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# The effect of ENSO activity on lower stratospheric water vapor

F. Xie<sup>1</sup>, W. Tian<sup>1,2</sup>, J. Austin<sup>3</sup>, J. Li<sup>4</sup>, H. Tian<sup>1</sup>, J. Shu<sup>1</sup>, and C. Chen<sup>1</sup>

<sup>1</sup>Key Laboratory for Semi-Arid Climate Change of the Ministry of Education, College of Atmospheric Sciences, Lanzhou University, China

<sup>2</sup>ICAS, School of Earth and Environment, University of Leeds, UK

<sup>3</sup>NOAA Geophysical Fluid Dynamics Laboratory, Princeton, NJ, USA

<sup>4</sup>State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

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Correspondence to: F. Xie (xie83@126.com)

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## Abstract

Using the ECMWF/NCEP reanalysis data, satellite observations from AURA MLS and UARS HALOE, and Oceanic Niño Index (ONI) data, the effects of El Niño and La Niña events on the stratospheric water vapor changes are investigated. Overall, El Niño events tend to moisten the lower stratosphere but dry the middle stratosphere. La Niña events are likely to dry the lower stratosphere over a narrow band of tropics (5° S–5° N) but have a moistening effect on the whole stratosphere when averaged over a broader region of tropics between 25° S–25° N. The moistening effect of La Niña events mainly occurs in lower stratosphere in the Southern Hemisphere tropics where a significant 20% increase in the tropical upwelling is caused by La Niña events. El Niño events have a more significant effect on the tropical upwelling in the Northern Hemisphere extratropics than in Southern Hemisphere extratropics. The net effect of ENSO activities on the lower stratospheric water vapor is stronger in the Southern Hemisphere tropics than in the Northern Hemisphere tropics.

## 1 Introduction

Due to its radiative and chemical significance the stratospheric water vapor has been widely studied in recent years in various aspects (e.g., Shindell, 2001; Forster and Shine, 2002; Stenke and Grewe, 2005; Tian et al., 2009). Sounding observations at Boulder indicate increasing lower stratospheric water vapor since 1981 (Oltmans et al., 2000). However, Boulder data and satellite observations from the Halogen Occultation Experiment (HALOE), Stratospheric Aerosol and Gas Experiment II (SAGE II) as well as Polar Ozone and Aerosol Measurement III (POAM III) reveal that the lower stratospheric water vapor decreases after 2000 (e.g., Randel et al., 2006; Dhomse et al., 2008; Solomon et al., 2010; Hurst et al., 2011). To understand observed stratospheric water vapor trends, factors impacting or controlling stratospheric water vapor changes become a subject of much interest in recent years (e.g., Fueglistaler and Haynes, 2005;

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Oltmans and Hofmann, 1995; Oltmans et al., 2000; Randel et al., 2006; Rosenlof et al., 2001; Tian and Chipperfield, 2006; Dhomse et al., 2008). Apart from the changing methane in the stratosphere which can cause water vapor changes via methane oxidation processes, it is found in those previous studies that the changes in tropopause temperatures, tropical upwelling and deep convective activities have a large impact on the stratospheric water vapor.

It is well known that El Niño-Southern Oscillation (ENSO) has a large impact on the global circulation. Previous studies have pointed out that ENSO can modulate the stratospheric water vapor due to its adjust on temperature and transport processes within the tropopause region (e.g., Gettelman et al., 2001; Sassi et al., 2004). Observational and comprehensive modeling studies (Gettelman et al., 2001; Geller et al., 2002; Hatsushika and Yamazaki 2003; Scaife et al., 2003; Fueglistaler and Haynes, 2005) found that strong El Niño events (warm phases of ENSO) have a moistening impact on the lower stratosphere while La Niña events (cold phases of ENSO) lead to a reverse change in the lower stratospheric water vapor. However, how and to what an extent ENSO activities influence the stratospheric water vapor is still under debate. Scaife et al. (2003) simulated contributions of ENSO on increasing stratospheric water vapor, but they did not distinguish the different effect of El Niño activities and La Niña activities on the lower stratospheric water vapor. Using NCEP reanalysis and a general circulation model, Gettelman et al. (2001) studied the effect of the El Niño and La Niña activities on the tropical tropopause layer and they found that the thermal tropopause during a La Niña cold event was not an isentropic surface while El Niño events could change the location of the water vapor minimum in the upper troposphere through modifying the large scale circulation and convection in the central Pacific. Some other studies found convincing evidence that SST changes associated with ENSO can modify Brewer-Dobson (BD) circulation in the tropical stratosphere (e.g., Manzini et al., 2006; García-Herrera et al., 2006). It is apparent from those previous studies that transport changes caused by anomalous SSTs associated with ENSO can affect the lower stratospheric water vapor. However, contributions of anomalous BD circulation

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during ENSO events on stratospheric water vapor have not been discussed in detail in previous studies. Furthermore, the relative importance of ENSO warm and cold phases in affecting the lower stratospheric water vapor and the main entry locations of tropospheric air into lower stratosphere during ENSO warm and cold phases are remain unclear.

In this paper, the effect of El Niño activities on the lower stratospheric water vapor and temperature is further analyzed and then compared to the corresponding effect of La Niña activities. The BD circulation changes associated with ENSO activities are also examined and their effects on the lower stratospheric water vapor are discussed. Section 2 describes the data used in this study; Section 3 discusses lower stratospheric temperature changes caused by ENSO activities and associated water vapor changes in the upper troposphere and lower stratosphere (UTLS). Section 4 analyses the changes in the BD circulation associated with ENSO activities and their effects on lower stratospheric water vapor changes. In Sect. 5 we discuss net effect of ENSO activities on lower stratospheric water vapor. Section 6 gives conclusions.

## 2 Data

The monthly mean European Center for Medium range Weather Forecasting (ECMWF) reanalysis data from 1961–2000 (ERA-40) are mainly analyzed in this paper. The National Centers for Environmental Prediction (NCEP) reanalysis-2 data, which have longer time period extending to 2008, are employed as a supplement when analyzing lower stratospheric water vapor trends. As the assimilated water vapor data from ECMWF/NCEP reanalysis may have systematic biases compared to real observations (Gettelman et al., 2010), the water vapor measurements from Microwave Limb Sounder (MLS) on AURA satellite and from the Halogen Occultation Experiment (HALOE) on the Upper Atmosphere Research Satellite (UARS) are also analyzed for comparisons.

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ENSO (El Niño and La Niña) activities are decided by the ONI data which are defined as the three-month running-mean SST departures in the Niño 3.4 region (5° N–5° S, 170° W–120° W) (Smith and Reynolds, 2003). El Niño events are characterized by a positive ONI greater than or equal to +0.5°C and La Niña events are characterized by a negative ONI less than or equal to –0.5°C. The SST departures are based on a set of improved homogeneous historical SST analyses (Extended Reconstructed SST – ERSST.v3) from NOAA (Smith et al., 2008). According to the ONI, long-term time series of ERA-40 data are divided into three groups with 122 months of data marked with El Niño events, 134 months of data marked with La Niña events and the other 224 months of data for normal conditions. The El Niño and La Niña anomalies are calculated by compositing together the detrended and deseasonalized time series for El Niño and La Niña months, respectively.

## 2.1 Water vapor anomalies in the UTLS region associated with ENSO

Before analyzing water vapor anomalies associated with ENSO from ERA-40 reanalysis, it is necessary to check whether the assimilated water vapor data resembles satellite measured water vapor in the tropical UTLS region. Figure 1 shows horizontal distributions of ERA-40 water vapor (averaged over 1961–2000) and MLS water vapor (averaged over 2005–2010) at 100 hPa. The latitude-height cross sections of zonal mean water vapor from ERA-40 reanalysis and MLS measurements are also given in Fig. 1. It is apparent that both the horizontal distribution at 100 hPa and vertical distribution of ERA-40 water vapor are overall in agreement with MLS water vapor, although the magnitudes of water vapor from the two datasets are slightly different. One possible reason for this discrepancy is that the two datasets span different time periods. It should be pointed out that ERA-40 water vapor values are poorly constrained by observations particularly in the UTLS region (e.g., Trenberth et al., 2005) while water vapor values in the UTLS generated by various numerical models also have large spreads in magnitudes (Gettelman et al., 2010). However, we can see from Fig. 1 that the spatial distributions of ERA-40 water vapor are in agreement with MLS water vapor.

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In this study, we mainly focused on the relative changes of the stratospheric water vapor caused by ENSO activities rather than analyzing absolute water vapor values. Therefore, an analysis of ERA-40 water vapor is still helpful since it has a longer time period than MLS and HALOE water vapor for the purpose of composite analysis. In the following, ERA-40 water vapor and cold point tropopause (or 100 hPa) temperatures, which directly control stratospheric water vapor values in ERA-40 data, will be analyzed combined with MLS and HALOE water vapor data in an attempt to cross check the robustness of results obtained.

Figure 2 first shows 100 hPa temperature and water vapor anomalies associated with El Niño and La Niña events. It is apparent that ENSO in different phases have different impacts on the 100 hPa temperature and water vapor at different tropical regions. An evident cooling can be noted in the middle and eastern Pacific at 100 hPa during El Niño events, while in the western Pacific region, where it is typically referred as the cold trap region (Newell and Gould-Stewart, 1981), the 100 hPa temperature shows a  $\sim 0.6$  K warming (Fig. 2a). The spatial pattern and magnitude of the temperature anomalies exhibit in Fig. 2a are in accordance with those in previous studies (e.g., Randel et al., 2000; Scaife et al., 2003). The 100 hPa water vapor anomalies during El Niño events (Fig. 2b) are overall consistent with the 100 hPa temperature anomalies (Fig. 2a), i.e., negative/positive temperature anomalies at 100 hPa are accompanied by negative/positive water vapor anomalies. As expected, La Niña events have an opposite effect on the temperature and water vapor at 100 hPa as that of El Niño events (Fig. 2c and d). Figure 2e, f, g and h shows the cold point tropopause temperature and water vapor anomalies associated with El Niño and La Niña events. We can see that the distributions and magnitudes of cold point tropopause temperature and water vapor anomalies are nearly the same as corresponding anomalies at 100 hPa, possibly due to relatively coarse vertical resolution of ERA-40 data in the UTLS region.

Figure 2 indicates that the ENSO signals in 100 hPa temperature are of opposite signs to those in tropical SSTs. Previous studies have also showed an opposite ENSO signal in the tropical lower stratosphere (Reid et al., 1989; Yulaeva et al., 1994).

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Calvo et al. (2004) pointed out that the cooling of the tropical lower stratosphere over the eastern Pacific during warm phases of ENSO is related to internal equatorial waves forced by anomalous convection in the troposphere associated with SST changes. For the entry of water vapor into the lower stratosphere, it is mainly controlled by the tropopause temperature. Newell and Gould-Stewart (1981) first proposed that the favorable location for tropical tropospheric water vapor entering stratosphere is over the tropical western Pacific. During warm/cold phases of ENSO, the 100 hPa temperature over the tropical western Pacific shows positive/negative anomalies implying a moistening/drying of the lower stratosphere. However, Gettelman et al. (2000) pointed out tropospheric water vapor can enter into the stratosphere over all tropical longitudes. Since there are negative/positive water vapor anomalies at 100 hPa over the centre and eastern Pacific during warm/cold phases of ENSO, one may wonder what is the net effect of El Niño (or La Niña) events on the tropical lower stratospheric water vapor. On the other hand, although there are negative/positive water vapor anomalies at 100 hPa during the warm/cold phases of ENSO, it does not necessarily imply a decrease/increase in the lower stratospheric water vapor. The tropopause may lie above/below 100 hPa during the warm/cold phases of the ENSO due to intensified/weakened convection which acts to lift/suppress tropopause to a higher/lower level.

Figure 3 further shows the longitude-height cross sections of water vapor anomalies during different phases of ENSO. The anomalies averaged over the Northern Hemisphere tropics (25° N–2.5° N) and the Southern Hemisphere tropics (2.5° S–25° S) are shown in Fig. 3a and c and Fig. 3b and d, respectively. We can see that water vapor increases in the western Pacific and Indian Ocean from 360 K to 390 K isentropic surfaces but decreases in the middle and eastern Pacific above 370 K isentropic surface during El Niño events. As is pointed out in previous literatures, 360–390 K isentropic surfaces are overall lie in the lower stratosphere (e.g., Holton and Gettelman, 2001). Figure 3 suggests that El Niño events tend to moisten the lower stratosphere in broad regions of tropics except over the middle and eastern Pacific where the lower

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stratospheric water vapor decreases. La Niña events do an opposite effect as El Niño events, i.e, moistening the lower stratosphere over the middle and eastern Pacific but drying the lower stratosphere over the western Pacific and Indian Ocean.

Also note that magnitudes of water vapor anomalies in the Southern Hemisphere tropics are overall larger than those in the Northern Hemisphere tropics. On the 380 K isentropic surface, the maximum positive water vapor anomaly over the western Pacific and Indian Ocean during El Niño events is 0.10 ppm (parts per million by mass) in the Northern Hemisphere tropics, but it reaches 0.14 ppm in the Southern Hemisphere tropics. The minimum negative water vapor anomalies in the middle and eastern Pacific during El Niño are -0.19 ppm in the Northern Hemisphere tropics and -0.31 ppm in the Southern Hemisphere tropics. The similar features can be noted during La Niña events. The result here suggests that the influence of ENSO activities on the lower stratospheric water vapor is stronger in the Southern Hemisphere tropics than in the Northern Hemisphere tropics.

It is interesting that the effect of ENSO on the water vapor over the western Pacific and Indian Ocean is most pronounced below 390 K isentropic surface while over the middle and eastern Pacific significant water vapor anomalies can be noted well above 390 K isentropic surface. Further check on the temperature anomalies on 370 K isentropic surface (Fig. 3e) indicates that the temperature anomalies over the middle and eastern Pacific are much larger than the anomalies in the western Pacific and Indian Ocean, consequently, the water vapor anomalies over the middle and eastern Pacific are much larger than those over the western Pacific and Indian Ocean on the same isentropic surface. The vertical velocity fields during ENSO events (Fig. 3f) show a strong upward motion around the middle and eastern Pacific, and a relatively weak upward motion over the western Pacific and Indian Ocean in ENSO situations suggesting that vertical transport of water vapor is stronger over the middle and eastern Pacific than that over the western Pacific and Indian Ocean during ENSO events. This may be the possible reason that water vapor anomalies over the middle and eastern Pacific can be noted well above the 370 K isentropic surface. Note that the vertical velocity fields

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along the tropical longitudes look to be in accordance with the pattern of the Walker circulation in ENSO situations (Webster and Chang, 1988) suggesting that the Walker circulation also plays an role in modulating the tropical lower stratospheric water vapor.

It is apparent from Figs. 2 and 3 that ENSO's effects on the lower stratospheric water vapor have large spatial variations. To estimate the net effect of El Niño/La Niña events on the lower stratospheric water vapor, the zonal mean water vapor anomalies averaged over different latitude bands in the tropics are shown in Fig. 4. We can see that El Niño activities result in positive water vapor anomalies at the tropical lower stratosphere. The result is consistent with previous studies, i.e., El Niño events have a moistening impact on lower stratospheric water vapor (e.g., Fueglistaler and Haynes, 2005; Gettelman et al., 2001; Geller et al., 2002; Hatsushika and Yamazaki, 2003). However, Fig. 4a shows that El Niño activities tend to dry the tropical middle stratosphere. The zonal mean water vapor anomalies during La Niña events (Fig. 4b) show a quite different pattern from that during El Niño events. As expected, La Niña events result in a negative water vapor anomaly at the lower stratosphere over the equator between 5° S–5° N (solid line). In the Southern Hemisphere tropics (2.5° S–25° S, dashed line) a large positive anomaly of lower stratospheric water vapor can be noted, while in the Northern Hemisphere tropics (2.5° N–25° N, dotted line) there are no significant stratospheric water vapor anomalies. Note that zonal mean water vapor anomalies during La Niña events averaged between the 25° S–25° N latitude band are all positive in the whole stratosphere. The result suggests that La Niña events tend to dry the lower stratosphere over a narrow band of tropics (5° S–5° N) but overall tend to moisten the whole stratosphere over a broader region of tropics between 25° S–25° N.

Although MLS water vapor time series span a short time period from 2005–2010, they can still be composited together with regard to El Niño and La Niña events for this 6-yr time period to provide more evidence on ENSO's effects on the lower stratospheric water vapor. Figure 5a and b shows 100 hPa MLS water vapor anomalies associated with El Niño and La Niña events. We can see that the spatial distributions of MLS water vapor anomalies at 100 hPa are generally in accordance with the corresponding

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ERA-40 water vapor anomalies (Fig. 2b and d). An exception is that the MLS water vapor anomalies are much larger than ERA-40 water vapor anomalies over the western Pacific and Indian Ocean, possibly because MLS water vapor time series are too short. The longitude-height cross sections of MLS water vapor anomalies averaged between the 25° N–25° S latitude band composited for El Niño and La Niña events are shown in Fig. 5c and d. Note that the vertical distributions of MLS water vapor anomalies exhibit a similar pattern as that of ERA-40 water vapor anomalies (Fig. 3a and b and Fig. 3c and d), with ENSO anomalies over the western Pacific and Indian Ocean being most pronounced at the lower stratosphere while over the middle and eastern Pacific significant water vapor anomalies existing well in the middle stratosphere.

To further verify the results obtained from ERA-40 data, 12-yr HALOE water vapor time series, which cover the time period 1993–2004, are composited with respect to ENSO events. Figure 5e and f shows the zonal mean HALOE water vapor anomalies averaged over different latitude bands composited for El Niño and La Niña events, respectively. Consistent with Fig. 4, HALOE water vapor anomalies in Fig. 5 also show that El Niño events tend to moisten the lower stratosphere but dry the middle stratosphere, while La Niña events have a moistening effect on the whole stratosphere when averaged over a broad region of tropics between 25° S–25° N. However, HALOE water vapor anomalies averaged over latitude band of 5° S–5° N indicate that the low stratosphere is not moistened during El Niño events and this is not in agreement with the results in previous studies and in Fig. 4a. It is worth to point out there are many missing values in the HALOE water vapor data between 5° S–5° N, particularly below 100 hPa. Furthermore, HALOE water vapor retrievals below tropical tropopause is largely contaminated by clouds (e.g., Randel et al., 2001). Therefore, the HALOE water vapor anomalies averaged between 5° S–5° N may be lack of robustness below 100 hPa. However, we can see from above analysis that the results obtained from ERA-40 reanalysis are overall supported by MLS and HALOE water vapor observations.

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### 3 BD circulation changes associated with ENSO

A noticeable feature in Fig. 4 is that the moistening effect of La Niña events mainly occurs in the lower stratosphere in the Southern Hemisphere tropics. To understand this asymmetric effect of La Niña events on stratospheric water vapor, we further analyze ENSO's effects on the BD circulation which is another important factor controlling the stratospheric water vapor change.

It has been reported in previous studies that during warm phases of ENSO planetary wave activities can be significantly enhanced (Van Loon and Labitzke, 1987; Hamilton, 1993; Camp and Tung, 2007; Garfinkel and Hartmann, 2007; Free and Seidel, 2009; Sassi et al., 2004; Manzini et al., 2006; García-Herrera et al., 2006; Taguchi and Hartmann, 2006) and hence, resulting in a stronger BD circulation in the stratosphere. Figure 6 shows ENSO-induced anomalies of vertical velocity of the BD circulation as well as corresponding E-P flux and zonal wind anomalies. Consistent with the previous studies (Manzini et al., 2006; Garfinkel and Hartmann, 2007; Free and Seidel, 2009), the vertical velocity of BD circulation between 15° S–15° N is significantly enhanced/weakened during El Niño/La Niña events (Fig. 6a and c). A more interesting feature in Fig. 6 is the hemispheric asymmetry of the E-P flux anomalies caused by ENSO events (Fig. 6b and d). El Niño events enhance the poleward/equatorward propagation of wave activities in the Northern/Southern Hemisphere. Consequently, the northern polar vortex is warmed and weakened with negative zonal wind anomalies while the southern polar vortex is not significantly affected. Cagnazzo et al. (2009) also reported a warming of the northern polar vortex during strong warm phases of ENSO. The result in Fig. 6b suggests that El Niño events have a more significant impact on the northern polar vortex than on the southern polar vortex. Compared to El Niño events, La Niña events have an overall opposite effect on the E-P flux and zonal mean zonal wind with a strengthened southern polar vortex (Figs. 6d). Note that the significant zonal wind anomalies in the tropical lower stratosphere should be also related to the quasi-biennial oscillation (QBO) (García-Herrera et al., 2006).

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As mentioned in Sect. 3, La Niña events actually have a moistening effect in the southern hemispheric lower stratosphere. Figure 6a and c suggests that this moistening effect is closely related to changes in the tropical upwelling caused by ENSO events. We can see from Fig. 6a and c that the climate mean of tropical upwelling with an upward vertical velocity of the BD circulation ( $w^*$ ) covers a wide area from 25° S–25° N. However, the anomalous upwelling ( $w^*$ ) caused by El Niño/La Niña events is positive/negative (enhanced/weakened tropical upwelling) only between 15° S–15° N, while at the latitude bands 25° S–15° S and 15° N–25° N, El Niño/La Niña events tend to weaken/enhance the upwelling. Also note that the effect of El Niño events on the  $w^*$  is more significant in the Northern Hemisphere extratropics than in the Southern Hemisphere extratropics (Fig. 6a) and La Niña events have a more significant effect on  $w^*$  in the Southern Hemisphere extratropics (Fig. 6c). Further analysis of the anomalous tropical upwelling  $w^*$  at 100 hPa reveals that both El Niño and La Niña events cause a weakening of  $w^*$  averaged over the Northern Hemisphere tropics between 2.5° N–25° N, with a 3% and 10% decrease relative to normal conditions. However, the  $w^*$  averaged over the Southern Hemisphere tropics between 2.5° S–25° S is increased by 6% during El Niño events and increased by 20% during La Niña events. It is apparent that the effect of La Niña events on the tropical upwelling is more significant than that of El Niño events, particularly in the Southern Hemisphere tropics. The significant enhancement of upwelling in the Southern Hemisphere tropics between 2.5° S–25° S will cause an increase of water vapor in the stratosphere despite that tropopause temperature changes caused by La Niña events may do an opposite effect, and this may be the main reason that La Niña events have a moistening effect on the stratosphere in the Southern Hemisphere tropics (Fig. 4b). The results here also imply that the effect of El Niño events on the lower stratospheric water vapor is more dominated by tropopause temperature changes while the effect of La Niña effect is more related to the changes in tropical upwelling.

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## 4 Integrated effect of ENSO activities on lower stratospheric water vapor

It is evident from the above analysis that the lower stratospheric water vapor anomalies caused by El Niño and La Niña events have an over all opposite spatial distributions. It is necessary here to examine the integrated effect of ENSO on the stratospheric water vapor. Figure 7a shows the longitude-latitude cross section of temperature anomalies at 100 hPa composited from all El Niño and La Niña events selected from 40 yr of ERA-40 reanalysis. We can see that the integrated effect of ENSO give rise to warmer 100 hPa temperatures over the middle and eastern Pacific between the latitude band 25° S–25° N. Over other regions of tropics ENSO events cause a decrease in 100 hPa temperatures except for two regions (12.5° N–25° N, 0–160° W and 12.5° S–25° S, 0–160° E). Randel et al. (2000) analyzed tropical tropopause temperature changes associated with ENSO events and found that ENSO events cause a warming of the tropopause in the middle and eastern Pacific regions and a cooling in the western Pacific and maritime continent areas. The spatial pattern of tropopause temperature changes associated with ENSO showed by Randel et al. (2000) is quite similar as that of 100 hPa temperature changes shown in Fig. 7a.

Figure 7b and c shows zonal mean water vapor and temperature anomalies averaged between the 5° S–5° N and 25° S–25° N latitude bands, respectively. Again, these anomalies are composited from all El Niño and La Niña events during the period from 1961–2000. The integrated effect of ENSO has no significant impacts on equatorial lower stratospheric water vapor (5° S–5° N) because the effect of El Niño activities partly offsets the effect of La Niña activities. While in the middle stratosphere, El Niño and La Niña activities together cause a slight decrease of water vapor. The integrated effect of ENSO activities gives rise to small and negative temperature anomalies in the lower and middle stratosphere. Gettleman et al. (2001) and Scaife et al. (2003) also showed that zonal averaged ENSO temperature anomalies in the lower stratosphere are small but negative at the equator. When zonal mean water vapor and temperature anomalies are averaged between the 25° S–25° N latitude band (Fig. 7c), the integrated

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effect of ENSO causes water vapor increases in the lower stratosphere and decreases in the middle stratosphere. The averaged temperature anomalies between the 25° S–25° N latitude band show a slight increase in the lower stratosphere and a decrease in the middle stratosphere. Figure 7b and c further confirms that the effects ENSO activities on the stratospheric water vapor and temperature have a latitudinal dependence within the tropics.

At this stage, it may be also instructive to examine whether ENSO events have an impact on long-term trends of the stratospheric water vapor. A qualitative analysis of linear trends of ERA-40 and NCEP reanalysis-2 cold point tropopause temperatures and water vapor reveals that those trends are quite different when the data recorder marked with ENSO activities being either included or excluded implying that ENSO activities may have an ineligible impact on trends of cold point tropopause temperature and hence on stratospheric water vapor trends (not shown). However, the assimilated water vapor data from ECMWF/NCEP reanalysis have systematic biases compared to real observations (Gettelman et al., 2010) while the time series of observed stratospheric water vapor are too short for trend analysis. Even the trends of cold point tropopause temperatures from ERA-40/NCEP reanalysis, which directly affect stratospheric water vapor, have uncertainties (Gettelman et al., 2009). This issue is worthy further investigation.

## 5 Summary and conclusions

Through composite analysis of ERA-40 reanalysis, and NCEP reanalysis-2 data based on Oceanic Niño Index, the potential effects of ENSO events on the stratospheric water vapor are investigated. In agreement with earlier studies, El Niño events tend to moisten the lower stratosphere. However, it is found that El Niño events are likely to dry the middle stratosphere. La Niña events tend to dry the lower stratosphere over a narrow band of tropics (5° S–5° N) but the average effect over a broader region of tropics

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between 25° S–25° N is to moisten the whole stratosphere. The above results are also supported by AURA MLS and UARS HALOE water vapor observations. The moistening effect of La Niña events mainly occurs in the lower stratosphere in the Southern Hemisphere tropics. The effects of El Niño and La Niña activities on lower stratospheric water vapor are likely to offset each other over the equator (5° S–5° N), but the average effect between the latitude band 25° S–25° N tends to moisten the lower stratosphere. Apart from tropopause temperature changes associated with ENSO which cause changes in the lower stratospheric water vapor, it is found that ENSO activities can modulate the stratospheric water vapor though changing the tropical upwelling. A 6% increase in the tropical upwelling averaged over the Southern Hemisphere tropics between 2.5° S–25° S can be noted during El Niño events while La Niña events can cause a significant 20% increase in the tropical upwelling in the Southern Hemisphere tropics and lead to a moistened lower stratosphere. The effect of La Niña events on the tropical upwelling is more significant than that of El Niño events, particularly in the Southern Hemisphere tropics.

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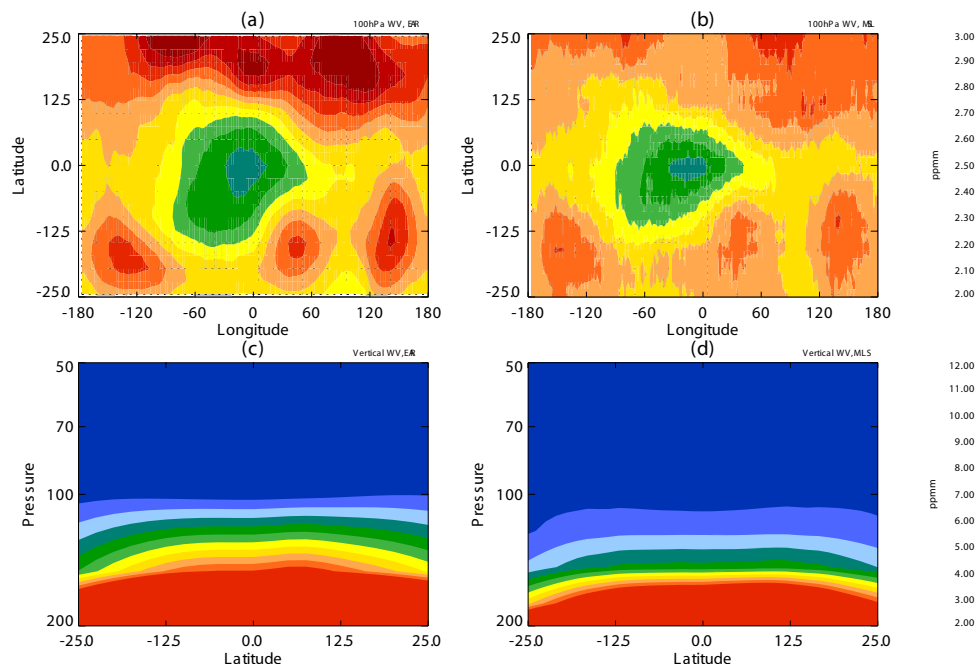
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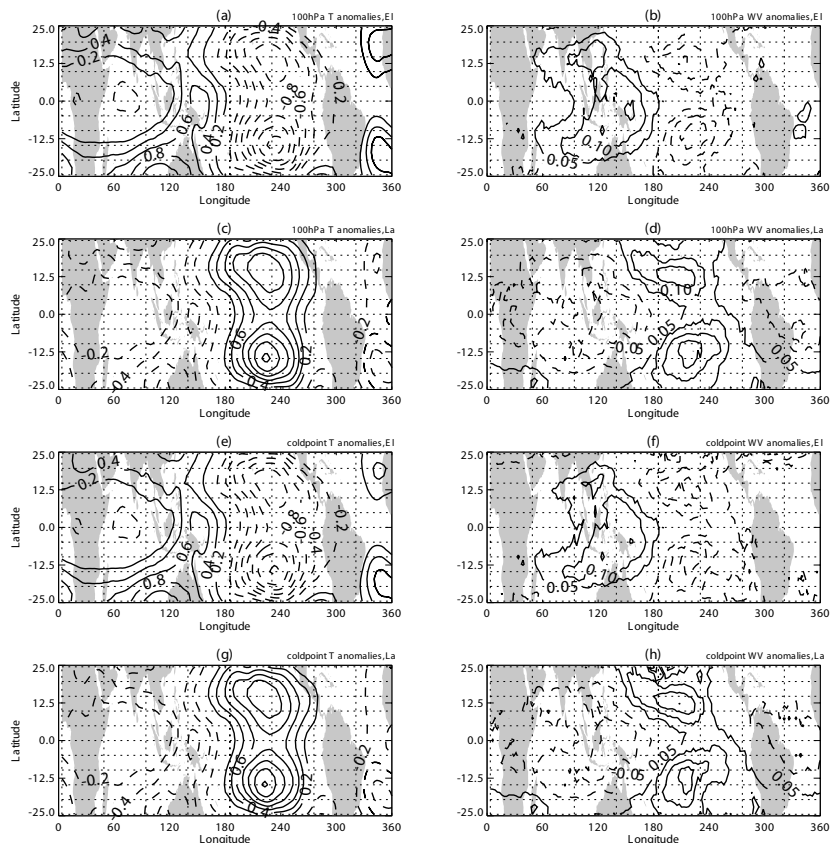
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**Fig. 1.** (a) ERA-40 water vapor distributions at 100 hPa averaged for the period 1961 to 2000. (b) MLS water vapor distributions at 100 hPa averaged for the period 2005 to 2010. (c) Longitude-height cross-sections of ERA-40 water vapor and (d) MLS water vapor. Contour intervals are 0.1 ppm (parts per million by mass) for (a)/(b) and 1 ppm for (c)/(d).

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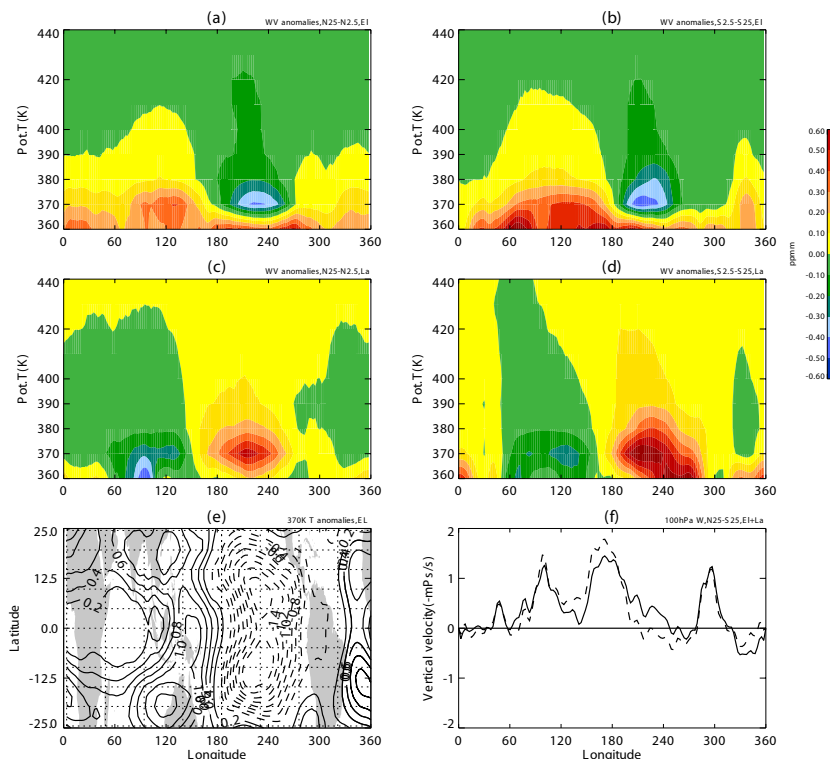


**Fig. 2.** (a, c) Temperature and (b, d) water vapor anomalies at 100 hPa composited for (a, b) El Niño and (c, d) La Niña events based on ERA-40 data. Contour intervals for temperature and water vapor anomalies are  $\pm 0.2$  K and  $\pm 0.05$  ppmm, respectively. (e, g) as (a, c), but for cold point tropopause temperature. (f, h) as (b, d), but for cold point tropopause water vapor.

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**Fig. 3.** Longitude-height cross sections of water vapor anomalies averaged between **(a, c)** 25° N–2.5° N and **(b, d)** 2.5° S–25° S latitude bands composited for **(a, b)** El Niño and **(c, d)** La Niño events based on ERA-40 data. Contour interval is  $\pm 0.1$  ppmv. **(e)** The temperature anomalies at 370 K isentropic surface for El Niño events based on ERA-40 data. Contour interval is  $\pm 0.2$  K. **(f)** Longitudinal variations of the 100 hPa vertical velocity averaged between the 25° N–25° S latitude band for (solid) El Niño events and (dashed) La Niña events based on ERA-40 data.

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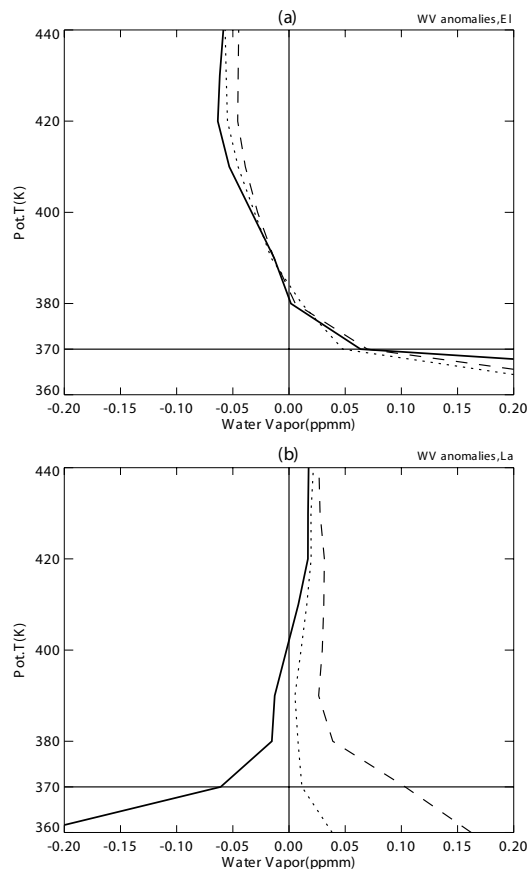
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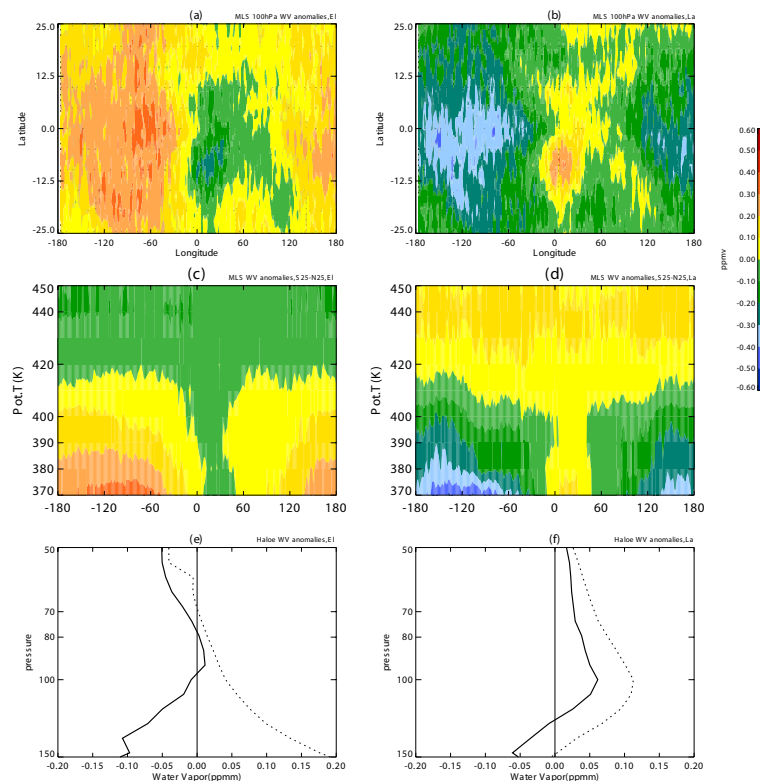
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**Fig. 4.** (a) Vertical profiles of zonal mean water vapor anomalies for (a) El Niño events and (b) La Niña events based on ERA-40 data. Solid, dashed and dotted lines are for zonal mean anomalies averaged between 5° N–5° S, 2.5° N–25° N, and 2.5° S–25° S, respectively. 370 K potential temperature, which roughly represents the tropical tropopause level, is delineated in each panel with solid lines.

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**Fig. 5.** MLS water vapor anomalies at 100 hPa composited for **(a)** El Niño and **(b)** La Niña events. Longitude-height cross sections of MLS water vapor anomalies averaged between the 25° N–25° S latitude band composited for **(c)** El Niño and **(d)** La Niña events. Contour intervals are  $\pm 0.1$  ppmv (parts per million by volume). Vertical profiles of zonal mean HALOE water vapor anomalies for **(e)** El Niño events and **(f)** La Niña events for the time period 1993–2004. Solid and dotted lines are for zonal mean anomalies averaged between 5° N–5° S and 25° S–25° N, respectively.

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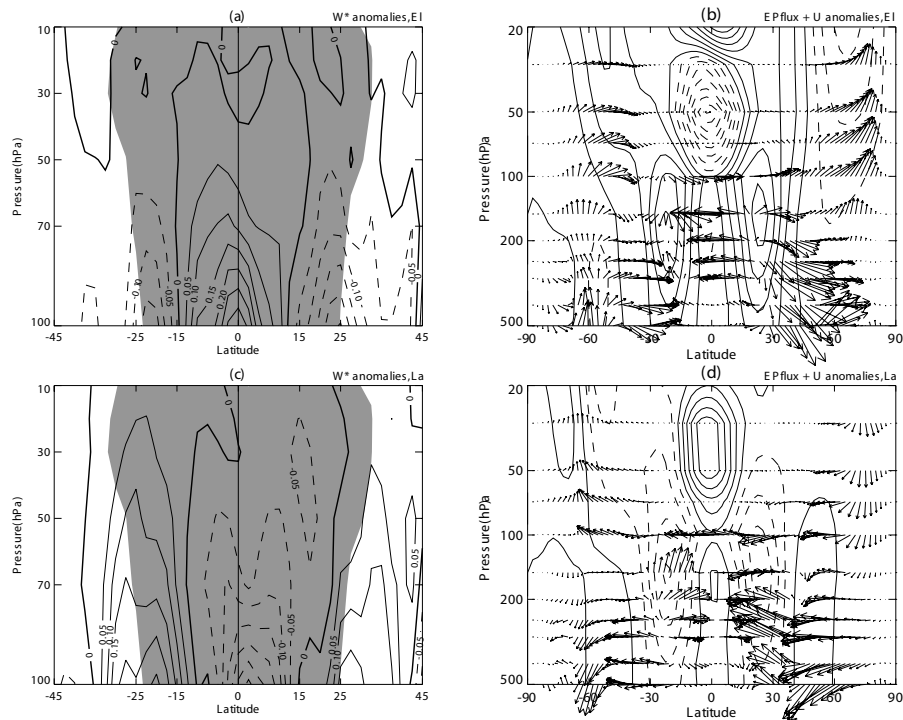
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**Fig. 6.** Vertical velocity anomalies of BD circulation ( $w^*$ ) for **(a)** El Niño events and **(c)** La Niña events based on ERA-40 data. The contour interval is  $\pm 0.05 \text{ mPa s}^{-1}$ . The zero contour lines are delineated as thick black solid lines. Positive and negative contours are represented by thin solid lines and dashed lines, respectively. The regions where climate mean vertical velocity of BD circulation ( $w^*$ ) is upward are shaded. Composites of the E-P flux and zonal wind for **(b)** El Niño events and **(d)** La Niña events based on ERA-40 data. The unit of horizontal vector is  $10^7 \text{ kg s}^{-1}$  and vertical vector is  $10^5 \text{ kg s}^{-1}$ . The contour interval for zonal wind anomalies is  $\pm 0.5 \text{ m s}^{-1}$ . Solid lines and dashed lines in (b) and (d) represent positive and negative zonal wind anomalies, respectively.

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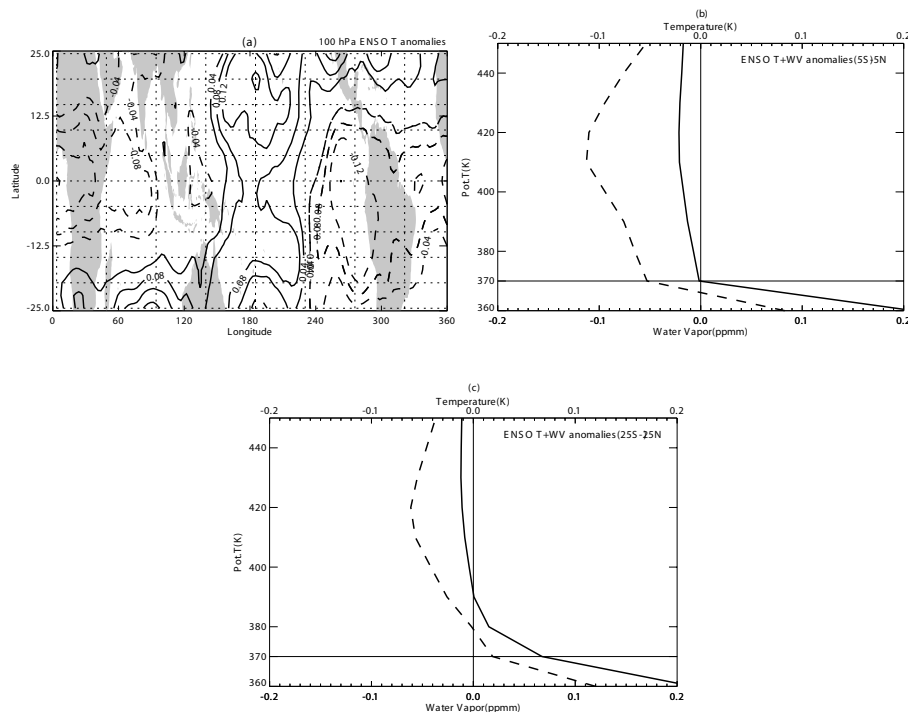
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**Fig. 7.** (a) The latitude-longitude cross section of temperature anomalies at 100 hPa composited from all El Niño and La Niña events during the period from 1961–2000 based on ERA-40 data. Positive and negative contours are represented by solid and dashed lines, respectively. Contour interval is  $\pm 0.04$  K. (b) Vertical profiles of zonal mean water vapor (solid line) and temperature (dashed line) anomalies (composited from all El Niño and La Niña events) averaged between the latitude band  $5^{\circ}\text{N}$ – $5^{\circ}\text{S}$  based on ERA-40 data. (c) Same as (b), but averaged over latitude band  $25^{\circ}\text{N}$ – $25^{\circ}\text{S}$ . 370 K potential temperature, which roughly represents the tropical tropopause level, is delineated in (b) and (c) with solid lines.

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