Response to reviewer 2:

We deeply appreciate your valuable suggestions on our manuscript, which has contributed greatly to the improvement of our manuscript.

We have carefully read these comments and suggestions. According to your suggestions, we revised our manuscript, and presented a point-to-point reply to your comments. The comments from the referee are highlighted in blue. Our responses and a brief summary of related changes to the manuscript are given below. Meanwhile, we also provided a revision with tracking the changes.

Review of Du et al. "Water vapor anomaly over the tropical western Pacific in El Nino winters from radiosonde and satellite observations". This study uses a combination of radiosonde, reanalysis, and satellite measurements to better understand how tropospheric water vapor changes over the tropical western Pacific during boreal winter. It is very helpful that this works seeks to pull apart the contributions from the Hadley, Walker, and monsoon circulations in these water vapor anomalies. It is a useful analysis but the difficult part is that over this 15 years there are only a few events and some are different types so there is a real struggle to determine what responses are most robust. The grammar is not clear in many places in the text and could use additional work. I have some suggestions for the authors to consider in order to recommend publication but it should be of interest to the ACP readership.

We thank you for your encouragement, and do our best to improve our manuscript according to the review and editor valuable suggestion.

Comments:

1. The title indicates using radiosonde and satellite observations but the abstract talks about radiosonde and reanalysis with a brief mention of satellite observations at the end, maybe adding reanalysis to the title would be best or include some big picture details related to the satellite analysis in the abstract.

According to your suggestion, the title is changed as "Water vapor anomaly over the tropical western Pacific in El Niño winters from radiosonde and satellite observations and ERA5 reanalysis data" in the revision.

In the abstract, we add the description of "In addition, a detailed comparison of water vapor in the reanalysis, radiosonde and satellite data shows a fine confidence level of the datasets".

2. The authors present a nice set of measurements that are included in the analysis. As I mentioned the main struggle is that in 15 years there are just a handful of events and some are different types. It is more difficult to gauge the robustness in the details because of this. The use of reanalysis does go back to much earlier time periods.

According to your suggestion, we go back to investigate the reanalysis data and the El Niño events from 1979. There exist 6 EP El Niño events (1982/1983, 1986/1987, 1991/1992, 1997/1998, 2006/2007 and 2015/2016 winters) and 5 CP El Niño events (1994/1995, 2002/2003, 2004/2005, 2009/2010 and 2018/2019 winters) in 1979-2019. Similar to Fig. 10 in the revision (also Fig. 9 in the previous manuscript), Fig. R21 (only in this Response) shows the indices of the Hadley, Walker, monsoon and total tropical circulation anomalies in the velocity potential at 850 hPa and CWV anomalies averaged at the five radiosonde stations in the 11 EP El Niño winters during 1979-2019.

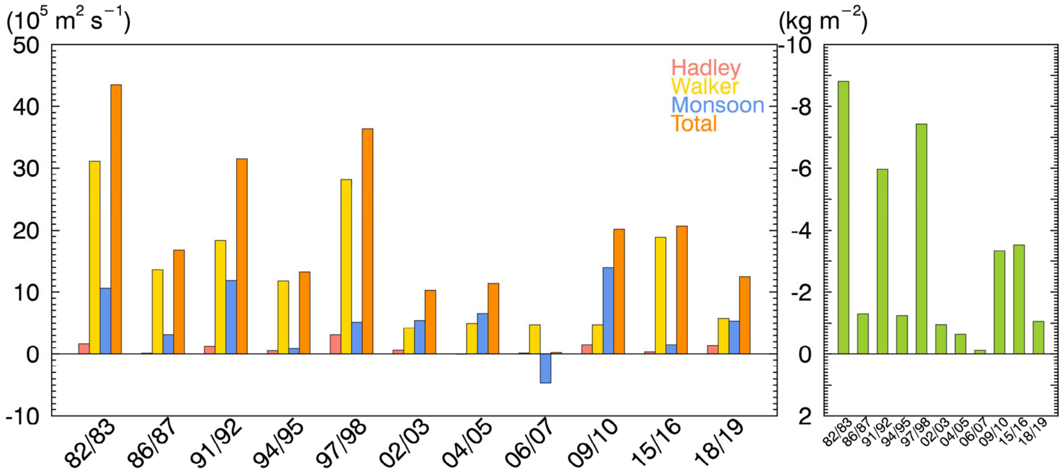

Figure R21. (Left) Indices of (red) Hadley, (yellow) Walker, (blue) monsoon and (orange) total circulation anomalies and (right) CWV anomalies derived from reanalysis data at five radiosonde stations in 11 El Niño winters during 1979-2019.

Overall, there are very strong three EP El Niño events in the 1982/1983, 1991/1992 and1997/1998 winters, corresponding to strong total circulation anomaly index and CWV anomaly. From Fig. R21, we can draw three conclusions: 1) "The variability of the Hadley circulation is quite small and has little influence on the water vapor anomaly" (in the manuscript) in the 11 events; 2) "The anomaly of the Walker circulation makes a considerable contribution to the total anomaly in all El

Niño winters, especially in the eastern-Pacific (EP) El Niño events” (in the manuscript), which is very obvious in the 6 winters of 1982/1983, 1986/1987, 1991/1992, 1997/1998, 2006/2007 and 2015/2016 EP events; and 3) “The monsoon circulation shows a remarkable change from one event to another” (in the manuscript). Therefore, the main results in the manuscript can further be demonstrated by the 41 year data, in other words, the data spanning 40 years presents the consistent results with the 15 year data in the manuscript.

The considerable contribution from the Walker circulation anomaly is understandable since the Walker circulation located over the Pacific Ocean is directly related to water vapor transport over the Pacific. The remarkable change of the monsoon circulation from one event to another is also reasonable because the monsoon circulation can be significantly affected by more factors, for example, sea-land heat contrast, SST warming position, seasonal movement of the subtropical high, and even possible interoceanic coupling and linkage. However, the specific causes of the monsoon circulation anomaly in different events, particularly in different CP events, needs to be explored deeply and systematically, and please permit us to present the definite reason in the next work after compare and analyze each event in detail.

Considering your valuable suggestion, we add the investigation of composite EP and CP El Niños from the 6 EP El Niño events and 5 CP El Niño events based on the 41 year reanalysis data. The main results shown in the composite EP and CP events, such as little variability of the Hadley circulation, major contribution of the Walker circulation anomaly, especially in the EP events, and relatively important role of the monsoon circulation in the CP event compared with in EP event, are in agreement with the case study. In the revision, we add Fig. 10 and corresponding description I Section 4.3, as follows,

“In order to obtain the general features of water vapor and circulation anomalies in the EP and CP El Niño events, we extend the reanalysis data back to 1979 to examine two types of composite El Niño events. There are six EP El Niño events in the winters of 1982/83, 1986/87, 1991/92, 1997/98, 2006/07 and 2015/16, and five CP El Niño events in the 1994/95, 2002/03, 2004/05, 2009/10 and 2018/19 winters for 41 years from 1979 to 2019, which are averaged as the composite EP and CP El Niños, respectively. We calculate the CWV anomalies in the two composite events based the climatic mean CWV in 41 winters, and the corresponding velocity potential and divergent wind anomalies of the Walker, monsoon and total circulations from the reanalysis horizontal wind at 850 hPa, which are shown in Fig. 10. The Hadley circulation anomaly (not presented) is very small, and its patterns in the composite EP and CP El Niños are also analogous to those in the EP and CP events shown in Fig. 6, respectively. On the whole, Figure 10 illustrates that the total circulation anomaly is stronger in EP event than in CP event, and then the CWV anomaly is larger in EP event relative to that in CP event. The Walker circulation plays an important role in the total circulation anomaly, especially in EP El Niño. Despite significant variability from one event to another, the monsoon circulation anomaly has not only a larger proportion of the total anomaly but also slightly higher intensity in CP El Niño than in EP El Niño. At the five radiosonde stations, the composite events indicate that the CWV anomaly is about -4.36 and -1.74 kg m^{-2} in EP and CP El Niños, respectively. The index of the Walker circulation anomaly accounts for about 75.8% (47.8%) of the total anomaly index in EP (CP) El Niño, while for the monsoon circulation, the anomaly index of 6.16 (4.66) units contributes to 49.6% (18.4%) of the total anomaly index in CP (EP) El Niño. Therefore, the relative importance of the Hadley, Walker and monsoon circulation anomalies in the composite El Niños is roughly in accord with that in the case study above.”

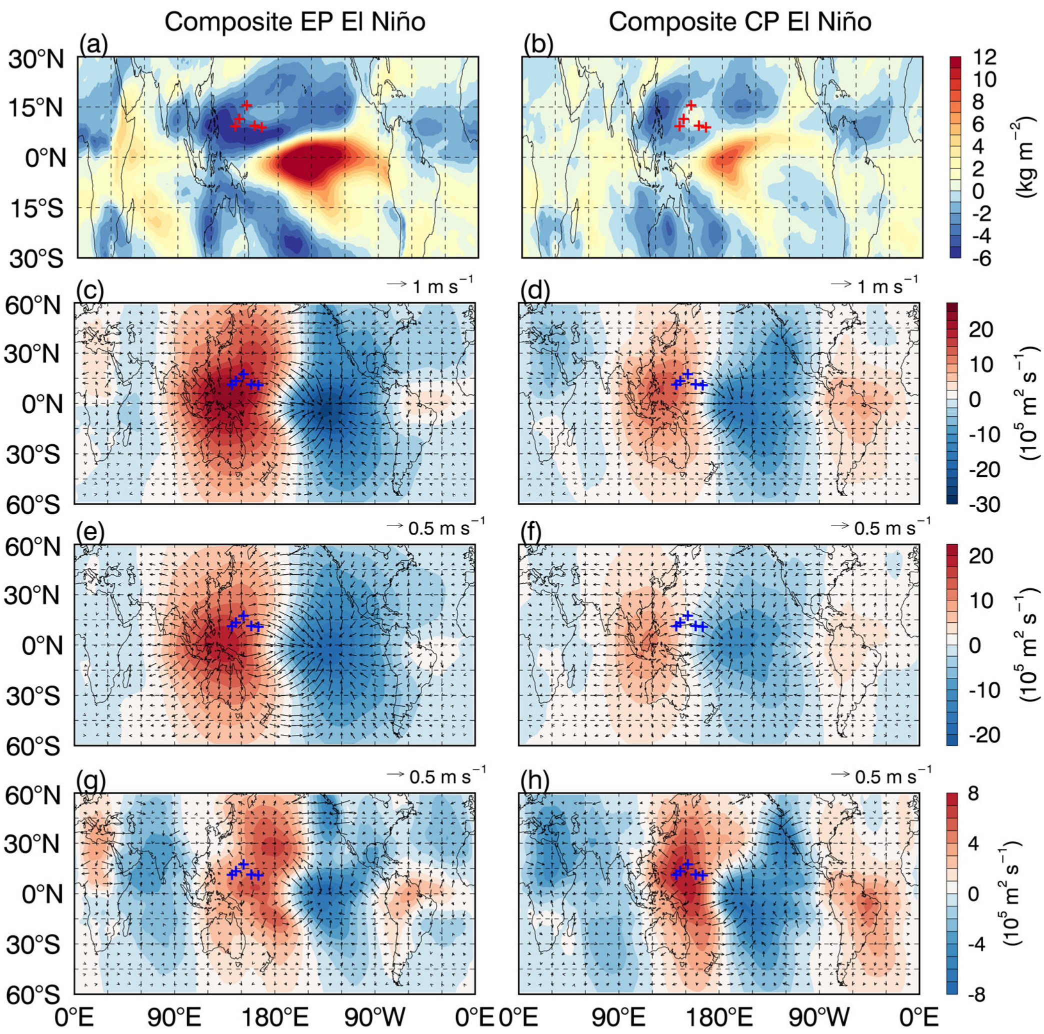

Figure 10. Anomalies of (a, b) CWV and velocity potential and divergent wind at 850 hPa in (c, d) total, (e, f) Walker and (g, h) monsoon circulations for composite EP and CP El Niños derived from reanalysis data. The left and right columns correspond to the composite EP and CP El Niños, respectively. The shading and arrow in Fig. 10 (c-h) denote the velocity potential and divergent wind anomalies, respectively. The red and blue plus denotes the five radiosonde stations.

3. While it is nice to see the analysis in trying to pull apart the contributions related to Hadley, Walker, and monsoon circulations, a better explanation of the methodology and how it is applied here would be helpful.

In the revised manuscript, we describe this methodology in more detail.

“Based on the different driving mechanisms and movement features, Tanaka et al. (2004) introduced the definitions of the Hadley, Walker and monsoon circulations, which have an advantage to quantitatively evaluate the intensity of the three tropical circulations by means of the separation of the velocity potential into three orthogonal spatial patterns. Thus, we follow the definitions and methodology proposed by Tanaka et al. (2004) to obtain these tropical circulations for investigating their contributions to the observed water vapor anomaly in the four El Niño events." is rewritten as follows

"Based on the different driving mechanisms and movement features, Tanaka et al. (2004) decomposed the tropical circulation in the upper troposphere (200 hPa) into the Hadley, Walker and monsoon circulations, which have an advantage to quantitatively evaluate the intensity of the three tropical circulations by means of the separation of the velocity potential into three orthogonal spatial patterns. Subsequently, Takemoto and Tanaka (2007) used these circulation definitions to analyze the Hadley, Walker, and monsoon circulations at 850 hPa of the lower troposphere, and compared the three circulation components with those in the upper troposphere (200 hPa), which indicated that the velocity potential intensities could be an index of each circulation in the lower troposphere without a notable influence from the surface. Considering that atmospheric water vapor is mainly distributed below 8 km, directly relevant to the lower tropospheric circulation, we follow the definitions and methodology proposed by Tanaka et al. (2004) to obtain these tropical circulations at 850 hPa level for investigating their contributions to the observed water vapor anomaly in the four El Niño events."

And, "According to Eq. (6), we calculate the time series of the divergent wind and velocity potential at 850 hPa from 2005 to 2019 by using the reanalysis horizontal wind data, and then their monthly climatic normal is derived from their time series, respectively." is added to be

"We firstly calculate the divergence field of the horizontal wind at 850 hPa from 2005 to 2019 by using the reanalysis horizontal wind data, and then the velocity potential is deduced according to Eq. (6), which is equivalent to solving Poisson equation. Next, according to Eq. (7), the velocity potential filed is decomposed into the Hadley, Walker and monsoon circulation components. In this way, their monthly climatic mean is derived from their time series, respectively."

4. Line 197 how consistent is the delay between ONI and CWV, do event types make the delay differ.

In the manuscript, the delay between ONI and reanalysis CWV anomaly is 2-3 months derived from 180-month data in 2005-2019. Similarly, we examine the delay by using 492-month data during 1979-2019 period, and the computation shows that the correlation coefficient is -0.57 (-0.56) with a lag of 2 (3) months, which is in agreement with the result in the manuscript.

It is difficult to separately calculate the correlation of ONI with CWV anomalies in different types of El Niño. As you implied, the delay may be a little different from one event to another. However, we compare the delay between the negative CWV anomaly peaks and ONI peaks in 11 El Niño events during 1979-2019.The averaged lag is 2.16 months in 6 EP El Niño events, and 2.3 months in 5 CP El Niño events. Hence, the difference is not very obvious in the different types of El Niño, and the corresponding conclusion is also reasonable in the manuscript.

5. Figure 6 which dataset(s) does this derive from and include in caption.

Caption in Fig. 6 is added as "(Black) Velocity potential and (orange) anomaly index of Hadley circulation at 850 hPa derived from reanalysis data in (a) 2006/07, (b) 2015/16, (c) 2009/10 and (d) 2018/19 winters."

6. Figure 9 - Why is the monsoon contribution so large in 2009/10 is it coupled to Indian Ocean Dipole changes or something else.

We apologize for presenting a wrong Fig. 4. At the beginning, we also wanted to examine the Indian Ocean effect coupled to the observational station, and then calculated the circulation anomalies in in summer (June, July and August) and winter for comparison. The circulation anomaly in summer shown in Fig. 4 is incorrectly given as the anomaly in winter, and the error is corrected in the revised manuscript.

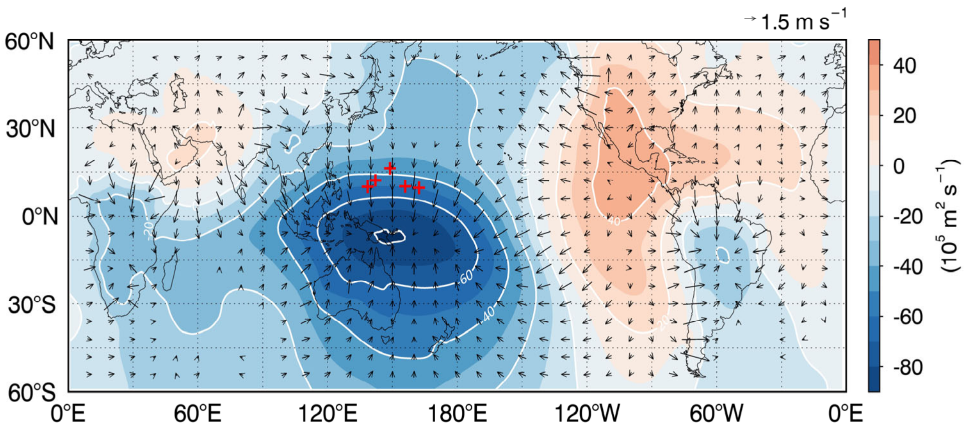

Figure 4. Climatic means of (shading) velocity potential and (arrow) divergent wind fields at 850 hPa in DJF derived from reanalysis data during 2005-2019. The red plus denotes the five radiosonde stations.

As shown in Fig. 4 in the last manuscript, the Indian Ocean Dipole effect is clear in summer, but unapparent in winter, as depicted in Fig. 4 in the revision. This is consistent with previous studies (Guan and Yamagata, 2003; Tokinaga and Tanimoto, 2004).

In light of the Indian Ocean Dipole events is the Indian Ocean counterpart of the Pacific El Niño and La Niña (Schott et al., 2009), its magnitude is generally with Dipole Mode Index (DMI). Similar to Gebregiorgis et al., (2019), we calculate the correlation of the monsoon anomaly index averaged over the five radiosonde stations with the ONI and the DMI from the DJF mean anomalies in winters of 1979-2019. The results indicate a high correlation coefficient of 0.61 between the ONI and monsoon anomaly index, but only a correlation coefficient of 0.02 between the DMI and monsoon anomaly index. Meanwhile, we also compute the correlation between the monsoon anomaly index and DMI in summers of 1979-2019, with a coefficient value of 0.33. Hence, at the chosen observational stations, the monsoon circulation is greatly affected by the ONI but little by DMI in winter, while the Indian Ocean Dipole has a significant effect on the monsoon circulation variation in summer, which is in good agreement with the circulation anomaly pattern in Fig. 4 in the last and revised manuscripts.

The 2009/10 CP event is the strongest CP El Niño from the 1980s, as observed by satellite measurements (Lee and Mcphaden, 2010). The composite El Niño events demonstrate that as a whole, the monsoon circulation anomaly can play substantial role and make a contribution of about 50% to the total anomaly in CP event. In this way, it is possible for the strongest CP El Niño in the winter of 2009/10 to cause a very strong monsoon circulation anomaly.

Thus, we add the corresponding explanation in the revision as,

"In addition, at the radiosonde sites, the CP El Niño can generally cause an intense monsoon circulation anomaly, which is comparable to and even larger than the Walker circulation anomaly, thus the CP El Niño in the winter of 2009/10 may induce a quite strong monsoon circulation anomaly now that the 2009/10 event is the strongest CP El Niño from the 1980s, as observed by satellite (Lee and Mcphaden, 2010).”

7. Related to lines 338-341 did you examine this with respect to Indian Ocean Dipole changes.

Figure R22 presents the time series of Dipole Mode Index (DMI) averaged in winter. Intuitively, in the winters of 1994/95 and 1997/98, the largely positive DMI seems to be related to the small monsoon circulation anomaly, and in the winter of 2004/05, the negative DMI seems to be connect with the considerable contribution of the monsoon circulation anomaly, as shown in Fig. R21. However, this correspondence does not apply in the winter of 2009/10 with moderately positive DMI but large monsoon circulation anomaly, and the winter of 2015/16 with moderately negative DMI but small monsoon circulation anomaly. Hence, the monsoon circulation change is influenced by many factors, and the Indian Ocean Dipole may not play a key role in the strong monsoon circulation anomaly in the 2009/10 event.

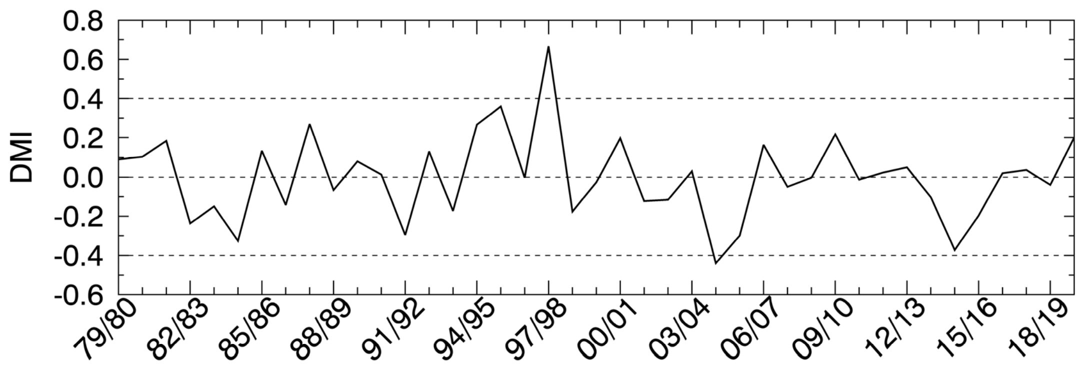

Figure R22. Time series of DMI averaged in winter.

8. More analysis related to different monsoon circulation contributions would be helpful.

As shown in the case and composite event investigation, the monsoon circulation anomaly can make an average contribution of about 50% to the total anomaly in CP event, and exhibits a remarkable variation from one event to another. The analysis indicates that when the Dipole Mode Index (DMI) is strong, the Indian Ocean Dipole seems to have a visible influence with opposite changes between the monsoon circulation anomaly and DMI. If the DMI is moderate or weak, the effect of the Indian Ocean Dipole is confused by the other influences due to its small impact at the observational stations. Since the monsoon circulation can be significantly affected by many factors, please permit us to provide clearly the causes by systematically examining each event in the next work.

9. Lines 346 -348 Is there too few events in this short record to understand if these differences in events are robust.

According to your valuable suggestion, we add the analysis of the composite EP and CP El Niños, which shows that the Walker circulation anomaly accounts for about 75.8% (47.8%) of the total anomaly in EP (CP) El Niño, while the monsoon circulation anomaly contributes to 49.6% (18.4%) of the total anomaly in CP (EP) El Niño. Hence, the difference is further confirmed through the composite events.

In the revision, “Therefore, the Hadley, Walker and monsoon circulation anomalies may have the remarkable differences in the contributions to the water vapor variation in different El Niño events.” in Lines 346-348 is rewritten as follows

“Therefore, except the Hadley circulation anomaly, the Walker and monsoon circulation anomalies may have the considerable differences in the contributions to the water vapor variation in different El Niño events”.

10. Lines 351-353 I think more quantitive analysis could be done rather than speculate here.

According to your suggestion, we perform a thorough comparison of the CWV and CWV anomaly from the ERA5 reanalysis, radiosonde and satellite data, which is presented in the added Section 6, including added Figure 13.

Please see Section 6 in the revised manuscript.

Here, we rewrite the sentence of “However, in the first two events, there is a distinct difference between the reanalysis and radiosonde data. At least in the 2009/10 winter, we speculate that the reanalysis data may underestimate the tropospheric water vapor over the five stations, which can further be confirmed by the changes in the cloud and OLR data.” to be

“However, in the first two events, there is a distinct difference of the CWV anomaly between the reanalysis and radiosonde data, and we will discuss the discrepancy in detail below.”

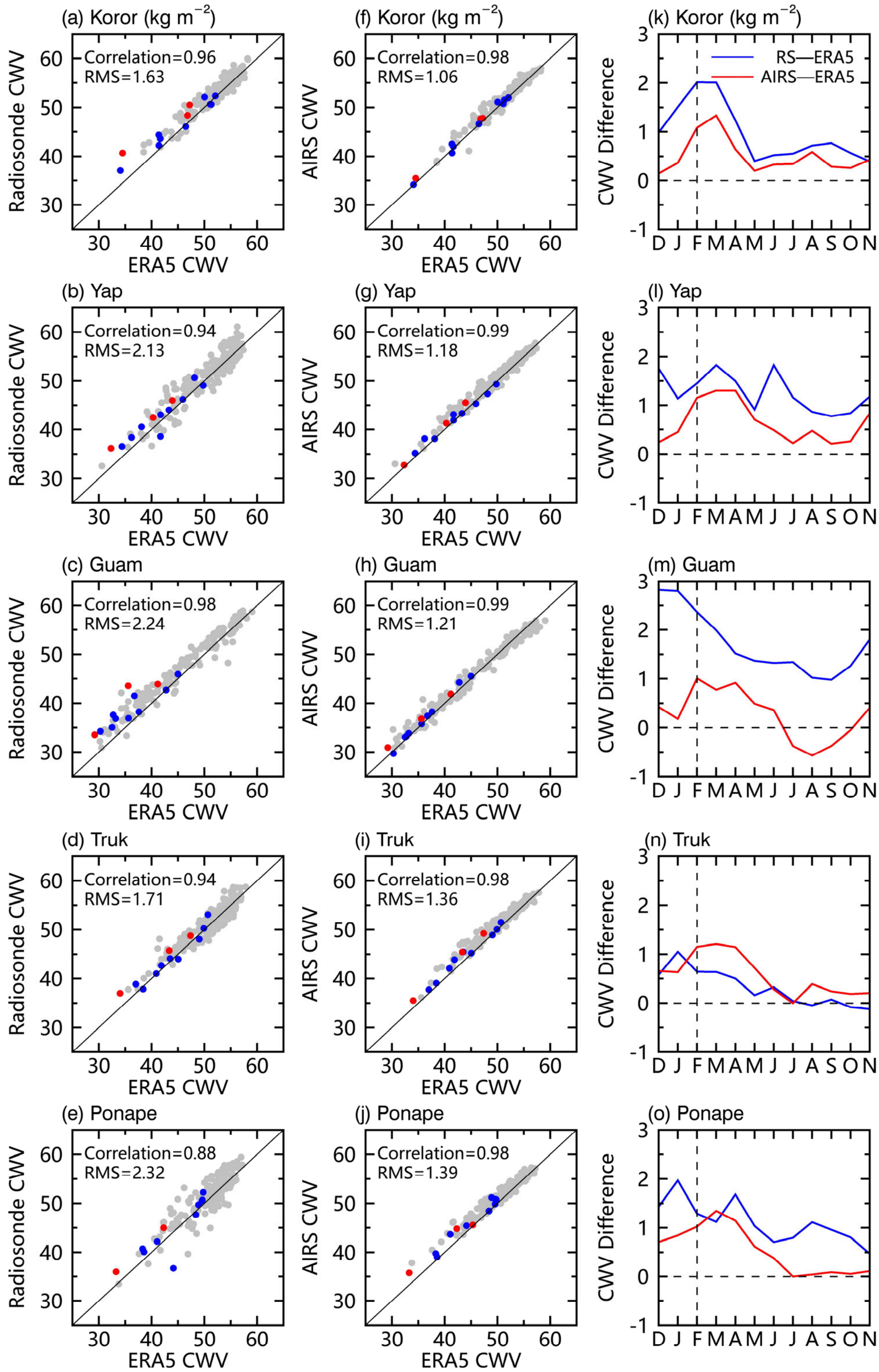

Figure 13. Scatterplots of monthly mean CWV in winter derived from (a-e) radiosonde and (f-j) AIRS observations against corresponding CWV from ERA5 reanalysis and (k-o) climatic mean CWV difference (blue lines) between radiosonde and ERA5 reanalysis data and (red lines) between

AIRS and ERA5 reanalysis data at five stations during 2005-2019. In Figs. (a-j), the red, blue and gray dots denote the CWV values in the 2009/10 winter, the 2006/2007, 2015/2016 and 2018/2019 winters, and the other winters, respectively.

11. Section 5 - It seems like additional useful analysis could be done here to look at high cloud anomalies and their relationship to the position of the SST anomalies in these different event types. You are still dealing with single or few cases but worth looking at.

In the manuscript, by using the CALIPSO L3 cloud occurrence product, we calculate the mean cloud fraction between 0-15°N in the three El Niño winters to analyze the distribution of cloud occurrence, which clearly shows a clear response of cloud to the water vapor anomalies.

We also derive the high cloud occurrence anomalies at the level above 440 hPa (Rossow and Schiffer, 1991) from CALIPSO L3 cloud occurrence from June 2006 to December 2016, and Figure R23 (only presented in the response) depicts the spatial distribution of high cloud anomalies in the three events. The positive and negative cloud anomaly centers are consistent with the ascending and descending motion anomalies of the circulation in Fig. 5, respectively. In other words, the cloud anomaly shows the results similar to that in Figure 11.

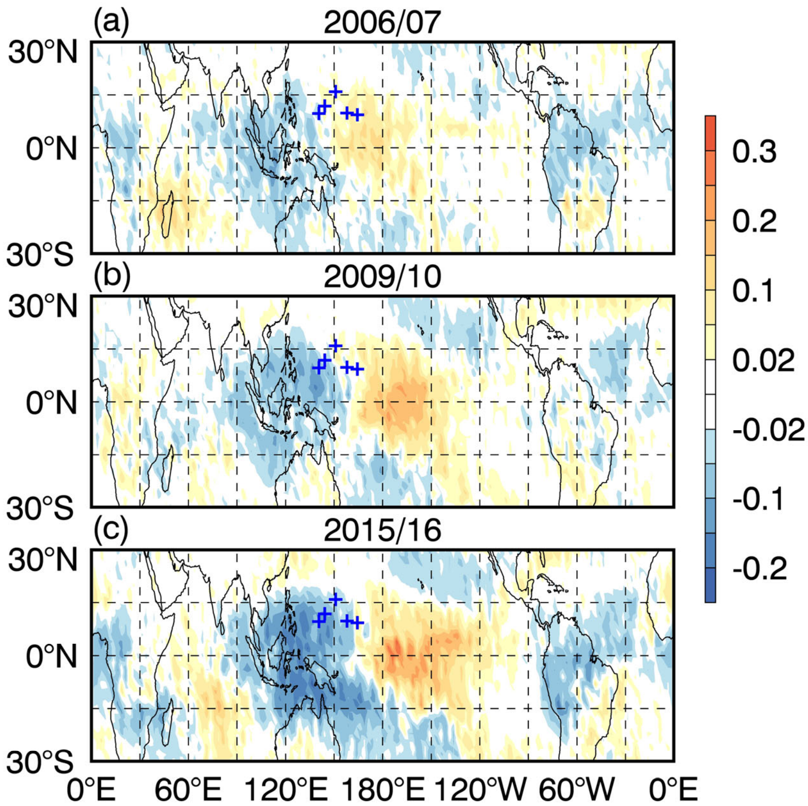

Figure R23. Distribution of high cloud anomalies in (a) 2006/07, (b) 2009/10 and (c) 2015/16 winters derived from CALIPSO.

12. Is there a particular reason the 5 radiosonde locations were chosen, are there others in this region that would be helpful for the analysis. If you look at figure 2 while they are close, areas a bit to the west exhibit larger integrated water vapor anomalies.

The variations in water vapor and precipitation are closely related to ENSO. Moreover, many studies showed that Dipole Mode Index associated with Indian Ocean Dipole (IOD) has also a significant influence on the monsoon rainfall and water vapor distribution in the area west 130°E, such as Indian, the eastern Indian Ocean, the East and Southeast Asia countries (Guan and Yamagata, 2003, Gadgil et al., 2004, Vinayachandran et al., 2007), as you implied above. In order to focus on the ENSO-related CWV anomalies with minimizing the effect of IOD, we choose the radiosonde stations located eastward of 130°E over the western Pacific, and there are only five stations in total.

We have planned and started to investigate the impacts of the ENSO and IOD combination on the water vapor and precipitation anomalies in the area west 130°E, as you suggested. Please allow us to present the investigation as a separate work in the near future.

A few example to work to improve grammar and clarity.

1. Line 34 and line 385 change supper to super

Sorry, the error is corrected in the revised manuscript.

2. Line 36 change less cloud amount to something like “lower cloud amounts”

“less cloud amount” is changed as “lower cloud amounts”.

3. Line 40 need to reword “variable trace composition”

According to your suggestion, “Water vapor is a variable trace composition of the atmosphere, whereas it has⋯” is rewritten as

“As a dominant greenhouse gas in the atmosphere, water vapor has⋯”.

4. Line 45 change to region of abundant water vapor

"abundant water vapor region" is changed as "a region with abundant water vapor".

5. Line 45 change anomaly to anomalies

"anomaly" is corrected to be "anomalies".

6. Line 88 change has the important to had important

"has the important influences" is changed as "had important influences".

7. Line 197 add sign after opposite

"tends to vary in opposite to the ONI" is rewritten to be "a negative correlation to the ONI".

8. Line 270 need to reword "meaning the divergence center and the sinking motion over there"

"meaning the divergence center and the sinking motion over there" is addressed as "meaning a downward motion associated with the divergence center over there".

9. Line 362 change cloudy to clouds

"cloudy" is replaced with "clouds".

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