langford et al., Modulation of middle and upper troposphere ozone at Northern midlatitudes by the El Nino/Southern Oscillation, *Geophys. Res. Lett.*, 25, 2667-2670, 1998.
- Levelt, P. F., et al., The Ozone Monitoring Instrument, *IEEE Trans. Geosci. Rem. Sens.*, 44, no. 5, 1199-1208, 2006.
- Peters W., M. Krol, F. Dentener, J Lelieveld, Influence of an El Nino Southern Oscillation signal in a multiyear global simulation of tropospheric ozone, *J. Geophys. Res.*, 106, 10389-10402, 2001.
- Schoeberl, M. R., et al., Earth observing systems benefit atmospheric research, *EOS*, 85, 177-178, 2004.
- Su, H., W.G. Read, J.H. Jiang, J.W. Waters, D.L. Wu, E.J. Fetzer, Enhanced positive water vapor feedback associated with tropical deep convection: New evidence from Aura MLS, *Geophys. Res. Lett.* 33, L05709, doi:10.1029/2005GL025505, 2006.
- Thompson, A. M., et al., Tropical tropospheric ozone and biomass burning, *Science*, 291, 2128-2132, 2001.
- Waters, J. W., et al., The Earth Observing System Microwave Limb Sounder (EOS MLS) on the Aura satellite, *IEEE Trans. Geosci. Rem. Sens.*, 44, no. 5, 1075-1092, 2006.
- Zeng, G., and J. A. Pyle, Influence of El Nino Southern Oscillation on stratosphere/troposphere exchange and the global tropospheric ozone budget, *Geophys. Res. Lett.* 32, L01814, doi:10.1029/2004GL021353, 2005.
- Ziemke, J. R., S. Chandra, and P. K. Bhartia, 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, 1998.
- Ziemke, J. R., and S. Chandra, La Nina and El Nino-induced variabilities of ozone in the tropical lower atmosphere during 1970-2001, *Geophys. Res. Lett.* 30, 1142, doi:10.1029/2002GL016387, 2003.
- Ziemke, J. R., et al., 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, 2006.

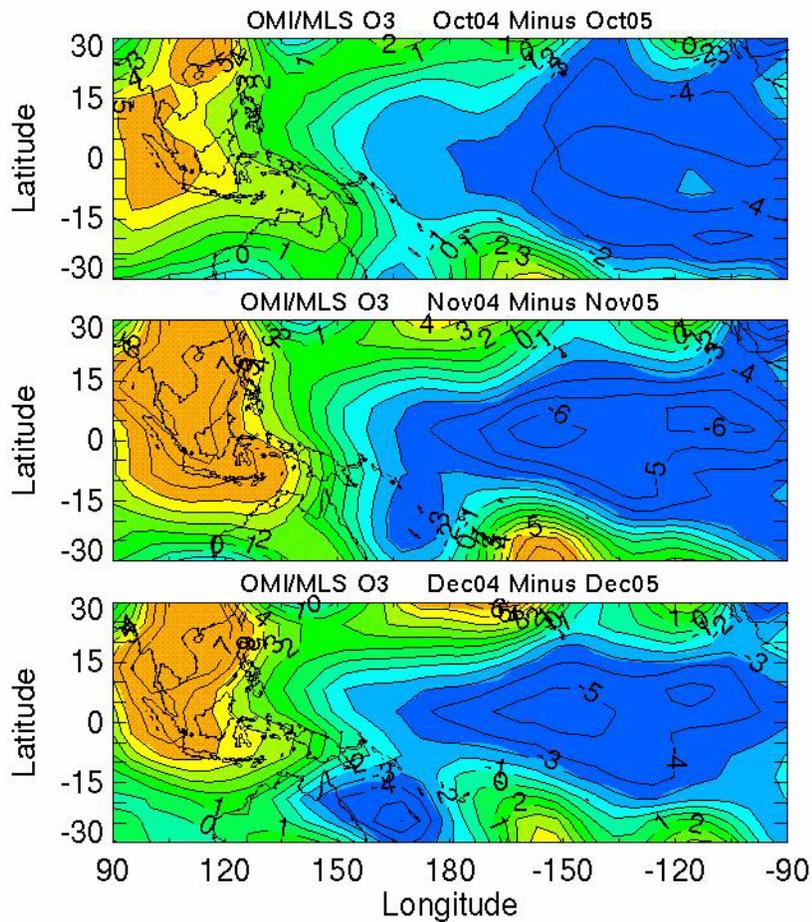


Figure 1. El Nino related changes in tropospheric O₃-AVMR over the Pacific region (90° W to 90° E) covering the latitude range ±30°. The three panels show relative changes in October, November and December months in 2004 with respect to corresponding months in 2005 (a non-El Nino year). The contour lines are in ppbv. The colors are used to highlight main features.

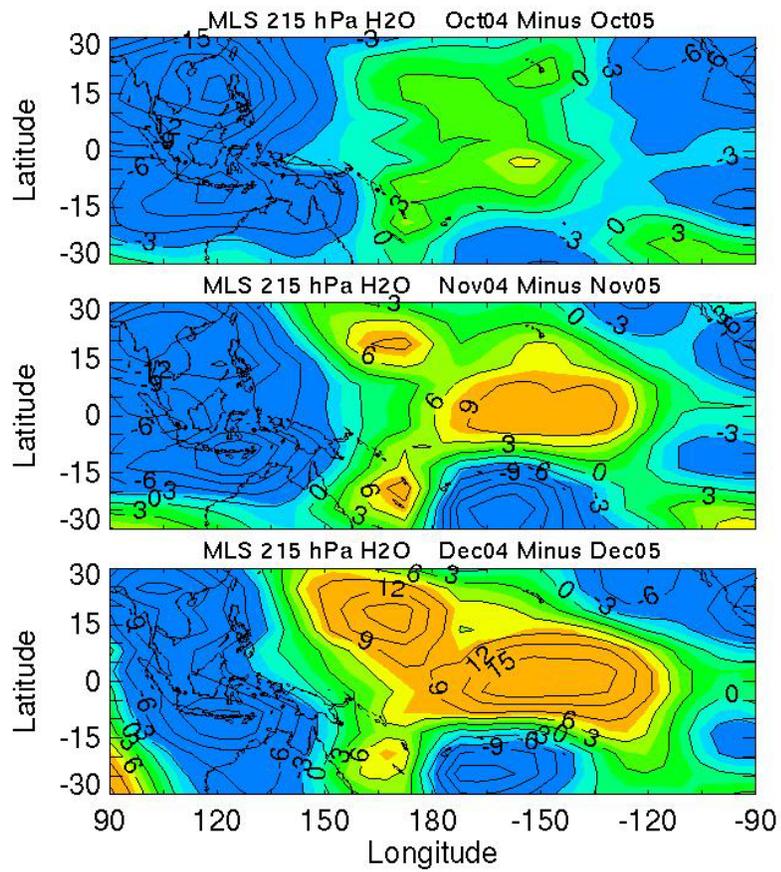


Figure 2. The same as Figure 1 but for H₂O at 215 hPa. The contour lines are in ppmv.

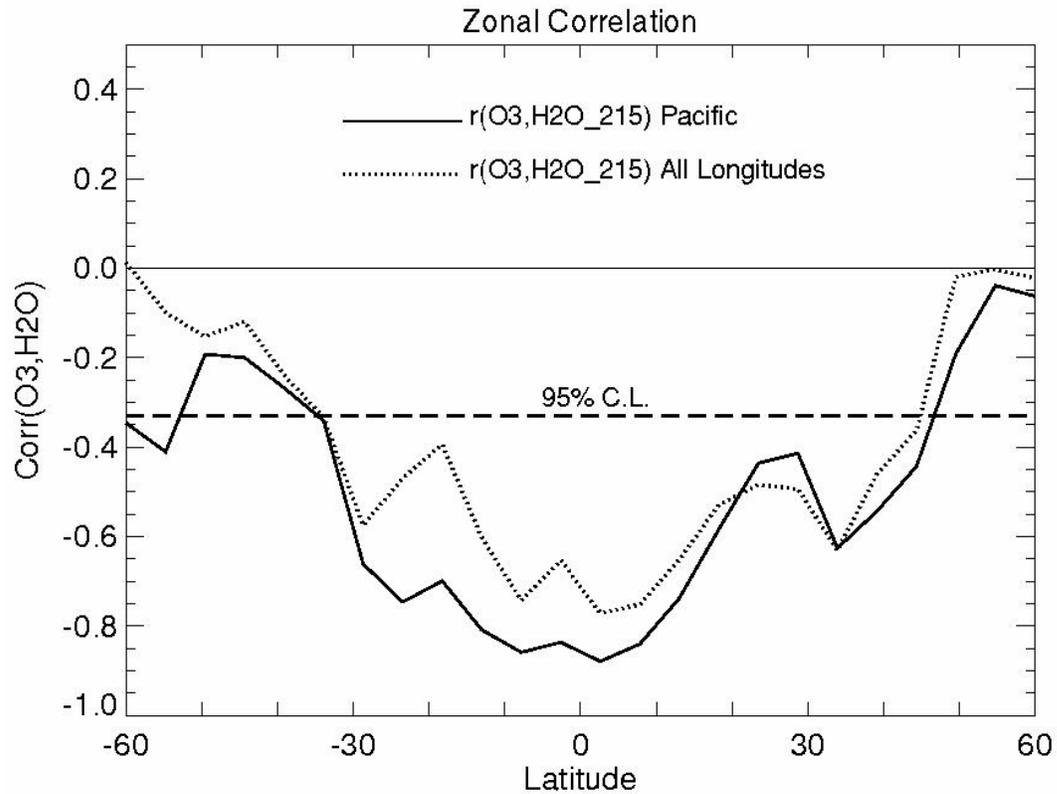


Figure 3. The correlation coefficient of El Niño related changes in O₃-AVMR and 215 hPa H₂O mixing ratio. The dotted line includes all data between longitudes ±180°. The solid line includes only the Pacific data (90°W-90°E) as in Figures 1 and 2. The dashed line represents the 95% confidence level.

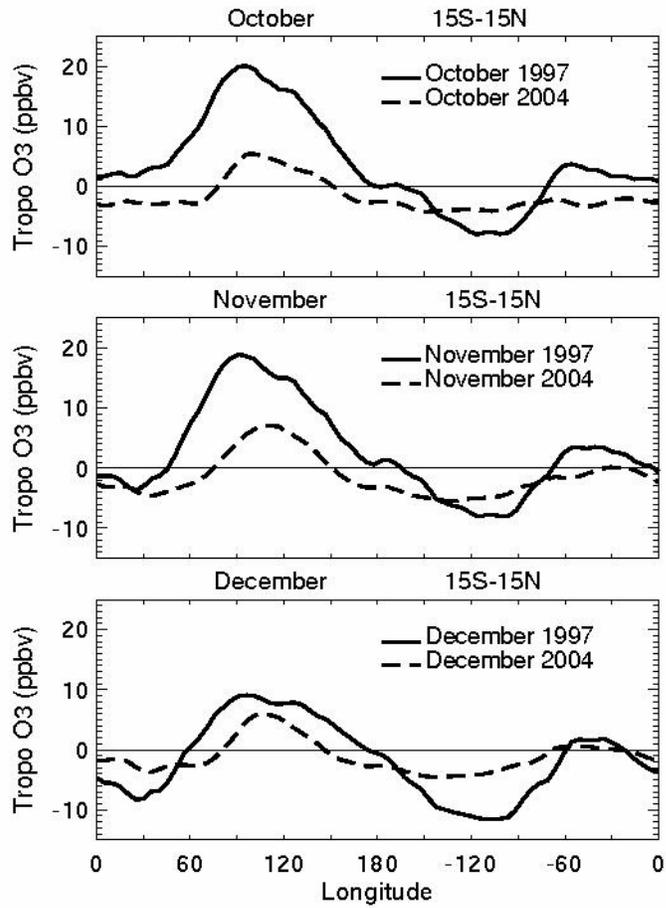


Figure 4. Comparison of relative changes in O₃-AVMR for the 1997 and 2004 El Nino events. The 1997 values are derived from the version 8 total column ozone data using the Convective Cloud Differential (CCD) method [Ziemke *et al.*, 1998].