Replies to the Comments

April 26, 2016

We are very grateful to the two reviewers for their detailed comments and suggestions to significantly improve our manuscript.

We have made two substantial changes to the manuscript, which are shown below. All detailed changes and point-to-point answers to the reviewers' comments are detailed below. A revised manuscript with all tracked changes is attached.

(1) A complete analysis of confidence intervals and significance testing

Time series in Figures 1 and 3 were updated with standard deviation intervals. We have also added significance test for the differences of diabatic heating between August and June in Figure 4b. The results turn out to be very robust and overall conclusions are not critically impacted.

(2) Direct comparison of tropopause temperatures on the east and west side

We have also added a direct comparison of tropopause temperature on the east and west side of the Asian monsoon to Figure 3b. The domains for the two sides are shown in Figure 2.

Reply to anonymous Referee #1 (acp-2016-21-RC1)

General comments:

This paper discussed the contribution of the geographic variation of convection and the associated geographic variation of dehydration locations to the water vapor over Asian monsoon region in the lower stratosphere during boreal summer. The trajectory model simulation provided clear proof of the east-to-west shift of the dehydration location at the intra-seasonal time scale. Further SVD analysis confirms the connection between the convection pattern and the water vapor anomalies. The main concern from my perspective is the statements in many places of the paper like 'warmer tropopause temperature in the west of Asian monsoon region', e.g. Page 1 line 20-24, Page 6 line 16-17 and Page 8 Line 25-26. It seems to me that the author is comparing the tropopause temperature in the west side to that in the east side. However, it is not clear in which region, which latitude or which period it is compared. The author divided the east side and west side of Asian monsoon region by 80-90_E according to the caption of Figure 3. However, from the tropopause temperature shown in Figure 2, the differences of the tropopause temperature between the east side and the west side are not significant. And the author also pointed out that the convection increases over the west side of Asian monsoon region which increases the local diabatic heating. From my understanding, the anomalous convection over the west Asian monsoon region should lead to stronger upwelling and relatively cold temperature in the tropopause layer, which controls the dehydration. Actually, the pattern of dehydration location and of the tropopause temperature is associated with each other. That means when the convection increases over western side of Asian monsoon region, the cold point temperature should correspondingly decreases to some degree. I suggest author gives a direct comparison of the tropopause temperature of east side and west side to clarify this point.

Furthermore, Figure 1 shows the variation of tropopause temperature is not able to fully explain the variation of seasonal water vapor variation, which is the motivation of the work.

I have some questions concerning the domain and the magnitude of interannual variabilities, which are specified in the following part.

The paper describes interesting result, which contributes to complete the picture of moisture center over Asian summer monsoon region. Overall, the paper is nicely structured and presented. I suggest it is published after clarifying the questions above.

Reply:

Thanks for those helpful comments.

We've added a direct comparison of the weighted tropopause temperature of east side and west side to the revised manuscript, see Figure 3b in the revised manuscript. In order to avoid the artificial effects of the domain selections, we calculated the average tropopause temperatures in the two domains by taking dehydration frequencies into consideration as weights. We agree with the reviewer that when the convection increases over the west side of the Asian monsoon region, the cold point temperatures could correspondingly decrease by some degrees. But overall, the temperatures over the west side are higher than those over the east side. In addition, the magnitude of temperature differences is larger than the sub-seasonal variations (see Figure 3b). Therefore, an increase of dehydration frequencies over the west side of the Asian monsoon region would increase the fraction of air parcels dehydrated at relatively warmer temperatures. And this positive impact is significantly larger than the potential offset influence of decreased tropopause temperature induced by increased convection.

Specific comments:

• Pg. 2, line 21: A recent paper (Ploeger et al. 2015, ACP) intensively discussed the variability of a PV-based transport barrier of Asian monsoon anticyclone. This study is highly related here and I recommend to cite this study. doi:10.5194/acp-15-13145-2015

Reply:

Yes, we have added the citation to Pg. 2, line 26.

• Pg. 3 , line 28: I suppose the OLR data is also daily anomalies according to the section 3.2. So add 'of' after 'water vapor and' in order to avoid the misunderstanding.

Reply:

Done, see Pg. 4, line 10.

• Pg. 4, line 29: Is the weighting functions the weighting matrix of MLS averaging kernels? If yes, please clarify here.

Reply:

Yes, we used the weighting matrix of the MLS averaging kernals and we have clarified this in Pg. 5, line 2.

• Figure 1: First, this figure shows the 9-year climatology of water vapor and tropopause temperature. The intra-seasonal variations are usually can be 'offset' by averaging over several years. Can you comment on how large is the interannual variability of temperature? Does this strong intra-seasonal variations of temperature attribute to some particular year or is it a common feature for this domain during boreal summer? Perhaps it worth to add the standard deviation to the tropopause temperature.

Reply:

We have added standard deviation intervals for the tropopause temperature in Figure 1. We have checked individual years; such an intra-seasonal variation of temperatures is a common phenomenon during the period 2005-2013. We are not sure what caused such an intra-seasonal feature, which may be linked to some intraseasonal oscillation features in the Asian monsoon region (e.g., Lau and Chan, 1986; Kikuchi et al., 2012).

• Figure 1: Second, you mention that the same domain used for area-averaging the tropopause temperatures as R15, which is 15-32_N, 70-120_E. However, I checked R15 and the domain 15-30_N, 70-120_E is used. Besides, you also use 15-30_N in Figure 4 of averaging the diabatic heating rate. From Figure 2, it is seen that the gradient of tropopause temperature around 30_N is very large and the 2 degrees could influence the variation of temperature shown in this plot. I suggest to show the tropopause temperature averaged over 15-30_N, 70-120_E. Otherwise the author could compare the results between the 2 domains and clarify the results stays the same.

Reply:

Thanks for pointing this out. 32°N was a typo and it has been corrected.

• Figure 2 and 3: I suggest to add boxes in Figure 2 to show the domains of west side and east side mentioned in the caption of Figure 3.

Reply:

Thanks for this great suggestion. We have added two boxes in Figure 2 to indicate the domains of west side and east side of the Asian monsoon region.

• Figure 5: the subfigures are too small. It is better to enlarge the figure, especially those color bars.

Reply:

Thanks for this suggestion. We have rearranged the order of Figure 5 to make figures bigger.

• Pg. 8, line 10: it should be '(Fig.1 and Fig.6a-b)'

Reply:

Changed.

Reply to anonymous Referee #2 (acp-2016-21-RC2)

First, my apologies to the authors and the editor for the long delay in publishing this review.

This manuscript examines how changes in the distribution of convective sources and dehydration locations of air in the Asian monsoon upper tropospheric anticyclone affect the amount of water vapour entering the lower stratosphere in this region. The concept is worthwhile, and the paper makes some valid points about how seasonal and intraseasonal variability in convective sources influence the moisture content of air near the tropopause. However, some aspects of the methodology and argument are problematic, and require more justification at the very least.

The biggest weakness of this paper is that it takes water vapour variations at 100 hPa to be representative of the 'lower stratosphere', neglecting previous work indicating that final dehydration for air entering the tropical stratosphere via this region typically occurs at lower pressures / higher altitudes. This does not necessarily invalidate the core conclusions of this paper (the processes controlling water vapour variability at 100 hPa are also important to understand, particularly if they propagate to higher levels), but it does imply strong limitations on their applicability that are not effectively communicated or explored in the paper. At the very least, the authors should clarify that 'LS' in this case means 100 hPa, and discuss the limitations that that entails. Even better, the authors could use their trajectory simulations to connect the results and conclusions at 100 hPa to final dehydration statistics and stratospheric entry mixing ratio. In other words: do these intraseasonal differences in source location / temperature distribution / transport affect the amount of water vapour entering the global stratosphere via the Asian monsoon anticyclone, and, if so, how much? These additions would help tremendously in establishing how this work fits in the context of other studies of water vapour transport and variability in this region.

Reply:

Thanks very much for these very helpful comments and suggestions. We have clarified in the manuscript that we use 100 hPa to represent lower stratosphere in Page 5, Line 12 in the beginning of the Results Section.

Although our focus is on the monsoon water vapor at 100 hPa, we have also examined the corresponding results at higher levels. Results at 82 hPa are almost the same as the 100 hPa. This was mentioned at Page 8, Line 8 in the original manuscript.

We mainly focus on the LS, particularly at 100 hPa and 82 hPa, because we could typically observe the moisture center over the Asian monsoon region during summer at 100 hPa and 82 hPa, with much a more weakened phenomenon at 68 hPa and even disappeared at higher levels based on Aura MLS observations. The variability is much smaller above 68 hPa than lower levels. In previous papers (e.g., Dessler et al., 2013; Randel et al., 2015), they usually use 100 hPa or 82 hPa to represent the LS. Our use of 100 hPa was influenced by the study of Randel et al. (2015) that used 100 hPa to represent the LS.

Regarding the final dehydration height, a recent paper using the same trajectory model (Dessler et al., 2016) states that "Dehydration events at altitudes above 93 hPa do occur, but they remove relatively small amounts of water: the water vapor mixing ratio at 79 hPa is within a few percent of the value at 93 hPa." Therefore, water vapor variations at 100 hPa and 82 hPa are representatives of water vapor variations in the 'LS'.

In the study of Dessler and Sherwood (2004), they calculated stratospheric entry mixing ratio of water vapor in the trajectory simulations by averaging the H2O mixing ratio of parcels between 75 and 91 hPa (16.8–18.5 km), similar to the MLS 82 hPa weighting function. Therefore, they assumed ~82 hPa water vapor values in the trajectory model to be the entry values into the stratosphere. Since **our results are very robust for 82 hPa**, we believe that the influence of geographic dehydration variations could also impact the stratospheric entry mixing ratio in a similar way, especially over the Asian monsoon region, i.e., the entry values for western trajectories would be significantly higher than those with convective sources over the eastern side of the region. While the amount of LS water vapor in the Asian monsoon region is our focus, further studies are still needed to investigate the influence of Asian monsoon water vapor abundance (or entry mixing ratio) on global LS water vapor. We appreciate that you pointed out the limitations. The influence of the seasonal and intraseasonal differences in convective and dehydration center on the amount of water vapor transport to the global stratosphere is a future study.

1 General comments

1. My main concern is that the analysis focuses almost exclusively on water vapour at 100 hPa, and particularly that this is assumed to represent lower stratospheric water vapour. The vertical location of dehydration for air entering the stratosphere varies quite a lot, and is typically higher (in altitude) than 100 hPa. Would the results still be valid for variations in water vapour at 83 or 68 hPa, or are they only relevant to a shallow layer bracketing the tropopause? If I have understood the analysis correctly, this might be checked by analyzing the 'final dehydration' locations and temperatures for these trajectories during transit to the stratosphere in addition to the 'latest dehydration' locations and temperatures for the model results at 100 hPa. Are the statistics of final dehydration for these trajectories significantly different from those with convective sources over the eastern side of the region? Regardless, more needs to be done here, either to connect these results more clearly to stratospheric entry mixing ratio (post-final dehydration) or clearly distinguish between studies for which 'LS' means 'above the tropopause layer' and/or 'after final dehydration' and this study (where 'LS' means 100 hPa, well within the tropopause layer and likely prior to final dehydration).

Reply:

As mentioned above, the results are still valid for water vapor variations at 82 hPa. And we also found that most of the relatively wet parcels at 68 hPa are from the dehydration over the west side with warmer tropopause temperatures. The reasons why we use 100 hPa and 82 hPa to represent LS in the Asian monsoon region can be found in the above reply.

The concept to use trajectory model to look at dehydration locations in this study is different from previous studies (Schoeberl et al., 2012; Wang et al., 2015), in which, they define final dehydration points as where parcels underwent final dehydration and stayed at altitudes higher (pressure lower) than 90 hPa for at least 6 months since the last time they were dehydrated (FDP). This guarantees that parcels already crossed the cold-point tropopause (~380 K or ~100-94 hPa) and experienced their final dehydration (Wang et al., 2015). In this way, the greatest FDP frequency would mostly occur at locations with extremely low temperatures (eg., tropical cold-point tropopause layer), as the trajectory model only records the final dehydration points at the long paths. Besides, in reality, for example, most of the air parcels at 100 hPa (or 82 hPa) haven't gone through the final dehydration presented in the above studies. Thus, in order to study observed water vapor variations at those levels, most recent dehydration (MRD) instead of FDP statistics may be more applicable. In our paper, we select all the air parcels at 100 hPa (or 82 hPa), and find out the MRD statistics that determine the amount of water vapor in each air parcel. This should be the correct way to study what really controls the variations of water vapor at a particular level in details.

2. I'm not convinced that the idealized experiments that separate the dehydration temperatures and dehydration locations are viable in this case. This approach works well when either temperature changes or circulation changes are dominant (and therefore separable), but has little meaning when temperature and circulation changes are tightly coupled. Another way of thinking about this is that separability is a justifiable assumption in situations where changes in dehydration location are dominated either by (1) an unchanged circulation sampling a modified temperature distribution or (2) a modified circulation sampling an unchanged temperature distribution. Too much overlap between these situations results in degeneracy, at which point the contributions of temperature changes and circulation changes cannot be reliably distinguished. My expectation is that in this case the tight couplings among convection, circulation (especially diabatic heating) and temperature at 100 hPa violate separability, as also briefly mentioned by reviewer #1. I am willing to be convinced otherwise, but additional justification for these simulations is needed if they are to be used as supporting evidence here.

Reply:

The idealized experiments were designed to compare the relative impact of dehydration locations and temperature changes on water vapor increase from June to August. The concept was very simple, i.e., to look at how the westward shift of dehydration locations changes the water vapor entering the LS on seasonal scale. We agree that convection, circulation and temperature are tightly coupled. The experiments were not designed to separate the influence of convection, circulation and temperature. The concept is especially useful when one wants to assess the stratospheric water vapor changes from the large-scale tropopause temperature changes, while neglecting the changes of dehydration locations. We have added one sentence to Pg. 7, Line 11, "*These idealized experiments indicate that we may underestimate the water vapor variations solely based on the large-scale temperature changes without considering the changes of dehydration statistics associated with the large-scale circulation changes.*"

3. This work would benefit from a more complete analysis of confidence intervals and significance testing. As also noted by reviewer #1, many of the arguments rely on changes and/or differences that are relatively small. This is particularly relevant for the time series in Fig. 3 and the August minus June differences shown in Fig. 4 and Table 1, and otherwise reported in the text.

Reply:

Yes. We have added the standard deviation intervals and significance tests for those changes and differences to Figures 1-4.

4. The text is clear for the most part, but the manuscript would benefit from English-language editing by a colleague or professional editor. There are a few points where editing will be necessary to improve the clarity; see technical comments below.

Reply:

Thanks for this suggestion. We have edited the languages in this paper again according to your suggestion.

2 Specific comments p.2, l.24-25: this sentence is vague and should be reworded for clarity — at seasonal time scales and large spatial scales both the temporal evolution and geographic distribution of LS water vapour are correlated with convective activity, it's just that these correlations do not generally extend to variability within the anticyclone itself.

Reply:

We have rephrased the sentence. Please see Pg.3, Line 2.

p.2, l.28: Given the uncertainties and competing hypotheses put forward by subsequent studies, it would be more appropriate to change 'they can' to 'they proposed that this convection can'

Reply:

Changed. Please see Pg. 3, Line 6.

p.3, l.6: Wright et al. (2011) did find large discrepancies among the different reanalysis data sets, but the qualitative results were robust: trajectories originating from convection over Tibet were consistently moister but less numerous than trajectories originating from convection over the other regions, so that these trajectories had relatively limited impacts on water vapour in the global tropical LS.

Reply:

We have modified the sentence. Please see Pg. 3, Line 14.

p.3, l.23: It would be useful to note also the relative precision here (as xx–yy%)

Reply:

We have added percentage precisions to Pg. 4, Line 6.

p.4, l.16: In this case, since the focus is on the evolution at 100 hPa, I presume that 'latest dehydration' refers to most recent dehydration rather than final dehydration. This choice should be stated explicitly to prevent confusion – 'latest dehydration' is by itself too vague, as it could mean either 'most recent' or 'final'.

Reply:

We have changed "latest dehydration" to "most recent dehydration (MRD)" in the revised version to avoid confusion.

p.4, l.18-19: How is this done, by gridding the simulated water vapour mixing ratios and then applying the averaging kernels to construct a vertical grid? I recommend expanding slightly on this description. Also, as noted later on this page, the exclusion of simulated values below 100 hPa results in a dry bias. I assume this statement is based on testing the sensitivity to whether those values are included. Does this testing indicate whether including/excluding the simulated values at lower levels has any impact on the qualitative evolution of the variability?

Reply:

Yes, we first gridded the simulated water vapor mixing ratios and then applied the MLS averaging kernels to the gridded water vapor fields to construct the same vertical grids as the Aura MLS data. We have expanded the description, please see to Pg. 5, Line 3.

Yes, excluding the simulated values at lower levels does have impact on the water vapor variability. We have added a note to Pg. 8, Line 27.

p.5, l.5-9: It is very difficult for the reader to evaluate the statement that '100 hPa temperatures over the southeastern flank of the anticyclone ... do not show as significant increase as water vapour from May and June to August'. This argument should be made more quantitative. This could be as simple as a calculation relating the May/June to August mean temperature change to a fractional change in mean saturation specific humidity (with appropriate uncertainty estimates), which can then be compared to the fractional change in simulated water vapour mixing ratio at 100 hPa (with appropriate uncertainty estimates).

Reply:

We have rephrased the sentence to make it more accurate, please see Pg. 5, Line 27. And we have added Figure 2e to compare with the time series of temperatures shown in Figure 1.

p.5, l.13: (Fig. 2) Does 'tropopause temperatures' mean '100 hPa temperatures', or are these evaluated at a diagnosed tropopause?

Reply:

The tropopause temperatures were calculated from ERA-Interim temperature fields based on the WMO tropopause definition.

p.5, l.20: (Fig. 3) Here it would be helpful to include also the evolution of mean 'latest dehydration' temperatures over the eastern and western parts of the domain, with uncertainty estimates. This would help to clarify that it is in fact the shift in dehydration location (and not the temperature evolution) that dominates the seasonal evolution of water vapour at 100 hPa, and could perhaps supplement or replace the idealized simulations in the overall argument.

Reply:

Yes, we have added the evolution of weighted tropopause temperatures with uncertainty intervals over the east and west side of the Asian monsoon region to Figure 3. This would supplement the idealized simulations with further clarifications.

p.5, l.26: (Table 1) If using these simulations, it would be useful also to include the August–August results to give a quantitative benchmark for evaluating the idealized June–August and August–June simulations. I know that these are shown in Fig. 1, but so are the June–June results. I could not find this number reported anywhere in the text.

Reply:

Yes, we now have included the August-August results in the revised manuscript.

p.6, l.12: (Fig. 4) Is there any benefit to including the profiles of diabatic heating below 300 hPa? Including these estimates requires the use of a relatively large scale, and makes it difficult to distinguish the variations in the UTLS (which is what we are particularly interested in). Moreover, there is a negative anomaly centered around 70 hPa above the location with enhanced convective activity in August relative to June. Is this negative anomaly significant? If so, this suggests that upward motion in this region is weaker than during June above 100 hPa, which might mean that the trajectories involved circuit the anticyclone more times during ascent. This relates to general comment #1 above: how much does this westward shift of convective source location ultimately impact stratospheric entry mixing ratios?

Reply:

One benefit to include the profiles of diabatic heating below 300 hPa is that we could look at the large-scale convection changes in the whole column of the troposphere. The negative anomaly at 70 hPa is significant, please see the significance test in the revised Figure 4. This indeed would slow down the ascending motion above 100 hPa a little bit. It also involves tight coupling with temperature fields and anticyclonic circulation. We don't know how this convection induced diabatic heating changes in the LS would influence stratospheric entry mixing ratio. We decide to leave this interesting topic for future studies.

p.6, l.20: (Fig. 5) The use of colours here is confusing, with red sometimes meaning a positive change and sometimes a negative change. Moreover, 'physically consistent with a moist anomaly in the UT' is sometimes indicated by the yellow/orange/red half of the colour scale and sometimes by the green/blue/purple half of the color scale. I recommend that you either make the use of this default colour table logically consistent across panels or use different colour tables for anomalies in different quantities. I also agree with reviewer #1 that the fonts are too small and difficult to read in several of the panels included in Fig. 5, and I can barely even see the variations of the lines in panel (f). If the variations for all of the years are necessary, perhaps it would be better to make panel (f) a separate figure and split it into multiple panels, one for each year? If not, it might be best to show the variations for a selected time period covering one or two years, so that those variations are easier to identify in the figure.

Reply:

In the revised manuscript, we have reordered the figures in Figure 5. Moreover, we change the color bars to indicate red (blue) color as increase (decrease). Figure 5f has also been enlarged to have a clear view of the intraseasonal variation.

p.7, l.1: Which data is used to identify the increase in cirrus clouds?

Reply:

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) 2006-2013 daily observations was used to identify the increase of cirrus clouds. I have added this information to the revised paper. Please see Pg. 8, Line 7.

p.7, l.3: What mechanism drives the enhanced ascending motion? Enhanced latent heating above 370 K? Enhanced cloud radiative heating? Is this enhanced ascending motion consistent between ERA-Interim and MERRA? This could be explored by looking at the components of the heat budget — both ERA-Interim and MERRA provide clear-sky and all-sky radiative heating products.

Reply:

Most of the enhanced latent heating above 370 K and below 380 K is still due to latent heating. While beyond the 380 K, the radiative heating dominates. We will not discuss too much here as we will have a separate paper to be submitted systematically talking about the relationships between convection and diabatic heating in the atmosphere. Yes, the enhanced ascending motion is consistent between ERA-Interim and MERRA.

p.7, l.9: (Fig. 6) For clarity, the definitions of 'wet' and 'dry' days should perhaps be moved from l.20 to here.

Reply:

Done.

p.7, l.18-19: It would be useful to include the correlation for traj_MERRA if data from the mismatched period in 2006 is excluded.

Reply:

The correlation for traj_MERRA is calculated by including all the period between 2004-2013, same as traj_ERAi. 2006 is not excluded here, that's why the correlation is lower than traj_ERAi.

p.8, l.25: The presented work only supports this statement if we consider 100 hPa to be representative of the LS in this region — no confirmation has been shown that this seasonal evolution in the convective source extends to lower pressures / higher altitudes, which should also be considered part of the LS.

Reply:

Please see the reply to comment #1.

p.9, l.4: What is meant by 'cold-point' here? The coldest temperatures in the geographic distribution between 370 K and 100 hPa? The vertical cold point tropopause?

Reply:

We have changed it to "cold-point tropopause temperatures over southeast Asia".

3 Technical suggestions

page 1 l.24: recommend changing this to 'Due to the warmer dehydration temperatures, anomalously moist air enters...' l.25: typo: 'frank' ! 'flank'

Reply:

Changed.

page 2 l.13: 'moist' ! 'moisture' l.18: recommend moving 'controlling transport' to after 'processes' instead of before l.24: 'ascent' ! 'ascends'

Reply:

Changed.

page 3 l.1: recommend moving 'over the Bay of Bengal and Southeast Asia' to after 'direct convective injection' for readability. page 4 l.25: recommend deleting 'It is featured with' for clarity

Reply:

Changed.

page 5 l.7: 'as significant increase' ! 'as significant of an increase'

Reply:

Changed to "increase concurrently with" to make the statement more accurate. Please see Pg. 5, Line 27.

page 6 l.20: 'described in Section 2 to the data' ! 'to the data as described in Section 2' l.28: typo: 'principle' ! 'principal'

Reply:

Changed.

page 7 l.3: typo: 'dehydration' ! 'dehydrated' page 8 l.3: typo: missing 'mid' or 'late' in 'early-to-summer moistening'?

Reply:

Changed.

page 9 l.6: the meaning of 'convective protrusion' here is not clear — do you mean that convection over these regions is particularly deep relative to other parts of the monsoon domain, that convection is particularly frequent in these regions, or something else?

Reply:

Yes, we have changed the "convective protrusion" to "frequent and deep convective protrusions" to make it more clear.

l.11: typo: 'studies' ! 'study'

Reply:

Changed.

Reference

Dessler, A., Ye, H., Wang, T., Schoeberl, M., Oman, L., Douglass, A., Butler, A., Rosenlof, K., Davis, S., and Portmann, R.: Transport of ice into the stratosphere and the humidification of the stratosphere over the 21st century, Geophys. Res. Lett., 2016.

Dessler, A. E., and Sherwood, S. C.: Effect of convection on the summertime extratropical lower stratosphere, J. Geophys. Res., 109, D23301, 2004.

Dessler, A. E., Schoeberl, M. R., Wang, T., Davis, S. M., and Rosenlof, K. H.: Stratospheric water vapor feedback, Proc. Nat. Acad. Sci., 110, 18087-18091, 2013.

Kikuchi, K., Wang, B., and Kajikawa, Y.: Bimodal representation of the tropical intraseasonal oscillation, Clim. Dyn., 38, 1989-2000, 2012.

Lau, K.-M., and Chan, P.: Aspects of the 40-50 day oscillation during the northern summer as inferred from outgoing longwave radiation, Mon. Wea. Rev., 114, 1354-1367, 1986.

Randel, W. J., Zhang, K., and Fu, R.: What controls stratospheric water vapor in the NH summer monsoon regions?, J. Geophys. Res.: Atmos., 2015.

Schoeberl, M. R., Dessler, A. E., and Wang, T.: Simulation of stratospheric water vapor and trends using three reanalyses, Atmos. Chem. Phys., 12, 6475-6487, 2012.

Wang, T., Dessler, A. E., Schoeberl, M. R., Randel, W. J., and Kim, J. E.: The impact of temperature vertical structure on trajectory modeling of stratospheric water vapor, Atmos. Chem. Phys., 15, 3517-3526, 10.5194/acp-15-3517-2015, 2015.

Impact of geographic variations of the convective and dehydration center on stratospheric water vapor over the Asian monsoon region

K. Zhang[1], R. Fu[1], T. Wang[2*], Y. Liu[3]

[1] Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas, United States.
[2] Department of Atmospheric Sciences, Texas A&M University, College Station, Texas, United States.
[3] State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China.
[*] Now at Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, United States.

Correspondence to: K. Zhang (kzkaizhang@utexas.edu)

Abstract. The Asian monsoon region is the most prominent moisture center of ~~lower stratospheric (LS)~~ water vapor in the lower stratosphere (LS) during boreal summer. Previous studies have suggested that the transport of water vapor to the Asian monsoon LS is controlled by dehydration temperatures and convection mainly over the Bay of Bengal and Southeast Asia. However, there is a clear geographic variation of convection associated with the seasonal and intra-seasonal variations of the Asian monsoon circulation, and the relative influence of such a geographic variation of convection vs. the variation of local dehydration temperatures on water vapor transport is still not clear. Using satellite observations from the Aura Microwave Limb Sounder (MLS) ~~satellite observations~~ and a domain-filling forward trajectory model, we show that almost half of the seasonal water vapor increase in the Asian monsoon LS are attributable to ~~the~~ geographic variations of convection and resultant variations of the dehydration center, of which the influence is comparable to the influence of the local dehydration temperature increase. In particular, dehydration temperatures are coldest over the southeast and warmest over the northwest ~~within the~~ Asian monsoon region. Although the convective center is located over ~~the~~ southeastern Asia, an anomalous increase of convection over the northwestern Asian monsoon region increases ~~the~~ local diabatic heating in the tropopause layer and air ~~mass~~ masses entering the LS ~~that is~~ are dehydrated at relatively warmer temperatures. Due to warmer dehydration temperatures, anomalously moist air enters the LS and moves eastward along the northern flank of the monsoon anticyclonic flow, leading to wet anomalies in the LS over the Asian monsoon region. ~~The warmer dehydration temperatures allow anomalously moist air enters the LS and then moves eastward along the northern frank of the monsoon anticyclonic flow, leading to wet anomalies in the LS over the Asian monsoon region.~~ Likewise, when convection increases over

the southeastern Asian monsoon region, dry anomalies appear in the LS. On a seasonal scale, this feature is associated with ~~the march of~~ the monsoon circulation, convection and diabatic heating marching towards the northwestern Asia monsoon region from June to August~~, –~~. The march of convection leads ~~leading~~ to an increasing fraction of the air mass to be dehydrated at warmer temperatures over the northwestern Asian monsoon region. Work presented here confirms the dominant role of temperatures on water vapor variations and ~~also~~ emphasizes that ~~one~~ further studies should take ~~the~~ geographic variations of the dehydration center into consideration when studying water vapor variations in the LS~~,~~ as it is linked to changes of convection and large-scale circulation patterns.

1 Introduction

Water vapor variation in the lower stratosphere (LS) contributes significantly to ~~the~~ global climate change through altering the radiation budget (Forster et al., 1999; Solomon et al., 2010; Dessler et al., 2013) and chemical processes, particularly ~~for~~ ozone depletion (Evans et al., 1998; Dvortsov and Solomon, 2001; Shindell, 2001; Stenke and Grewe, 2005; Anderson et al., 2012). Water vapor in the LS exhibits a localized maximum over the Asian monsoon region from May to September (Rosenlof et al., 1997; Randel et al., 2001; Dessler and Sherwood, 2004; Milz et al., 2005; Park et al., 2007; Randel et al., 2015). This center of maximum water vapor is an important moisture ~~moist~~ source for the global stratosphere (e.g., Randel et al., 2001; Gettelman et al., 2004; Ploeger et al., 2013), although its contribution relative to that of the tropical LS is still a subject of active research (Rosenlof et al., 1997; Fueglistaler et al., 2005; Wright et al., 2011). ~~The global~~ Global models have suggested the importance of the Asian monsoon for water vapor transport to the tropics and global stratosphere (Dethof et al., 1999; Bannister et al., 2004; Gettelman et al., 2004; Ploeger et al., 2013). Therefore, it is important to understand the ~~controlling transport~~ processes controlling transport of water vapor into the Asian monsoon LS.

The maximum LS water vapor concentration in the Asian summer monsoon region ~~LS~~ is a result of convective transport of moist air trapped by strong monsoon anticyclonic circulation (Dunkerton, 1995; Jackson et al., 1998; Dethof et al., 1999; Park et al., 2007; Ploeger et al., 2015). However, ~~its~~ these convective transport pathways are still debatable. ~~Most of convection~~Convection within the Asian monsoon region predominantly ~~only~~ reaches about 200 hPa (~12.5 km above ~~the~~ sea-level) (e.g., Fu et al., 2006; Park et al., 2007; Wright et al., 2011). Moist air transported by convection at this level would be dehydrated as it slowly ~~ascent~~ ascends to the tropopause (Holton and Gettelman, 2001). Consequently, the occurrence of deep convection is ~~not significantly~~ less correlated with the variation of ~~LS~~ water vapor in the LS than in the upper troposphere ~~water vapor~~ within the Asian monsoon region (Park et al., 2007).

The relative impact of convection and temperatures on LS water vapor variations is an ongoing ~~still an undergoing~~ study. Fu et al. (2006) suggested that deep convection over the Tibetan Plateau and south slope of the Himalayas can reach the tropopause more frequently. They proposed that the deep convection ~~Together~~ (in combination with warmer tropopause temperatures~~), they can~~ could be the main source of water vapor for the LS over the Asian monsoon region. Some studies suggest that ~~over the Bay of Bengal and Southeast Asia~~ water vapor can be transported into the LS via direct convective injection over the Bay of Bengal and Southeast Asia (Park et al., 2007; James et al., 2008; Devasthale and Fueglistaler, 2010). Wright et al. (2011) ~~have~~ compared the relative contributions of three distinct convective regimes within Southeast Asia (i.e., South Asian subcontinent, the South China and Philippine Seas, and the Tibetan Plateau and South Slope of the Himalayas) to the seasonal variation of water vapor in the tropical LS ~~lower stratosphere~~. They concluded that air parcels emanating from convection over the Tibetan Plateau were most moist but least numerous; air parcels originating from convection over Southeast Asia and the tropical tropopause were driest but most prominent summer source of tropospheric air to the tropical stratosphere. ~~They found large discrepancies among the three most commonly used reanalysis products.~~

Recently, Randel et al. (2015) ~~shows~~ showed that there is a dominant influence ~~impact~~ of temperatures over the southeastern flank of the Asian anticyclone on ~~the~~ intra-seasonal variations of stratospheric water vapor over the Asian monsoon regions~~, ;and~~ overshooting deep convection ~~plays~~ was found to play a relatively minor role. However, ~~the~~ seasonal temperature changes in this region cannot fully explain the continuous increase of LS water vapor in the Asian monsoon region during summertime, ~~which~~ as will be shown in this paper. Besides, there is a clear geographic variation of convection associated with the seasonal and intra-seasonal variations of the Asian monsoon circulation~~, .and~~ However, the relative influence of such geographic variation of convection vs. the variation of local dehydration temperatures on water vapor transport is still not clear. In this study, we aim to clarify this question and the role of convection by analyzing water vapor transport based on the Aura Microwave Limb Sounder (MLS) daily observations and a domain-filling forward trajectory model.

2 Data and Methodology

In order to examine the relationships between water vapor, temperatures and convection over the summertime Asian monsoon region, we ~~use~~ analyze water vapor observations from the Aura MLS and outgoing longwave radiation (OLR) from NOAA (National Oceanic and Atmospheric Administration) ~~in~~ for the 2005-2013 boreal summers (May – September). We grid level 2 version 3.3 daily MLS water vapor to 10°x5° longitude by latitude from 215 hPa to 100 hPa. Within this vertical range, the MLS H_2O precisions are 0.5–0.9 ppmv, ranging from 15% at 100 hPa to 40% at 215 hPa (Livesey et al., 2011). NOAA interpolated daily OLR in 2.5°x2.5° horizontal resolution is used as a proxy for convection. The diabatic heating data used for analysis is from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim Re-Analysis (ERA-Interim) archive (output from the reanalysis model forecast fields) (Dee et al., 2011). Singular value decomposition (SVD) (Bretherton et al., 1992) is applied to the covariance matrix between daily anomalies of water vapor and of OLR to objectively identify the coupled patterns and the maximum covariance.

~~To explain the observational relationships, we~~ We use a domain-filling forward trajectory model to identify the water vapor transport pathways over the summertime Asian monsoon region. The trajectory model used here follows the description from ~~the details described in~~ Schoeberl and Dessler (2011), with trajectory integration calculated from Bowman trajectory code (Bowman, 1993; Bowman et al., 2013). Two trajectory runs driven by different circulation and temperature fields from two reanalyses are compared to evaluate the uncertainties: (1) ~~using~~ ERA-Interim fields (Dee et al., 2011), denoted as traj_ERAi; (2) ~~using~~ Modern Era Retrospective Analysis for Research and Applications (MERRA) fields (Rienecker et al., 2011), denoted as traj_MERRA. Previous studies have shown that this model is able to simulate both water vapor (Schoeberl and Dessler, 2011; Schoeberl et al., 2012; Schoeberl et al., 2013; Wang et al., 2015) and chemical tracers (Wang et al., 2014) in the LS very well. In this study, we analyze results from diabatic ~~run~~ runs in isentropic coordinates, in which the potential temperature tendency is converted from the diabatic heating rates as vertical velocity. Parcels are initialized at the tropical 370K isentropic level, which is above the level of zero radiative heating (~355-365K) (Gettelman et al., 2002) but below the tropical tropopause (~375-380K). Along the trajectory integration, we use 100% saturation level with respect to ice to remove excess of water vapor instantly, i.e. the “instant dehydration”, which has been proven effective in simulating stratospheric water vapor (e.g., Fueglistaler et al., 2005; Schoeberl et al., 2014). In this study, we screen all the air parcels in the Asian monsoon region at 100 hPa each day and determine their “most recent dehydration” (MRD) statistics. The term ~~“last dehydration”~~ MRD is used ~~in this study~~ to indicate the ~~latest~~ most recent dehydration event along the historical travel path of an air parcel before it reaches 100 hPa. Therefore, the MRD statistics solely determine the amount of water vapor for each air parcel in the trajectory model. Details of parcel initialization and removal criterion for water vapor along the trajectories can be ~~referred to~~ found in Wang et al. (2015). ~~All outputs~~Water vapor in the trajectory model have been gridded and weighted by the weighting matrix of the MLS averaging kernels ~~MLS average kernels~~ for fair comparison. Since the trajectory model has larger uncertainties in simulating water vapor below 100 hPa, we applied weighting functions only to levels above 100 hPa. This would cause some dry biases compared with MLS values, which will be discussed case by case in the results part.

3 Results

3.1 Seasonal enhancement of LS water vapor over the Asian monsoon region

During boreal summer, there is an isolated moisture center observed in the LS over the Asian monsoon region (Rosenlof et al., 1997; Randel et al., 2001; Dessler and Sherwood, 2004; Milz et al., 2005; Park et al., 2007; Randel et al., 2015), primarily at 100 hPa and 82 hPa but weakened at higher levels based on the Aura MLS observations. In this study, we use 100 hPa to represent the LS over the Asian monsoon region. ~~It is featured with~~ LS water vapor increases continuously throughout the summertime from May to August (e.g., Randel et al., 2015)~~,~~ as shown by the black line in Figure 1. Similar ~~The similar~~ temporal ~~variation~~variations~~,~~ – although ~~with~~ containing dry biases~~,~~ – can also be simulated by the trajectory model (blue and green lines in Fig. 1), in which water vapor is determined by temperatures at last dehydration locations. ~~Since the trajectory model has larger uncertainties in simulating water vapor below 100 hPa, we applied weighting functions only to levels above 100 hPa~~ The outputs are weighted vertically by excluding the simulated values below 100 hPa.~~, which~~ This makes ~~air slightly drier~~ water vapor values slightly lower than those in the Aura MLS due to less convective influences from air below. The agreement between the trajectory model simulations and ~~observed~~ observations of water vapor variations imply ~~implies~~ that temperatures, rather than convective injection, dominate~~s~~ the observed seasonal enhancement over the Asian monsoon region. Both observations and trajectory model simulations ~~calculations~~ of the Asian monsoon ~~have shown~~ show that dehydration primarily occurs on the cold (equatorward) side of the LS anticyclonic circulation (Wright et al., 2011; Randel et al., 2015). However, the seasonal changes of 100 hPa temperatures over the southeastern flank of the anticyclone (15-~~32ºN~~30ºN, 70-120ºE, the red line in Fig. 1), which are expected to dominate dehydration of the LS over the Asian monsoon region (Randel et al., 2015), do not ~~show as significant~~ ~~increase~~ increase concurrently with ~~as~~ water vapor from May ~~and June~~ to August. ~~Thus~~Therefore, temperatures at this location cannot fully explain the continuous ~~increase~~ increase of water vapor in the LS of the Asian monsoon region from early to late summer.

To identify the temperature-controlled ~~temperature controlling~~ areas for each month, we use the trajectory model to determine the ~~last dehydration~~MRD locations for all the air parcels at 100 hPa over the Asian monsoon region (20-40ºN, 40-140ºE). Figure 2 a-d show~~s~~ the probability density distribution of ~~last dehydration~~ the MRD locations during May to August (white contours) and the average~~d~~ tropopause temperatures (color shadings). A common feature is that dehydration mostly occurs on the cold (equatorward) side of the Asian monsoon anticyclonic circulation, consistent with Wright et al. (2011). This behavior of dehydration through the cold temperatures is similar to the freeze-drying process near the cold-point tropopause over the western Pacific (Holton et al., 1995; Holton and Gettelman, 2001). During May, most of the air parcels are dehydrated over ~~the~~ southeastern Asia, where temperatures are lower than other Asian monsoon areas. The center of dehydration shifts north-westward to the Bay of Bengal in June (Fig. 2b), ~~then~~ expands to the Bay of Bengal/north India in July (Fig. 2c) and finally shifts to ~~the~~ north India during August (Fig. 2d). Figure 2e shows the time series of tropopause temperatures following the dehydration locations in both traj_ERAi and traj_MERRA; these were calculated by weighting tropopause temperatures based on time-varying MRD frequency statistics for each day. The continuous increase of weighted tropopause temperatures is consistent with the seasonal increase of 100 hPa water vapor shown in Figure 1. A statistical view of the westward shift of dehydration is shown in Figure 3a. From early to late summer, the fraction of air parcels that are dehydrated over the west side of the Asian monsoon region (red line) ~~is increasing~~ increases gradually~~, opposite to~~ but decreases over the east side (blue line). During September, the dehydration starts to retreat from the west side towards the east side. The domains for the west side and east side are outlined in the grey boxes in Figure 2. Tropopause temperatures are generally warmer over the west side compared to the east side of the Asian monsoon region (Figure 3b). Thus, as dehydration shifts westward toward warmer temperatures, more water vapor can enter the LS over the Asian monsoon region. Within each domain, dehydration locations vary from early to late summer, which leads to a continuous increase of the weighted tropopause temperatures shown in Figure 3b and similar to Figure 2e.

In order to quantify the relative impact of geographic variations of the dehydration center and local temperature changes on water vapor increase from June to August ~~respectively~~, we conduct~~ed~~ three idealized experiments based on traj_ERAi and traj_MERRA (Table 1). Taking traj_ERAi as an example, ~~CTL is a~~ we set our control experiment (CTL) ~~with~~ to the dehydration pattern (i.e. ~~last dehydration~~MRD locations) and temperatures ~~set the same as~~ observed in June. When only temperatures are changed to ~~temperatures~~ those observed in August (Exp_TEM) ~~and everything else is unchanged~~, the averaged water vapor in the Asian monsoon LS is increased by ~~on~~ an average of ~0.49 ppmv (where the standard deviation is σ= 0.21 ppmv).~~, suggesting~~ This suggests a moistening effect of the local dehydration temperature changes from June to August. Similarly, when the dehydration pattern is modified by replacing the dehydration locations ~~for all air parcels~~ during June by those in August, while keeping the dehydration temperatures unchanged from those of June (Exp_LOC), the averaged water vapor is increased by on average ~ 0.59 ppmv (σ= 0.24 ppmv).~~,~~ This also ~~showing~~ shows a moistening effect of the geographic shift of dehydration center from June to August. These combined moistening effects cause the average water vapor during August to be approximately 4.81 ppmv (Exp_TEM_LOC). Thus, the westward geographic shift of the dehydration center toward warmer temperatures over the western Asian monsoon region could contribute to a significant increase of the total LS water vapor from June to August~~,~~; this is comparable to the contribution of the local temperature changes. Results from ~~the~~ traj_MERRA are consistent with traj_ERAi~~,~~ even~~ with some~~ when accounting for minor differences (Table 1). ~~But~~ However, both trajectory runs indicate that the westward shift of dehydration significantly enhances water vapor in the Asian monsoon LS from early to late summer. These idealized experiments indicate that we may underestimate the water vapor variations solely based on the large-scale temperature changes without considering the changes of dehydration statistics associated with the large-scale circulation changes.

~~The d~~Diabatic heating, which drives the vertical transport in the trajectory model, also shows a westward shift with stronger enhancement of rising motion over the west side of the Asian monsoon region during August compared to that ~~during~~ of May and June (Fig. 4). This suggests a westward migration of vertical transport associated with a gradual increase (decrease) of convection over the northwestern~~ and gradual decrease of convection over the~~ (southeastern) Asian monsoon region from early to late summer. Such an anomalous shift of convection and diabatic heating near the tropopause towards the northwest side is a common feature over the Asian monsoon region during the boreal summer (e.g., Qian and Lee, 2000).~~,~~ This lead~~sing~~ to an increasing fraction of air mass in the LS coming from the warmer west~~ part than the colder east part~~ section of the Asian monsoon region.

3.2 Intra-seasonal variations of LS water vapor over the Asian monsoon region

To evaluate the relationships between the lower stratospheric water vapor variation~~, and~~ convection and diabatic heating objectively, we applied SVD analysis to the data as described in Section 2 to the data. Figure 5 shows the dominant mode of SVD for MLS water vapor anomalies in the UT/LS and OLR anomalies. The pattern of water vapor anomalies at 100 hPa in Figure 5a shows uniform anomalies over the entire Asian monsoon region with largest values over the western region. The corresponding OLR anomaly pattern (Fig. 5d) illustrates a zonal east-west dipole pattern, i.e., anomalously strong convection in the southwest and anomalously weak convection in the southeast of the Asian monsoon region, respectively. The statistics of the first SVD mode confirm that water vapor anomalies at 100 hPa over the Asian monsoon region during summer are significantly correlated with OLR anomalies (r = 0.41, p<0.01). This first SVD mode accounts for a significant 42.63% of the total water vapor variance. By regressing 147 hPa water vapor anomalies onto the ~~principle~~ principal component of the OLR SVD mode, we obtain the heterogeneous map of water vapor anomalies at 147 hPa (Fig. 5b). ~~There~~ Due to the westward shift of convection, there is anomalously higher humidity in the entire UT over the southwestern Asian monsoon region, where an increase of cirrus clouds also occurs based on Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) observations from 2006 to 2013 (not shown here) ~~(not shown), associated with a westward shift of convection~~. The heterogeneous maps of diabatic heating and dehydration frequency anomalies are consistent with the westward shift of convection, suggesting the latter probably enhances ascending motion and ~~hence~~ therefore the fraction of air mass being ~~dehydration~~ dehydrated over the western Asian monsoon region (Figs. 5c-d). The consistent wet anomalies from the UT to the LS~~,~~ – along with enhanced diabatic heating and dehydration over the western Asian monsoon region~~,~~ – suggest that the increase of LS water vapor over the Asian monsoon region is associated with enhanced water vapor transport driven by anomalous convective diabatic heating over the western monsoon region.

To further look at the intra-seasonal oscillation of the dehydration center associated with the LS water vapor changes, we compared the behavior of ~~last dehydration~~MRD locations during wet and dry days (Fig. 6). We use the trajectory runs to identify the ~~last dehydration~~ MRD locations for all the air parcels at 100 hPa in the Asian monsoon region during wet and dry days, respectively, and compare their differences. We first evaluate the performance of the model simulation on 100 hPa water vapor variations over the Asian monsoon region (20-40ºN, 40-140ºE). Figures 6a-b show the time series of 100 hPa water vapor anomalies in the Asian monsoon region during summer from the trajectory runs (red line) compared with the Aura MLS observations (black line, same as Figure 4a in Randel et al. (2015)). The trajectory model can simulate both interannual and intra-seasonal variations of water vapor in the Asian monsoon very well (r = 0.6 for traj_ERAi and r = 0.51 for traj_MERRA), including most wet and dry extremes, which also further confirms the dominant role of temperatures on controlling the LS water vapor variations. The traj_MERRA has ~~a bad performance~~ larger biases during 2006 compared to traj_ERAi, ~~leading~~ which leads to the relatively low correlation with the observations. The correlations shown here could also be impacted by excluding the simulated values at lower levels when the MLS weighting matrix is applied to the trajectory outputs. By selecting the wet and dry events (those above and below one standard deviation, denoted by the red and blue dashed lines) in the trajectory runs, we further investigate the different dehydration and initialization behavior during different moist states in the LS. As shown in Figures 6c-d, ~~during wet events,~~ there is more dehydration over the western Asian monsoon region and less over the eastern region during the wet events compared with dry events, implying a westward shift of dehydration. The underlying initialization behavior at 370K also shows a westward shift of the air source with more air from the west side and less air from the east side during wet events than dry events (Figs. 6e-f). ~~Such a~~The clear westward shift of initialization and dehydration activities during wet events is consistent with the observational results of enhanced water vapor transport over the west side shown in Figure 5. This west-east oscillation of vertical transport is associated with changes of the large-scale circulation forced by diabatic heating in the trajectory model. These results are consistent between traj_ERAi and traj_MERRA, which further confirms ~~confirming~~ the robust physical links between convection, dehydration and water vapor transport. It is important to consider the west-east oscillations of the anomalous convective activity and dehydration center, in order to fully explain the changes of the LS water vapor at both seasonal and intra-seasonal time scales.

4 Conclusions and Discussion

Water vapor in the Asian monsoon LS significantly influences water vapor of the global stratosphere (Dethof et al., 1999; Bannister et al., 2004; Gettelman et al., 2004; Ploeger et al., 2013), but significant uncertainty still exists as to what processes ~~that~~ control its transport. This paper clarifies that the changes ~~impact~~ of dehydration locations~~ – especially its geographic variations –~~ –in addition to the changes of local dehydration temperatures – have significant influence on water vapor transport to the LS through a joint analysis of satellite data and trajectory model simulations. Although our focus is at 100 hPa, we have also examined the results for water vapor variations at 82 hPa and found similar results.

First, our results confirm~~s~~ the dominant role of temperatures on the LS water vapor variations (Fig. 1 and Fig. 6a-b). This is consistent with the study of Randel et al. (2015) in terms of temperature control of water vapor that enters the lower stratosphere. However, ~~this~~ our study suggests that aside from ~~the~~ local temperatures changes, the variation of the dehydration locations~~, especially its west-east oscillation, also~~ plays a significant role in both the intra-seasonal and early-to-late summer moistening of the LS over the Asian monsoon region, especially its west-east oscillation. In particular, the dehydration locations vary with time and are ~~,~~ characterized by a westward migration from the southeastern Asian monsoon region with colder temperatures in May to northwestern India with warmer temperatures in August (Figs. 2-3). The ~~westward~~ geographic shift of the dehydration center to ~~warmer temperatures over~~ the western Asian monsoon region with warmer tropopause temperatures could increase water vapor significantly~~,~~. ~~which~~ This is comparable to the influence of local temperature changes (Table 1). This sub-seasonal migration of dehydration is associated with a westward migration of vertical motion (as shown in Figure 4), which ~~corresponding~~ corresponds to the seasonal march of the Asian monsoon convective systems (e.g., Qian and Lee, 2000). Second, we confirm the physical link between convection, diabatic heating and large-scale transport. At an intra-seasonal time scale, the westward shift of convection appears to enhance the diabatic heating and the ascending motion in the tropopause layer~~, which~~. This in turn enhances the vertical transport of water vapor and dehydration frequency over the west side of the Asian monsoon region. The less dehydrated air ascends and ~~transports~~ travels eastward, eventually increasing LS water vapor over the entire Asian monsoon region (Fig. 5). ~~More~~ Additional transport and dehydration under warmer tropopause temperatures in the west of the Asian monsoon region would contribute to the wet anomalies in the LS (Fig. 6). The east-west oscillation of convection and dehydration patterns is similar to the well-known Boreal Summer Intraseasonal Oscillation in the Asian monsoon region (e.g., Lau and Chan, 1986; Lawrence and Webster, 2002; Kikuchi et al., 2012), which suggests ~~suggesting~~ a link between large-scale monsoon circulation ~~with~~ and water vapor transport into the LS. In summary, ~~by confirming the dominant role of temperatures on water vapor variations in the LS, we emphasize the importance of the role of convection on temperature changes and the geographic locations of dehydration~~ our study suggests that water vapor transport to the LS is controlled by both tropopause temperatures and the geographic variations of the dehydration center driven by diabatic heating of convection over the Asian monsoon region.

~~Most~~ The majority of the moist air is from the dehydration over the western Asian monsoon region where the temperatures are warmer than the cold-point tropopause temperatures over the Southeast Asia. However, the source region of the moist air remains unclear. The Bay of Bengal and Southeast Asia have previously been identified as primary source regions of air parcels over the Asian monsoon LS due to ~~convective protrusion~~ frequent and deep convective protrusions (Park et al., 2007; James et al., 2008; Devasthale and Fueglistaler, 2010). Some of the air from this region detrains in the upper troposphere ~~UT~~ and is advected south-westward ~~(e.g., Park et al., 2009),~~ (e.g., Park et al., 2009). This could possibly ~~contributing~~ contribute to the moist air entering the LS over the western Asian monsoon region shown in this study. Meanwhile, some of the air entering the LS over the Bay of Bengal and Southeast Asia, is dry mostly due to the substantial dehydration by cold-point temperatures.

This study ~~studies~~ implies that geographic changes in convection patterns within the South Asian monsoon region could change the abundance of water vapor in the LS of the Asian monsoon without changing the strength of convection. For example, a westward convection shift would likely enhance water vapor transport through a warmer pathway from the UT to the LS over the west side of the Asian monsoon region. Some studies indicate long-term changes in precipitation over the western and surrounding regions in the past decades (e.g., Ramanathan et al., 2005; Goswami et al., 2006; Gautam et al., 2009; Bollasina et al., 2011; Turner and Annamalai, 2012; Zuo et al., 2013; Walker et al., 2015). However these changes are not clearly evident due to large discrepancies between different datasets (Walker et al., 2015). How these changes influence LS water vapor is also unknown. Moreover, further research is required to evaluate how seasonal and long-term dehydration statistical changes over the Asian monsoon influence the water vapor mixing ratio entering the global stratosphere. Therefore, studies of convection regime variation will have important implications for predicting future stratospheric water vapor changes in the Asian monsoon regions, and possibly over the globe.

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References

Anderson, J. G., Wilmouth, D. M., Smith, J. B., and Sayres, D. S.: UV dosage levels in summer: increased risk of ozone loss from convectively injected water vapor, Science, 337, 835-839, 2012.
Bannister, R., O'neill, A., Gregory, A., and Nissen, K.: The role of the south‐east Asian monsoon and other seasonal features in creating the 'tape‐recorder'signal in the Unified Model, Q. J. Roy. Meteorol. Soc., 130, 1531-1554, 2004.
Bollasina, M. A., Ming, Y., and Ramaswamy, V.: Anthropogenic aerosols and the weakening of the South Asian summer monsoon, Science, 334, 502-505, 2011.
Bowman, K. P.: Large‐scale isentropic mixing properties of the Antarctic polar vortex from analyzed winds, J. Geophys. Res.: Atmos., 98, 23013-23027, 1993.
Bowman, K. P., Lin, J. C., Stohl, A., Draxler, R., Konopka, P., Andrews, A., and Brunner, D.: Input Data Requirements for Lagrangian Trajectory Models, Bull. Am. Meteorol. Soc., 94, 1051-1058, 10.1175/bams-d-12-00076.1, 2013.
Bretherton, C. S., Smith, C., and Wallace, J. M.: An intercomparison of methods for finding coupled patterns in climate data, J. Clim., 5, 541-560, 1992.
Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M. A., Balsamo, G., and Bauer, P.: The ERA‐Interim reanalysis: Configuration and performance of the data assimilation system, Q. J. Roy. Meteorol. Soc., 137, 553-597, 2011.
Dessler, A. E., and Sherwood, S. C.: Effect of convection on the summertime extratropical lower stratosphere, J. Geophys. Res., 109, D23301, 2004.
Dessler, A. E., Schoeberl, M. R., Wang, T., Davis, S. M., and Rosenlof, K. H.: Stratospheric water vapor feedback, Proc. Nat. Acad. Sci., 110, 18087-18091, 2013.
Dethof, A., O'Neill, A., Slingo, J., and Smit, H.: A mechanism for moistening the lower stratosphere involving the Asian summer monsoon, Q. J. Roy. Meteorol. Soc., 125, 1079-1106, 1999.
Devasthale, A., and Fueglistaler, S.: A climatological perspective of deep convection penetrating the TTL during the Indian summer monsoon from the AVHRR and MODIS instruments, Atmos. Chem. Phys., 10, 4573-4582, 2010.
Dunkerton, T. J.: Evidence of meridional motion in the summer lower stratosphere adjacent to monsoon regions, J. Geophys. Res.: Atmos., 100, 16675-16688, 10.1029/95jd01263, 1995.
Dvortsov, V. L., and Solomon, S.: Response of the stratospheric temperatures and ozone to past and future increases in stratospheric humidity, J. Geophys. Res.: Atmos., 106, 7505-7514, 2001.
Evans, S. J., Toumi, R., Harries, J. E., Chipperfield, M. R., and Russell, J. M.: Trends in stratospheric humidity and the sensitivity of ozone to these trends, J. Geophys. Res.: Atmos., 103, 8715-8725, 1998.
Forster, F., Piers, M., and Shine, K. P.: Stratospheric water vapour changes as a possible contributor to observed stratospheric cooling, Geophys. Res. Lett., 26, 3309-3312, 1999.
Fu, R., Hu, Y., Wright, J. S., Jiang, J. H., Dickinson, R. E., Chen, M., Filipiak, M., Read, W. G., Waters, J. W., and Wu, D. L.: Short circuit of water vapor and polluted air to the global stratosphere by convective transport over the Tibetan Plateau, Proc. Nat. Acad. Sci., 103, 5664-5669, 2006.
Fueglistaler, S., Bonazzola, M., Haynes, P., and Peter, T.: Stratospheric water vapor predicted from the Lagrangian temperature history of air entering the stratosphere in the tropics, J. Geophys. Res.: Atmos., 110, 2005.
Gautam, R., Hsu, N., Lau, K.-M., and Kafatos, M.: Aerosol and rainfall variability over the Indian monsoon region: distributions, trends and coupling, Ann. Geophys., 2009, 3691-3703,
Gettelman, A., Salby, M. L., and Sassi, F.: Distribution and influence of convection in the tropical tropopause region, J. Geophys. Res.: Atmos., 107, ACL 6-1-ACL 6-12, 2002.

Gettelman, A., Kinnison, D. E., Dunkerton, T. J., and Brasseur, G. P.: Impact of monsoon circulations on the upper troposphere and lower stratosphere, J. Geophys. Res.: Atmos., 109, 2004.
Goswami, B. N., Venugopal, V., Sengupta, D., Madhusoodanan, M., and Xavier, P. K.: Increasing trend of extreme rain events over India in a warming environment, Science, 314, 1442-1445, 2006.
Holton, J. R., Haynes, P. H., McIntyre, M. E., Douglass, A. R., Rood, R. B., and Pfister, L.: Stratosphere-troposphere exchange, Rev. Geophys., 33, 403-439, 10.1029/95RG02097, 1995.
Holton, J. R., and Gettelman, A.: Horizontal transport and the dehydration of the stratosphere, Geophys. Res. Lett., 28, 2799-2802, 2001.
Jackson, D., Driscoll, S., Highwood, E., Harries, J., and Russell, J.: Troposphere to stratosphere transport at low latitudes as studies using HALOE observations of water vapour 1992–1997, Q. J. Roy. Meteorol. Soc., 124, 169-192, 1998.
James, R., Bonazzola, M., Legras, B., Surbled, K., and Fueglistaler, S.: Water vapor transport and dehydration above convective outflow during Asian monsoon, Geophys. Res. Lett., 35, 2008.
Kikuchi, K., Wang, B., and Kajikawa, Y.: Bimodal representation of the tropical intraseasonal oscillation, Clim. Dyn., 38, 1989-2000, 2012.
Lau, K.-M., and Chan, P.: Aspects of the 40-50 day oscillation during the northern summer as inferred from outgoing longwave radiation, Mon. Wea. Rev., 114, 1354-1367, 1986.
Lawrence, D. M., and Webster, P. J.: The boreal summer intraseasonal oscillation: Relationship between northward and eastward movement of convection, Journal of the Atmospheric Sciences, 59, 1593-1606, 2002.
Livesey, N. J., Read, W. G., Froidevaux, L., Lambert, A., Manney, G. L., Pumphrey, H. C., Santee, M. L., Schwartz, M. J., Wang, S., and Cofield, R. E.: Version 3.3 Level 2 data quality and description document, JPL D-33509, 2011.
Milz, M., Von Clarmann, T., Fischer, H., Glatthor, N., Grabowski, U., Höpfner, M., Kellmann, S., Kiefer, M., Linden, A., and Mengistu Tsidu, G.: Water vapor distributions measured with the Michelson Interferometer for Passive Atmospheric Sounding on board Envisat (MIPAS/Envisat), J. Geophys. Res.: Atmos., 110, 2005.
Park, M., Randel, W. J., Gettelman, A., Massie, S. T., and Jiang, J. H.: Transport above the Asian summer monsoon anticyclone inferred from Aura Microwave Limb Sounder tracers, J. Geophys. Res.: Atmos., 112, 2007.
Park, M., Randel, W. J., Emmons, L. K., and Livesey, N. J.: Transport pathways of carbon monoxide in the Asian summer monsoon diagnosed from Model of Ozone and Related Tracers (MOZART), J. Geophys. Res.: Atmos., 114, 2009.
Ploeger, F., Günther, G., Konopka, P., Fueglistaler, S., Müller, R., Hoppe, C., Kunz, A., Spang, R., Grooß, J. U., and Riese, M.: Horizontal water vapor transport in the lower stratosphere from subtropics to high latitudes during boreal summer, J. Geophys. Res.: Atmos., 118, 8111-8127, 10.1002/jgrd.50636, 2013.
Ploeger, F., Gottschling, C., Griessbach, S., Grooß, J.-U., Guenther, G., Konopka, P., Müller, R., Riese, M., Stroh, F., and Tao, M.: A potential vorticity-based determination of the transport barrier in the Asian summer monsoon anticyclone, Atmos. Chem. Phys., 15, 13145-13159, 2015.
Qian, W., and Lee, D.-K.: Seasonal march of Asian summer monsoon, Int. J. Climatol., 20, 1371-1386, 2000.
Ramanathan, V., Chung, C., Kim, D., Bettge, T., Buja, L., Kiehl, J., Washington, W., Fu, Q., Sikka, D., and Wild, M.: Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle, Proc. Nat. Acad. Sci. U.S.A., 102, 5326-5333, 2005.
Randel, W. J., Wu, F., Gettelman, A., Russell, J. M., Zawodny, J. M., and Oltmans, S. J.: Seasonal variation of water vapor in the lower stratosphere observed in Halogen Occultation Experiment data, J. Geophys. Res.: Atmos., 106, 14313-14325, 2001.
Randel, W. J., Zhang, K., and Fu, R.: What controls stratospheric water vapor in the NH summer monsoon regions?, J. Geophys. Res.: Atmos., 2015.

Rienecker, M. M., Suarez, M. J., Gelaro, R., Todling, R., Bacmeister, J., Liu, E., Bosilovich, M. G., Schubert, S. D., Takacs, L., and Kim, G.-K.: MERRA: NASA's modern-era retrospective analysis for research and applications, J. Clim., 24, 3624-3648, 2011.

Rosenlof, K. H., Tuck, A. F., Kelly, K. K., Russell, J. M., and McCormick, M. P.: Hemispheric asymmetries in water vapor and inferences about transport in the lower stratosphere, J. Geophys. Res.: Atmos., 102, 13213-13234, 1997.

Schoeberl, M. R., and Dessler, A. E.: Dehydration of the stratosphere, Atmos. Chem. Phys., 11, 8433-8446, 2011.

Schoeberl, M. R., Dessler, A. E., and Wang, T.: Simulation of stratospheric water vapor and trends using three reanalyses, Atmos. Chem. Phys., 12, 6475-6487, 2012.

Schoeberl, M. R., Dessler, A., and Wang, T.: Modeling upper tropospheric and lower stratospheric water vapor anomalies, Atmos. Chem. Phys., 13, 7783-7793, 2013.

Schoeberl, M. R., Dessler, A. E., Wang, T., Avery, M. A., and Jensen, E. J.: Cloud formation, convection, and stratospheric dehydration, Earth and Space Sci., 2014.

Shindell, D. T.: Climate and ozone response to increased stratospheric water vapor, Geophys. Res. Lett., 28, 1551-1554, 2001.

Solomon, S., Rosenlof, K. H., Portmann, R. W., Daniel, J. S., Davis, S. M., Sanford, T. J., and Plattner, G.-K.: Contributions of stratospheric water vapor to decadal changes in the rate of global warming, Science, 327, 1219-1223, 2010.

Stenke, A., and Grewe, V.: Simulation of stratospheric water vapor trends: impact on stratospheric ozone chemistry, Atmos. Chem. Phys., 5, 1257-1272, 2005.

Turner, A. G., and Annamalai, H.: Climate change and the South Asian summer monsoon, Nature Climate Change, 2, 587-595, 2012.

Walker, J. M., Bordoni, S., and Schneider, T.: Interannual variability in the large-scale dynamics of the South Asian summer monsoon, J. Clim., 2015.

Wang, T., Randel, W. J., Dessler, A. E., Schoeberl, M. R., and Kinnison, D. E.: Trajectory model simulations of ozone (O3) and carbon monoxide (CO) in the lower stratosphere, Atmos. Chem. Phys., 14, 7135-7147, 10.5194/acp-14-7135-2014, 2014.

Wang, T., Dessler, A. E., Schoeberl, M. R., Randel, W. J., and Kim, J. E.: The impact of temperature vertical structure on trajectory modeling of stratospheric water vapor, Atmos. Chem. Phys., 15, 3517-3526, 10.5194/acp-15-3517-2015, 2015.

Wright, J. S., Fu, R., Fueglistaler, S., Liu, Y. S., and Zhang, Y.: The influence of summertime convection over Southeast Asia on water vapor in the tropical stratosphere, J. Geophys. Res.: Atmos., 116, 2011.

Zuo, Z., Yang, S., Zhang, R., Jiang, P., Zhang, L., and Wang, F.: Long-term variations of broad-scale Asian summer monsoon circulation and possible causes, J. Clim., 26, 8947-8961, 2013.

Table 1. Three idealized experiments based on traj_ERAi (values in bold) and traj_MERRA (values in brackets) to quantify the relative contributions of dehydration shift and dehydration temperatures on averaged water vapor over the Asian monsoon region.

Experiments	**Dehydration pattern**	**Dehydration temperatures**	**Averaged water vapor (unit: ppmv)**
CTL	June	June	**3.71** (3.80)
Exp_TEM	June	August	**4.20** (4.16)
Exp_LOC	August	June	**4.30** (4.22)
Exp_TEM_LOC	August	August	**4.81** (4.71)

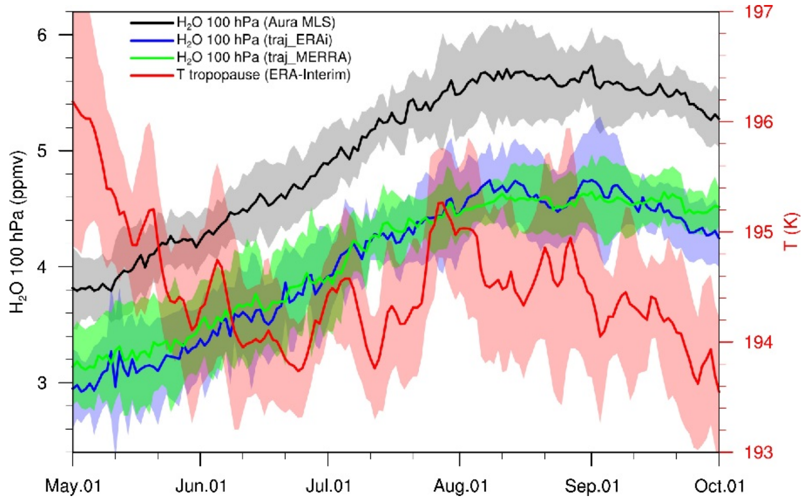

Figure 1. Climatological 100 hPa water vapor observed by the Aura MLS (black) and simulated by the traj_ERAi (blue) and traj_MERRA (green). The time series were averaged over the Asian monsoon region (20-40ºN, 40-140ºE) during May-September, 2005-2013. The red line denotes the time series of tropopause temperatures averaged over the same domain as in R15 (15-~~32ºN~~30ºN, 70-120ºE). The shadings indicate the corresponding standard deviation intervals.

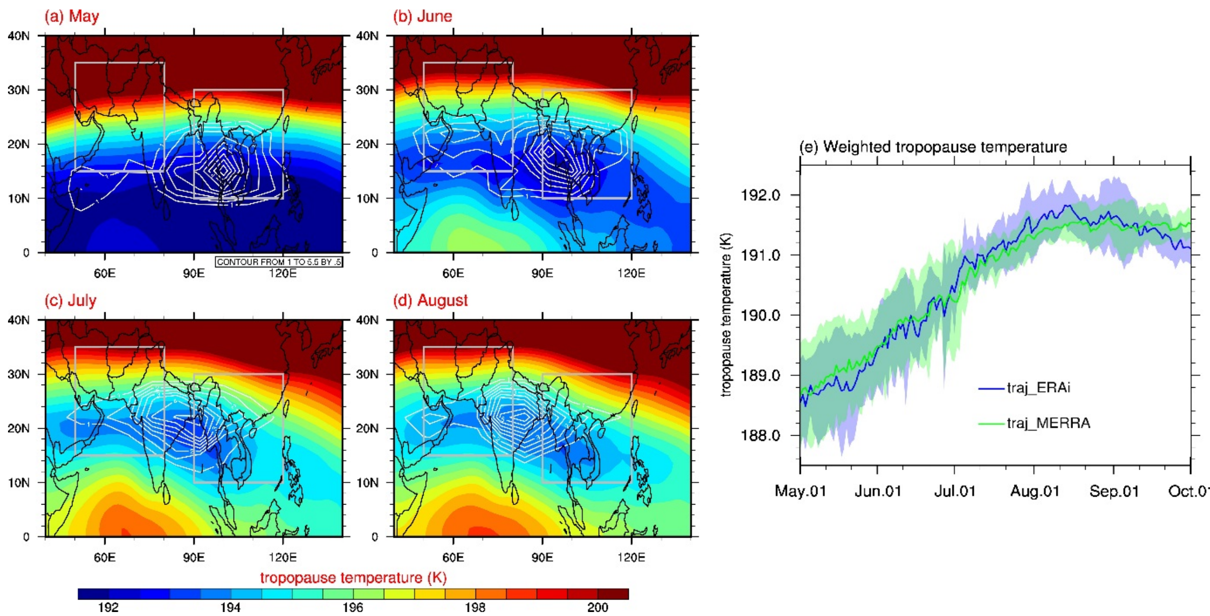

Figure 2. **(a)-(d)** **P**robability ~~Probability~~ density distributions of last dehydration locations for air parcels located at 100 hPa over the Asian monsoon region during May to August derived from traj_ERAi (white contours from 1% to 5.5% with an interval of 0.5%). Color shadings are averaged tropopause temperatures in ERA-Interim. The two boxes are the two domains distinguishing the west and east side of the Asian monsoon region in Figure 3. (e) is the average tropopause temperatures weighted by the dehydration frequency distributions in traj_ERAi (blue) and traj_MERRA (green) respectively. The color shadings indicate the corresponding standard deviation intervals.

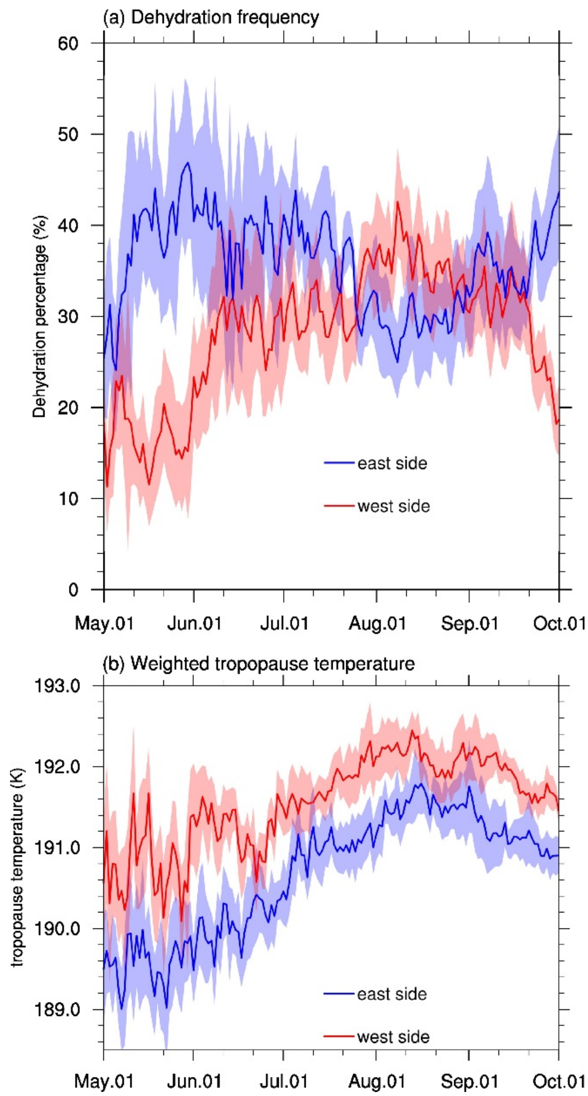

Figure 3. **(a)** Climatological time series of percentage of dehydration (%) located over the west side (15-35^{o}N, ~~40~~50-80^{o}E, red line) and the east side (10-30^{o}N, 90-120^{o}E, blue line) for air parcels located at 100 hPa over the Asian monsoon region based on traj_ERAi. (b) Average tropopause temperatures weighted by the dehydration frequency distributions over the west side and the east side respectively based on traj_ERAi. The color shadings indicate the corresponding standard deviation intervals.

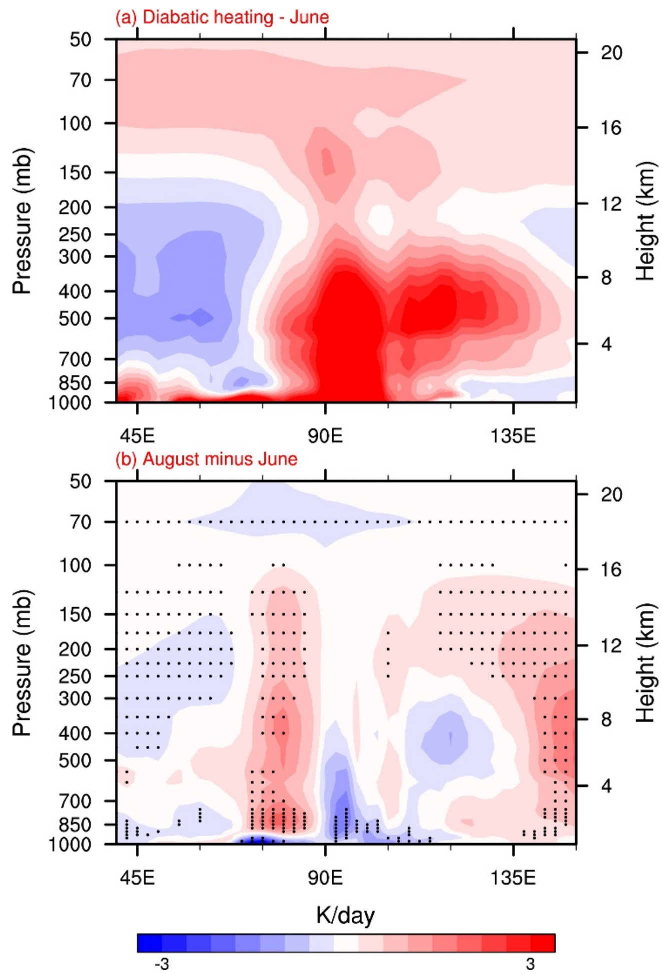

Figure 4. Vertical-longitude distribution of climatological diabatic heating averaged within 15-30°N in ERA-Interim for (a) June; (b) difference between August and June. The differences that are significant at 95% level based on student-t test are dotted.

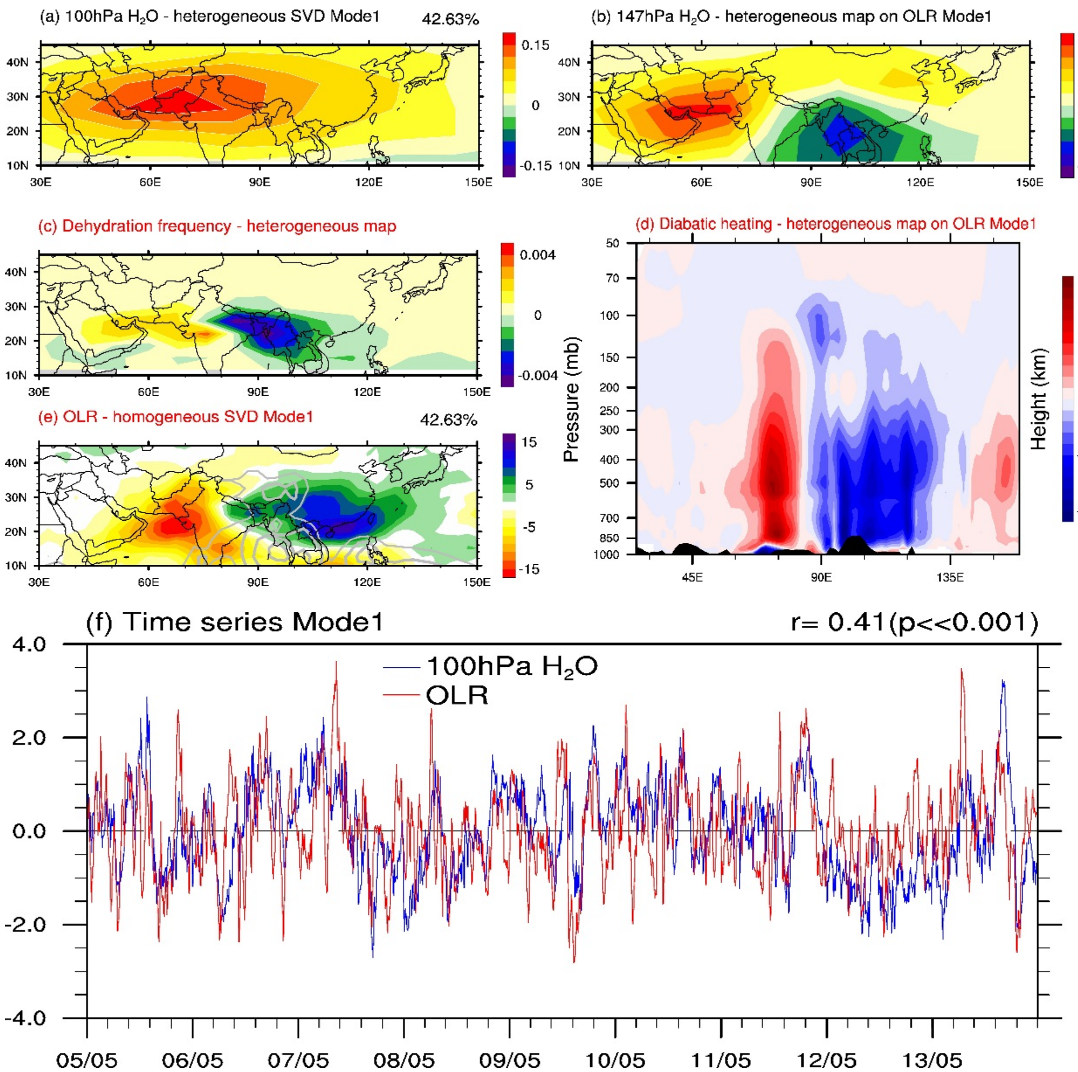

Figure 5. First SVD mode between water vapor anomalies (ppmv) and OLR anomalies (W/m^2) over the Asian monsoon region. (a-b) Heterogeneous map of water vapor at 100 hPa and 147 hPa on OLR SVD mode 1; (c) Heterogeneous map of dehydration frequency derived from traj_ERAi on OLR SVD mode 1; (d) Heterogeneous map of diabatic heating at 25^{o}N on OLR SVD mode 1; (e) homogeneous map of OLR SVD mode 1; (f) standardized time series of 100 hPa water vapor anomalies and OLR anomalies. Note that the color bar for OLR is reversed.

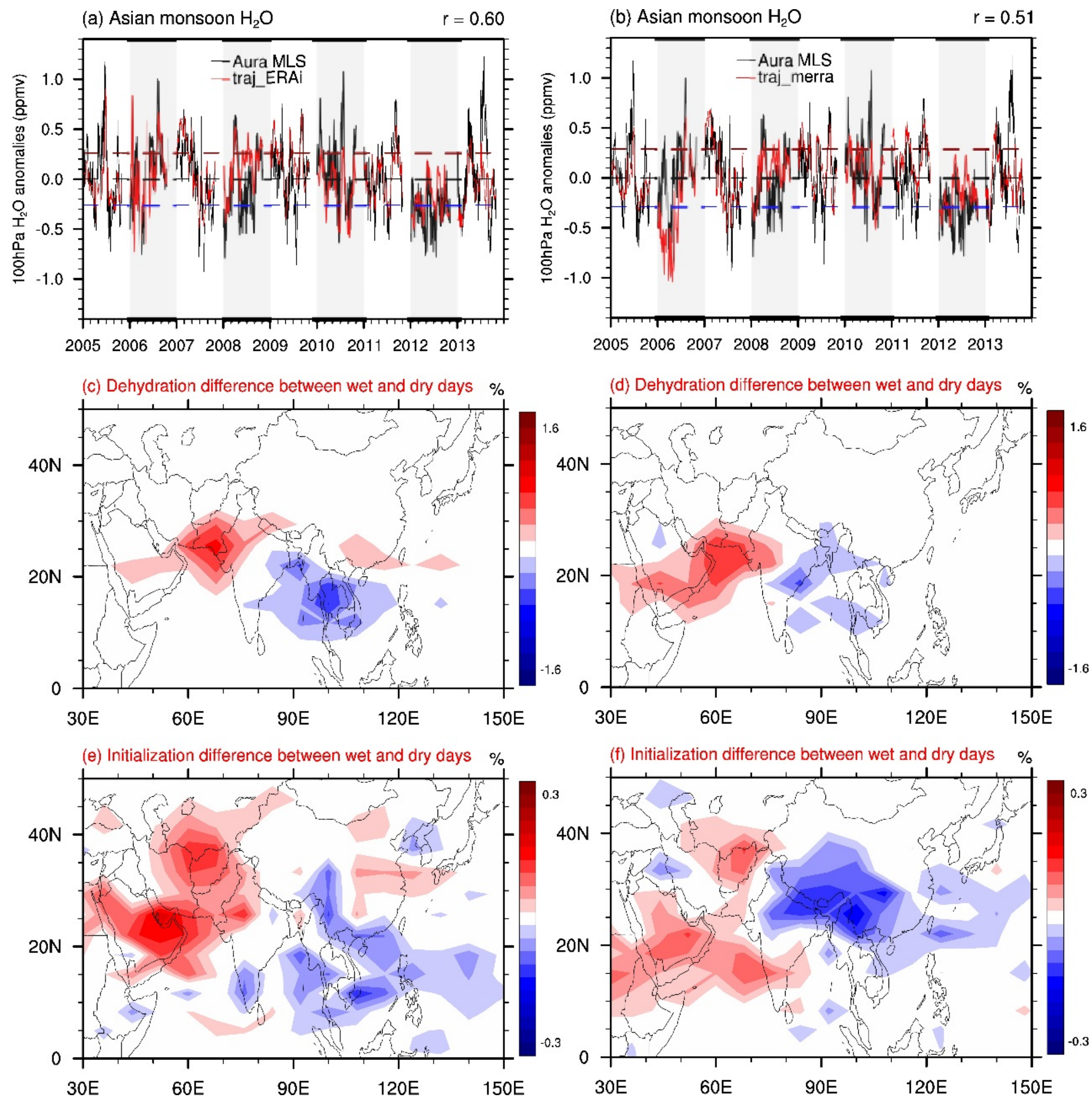

Figure 6. Left panel is from traj_ERAi, right panel is from traj_MERRA. (a-b) Time series of deseasonalized 100 hPa water vapor anomalies in the Asian monsoon region (20-40ºN, 40-140ºE) derived from Aura MLS observations (black line) and trajectory runs (red line). Dashed lines are at one sigma variability for water vapor time series in trajectory runs, and are used to identify wet and dry event (above and below one standard deviation, denoted by the red and blue dashed lines). (c-d) Anomalous frequency of occurrence of the last

dehydration locations between wet and dry days for air parcels located at 100 hPa over the Asian monsoon region. (e-f) are same as (c-d) but for initialized locations.