ENSO influence on zonal mean temperature and ozone in the tropical lower stratosphere

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[1] Analyses of a whole atmosphere chemistry-climate model simulation forced by historical sea-surface temperature variations show that tropospheric El Nino – Southern Oscillation (ENSO) events are linked to coherent variations of zonal mean temperature and ozone in the tropical lower stratosphere, tied to fluctuations in tropical upwelling. ENSO temperature variations in the lower stratosphere are out of phase with tropospheric variations, and stratospheric ozone and temperatures are in phase. These model results motivated revisiting observational data sets for both temperature and ozone, and the observational data reveal coherent signals in the tropical stratosphere, very similar to the model results. The stratospheric ENSO variability has been masked in the observational data to some degree by the volcanic eruptions of El Chichon (1982) and Pinatubo (1991), which both occurred during ENSO warm events. The coherent temperature and ozone signals are evidence that ENSO modulates upwelling in the tropical lower stratosphere.
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1. Introduction

[2] A prominent source of interannual variability in tropospheric weather and climate is associated with the El Nino – Southern Oscillation (ENSO) phenomenon, which is linked to variations in tropical sea surface temperatures, convection, and atmospheric temperature and circulation throughout the global troposphere. ENSO has its origins in the tropics, linked to coupled atmosphere-ocean dynamics, but strong circulation effects are also observed in the extratropics associated with Rossby wave propagation [e.g., *Trenberth et al.*, 2002]. The spatial pattern of ENSO influence on atmospheric temperatures has been documented by *Yulaeva and Wallace* [1994] and *Calvo et al.* [2004], using satellite observations from the Microwave Sounding Unit (MSU), to highlight overall warming of the tropical troposphere superimposed on equatorially symmetric subtropical Rossby wave gyres for ENSO 'warm events'. Lower stratospheric MSU temperatures show an overall mirror image of the tropospheric pattern, particularly for the zonally asymmetric wave structure. Other studies have sought to quantify ENSO influence on stratospheric circulation, especially in the winter extratropics, although the statistical evidence based on observations has given mixed results: *Hamilton* [1993] and *Baldwin and O'Sullivan* [1995] find weak ENSO signals, while *Camp and Tung* [2007] and M. Free and D. Seidel (The observed ENSO temperature signal in the stratosphere, submitted to Journal of Geophysical Research, 2009) note significant Arctic winter effects. Some global circulation models with a well-resolved stratosphere find a significant influence of ENSO in the winter polar stratosphere, such that the ENSO 'warm events' are linked to enhanced planetary waves and disturbed polar vortex conditions [*Sassi et al.*, 2004; *Bronnimann et al.*, 2004; *Manzini et al.*, 2006; *Ineson and Scaife*, 2009]. There has been less emphasis on observations or model results of ENSO effects in the tropical stratosphere, although *Reid et al.* [1989] and *Reid* [1994] show statistical evidence of ENSO in the lower stratosphere based on tropical radiosonde observations.

[3] Recently, *Garcia and Randel* [2008] have analyzed a model simulation of the period 1950–2003, focused on understanding mechanisms for long-term increases in the stratospheric tropical upwelling (Brewer-Dobson) circulation. In addition to the long-term increases, time series of the model upwelling near the tropical tropopause showed strong variability linked to ENSO (forced by sea surface temperatures imposed in the model). These variations in upwelling are in-turn linked to fluctuations in zonal mean temperature and ozone above the tropical tropopause [*Marsh and Garcia*, 2007], with characteristic spatial structures, and also to coherent patterns in the extratropical lower stratosphere. These model results prompted examination of observational temperature and ozone data sets for ENSO signatures in the tropical stratosphere. The focus of this paper is to document the modeled and observed ENSO behavior in temperature and ozone, and discuss the implications for variability in the tropical stratosphere.

2. Data and Analyses

[4] The NCAR Whole Atmosphere Community Climate Model (WACCM) is a comprehensive chemistry-climate model covering the altitude range 0–140 km [*Garcia et al.*, 2007]. The simulation analyzed here (for 1960–2006) includes forcing by observed sea-surface temperatures (which contain observed ENSO variability), together with observed changes in greenhouse gases and halogen species relevant for stratospheric ozone chemistry. A stratospheric quasi-biennial oscillation (QBO) is imposed by relaxing (nudging) to observed winds. This simulation is one member of the ensemble considered for the SPARC CCMval model validation project (http://www.pa.op.dlr.de/CCMVal/).

[5] Analyses of observed temperatures are based on the Radiosonde Innovation Composite Homogenization (RICH) data set [*Haimberger et al.*, 2008]. These data are based on historical radiosonde observations, adjusted (using meteorological reanalyses and nearby radiosondes) to

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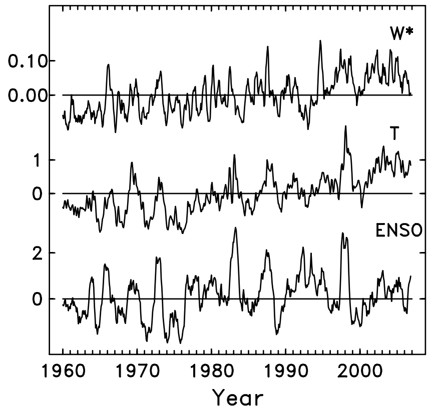

Figure 1. (bottom) Time series of the Multivariate ENSO Index (MEI) used to identify ENSO variability in the statistical regression analysis. (middle) WACCM zonal mean temperature anomalies (K) at 300 hPa, averaged over 30°N–30°S. (top) WACCM residual mean vertical velocity anomalies (mm/sec) at 100 hPa, averaged over 20°N–20°S.

account for artificial changes in instrumentation or observational practice. While the RICH data extend back to 1958, we note that there are substantial uncertainties in all the radiosonde data sets for the pre-satellite (pre-1979) era, especially for the data sparse tropics and SH [*Randel et al.*, 2009]. The data used here are monthly and zonal average temperature anomalies.

[6] Stratospheric ozone observations are from the Stratospheric Aerosol and Gas Experiment II (SAGE II) satellite, covering the period 1984–2005 [*McCormick et al.*, 1989]. These data are based on solar occultation measurements, providing high quality and high vertical resolution, but relatively sparse spatial sampling (taking approximately one month to sample the latitude range 50 N–50 S). Our analyses are based on monthly binned, zonally averaged data (described in more detail by *Randel and Wu* [2007]).

[7] ENSO and other climate signals in the various data sets are derived using a multivariate linear regression analysis, including terms to account for long-term trends, solar cycle (using the solar F10.7 radio flux as a proxy), two orthogonal time series to model the QBO [*Wallace et al.*, 1993], plus an ENSO term. For temperature long-term trends are modeled using a linear term, while for ozone we use equivalent effective stratospheric chlorine (EESC), as by *Randel and Wu* [2007]. ENSO variability is modeled using the Multivariate ENSO Index (MEI) from the NOAA Climate Diagnostics Center, http://www.cdc.noaa.gov/people/klaus.wolter/MEI/, with atmospheric variables lagged by two months. The MEI time series is shown in Figure 1, with positive values corresponding to warm SSTs and a warm tropical troposphere (so-called warm events). In the regression analyses we omit two years after each of the large volcanic eruptions (Agung in March 1963, El Chichon in April 1982 and Mt. Pinatubo in June 1991), in order to avoid influence from the associated large transient warming events in the stratosphere; this is an important detail, as there is significant cancellation between the latter two volcanic events and ENSO anomalies, as discussed further below. Uncertainty estimates for the statistical fits are calculated using a bootstrap resampling technique [*Efron and Tibshirani*, 1993], which includes the effects of serial autocorrelation.

3. Results

[8] The ENSO variability incorporated into WACCM via the imposed sea surface temperatures (SSTs) has a significant influence on global-scale temperature and circulation. A clear ENSO influence on zonal mean temperature in the tropical troposphere is illustrated in Figure 1, showing that WACCM temperatures at 300 hPa are closely coupled with the ENSO index. The spatial structure of the ENSO influence on WACCM zonal mean temperature (derived from the regression analysis) is shown in Figure 2a, revealing coherent in-phase behavior throughout the tropical troposphere (over approximately 30°N–30°S, up to the tropopause). There are also out of phase tropospheric temperature variations at middle latitudes in Figure 2a, and corresponding variations in subtropical jet intensity (stronger during ENSO warm events; not shown here). Figure 2a also shows a strong out-of-phase temperature variation in the tropical lower stratosphere (centered near 20 km over ~20°N–20°S), which is approximately twice as large as

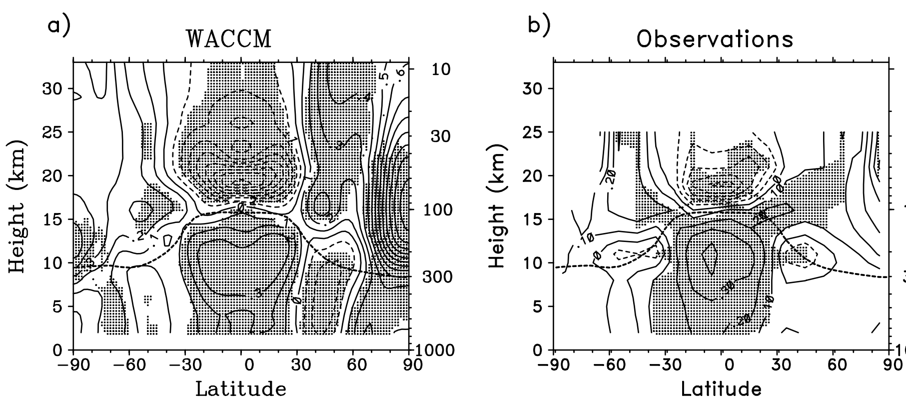

Figure 2. Meridional cross sections of zonal mean temperature regressed onto the Multivariate ENSO Index (MEI). Results are shown based on (a) the WACCM simulation, and (b) the RICH radiosonde observational data set. Contour interval is 0.1 K/MEI index, and shading denotes statistical significance above the 95% level. The thick dashed line in each panel denotes the tropopause.

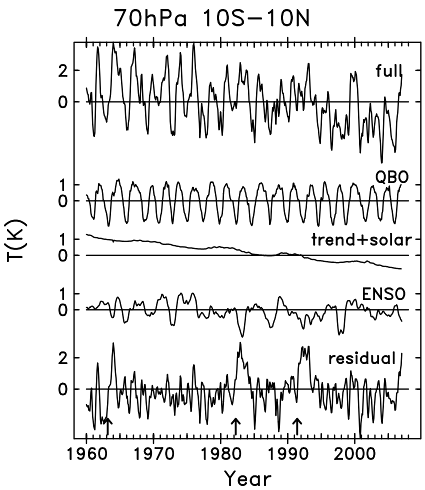

Figure 3. Top curve shows time series of zonal mean temperature at 70 hPa averaged over 10°N–10°S from the RICH radiosonde data set. The lower curves show components of variability derived from the multivariate regression fit, together with the residual. Note that the volcanic warming signals of Agung (1963), El Chichon (1982) and Pinatubo (1991) (noted by the arrows) are clearly seen in the residual time series, although not evident amid the other variability in the full time series.

the corresponding tropical tropospheric signal; there is a node in the ENSO pattern near the tropical tropopause. There are also coherent ENSO patterns at higher latitudes in the stratosphere, especially in the Northern Hemisphere (corresponding to a warmer, more disturbed polar vortex during ENSO warm events, as noted in previous WACCM simulations [e.g., *Sassi et al.*, 2004]). However, the focus here is on the ENSO signal in the tropical lower stratosphere.

[9] Regression analysis of the ENSO variability in the observed zonal mean temperature data is shown in Figure 2b, based on the period 1960–2006. The overall patterns and magnitudes of the ENSO signal in the observations is remarkably similar to the WACCM results in Figure 2a, including in-phase variation in the tropical troposphere and out-of-phase behavior in the tropical lower stratosphere, with a node near the tropopause. The magnitude of the observed and simulated ENSO signal is similar in the troposphere, while in the lower stratosphere the WACCM result is somewhat larger than observed. The observations (Figure 2b) also show evidence for the reversed phase behavior over middle latitudes (30°–60°N and S) seen in the WACCM results, particularly in the UTLS region. The high northern latitude ENSO signal is weaker and less statistically significant in the observations compared to WACCM. However, we note that much stronger ENSO effects are evident in the Arctic stratosphere if the analyses are focused on the winter season (as given by *Camp and Tung* [2007] and Free and Seidel (submitted manuscript, 2009)).

[10] Time series of observed zonal mean temperature anomalies at 70 hPa, 10°N–10°S are shown in Figure 3, together with the regression-derived components of variability associated with the QBO, decadal changes (trend plus solar), and ENSO, plus the residual variability (which is dominated by the transient warming events following the volcanic eruptions in 1963, 1982 and 1991). This decomposition reveals several aspects about the ENSO variability in this region, which contributes fluctuations of order ±1 K. First, ENSO is not at all evident among all the components of variability in the full time series; the QBO signal is equally sized in this region, and the net anomalies are often a combination of QBO and ENSO effects (this point was emphasized by *Reid* [1994]). Second, the ENSO-associated cooling at 70 hPa during the 1982–83 and 1992–95 ENSO events were to some degree masked by the transient warming following the El Chichon and Pinatubo volcanic eruptions; note that the volcanic signals do not stand out clearly in the full data record.

[11] ENSO variability in the WACCM zonal mean ozone is shown in Figure 4a, expressed as percent ozone change (per unit MEI index) compared to the local background zonal mean ozone. The largest signal is found in the tropics near and above the tropopause, with ozone fluctuations that are out-of-phase with ENSO (and in-phase with lower stratosphere temperature variations in Figure 2a). The maximum magnitude of the tropical ozone variations near 18 km is ~7%/MEI index, i.e. ENSO can account for local variations of ~±15% (given the MEI variations in Figure 1). There are also coherent positive ozone variations observed in the lower stratosphere over middle latitudes (~30°–60°N and S), similar to the patterns observed in temperature (Figure 2a). The overall coherent temperature-ozone variability in the lower stratosphere is a signature of the influence of ENSO variations in zonal mean upwelling near the tropical tropopause, as shown for the WACCM simulation in Figure 1.

[12] The ENSO ozone signal derived from the SAGE II satellite observations, covering the period 1984–2005, is shown in Figure 4b. The observed result is remarkably similar to the WACCM simulation, with a negative maximum centered above the tropical tropopause of almost the same magnitude, plus coherent positive patterns in the lower stratosphere over ~30°–50°N and S. While the SAGE II data record (1984–2005) is substantially shorter than the WACCM simulation (1960–2006), the overall similarity in patterns is unmistakable evidence of a coherent ENSO signature.

4. Discussion

[13] Many previous analyses of ENSO influence on the stratosphere have focused on the winter extratropics, where some models show enhanced planetary waves and a more disturbed polar vortex [*Sassi et al.*, 2004; *Bronnimann et al.*, 2004; *Manzini et al.*, 2006; *Ineson and Scaife*, 2009]. Statistical analysis of observations have suggested overall weak signals in high latitudes [*Hamilton*, 1993; *Baldwin and O'Sullivan*, 1995], although recent analyses of updated data sets reveal strong ENSO signals in the Arctic stratosphere during winter [*Camp and Tung*, 2007; Free and Seidel, submitted manuscript, 2009). There has been less focus on ENSO influence in the tropical stratosphere, especially for the zonal mean structure. The results here show a strong ENSO signal in zonal mean temperature and ozone in the tropical lower stratosphere in both the WACCM model and observational data sets. There is remarkably good agreement in the spatial patterns of ENSO

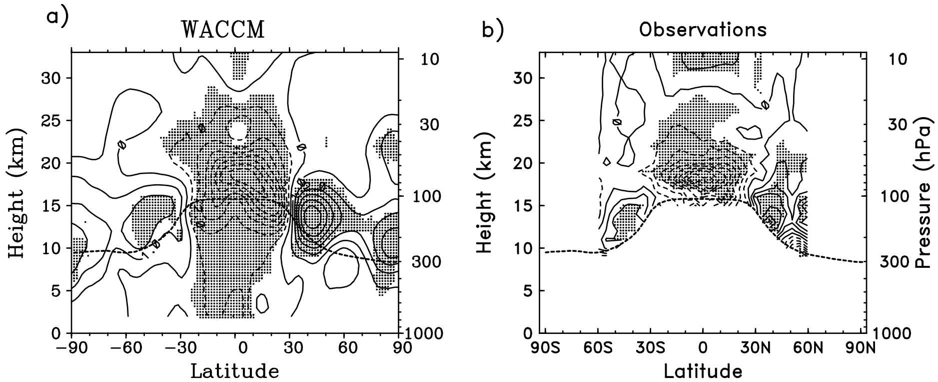

Figure 4. Meridional cross sections of zonal mean ozone regressed onto the Multivariate ENSO Index (MEI). Results are shown based on (a) the WACCM simulation, and (b) the SAGE II satellite observations (data only over 60°N–60°S). Ozone regressions are shown as local percent variations, with contour interval of 1%/MEI index, and shading denotes statistical significance above the 95% level. The thick dashed line in each panel denotes the tropopause.

signals between the model and observations for both temperature (Figure 2) and ozone (Figure 4), including the out-of-phase maxima in the midlatitude lower stratosphere for both quantities. The stratospheric zonal mean temperature signal is oppositely phased to that in the troposphere, with a node near the tropopause. ENSO temperature variations are an important component of variability in the lower stratosphere (as noted previously by *Reid et al.* [1989] and *Reid* [1994]), comparable to the influence of QBO and volcanic effects. Note that the stratospheric cooling associated with the ENSO events of 1982–83 and 1992–95 substantially masked the volcanic warming after the El Chichon and Pinatubo volcanic eruptions, and this accounts for the apparent absence of volcanic signals in the full time series at 70 hPa (Figure 3). We note that there can be substantial confusion of the ENSO and volcanic signals in shorter time series, but that was alleviated here by extension of the temperature time series back to 1960, and omission of the volcanic time periods in the regression analysis. *Marsh and Garcia* [2007] have also shown that there can be confusion between the ENSO and 11-year solar signals in relatively short data records, so that it is important to properly account for ENSO in statistical data analysis.

[14] The similarly-signed variations in temperature and ozone are a signature of ENSO-induced fluctuations in zonal mean vertical velocity near the tropical tropopause, as can be directly seen in the WACCM results (shown in Figure 1). Such upwelling variations will also be important for other trace constituents with strong vertical gradients near the tropical tropopause, such as carbon monoxide [e.g., *Randel et al.*, 2007]. Detailed analysis of the dynamical forcing of the ENSO-associated upwelling in WACCM is a topic of current research (N. Calvo et al., manuscript in preparation, 2009).

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