Response to Referee Comments of Referee 1

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Title: Signals of El Niño Modoki in the Tropical Tropopause Layer and Stratosphere

We are very grateful for the reviwer's helpful comments. We have modified our paper according to the comments and detailed point-by-point responses to those comments are summarized as below:

General Comments:

1. *The authors applied compositing analysis on a relatively short record of observational data, during which only a few El Nino events occurred. Given this relatively small sample size, it is crucial to assess the uncertainty and the robustness of the signals. For example, the temperature signals in high latitude stratosphere in Fig. 9 is less than 1K. But the temperature there can easily change by a few K from one year to another, then the seemingly El Nino signal may not be significant compared to the inter-annual variability, and could be resulted from an uneven sampling. In fact, the authors described their results as "significant" or "robust" on many occasions, but no uncertainty estimation or statistical significance analysis or any sensitivity tests are provided. Hence it is nor clear what ground those significance or robustness are based upon.*

The limitation of the observational data may be inevitable, and the authors did a good job to use model simulations to support their observational results. However, these simulations are run with one ensemble and for a relatively short period, and no uncertainty estimation is provided.

Response to General comment 1:

It is a very good comment. Indeed, our composite analysis based on a relatively short record of observational data. During this period, only a few El Nino events occurred. Thus, it is crucial to assess the robustness of the composite signals, like, the temperature anomalies. Though we used model simulations to support our observational results, yet our simulations are run for a relatively

short period. Actually, this problem also was pointed out by one of other referees.

In the revised paper, we done the significance test and extended our simulations' for longer time together to confirm our results are robust. The composite anomalies based to ERA-interim data and the simulation's results are tested by a Student's-t tested. On the other hand, we used the latest version of WACCM model (WACCM4) rerun the six experiments. Now, all the experiments were ran for 33 years with the first 3 years excluded for the model spin-up and the remaining 30 years are used for the analysis. The model climatologies are based on the last 30 years of the model output except when otherwise stated.

In the revised paper, significance test for the composite analysis based on ERA-interim data shows that the composite anomalies of circulation and temperature during El Niño Modoki events are statistically significant (See the Figure 1 below, it is Figure 8 in the revised paper). On the other hand, the results from those longer simulations also show statistically significant circulation anomalies (See Figure 2 below, it is Figure 10 in the revised paper). The significance test and extended simulations both illustrate that our results are reliable.

2. *In particular, the authors used the 6 years MLS data to assess the stratospheric water vapor distribution during canonical El Nino and El Nino Modoki events. During these 6 years, there is only one canonical El Nino event lasting 6 months and one El Nino Modoki event lasting 6 months. Give such small sample size, I don't think compositing analysis will give very meaningful results in this case. The difference between those 6 months and the 6-year average could be caused by other things besides El Nino, for example, QBO, or some other random internal variability. The authors claimed that the analysis of MLS data provides more robust results than ERA-Intrim data. I am not sure this is based on what ground because no uncertainty estimation is provided in the paper. I assumed the authors were referring to smaller spread within El Nino group in MLS data, but that is because those MLS data in El Nino group are not independent from each other (since there is only one event).*

Response to General comment 2:

We agree with this comment. Considering that the time series of MLS data is too short for composite analysis, but the ERA-interim data and model's output may have systematic biases compared to real observations (Gettelman et al., 2010), we delete the analysis of the stratospheric water vapor anomalies caused by El Niño Modoki based on MLS data. However, we think this question deserve further analysis when longer observed stratospheric water vapor data can be available.

References:

Gettelman, A., et al, Multimodel assessment of the upper troposphere and lower stratosphere: Tropics and global trends, J. Geophys. Res., 115, D00M08, doi:10.1029/2009JD013638. 2010.

Specific comments:

1. *It would be helpful if the authors can provide some details of the compositing analysis, such as how many El Nino events are considered and when are those events? is there any overlapping between the canonical El Nino group and the El Nino Modoki group? Are the results sensitive to the choice of the El Nino index, or to the choice of the threshold of the index? I noticed that the authors chose a lower threshold compared to some recent similar compositing analysis (e.g., Hurwitz et al. 2011A, Zubiaurre and Calvo 2012).*

Response to Specific comment 1:

Thanks for the suggestion. The samples of canonical El Niño and El Niño Modoki events analyzed in the paper are listed in the table 1 now (See Table 1 below, it is also Table 1 in the revised paper). When we select the samples, we consider the relatively strong and long time continuous El Niño events (at least, the SST anomaly larger than 0.5°C and lasting for more than half year). The events with a relatively short time period are not included in our composite analysis.

According to the NINO3 and EMI index, indeed, there are overlapping canonical El Niño and El Niño Modoki events, i.e., both NINO3 and EMI indexes are larger than 0.5°C. However, when both NINO3 and EMI indexes are larger

than 0.5°C, it is recognized as an El Niño Modoki event. When canonical El Niño and El Niño Modoki events are overlapping, though the SST anomaly of eastern Pacific is larger than 0.5°C, the SST anomalies over center Pacific are overall larger than those over eastern Pacific and the largest SST anomaly is over center Pacific. Thus, in our study, when canonical El Niño and El Niño Modoki events are overlapping, we define them as El Niño Modoki events.

For EMI index, 0.5°C is not a lower threshold. This is because the EMI index defined as EMI = $[SSTA]_C - 0.5 \times [SSTA]_E - 0.5 \times [SSTA]_W$, where the subscripted brackets represent the area mean SSTA over the central Pacific region ($[SSTA]_C$: 10°S–10°N, 165°E–140°W), the eastern Pacific region ($[SSTA]_E$: 15°S–5°N, 110°W–70°W), and the western Pacific region ($[SSTA]_W$: 10°S–20°N, 125°E–145°E). Actually, when EMI equal to 0.5°C, the $[SSTA]_C$ is overall larger than 0.5°C. Thus, 0.5°C in EMI index is suitable for defining El Niño Modoki events. In Hurwitz et al. 2011A, they used $[SSTA]_C$ to define the El Niño Modoki events. In Zubiaurre and Calvo 2012, they used EMI index. However, they also set 0.5°C as the threshold for selecting El Niño Modoki events. If we use a larger threshold of EMI, like 0.7°C, there will be more few El Niño Modoki events.

References:

Hurwitz, M. M., P. A. Newman and L. D., Oman, A. M., Molod: Response of the Antarctic Stratosphere to Two Types of El Niño Events, J. Atmos. Sci., 68, 812-822,DOI: 10.1175/2011JAS3606.1., 2011A.

Zubiaurre, I., and N. Calvo: The El Niño–Southern Oscillation (ENSO) Modoki signal in the stratosphere, J. Geophys. Res., 117, D04104, doi:10.1029/2011JD016690. 2012.

2. P3631 L14-28: The authors showed that El Nino events have different effects on water vapor concentration in the lowermost, lower and middle stratosphere. It is not clear why the water vapor signals on different levels should be different given that they are all regulated by the tropopause temperature as suggested by the authors. Is there any physical basis to expect the different El Nino signals in the middle stratosphere and the lower stratosphere? Or is the difference between middle stratosphere and lower stratosphere resulted from sampling issue and not related to El Nino?

Response to Specific comment 2:

Thanks for the comment. We indeed not clearly explain the reason why stratospheric water vapor signals are different during two kinds of El Niño events.

Although stratospheric water vapor is mainly controlled by the tropopause temperature, it is also affected by the cross tropopause transport of the water vapor. Among others, the large scale Brewer-Dobison (BD) circulation has an important modulation of stratospheric constitutes including water vapor. El Nino events have an impact on both the tropopause temperature and BD circulation which have different effects on water vapor concentration in the lowermost, lower and middle stratosphere. A detailed analysis of the vertical distributions of stratospheric water vapor anomalies during El Niño events can be found in Xie et al., (2011). Nervertheless, the analysis of stratospheric water vapor anomalies during El Niño events based on MLS data has been deleted in the revised paper since the MLS data is too short for composite analysis.

References:

Xie, F., Tian W.S., Austin J., Li J.P., Tian H.Y., Shu J.C., Chen C.: The Effect of ENSO Activity on Lower Stratospheric Water Vapor, Atmos. Chem. Phys. Discuss., 11, 4141-4166,doi:10.5194/acpd-11-4141-2011., 2011.

3. *P 3634-3635 This discussion about the interaction of QBO and ENSO Modoki is very interesting. However, the results presented in this paper seems to be contrary to conclusions of a few recent studies (Hurwitz et al. 2011B, Zubiaurre and Calvo 2012, Sassi et al. 2004). These studies all used Chemistry Climate Models to study the El Nino Modoki signal in the stratosphere, and they concluded that the El Nino Modoki signal in the stratosphere is not sensitive to QBO phases. In particular, Sassi et al. (2004) used a similar model (WACCM1b) to what the authors used (WACCM3), and did not simulate or impose a QBO, but found significant warming in the SH polar stratosphere under El Nino Modoki events. It would strengthen the paper if the authors can comment on the difference against these studies.*

Response to Specific comment 3:

Thanks for the good suggestion. In the revised paper, our simulations further analyzed the interaction between El Niño Modoki signal and different phases of the QBO signial. We found, no matter in QBO west and east phase,

canonical El Niño causes the same zonal wind anomalies in the stratosphere (See Figure 2a and b below, it is Figure 10 in the revised paper). On contrast, El Niño Modoki leads to different zonal wind anomalies during QBO west and east phases (Figs. 2c and d). In the QBO west phase, the zonal wind anomalies caused by El Niño Modoki are similar with the anomalies resulted from canonical El Niño (Figs. 2c, a and b). However, in the QBO east phase, the negative zonal wind anomalies in the southern high-latitude stratosphere (weaker Antarctic polar vortex) caused by El Niño Modoki are much larger than those in the QBO west phase, and those negative anomalies extend to southern middle-latitude stratosphere (Figs. 2d, a and b). Also note that during the QBO east phase El Niño Modoki causes positive zonal wind anomalies in the northern high-latitude stratosphere (stronger Arctic polar vortex). The composite analysis based on our model simulations indicate that the canonical El Niño anomalies are not sensitive to QBO and El Nino Modoki anomalies are also not sensitive to the west phase QBO, but El Nino Modoki is sensitive to the east phase QBO. The above modeling results are in accordance with the corresponding results based on observations in the Southern Hemisphere high-latitude stratosphere (Hurwitz et al. 2011A). However, the modeling results in previous studies illustrated that the El Nino Modoki signal in the stratosphere is not sensitive to QBO phases (Hurwitz et al. 2011B, Zubiaurre and Calvo 2012, Sassi et al. 2004). This discrepancy is possibly due to that the different models from WACCM4 were used in those previous studies. The above points are clarified in the revised paper.

Compared with the result in Sassi et al. (2004), our simulations also found El Niño Modoki SST anomalies can force a warming in the SH polar stratosphere in the absence of QBO (See the Figure 3b below, it is Figure 11b in the revised paper), the SH polar vortex become weaker when simulation forced by El Niño Modoki SST anomalies without QBO. Actually, the weakening of SH polar vortex can also be found in the simulation forced by canonical El Niño SST anomalies without QBO (See the Figure 3a below, it is Figure 11a in the revised paper). However, if QBO are not included in simulation, we can see from Figs. 3a and 3b that at south middle-latitude and north high-latitude stratosphere the zonal wind anomalies during El Niño Modoki events are similar with that during canonical El Niño. Only when QBO is imposed in the simulation, the zonal wind

anomalies at south middle-latitude and north high-latitude stratosphere during El Niño Modoki events are significantly different with that during canonical El Niño, i.e., in QBO east wind phase (Fig. 2d). This phenomenon is not found in the simulations only consider El Niño Modoki SST anomalies without QBO forcing in Sassi et al. (2004). The four helpful papers have been cited in our revised paper.

References:

Hurwitz, M. M., P. A. Newman and L. D., Oman, A. M., Molod (2011A): Response of the Antarctic Stratosphere to Two Types of El Niño Events, J. Atmos. Sci., 68, 812-822,DOI: 10.1175/2011JAS3606.1.

Hurwitz, M. M., I. S. Song, L. D. Oman, P. A. Newman, A. M. Molod, S. M. Frith, and J. E. Nielsen (2011B), Response of the Antarctic stratosphere to warm pool El Niño events in the GEOS CCM, Atmos. Chem. Phys., 11, 9659–9669, doi:10.5194/acp-11- 9659-2011.

Sassi, F., D. Kinnison, B. A. Boville, R. R. García, and R. Roble (2004), Effects of El Niño-Southern Oscillation on the dynamical, thermal and chemical structure of the middle atmosphere, J. Geophys. Res., 109, D17108, doi:10.1029/2003JD004434.

Zubiaurre, I., and N. Calvo (2012), The El Nino-Southern Oscillation (ENSO) Modoki signal in the stratosphere, J. Geophys. Res., 117, D04104, doi: 10.1029/2011JD016690.

Technical issues:

1. *P3621 L15: temperatures – temperature*

Thanks. We have modified this.

2. *P3632 L15-16: vertical velocity is not in the above equations, while u, v, phi, f are in the equations but not explained.*

Thanks. We have revised the text in the paper.

3. *P3650 The text suggested this figures is based on MLS data, but the caption says it is based on ERA-Intrim data.*

Thanks. We have corrected.

Table 1. Samples of canonical El Niño (left column) and El Niño Modoki (right column) events from 1980 to 2010 analyzed in this paper.

Canonical El Niño	El Niño Modoki
JUL1982–AUG1983	SEP1990–DEC1991
DEC1986–JAN1988	APR1994–JUN1995
MAY1997–MAY1998	JUN2002–APR2003
AGU2006-JAN2007	JUN2004–DEC2004

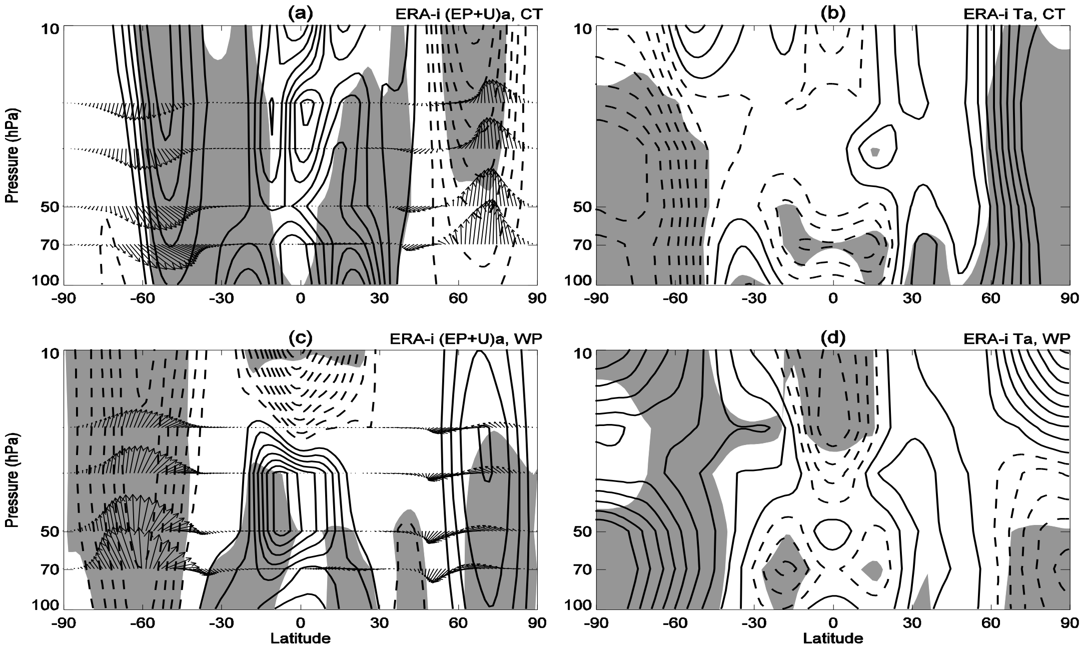

Figure 1. Composite anomalies of the E–P flux and zonal wind for (a) canonical El Niño events and (c) El Niño Modoki events, based on ERA-Interim data for 1979–2010. The unit horizontal vector is 10^7 kg s^{-1} and the unit vertical vector is 10^5 kg s^{-1}. The contour interval for zonal wind anomalies is ±0.25 m s^{-1}. Composite anomalies of temperature for (b) canonical El Niño events and (d) El Niño Modoki events, based on ERA-Interim data for 1979–2010. Contour interval for temperature anomalies, ±0.15 K. Anomalies that are significant at the 90% confidence level according to Student's t-test are shaded. Solid and dashed lines represent positive and negative anomalies, respectively.

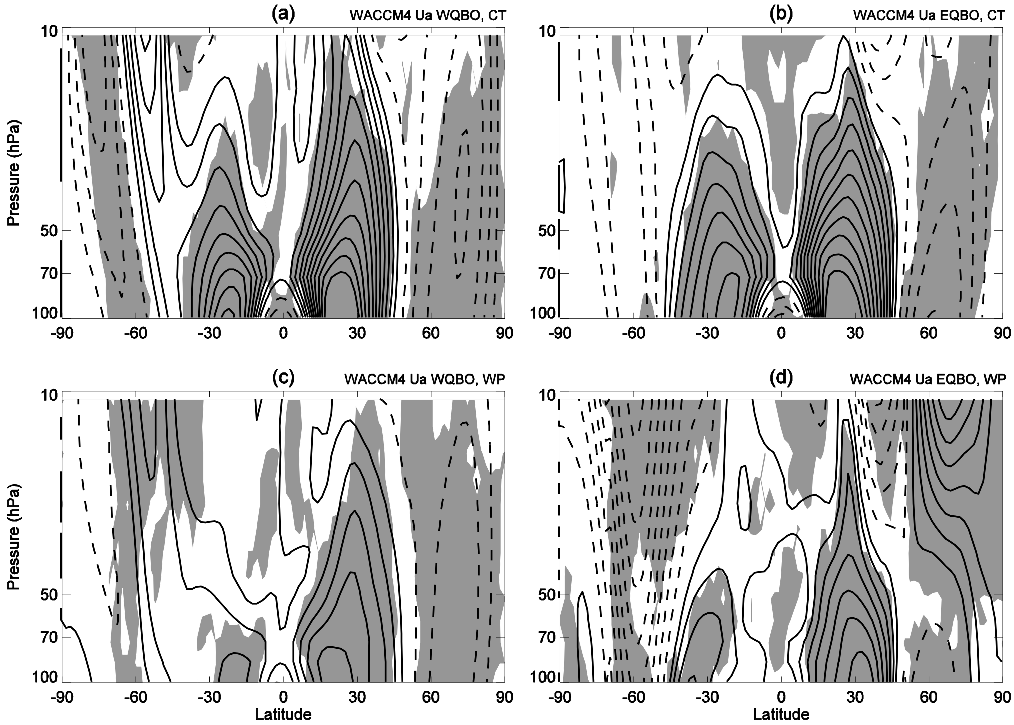

Figure 2. Differences of the zonal wind for R2 - R1 when QBO in (a) west phase and (b) east phase. The contour interval for zonal wind anomalies is ±0.25 m s^{-1}. Solid and dashed lines represent positive and negative anomalies, respectively. Anomalies that are significant at the 90% confidence level according to Student's t-test are shaded. (c) and (d) are same as (a) and (b), but for R3 – R1.

P.S.: R1 is the control experiment. The SST is observed monthly mean climatology for the time period from 1979 to 2010. In experiment R2, SST is as in R1, except that the tropical Pacific SST represents composite of observed SST associated with canonical El Niño conditions, for the period 1979–2010. In experiment R3, the SST is as in R1, but the tropical Pacific SST represents composite of observed SST associated with El Niño Modoki conditions. QBO phase signals for 28 months fixed circle are included in three experiments as an external forcing for zonal wind. Detail descriptions of experiments please see Section 2 in the revised paper.

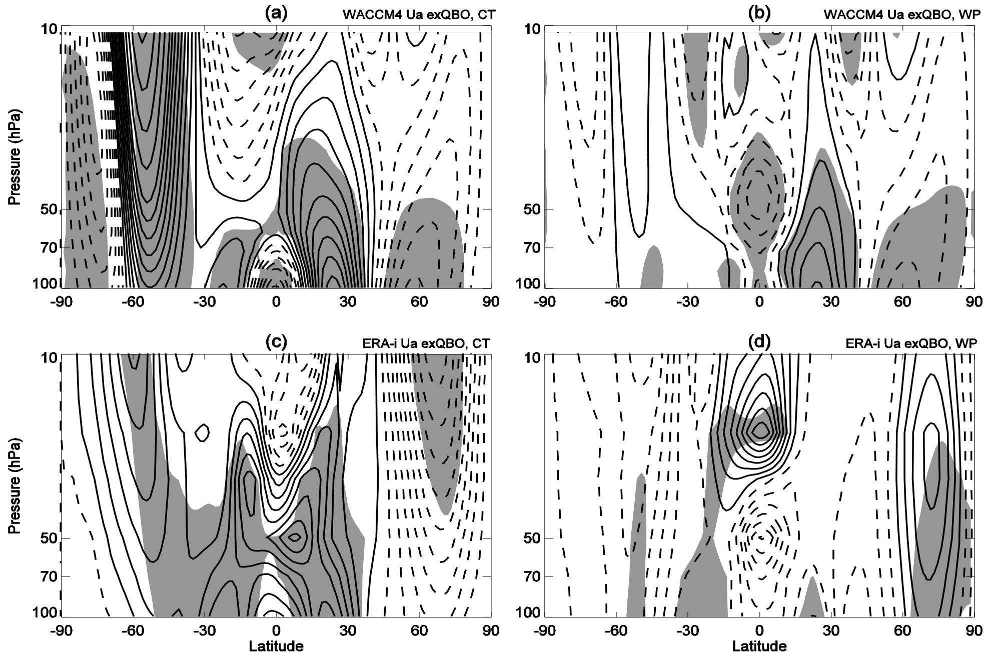

Figure 3. Differences of the zonal wind for (a) R5 – R4 and (b) R6-R4. Composite anomalies of zonal wind for (c) canonical El Niño events and (d) El Niño Modoki events, obtained using ERA-Interim data that filtered QBO (see text for details). The contour interval for zonal wind anomalies is ±0.25 m s^{-1}. Solid and dashed lines represent positive and negative anomalies, respectively. Anomalies that are significant at the 90% confidence level according to Student's t-test are shaded.

P.S.: The experiments R4, R5 and R6 have the same figuration as the experiment R1, R2 and R3, respectively, except that the experiments R4, R5, and R6 are run without impose a QBO forcing in the model.