Reply to anonymous Referee #1 (acpd-14-C11680–C11684)

This study compares trajectories in the TTL calculated with three different temperature datasets. The focus of the evaluation is on the statistical evaluation of the minimum temperature along the trajectories as they cross the tropical tropopause, and the corresponding water vapour entering the stratosphere. It is shown that the overall humidity values and in particular the seasonal cycle and interannual variability are only very weakly sensitive to the choice of the temperature dataset. The objective of the study is well justified and the results are in principle relevant; however, important aspects of the paper are not well explained and/or conceptually fuzzy - as outlined in my comments below. Therefore major revisions are required to turn this study into a fully consistent and convincing paper.

Reply:

Thanks for those helpful comments. We have made substantial changes to the manuscript to include answers to all aspects. The detailed answers for each question can be found below, with line numbers from the updated manuscript.

Major comments:

A) *Is this paper really about the impact of "temperature resolution"? First, the study only considers the vertical resolution aspect, and not the horizontal nor the temporal one. In particular temporal resolution might also matter, but this is not mentioned in the paper. Then, "resolution" to me sounds very technical (e.g., like running a model with two different resolutions). But this is not exactly the problem, nor what you do. My point is that if the MERRA assimilation cycle was running with a model with higher vertical resolution, then the resulting field would not necessarily capture more of the, e.g., gravity wave signals because capturing them is not only an issue of resolution but also of the representation of the wave triggering mechanisms. I would like the authors to discuss more critically and explicitly what they actually do. I think it is good and relevant, but it is not well described by "resolution". Maybe then the authors might also consider rephrasing the title of their study.*

Reply:

This is an excellent point. We intend to investigate the impacts of vertical variability of tropopause temperatures on trajectory modeling of water vapor. It is known that local tropopause temperature could experience much variability in the vertical, so the real question is that if the temperature datasets we used already captured enough variability in tropopause temperature. If not, how big impact could it be? In the updated manuscript, we have changed the title to "… temperature vertical variability…" to make the objective of this paper clearer.

B) *Three datasets are used and I am perfectly fine with the first two of them: MERRA is used because it is "standard", available for a long time period etc. GPS is used* *because it is based upon independent observations with fine vertical resolution. My expectation is that this data set should be as close to reality as possible. But then why use the synthetically created MERRA-Twave dataset? I understand that this dataset would be valuable if we did not have GPS. But since we have GPS what can this dataset tell us in addition? I suggest to better motivate the use of this third dataset, or to focus on the analysis with MERRA and GPS only.*

Reply:

We included both GPS and MER-Twave datasets because they have their own advantages and limitations. GPS provides sparse sampling in the tropics (only ~800-1100 profiles per day), which means the variability in GPS is smaller than reality, although its mean is more accurate given the precise profiling. In contrast, MER-Twave has better variability but not accurate mean, since it is designed to have similar temperature variability to radiosondes but with mean reserved to original MERRA data (Kim and Alexdander, 2013). In summary, the mean temperature is closer to reality in GPS than in MER-T and MER-Twave, but the temperature variability is closer to reality in MER-Twave than in MER-T and GPS. We have added this discussion in lines 240-249.

C) *The discussion of the impact of atmospheric waves is insufficient. The general statement at the beginning of section 2.2.2 "Waves are underrepresented in reanalyses" does not make sense. Clearly planetary and synoptic-scale waves are/should be perfectly captured by reanalyses. It remains unclear, which part of the wave spectrum is considered here. Kelvin waves, gravity waves? When discussing the role of, e.g., gravity waves on the temperature field in the TTL, then maybe also the temporal resolution should be discussed. Six-hourly fields, from MERRA or GPS, cannot capture the temporal propagation / evolution of waves. This could potentially also affect the minimum temperature along the trajectories.*

Reply:

The description of underrepresented waves can be found in Kim and Alexander, 2013. According to their results (their Fig. 1b-d), at reanalysis model levels temperature variability at time scales shorter than ~10 days are weaker than observations. Thus, underrepresented waves include a part of Kelvin waves, mixed Rossby-gravity waves, and gravity waves. However, the problem in using reanalysis data for trajectory simulations is associated not only with these waves (< 10 days), but also with slow-scale waves (>10 days), since it involves interpolation between reanalysis vertical levels. As shown in Kim and Alexander, 2013, conventional interpolation (either linear or higher order) in-between model vertical levels degrades temperature variability even at longer time scales (> 10 days). This is because observed temperature profiles have strong curvatures in-between coarse model levels due to the existence of fine vertical-scale waves.

We only considered a vertical resolution issue, since horizontal or temporal resolution of current reanalyses is good enough to resolve most of TTL waves (Note that we do not mean that horizontal and temporal resolutions are good enough to resolve wave generation mechanisms.). A large portion of TTL waves has horizontal and temporal scales much larger and longer than reanalysis resolution, therefore, temperature behaves almost linearly in-between model horizontal and temporal resolution. However, temperature does not behave linearly in vertical space due to the fact that a significant portion of TTL waves have vertical wavelengths shorter than ~4 km (see Figure S4 in supporting information of Kim and Alexander, 2015), which could make waves less represented by the ~1.2 km vertical resolution in reanalyses.

The above discussion has been included in section 2.2.2.

D) *The paper has not been very carefully written. Several sentences/formulations are unclear:*

- *p. 29210 line 11: what is meant by "finite resolution"? Every resolution is finite, do you mean "fine"? (This problem occurs in several places.)*

Reply:

Yes, we mean fine resolution. All "finite" have been corrected to "fine".

- *p. 29213 line 15: "the carrying methane" sounds odd to me. Not clear how the methane values are initialized in the trajectories.*

Reply:

Corrected. We have modified in lines 122-126 to include the whole story of methane carried in our model.

- *p. 29213 line 19: what is meant by "limited in the tropical 110-50 hPa"?*

Reply:

Tropical 110-50 hPa is where the most dehydration happens. Refer Fig. 5a-c.

- *p. 29213 line 28: "total diabatic heating rates from all sky": please explain this better.*

Reply:

It means total heating rates due to long-wave and short-wave radiation, moist physics, friction, etc. It has been modified in lines 95-97.

- *p. 29214 line 8: "not represented well in current coarse model levels": you probably mean "... in models with coarse vertical resolution"; but I think this is not really the point (see comment A): even with more levels MERRA would not correctly capture all gravity waves emitted from tropical convection.*

Reply:

Agree. See reply to question C and more detailed explanation in section 2.2.2.

- *p. 29217 line 5: what is "the curly nature" of a temperature profile?*

Reply:

The "curly nature" means the strong curvature of temperature profiles around the cold-point tropopause. This has been rephrased in line 253-255.

- *p. 29220 line 4: "We see slightly drier air in GPS run expected"?*

Reply:

Rephrased.

- *p. 29220 line 20: The sentence "Note that ..." is too long, and it is not clear what is meant by "the two are strongly coupled".*

Reply:

Rephrased. See lines 367-369.

E) *p. 29215 lines 24: This is an interesting result, but it is not well discussed. How can these happen? How can MERRA be too cold at model levels (compared to GPS) but too warm in between? MERRA values in between model levels are calculated by linear interpolation and therefore I would expect that a cold bias at the model levels is "transferred" to the layer in between.*

Reply:

MERRA doesn't assimilate GPS observations, which makes these two datasets independent from each other. Within the tropopause MERRA model levels are separated ~1.2 km apart, which might miss the temperature variations that could only be captured by data in finer vertical resolutions, such as GPS observations. Therefore, although MERRA is warmer at model levels, it doesn't necessarily mean MERRA should be warmer in-between. This is clearly shown in Fig. R11a-b below.

Moreover, the mean temperature differences depend on the location being examined. For example, if we only consider the deep inner tropics (10° N-S), MERRA shows warm biases throughout the entire tropopause layers (Fig. R11c). Either way, a clear fact is that MERRA is warm biased at the cold-point tropopause (~100-90 hPa).

This discussion has been added in the discussions of Fig. 2.

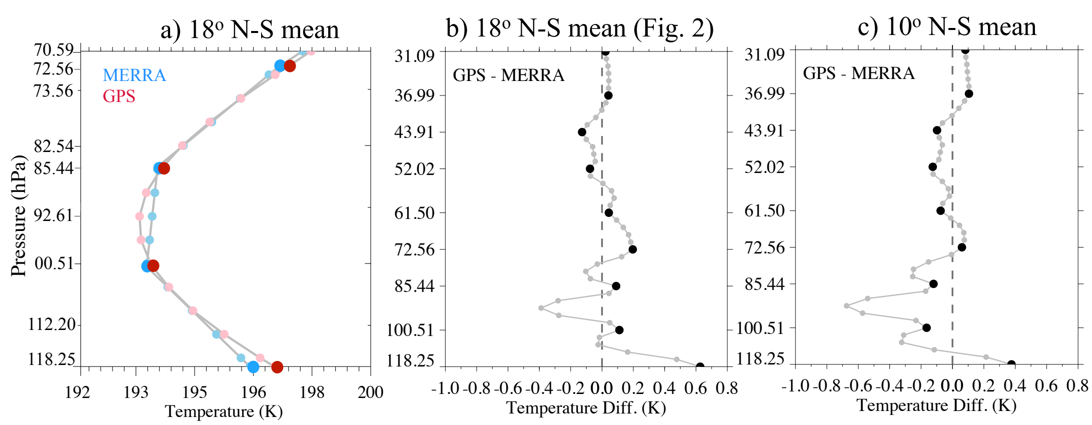

Figure R11. a) MERRA and GPS temperature averaged within 18° N-S in 2007-2013; b) the differences in a); and c) same as b) but averaged within 10° N-S. Clearly average within different latitudes results in different values, but the warm bias in MERRA cold-point tropopause always exists.

F) *In section 3.1 I have a problem in understanding the selection of the trajectories. My impression is that trajectories are selected if they reach the 90-hPa level (this is considered as the entry point in the stratopshere). This is fine with me, but this implies that (during the time period considered) some trajectories maybe don't reach the 60- hPa level. But then you determine FDP statistics up to 60 hPa! Does this not lead to a biased distribution? Should you not select trajectories that reach 60 hPa instead of 90 hPa?*

Reply:

Our trajectory model runs forward, and along time we kept records of any dehydration occurrences. Starting from the initiation level 370-K, parcels ascend to higher altitudes while crossing the tropopause, during which parcels experience multiple dehydrations whenever colder temperatures were encountered. On the other hand, parcel's water vapor is conserved when encountering warmer temperature. To isolate the FDP events, we chose parcels that were already above 90-hPa for at least six 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. This part has been modified accordingly in section 3.1, lines 276-283.

G) *p. 29218 line 19: The bimodal FDP distribution with MERRA data is interesting (Fig. 5). But in principle the distribution should be even more peaked! When using linear interpolation between model levels, then minimum temperature must occur exactly at one of the model levels. So the smearing out of the two peaks is an effect of the temporal resolution of the trajectory output. I assume that you determine the minimum temperature from 6-hourly values along the trajectories. Then of course it can happen that the time when the trajectory reaches the exact pressure of a model level is "hidden" (i.e., in between two times) and therefore the "real" location and value of the minimum temperature is missed. This indicates that the temporal resolution can play an important role, and I suggest that the role of temporal resolution (of the wind fields, of the trajectory output) is discussed in the paper.*

Reply:

This is an excellent point. Along the trajectory integration, FDP is where the coldest temperature is encountered along a parcel's path. This coldest temperature could be found either exactly at MERRA model levels or in-between levels during that step of integration, depending on the trajectory integration intervals. As shown in Fig. R12 below: during two steps of integration (from $t \rightarrow t+\Delta t$, and from $t+\Delta t \rightarrow t+2\Delta t$), the FDP could be found exactly at (Fig. R12a), above (Fig. R12b), or below (Fig. R12c) the MERRA cold-point level (85.4 hPa). Suppose our trajectory integration interval is as small as seconds then at some time steps parcels would inevitably travel to each of the MERRA model levels, and therefore the encountered coldest temperatures would always be at either of the two model levels in MERRA. In another word, the bimodal FDP distribution from MERRA run could be even more peaked when choosing smaller integration step. Two reasons that we didn't choose such small time step: 1) the wind and temperature data are only available 6-hourly or even daily (GPS), so much smaller time step introduces more uncertainties with more interpolation; 2) considering the balance between model running speed and computational resources. This has been addressed in context lines 312-322.

Currently we output trajectory results on daily basis, which is already fine enough to study the evolutions of FDP on monthly or seasonal basis. Besides, due to the domain-filling feature of our model, the FDP results are not sensitive to longer, such as 3-day or 5-day, or shorter, such as hourly, output intervals.

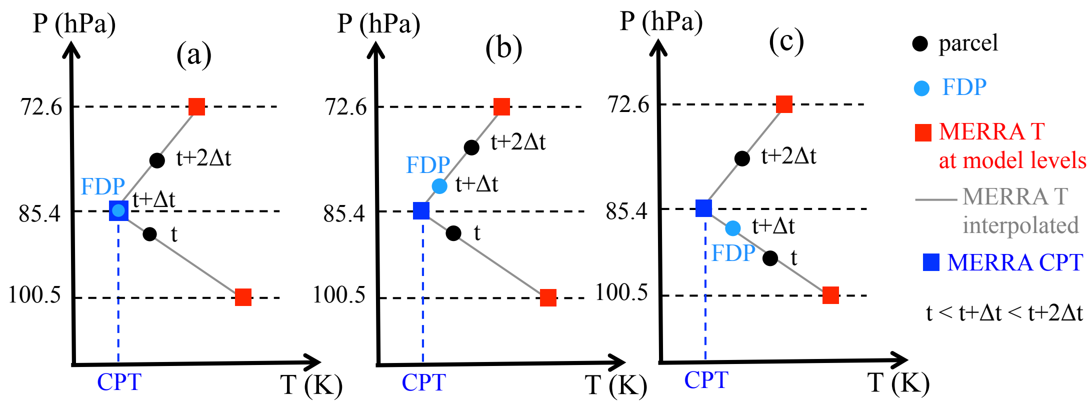

Figure R12. Illustration of the FDP locations in different scenario. Filled squares are MERRA temperatures at model levels, with cold-point tropopause (CPT) marked in blue and others in red. Grey lines are linearly interpolated temperatures in-between model levels. Parcels (black dots) travel from t, to t+Δt, and then to t+2Δt. During this process, FDP (blue dots) could be found exactly at MERRA model levels (a) or in-between MERRA model levels (b, c).

Minor comments:

1) *p. 29212 line 8: maybe a terminology detail: here you write about "resolved but underrepresented waves" - does this (see comment A) also indicate that your study is not mainly about resolution, but more about "effects of gravity(?) waves on the temperature field"?*

Reply:

We realized that "resolution" is not appropriate in expressing our objective, so we changed it to "vertical variability". The MER-Twave has more variability than standard MERRA temperatures.

2) *Section 2.2.2 is very difficult to understand. If you keep this MERRA-Twave dataset in your study, this paragraph should become less technical (for the technical aspects the reader can be referred to Kim and Alexander 2013). Here the reader should be able to learn the general concept.*

Reply:

Agree. Now we have shortened the technical explanations and replaced with more discussions of waves and temperature variability in section 2.2.2.

3) *Comparing Figs. 5 and 7b: something is probably not correct with the scales of the FDP events. Values in Fig. 7b are about 4 times smaller, but in both cases they should integrate to 100%.*

   Reply:

   For both Fig. 5 and Fig. 7b, the FDP occurrence frequencies are calculated as the ratio of FDP events at each 2-hPa bin relative to total FDP events, regardless of seasons, within the 110-60 hPa range. Therefore, the curves in Fig. 5 represent the mean FDP frequencies averages in all seasons, and the integration of each curve is 100% before being normalized to "%/hPa" (i.e., frequencies divided by 2-hPa). Fig. 7b, however, only shows the frequencies of FDP during SON relative to all season FDP, therefore its magnitude is about ¼ of total frequencies.

   In the updated manuscript, we have changed all normalized FDP frequency unit in Fig. 5 from "%/hPa" to "%", so each PDF profile integrate from bottom to up ends up with 100%.

Editorial comments:

- p. 29213 line 19: "Noted" should read "Note"

Reply:

Corrected.

- p. 29214 line 9: should read "... that use an idealized parameterization of ..."

Reply:

Corrected.

[Reference]

Kim, J.-E., and Alexander, J. M.,: A new wave scheme for trajectory simulations of stratospheric water vapor, Geophys. Res. Lett., 40, 5286–5290, doi:10.1002/grl.50963, 2013.

Kim, J.-E., and Alexander, J. M.,: Direct impacts of waves on tropical cold point tropopause temperature, Geophys. Res. Lett., doi:10.1002/2014GL062737, 2015.

Reply to anonymous Referee #2 (acpd-14-C9976–C9981)

This study discusses an important scientific question, namely inter annual variability of stratospheric water vapour. The particular focus is on trajectory calculations and on the question in how far the vertical resolution of the information on stratospheric temperatures influences the simulated freeze drying in the model. This is an interesting and important topic, which is of interest to the readership of ACP.

The descriptions of a trend in water vapour and interannual and seasonal variability are different things (e.g. Ploeger et al., 2011; Fueglistaler et al., 2013) and are likely influenced by different processes. And the issue of stratospheric water vapour trends is an important issue, which is alluded to in the manuscript, but somewhat underrepresented in the discussions here. Note that stratospheric trends of water vapour are rather uncertain (e.g., Hurst et al., 2011; Kunz et al., 2013; Urban et al., 2014; Hegglin et al., 2014). It would be important, if this paper could provide further and deeper insight into the interpretation of stratospheric water vapour trends. Alternatively, if the focus of the paper is solely on variability, this should be clearly stated in the paper.

Reply:

Like we said, the focus of our paper is to investigate the impacts of temperature datasets on the trajectory modeling of water vapor, so we have removed all discussion of "trend" in this version. It is not appropriate to analyze decadal trend based on only ~7 years of data. Besides those papers that discussed H_2O trend based on Boulder records (Hurst et al., 2011; Kunz et al., 2013), which were later proved to be problematic (Hegglin et al., 2014), we have a new paper published recently (Dessler et al., 2014) on the uncertainties of H_2O trend.

A major focus of the paper is on dehydration mechanisms of stratospheric air and Figure 5 is the central figure. However I have reservations about the figure and its interpretation (see also below). From the concept of FDP presented in this figure, it is not clear to me why the stratospheric water vapour levels can be so similar for the three temperature sources given the fact that the FDP curves are rather similar, but the FDP frequencies are rather different. I think the paper could be clearer here in its arguments.

Reply:

The different shapes of FDP curves are caused by whether the tropopause temperatures have enough variability in the vertical. In case of MERRA, the tropopause temperatures are constrained only at two discrete levels (100 and 85 hPa), and therefore the FDP peaks around them. In case of GPS and MER-Twave, enough variability in tropopause temperatures enables FDP to be found in a wider range, and therefore the FDP curves going through gradual transitions.

The dashed curves of FDP H_2O represent the stratosphere entry level of H_2O, controlled solely by the coldest temperatures that parcels encountered along their travelling paths. When FDP occurs at tropopause level (90-100 hPa), the entry level H_2O could have generally 0.1-0.4 ppmv differences comparing between MERRA and GPS

(Fig. 4 and Fig. 8), which is not easy to tell given the large upper x-axis range in Fig. 5. That's why the dashed curves look similar, but still different. In the updated Fig. 5, we have plotted FDP and FDP H_2O in four seasons as well as all season averages.

I also suggest that an actual reconstruction of a water vapour profile is presented in the paper not only FDP profiles or relative water vapour differences (Fig. 8). This should allow a better assessment of the quality of the simulated profiles.

Reply:

We have updated this figure as Fig. 7 in the updated manuscript to include the actual water vapour profiles from three different runs.

Further, I suggest the authors consider the effect of methane oxidation on the increase of water vapour with altitude. Note that the chemical conversion of methane to water vapour (which does not occur through photolysis, see below) does not have to happen at altitudes of 80 or 60 hPa. Rather aged air that has experienced methane oxidation will descend and could be mixed into these altitudes (Ploeger et al., 2012; Abalos et al., 2013). In the presented model study, this effect is likely only partly taken into account by just considering trajectories. Could this be relevant for the results of this paper? The effect should be easy to check in a model world by switching off methane oxidation in the model. I suggest that the authors conduct such a sensitivity test and compare with observed water vapour profiles.

Reply:

Aged air descending back to the tropics has very limited impacts on the dehydration and final water vapour abundances in the lower stratosphere. This has been shown in our previous paper (refer Fig. 6 in Schoeberl et al., 2012). A more quantitative impression can be understood in Fig. R21 below, where trajectory results are obtained from using GPS temperatures with methane oxidation turned on and off. It is clear that below 70 hPa (~19 km), aged parcels carrying H_2O from methane oxidation plays a trivial role in the overall abundances of water vapour. This has been addressed in the updated manuscript in lines 126-128.

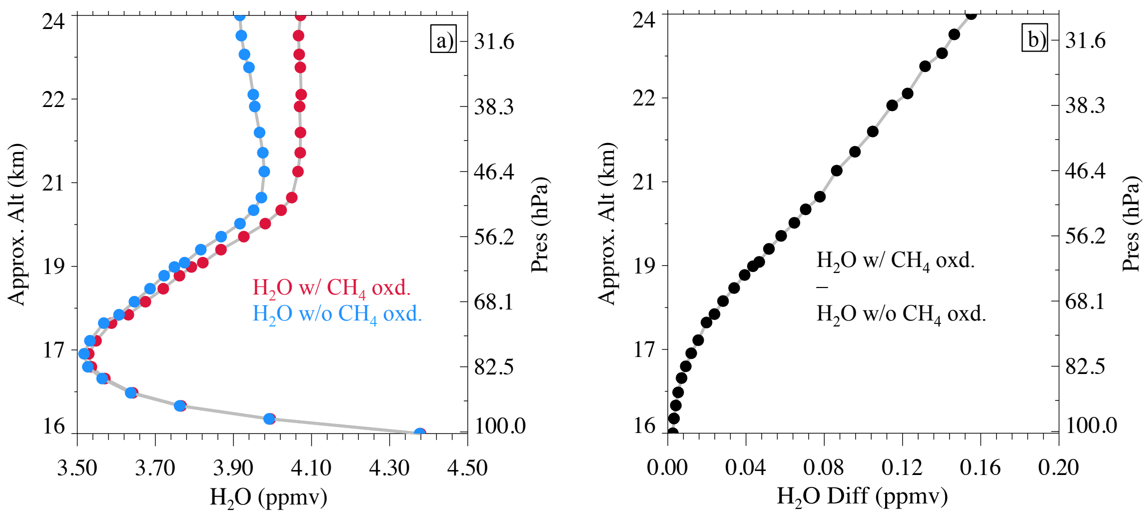

Figure R21. (a) Trajectory simulated water vapour from using GPS temperatures, with methane oxidation turned on (red) and off (blue); (b) The differences caused by methane oxidation. All data are averaged over the tropics (18^{o} N-S) in 2007-2013.

The paper also makes the point that inter annual variability is unchanged in the time series when the different temperature sets are employed and 'only' the absolute value is affected. First it should be discussed and stated in the paper that the absolute values are important for calculating the radiative forcing (and thus for the climate impact). In my opinion, the absolute values matter. Second, what is the conclusion from this observation? That high and low excursions in the interannual variability are equally affected by the resolution of the temperatures? Should this conclusion also hold for time series longer than the seven years shown in Fig. 9? For example, for time series over 30 years with pronounced variability?

Reply:

This is an excellent point. We have added discussions of the importance of H_2O abundances to the radiative forcing calculations.

One of the conclusions of this paper is that despite the different vertical resolutions of temperature, the predicted water vapour interannual variability is almost the same. This conclusion also holds for longer time period as shown in Fig. R22 below. This discussion has been added in section 3.2.

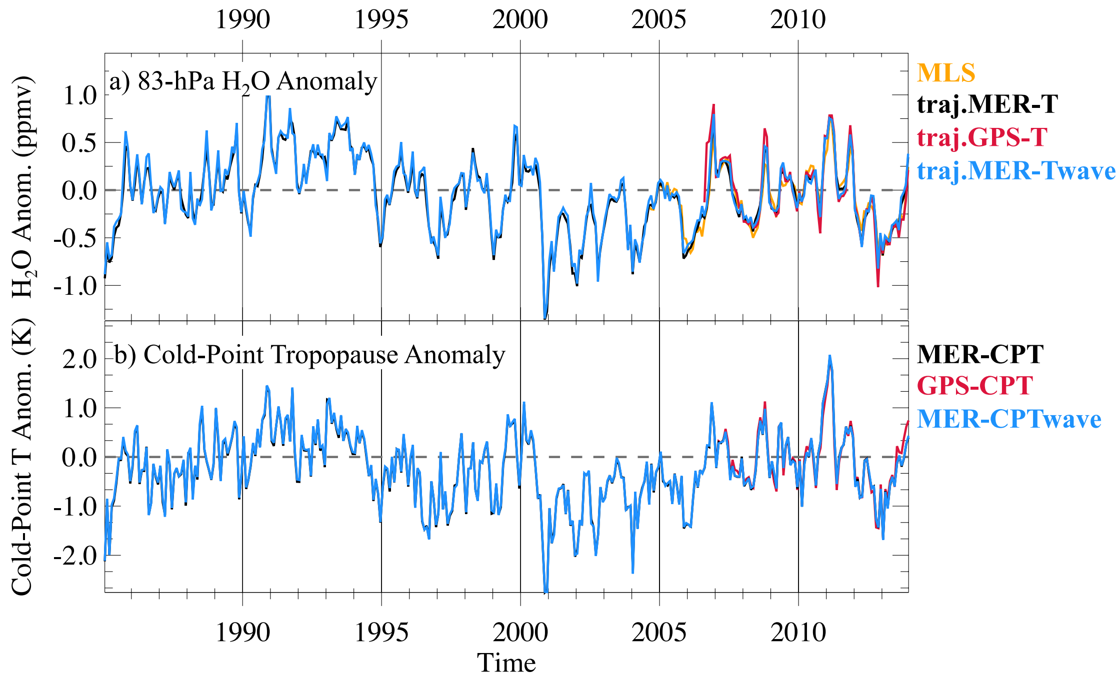

Figure R22. The H_2O anomaly (a) and the cold-point tropopause anomaly in longer period from different datasets.

Comments in detail

- *p. 29211., l. 4: Is immediate freeze out at 100% saturation assumed? This statement seems to imply that this is the case. How realistic is this assumption? For example Tompkins et al. (2007) argued for a different representation of dehydration in the ECMWF model and other trajectory studies have tested different dehydration assumptions.*

  Reply:

  We performed sensitivity tests to different saturation levels and it turns out that the simulated water vapour offset constant values but with identical interannual variability. Note that the major focus of this paper is to investigate the uncertainty introduced by using temperatures in different vertical resolutions. Despite the frequent occurrences of supersaturation (Jensen et al., 2013) and the re-evaporation of the condensate (e.g., Schoeberl et al., 2014), the comparison would be essentially the same as long as we keep the same criteria for different runs. This discussion is included in the update manuscript lines 116-120.

- *p. 29212., l. 20: It should be more explicitly stated which terms enter the calculation of the potential temperature tendency here; just clear sky heating rates?*

  Reply:

We used total diabatic heating rates from all sky, which include heating rates from long-wave and short-wave radiation, moist physics, friction, etc. This has been modified in lines 75-97 to be clear.

- *p. 29213., l. 18: The major chemical loss of methane in the stratosphere occurs through reactions with radicals, not through photolysis (e.g. Röckmann et al., 2004; Brasseur and Solomon, 2005); if the loss mechanism used here is really photolysis, the loss (and thus the water vapour production) is not correctly simulated.*

Reply:

Oxidation of hydrogen, mainly methane, is an important in situ source of water vapour in the stratosphere. To account for methane oxidation in our model, we independently track methane in each parcel and photolyze it using photochemical loss rates. The loss of each molecule of methane produces two molecules of H_2O (Dessler et al., 1994). The oxidation of H_2 formed from methane photolysis is implicitly included in this scheme. This has been stated in the updated manuscript lines 122-128.

Minor issues

- *Abstract, l. 11: 1.2 km is also finite, do you mean 'higher resolution'*
- *Abstract, l. 11: 'including' is incorrect, you only consider there tow data sets.*
- *p. 29211., l. 15: 'tracers that depend'*
- *p. 29211., l. 23: 'carrying H2O' is unclear*
- *p. 29212., l. 1: drop 'etc.'*
- *p. 29213., l. 2: why 're' entered?*
- *p. 29214., l. 9: 'that used' . . .*

Reply:

Done the above.

- *p. 2921., l. 27: state how the 0.4 ppmv bias was deduced*

Reply:

We have added temperature profiles in Fig. 2. Averaged over 18^{o} N-S, the largest temperature difference of 0.4 K shows at ~93 hPa (cold-point tropopause) when the GPS temperature is generally ~193 K. With 100% saturation level assumption, the C-C equation yields a 0.41 ppmv difference in H_2O. This has been added in the updated manuscript lines 193-197.

- *p. 29216: l. 19: how do we know it is 'realistic'?*

Reply:

The MER-Twave is designed to have similar temperature variability to radiosondes measurements based on Kim and Alexander, 2013. Temperature variability in radiosondes measurements can be treated as realistic.

- *Figure 5: The text states that the analysis was done using a large number of isentropic trajectories, nonetheless, Fig. 5 looks as if the analysis has been done on several discrete pressure levels. See for example the obvious kinks in the black solid line, which are spaced about 5 hPa apart. Further, it looks to me that the solid lines in Fig 7b and in Fig 5 are the same lines, although the x-axis is different. Please check.*

  Reply:

  We perform diabatic trajectories in isentropic coordinate to avoid the over dispersion in pressure coordinate. After that, we present results in pressure coordinate to be able to compare with reanalyses model levels, which are pressure levels.

  Fig. 5 is the FDP frequency averaged over 7 years, whereas Fig. 7b only shows the SON season. The reason that x-axis is different is because the frequencies are calculated with respect to the total FDP events in 7 years, therefore the magnitude in Fig. 7b is about ¼ of that in Fig. 5. This has been modified in the updated Fig. 5 to relative to the FDP events of each curve.

  In the updated Fig. 5, we have changed all normalized FDP frequency unit from "%/hPa" to "%", so each PDF profile integrate from bottom to up ends up with 100%.

- *p. 29221., l. 2: change 'stratospheric' to 'stratosphere'*

  Reply:

  Done.

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The impact of temperature ~~resolution~~ vertical variability on trajectory modeling of stratospheric water vapour

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Abstract

Lagrangian trajectories driven by reanalysis meteorological fields are frequently used to study water vapour (H_2O) in the stratosphere, in which the tropical cold-point temperatures regulate H_2O amount entering the stratosphere. Therefore, the accuracy of temperatures in the tropical tropopause layer (TTL) is of great importance for understanding stratospheric H_2O abundances ~~trajectory studies~~. Currently, most reanalyses, such as the NASA MERRA (Modern Era Retrospective-Analysis for Research and Applications), only provide temperatures with ~1.2 km vertical resolution in the TTL, which has been argued misses realistic variability in tropopause temperatures and therefore introduce uncertainties in our understanding of stratospheric H_2O. In this paper, we quantify this uncertainty by comparing the Lagrangian trajectory models using MERRA temperatures on standard model levels (*traj.MER-T*), to those using

temperatures with more vertical variability at the tropopause. This includes GPS temperatures (*traj.GPS-T*) in finer vertical resolution and adjusted MERRA temperatures with enhanced variability induced by underrepresented waves ~~but underrepresented by the current model levels~~ (*traj.MER-Twave*). It turns out that enhanced vertical variability in tropopause temperature more realistically simulates ~~captures~~ the dehydration of air entering the stratosphere. ~~pattern in, therefore the bimodal dehydration peaks in *traj.MER-T* due to limited vertical resolution disappear in *traj.GPS-T* and *traj.MER-Twave*, by allowing the cold-point tropopause to be found at finer vertical levels~~. ~~Comparing with *traj.MER-T*, *traj.GPS-T* has little impact on simulated stratospheric H_2O (changes~~ But the effect on H_2O abundances is relatively minor: comparing with *traj.MER-T, traj.GPS-T* tends to dry air by ~0.1 ppmv while *traj.MER-Twave* tends to dry air by 0.2-0.3 ppmv. Despite these differences in absolute values of predicted H_2O and vertical dehydration patterns, there is virtually no difference in the interannual variability in different runs. Overall, we find that tropopause temperature ~~in~~ with finer vertical ~~resolution~~ variability has limited impact on predicted stratospheric H_2O ~~in the trajectory model~~.

1. Introduction

Stratospheric water vapour (H_2O) and its feedback play an important role in regulating the global radiation budget and the climate system (e.g., Holton et al., 1995; Randel et al., 2006; Solomon et al., 2010; Dessler et al., 2013). It has been known since Brewer's seminal work on stratospheric circulation that tropical tropopause temperature is the main driver of stratospheric H_2O concentration (Brewer, 1949). As parcels approach and pass through the cold-point tropopause – the altitude at which air temperature is coldest, condensation occurs and ice falls out, thereby regulating the parcel's H_2O concentration to local saturation level (e.g., Fueglistaler et al., 2009, and references therein). This is the dehydration process. The role of tropopause temperature variation in tropical dehydration is most apparent in the annual variation in tropical stratospheric H_2O, also known as the "tape recorder" (Mote et al., 1996).

When air crosses enters the tropical tropopause layer (TTL), it experiences multiple dehydrations due to encounter of colder lower temperatures, and the final stratospheric H_2O mixing ratio is established after air passing through the coldest temperature along its path, which sets the strong relation between cold-point tropopause and the entry level H_2O (e.g., Holton and Gettelman, 2001; Randel et al., 2004, 2006).

The details of the transport and dehydration process can be understood by performing Lagrangian trajectory simulations, which track the temperature history of a large number of individual parcels. Unlike simulating simulation of chemical tracers that depends strongly on the transport imposed (Ploeger et al., 2011; Wang et al., 2014), the simulation of H_2O is primarily constrained by tropopause temperatures. Dehydration thus primarily depends on the air parcel temperature history, and stratospheric H_2O simulations ultimately require accurate analyses of temperatures particularly in the tropopause (e.g., Mote et al., 1996; Fueglistaler et al., 2005, 2009; Liu et al., 2010; Schoeberl and Dessler, 2011; Schoeberl et al., 2012, 2013).

In this paper, we use a forward, domain-filling trajectory model to study the detailed dehydration behavior of the humidity of air parcels ~~and the carrying H_2O in~~ entering the tropical lower stratosphere. Previous analyses have demonstrated that this model can accurately simulate many of the aspects of the observed stratospheric H_2O (Schoeberl and Dessler, 2011; Schoeberl et al., 2012, 2013). Despite the good agreements with observations, there are clear areas of uncertainty, such as the accuracy of circulation fields (Schoeberl et al., 2012), the details of the dehydration mechanisms (Schoeberl et al., 2014), the influences from convection (Schoeberl et al., 2011, 2014), and the impacts of unresolved temperature variability in the TTL, etc. In this paper, we investigate uncertainties introduced by the last one – the effect of vertical ~~resolution~~ variability of temperatures.

~~We will examine the impacts of reanalysis temperature in relatively coarse vertical resolutions on trajectory simulations of stratospheric H_2O.~~ This is accomplished by comparing trajectory results from using NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA) (Rienecker et al., 2011) temperatures at standard model levels, to using temperatures with finer vertical variability, which include GPS temperatures and the MERRA temperatures adjusted to account for resolved but underrepresented waves (Kim and Alexander, 2013) ~~to using GPS temperatures and the MERRA temperatures adjusted to account for resolved but underrepresented waves (Kim and Alexander, 2013), both in finer vertical resolution~~. This will help us to further understand the importance of tropopause temperature variability in dehydrating ~~dehydration of~~ air entering the stratosphere.

2. Trajectory Model and Temperatures Used

2.1 Trajectory model

The trajectory model used here follows the details described in Schoeberl and Dessler (2011) with ~~trajectories calculated~~ parcel positions integrated using the Bowman trajectory code (Bowman, 1993; Bowman et al., 2013). This model has been proven ~~to be able to simulate~~ capable of simulating stratosphere H_2O and its long-term variability (Schoeberl and Dessler, 2011; Schoeberl et al., 2012, 2013; Dessler et al, 2014), modeling chemical tracers transport in the lower stratosphere (Wang et al., 2014), and studying the stratosphere air age spectrum (Ray et al., 2014). Because of the overly dispersive behavior of kinematic trajectories (e.g., Schoeberl et al., 2003; Liu et al., 2010; Ploeger et al., 2010; Schoeberl and Dessler, 2011), we perform diabatic trajectories using isentropic coordinates, in which the vertical velocity is the potential temperature tendency converted from the diabatic heating rates via the thermodynamic equation (e.g., Andrews et al., 1987). Here we used total heating rates, which include heating due to long-wave and short-wave radiation, moist physics, friction, etc.

The parcel initiation level is chosen to be the 370-K isentrope, which is above the level of zero radiative heating (~355-365 K, Gettelman and Forster, 2002) and below the tropical tropopause (~375–380 K) in the tropics. Every day, parcels are initialized on equal area grids covering 40°N–40°S and advected forward in time by reanalysis winds. At the end of each day, any parcels that have descended below the 345 K (~250 hPa or ~10 km) level are removed since in most cases they have ~~re-~~entered the troposphere. The upper boundary is chosen to be 2200 K isentrope (~1 hPa or ~50 km) to cover the entire stratosphere. Parcels are initialized and added to the ensemble consecutively on every day and the combined set of parcels is then advected forward. This process is repeated over the entire integration period so that after 2-3 years the stratospheric domain is filled up with parcels – this is the concept of domain-filling, that which guarantees a robust statistics.

H_2O is conserved along the trajectories, except when saturation occurs; in that case, then excess of H_2O is instantaneously removed from the parcel to keep the relative humidity with respect to ice from exceeding 100%. This is sometimes referred as "instant dehydration" (e.g., Schoeberl et al., 2014), which This simple scheme that ignores detailed microphysics but has shown to and has been proven to be able to simulate many features of H_2O in the lower stratosphere (e.g., Fueglistaler et al., 2005; Jensen and Pfister, 2004; Gettelman et al., 2002). We chose the 100% saturation level because 1) different saturation levels offset the simulated H_2O constant values but with identical interannual variability; and 2) the focus of the paper is to investigate the uncertainty introduced by using different temperatures, which would be the same as long as we keep the same criteria for different runs.

In addition to H_2O, we also carry methane (CH_4) concentration for each parcel. We initiate CH_4 values increased from 1.76 ppmv in 2006 to 1.83 ppmv in 2013. For each parcel, we also consider H_2O oxidized from the carrying methane. As described in Schoeberl and Dessler (2011), we use photochemical loss rates supplied from Goddard two-dimensional stratospheric chemistry model (Fleming et al., 2007) to photolyze convert each methane molecule into two molecules of H_2O (Dessler et al., 1994). Noted that our analysis focus on the tropical lower stratosphere, ~~all results in this paper are limited in the tropical 110-50 hPa,~~ where methane oxidation has little impacts on the total H_2O abundances (Fig. 6 in Schoeberl et al., 2012).

Along each trajectory, we locate the point when air experiences coldest temperature as the final dehydration point (FDP), which determines the stratosphere entry level H_2O mixing ratio (FDP-H_2O) for that trajectory. As will be shown below, the entry level H_2O predicted by the trajectory model is affected by the vertical variability in temperature field.

2.2 Temperature datasets

In this paper, we use MERRA (Rienecker et al., 2011) circulation to advect parcels. This includes horizontal wind components and total diabatic heating rates. As shown in Schoeberl et al. (2012, 2013), trajectory model driven by this reanalysis yields excellent estimates of H_2O compared to observations by the Aura Microwave Limb Sounder (MLS) (Read et al., 2007).

Driven by the same circulation, we use three different temperature datasets to quantify the uncertainty induced by temperatures with different variability in the vertical: 1) MERRA standard temperatures on model levels (MER-T), denoted as *traj.MER-T*; 2) GPS radio occultation (RO) temperatures, denoted as *traj.GPS-T*; and 3) MERRA temperatures enhanced by wave scheme to recover the variability not represented well in current coarse model levels (Kim and Alexander, 2013), denoted as *traj.MER-Twave*. ~~Different from earlier papers that useds an idealized parameterizations of waves added to the temperature datasets (e.g., Schoeberl and Dessler, 2011), here we amplify waves that are underrepresented in the coarse vertical resolution of MERRA temperatures.~~ Note that MERRA does not assimilate GPS observations, which makes the two temperature datasets independent from each other. Trajectory runs with the three different temperature datasets are summarized in Table 1.

2.2.1 GPS temperature

Owing to its high vertical resolution, GPS temperature profiles capture the cold-point tropopause with high ~~in unprecedented~~ accuracy. In this paper we use GPS wet profile (wetPrf) retrieved at 100-m vertical resolution using ~~from~~ a one-dimensional variational technique based on ECMWF analysis. The wetPrf and GPS Atmospheric Profile (atmPrf, derived assuming no water vapor in the air) temperatures are essentially the same in 200-10 hPa but below 200 hPa the errors in atmPrf could be as high as ~ 3 K due to neglect of water vapour (Das and Pan, 2014). Despite being retrieved at 100-m resolution, the actual vertical resolution ranges from 0.5 km in the lower troposphere to ~1 km in the middle atmosphere (Kursinski et al., 1997).

The GPS radio occultation (RO) technique makes the data accuracy independent of platforms. ~~It has been reported that~~ That makes the biases among different RO payloads could be as low as 0.2 K in the UTLS (Ho et al., 2009). Therefore, to compensate the relatively lower horizontal resolution (relative to that of reanalysis), we include GPS RO from all platforms. This includes the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) (Anthes et al., 2008), the CHAllenging Minisatellite Payload (CHAMP) satellite (Wickert et al., 2001), the Communications/Navigation Outage Forecasting System (CNOFS), the Gravity Recovery And Climate Experiment (GRACE) twin satellites (Beyerle et al., 2005), the Meteorological Operational Polar Satellite–A (MetOp-A), the Satellite de Aplicaciones Cientifico-C (SACC) satellite (Hajj et al., 2004), and the TerraSAR-X (TerraSAR-X). There are ~2000-3500 profiles per day, mostly from COSMIC, with ~800-1100 profiles of these in the tropics.

Each day, GPS temperature profiles are binned to 200-m vertical resolution. Horizontally, we grid data into 2.5x1.25 (longitude by latitude) grids with 2-D Gaussian function weighting. This gridded dataset has been successfully used in diagnosing many detailed features of tropopause inversion layer (Gettelman and Wang, 2015). We use over 7 years of GPS data available from July 2006 to December 2013, and the trajectory run using it is denoted as *traj.GPS-T*.

Fig. 1 shows a snapshot of the 100-hPa GPS raw (panel a) and gridded (panel b) temperature on January 1st, 2010, compared with MERRA temperature (panel c). It demonstrates that the gridded GPS temperature ~~clearly~~ captures most of the variability, although some detailed structure might be lost due to its relatively sparse sampling.

Fig. 2 shows the GPS and MERRA temperatures in the TTL (panel a) and their differences (GPS–MERRA) (panel b, extended to 31 hPa) averaged over the deep tropics

($18^oS–18^oN$) during the GPS period. Here, we examine the values at the MERRA model levels (larger dots) as well as MERRA in-between levels (smaller dots), where both GPS and MERRA temperatures are linearly interpolated to the same pressure levels. Here we use linear instead of higher order, such as cubic, interpolation because linear scheme performs better (see Sect. 2.2.3). As we can see, due to the strong curvature in temperature profile, It shows that the GPS is at most ~0.4 K colder than MERRA around the cold-point tropopause (~93 hPa on average, in-between MERRA coarse levels), where temperature is ~193 K. This translates to at most a 0.4 ppmv wet bias in the entry level of stratospheric H_2O, assuming 100% saturation level. Note that the GPS temperatures at MERRA levels 100 and 85 hPa could be lower than that in MERRA if we average over $10^oS–10^oN$, but it does not change the fact that MERRA is always warm biased around the cold-point tropopause. Apparently, within the TTL GPS temperatures are warmer at MERRA model levels, but in-between the MERRA levels GPS temperatures are colder (as much as ~0.4 K) around the cold-point tropopause (generally between 100 and 85 hPa), which would bring at most 0.4 ppmv dry bias in the entry level of stratospheric H_2O assuming 100% saturation.

2.2.2 MERRA temperature adjusted by waves

Waves are underrepresented in reanalyses, therefore a further interpolation in the vertical significantly dampens even resolved waves due to relatively coarse vertical resolution (as seen in comparisons with high resolution radiosondes; Kim and Alexander, 2013). To overcome these limitations, a new wave scheme was developed by Kim and Alexander (2013) to recover the underrepresented variability, based on amplitude-phase

~~interpolation and amplification of waves in reanalysis datasets.~~

~~For each month's MERRA temperature profiles, we construct a 90-day time series at each level centered on that month. Then the Fourier transformation is applied on the time series to obtain amplitudes and phases in frequency domain. Those amplitude and phase profiles in real space are then interpolated separately into finer 200-m vertical levels to bring back the variability induced by waves. After reconstructing new complex functions from the interpolated amplitudes and phases, amplification factors for the four seasons are applied to enhance wave variability since waves are already weaker at reanalysis levels. The amplification factors are defined as the fractional differences between the square roots of power spectra in reanalysis and radiosonde data. Finally, the inverse Fourier transformation is applied to bring the time series back to the time domain. Applying this scheme on MERRA temperature records yields a new MERRA temperature dataset that has realistic variability induced by waves (Kim and Alexander, 2013) and the trajectory model performed on this temperature is denoted as **traj.MER-Twave**.~~

Wave-induced disturbances on tropopause temperatures are underrepresented by current reanalyses (Kim and Alexander, 2013). At the reanalysis model levels, temperature variability at time scales shorter than ~10 days are weaker than radiosondes observations (refer Fig. 1b-d in Kim and Alexander, 2013). Those underrepresented waves include a part of the spectrum of Kelvin waves, mixed Rossby-gravity waves, and gravity waves. Moreover, when used in trajectory simulations, conventional interpolation of model level temperatures to in-between levels, either linear or higher order, degrades temperature variability even at longer time scales (> 10 days). This is because observed temperature profiles have strong curvatures in-between coarse model levels due to the existence of fine vertical-scale waves.

To overcome these limitations, a scheme developed by Kim and Alexander, based on amplitude-phase interpolation and wave amplification from radiosonde observations, has been proven to be effective in recovering the underrepresented variability in reanalysis temperatures (refer Kim and Alexander, 2013 for more details). Applying this scheme on MERRA temperature records yields a new MERRA temperature dataset (MER-Twave) that has more realistic temperature variability induced by waves (refer Fig. 3 in Kim and Alexander, 2013). The trajectory simulation using this temperature dataset is denoted as *traj.MER-Twave*.

Note that we only considered the vertical resolution issue, since it is by far a limiting factor in representing waves in the TTL. A large portion of a TTL wave spectrum has horizontal and temporal scales much larger and longer than reanalysis resolution, therefore, temperature behaves almost linearly in-between model horizontal and temporal resolution. However, temperature does not behave linearly in vertical space due to the fact that a significant portion of TTL waves have vertical wavelengths shorter than ~4 km (see Figure S4 in supporting information of Kim and Alexander, 2015), which could make waves less represented by the ~1.2 km vertical resolution in reanalyses.

The wave scheme produces both positive and negative perturbations to the MERRA temperature profiles, depending on the phase of waves. Overall, the change in temperature induced by waves is less than 2 K (Fig. 3), although in rare cases it can reach 5-7 K. Importantly, however, about 80% of the changes in cold-point temperature are negative, with the wave scheme lowering the average cold-point temperatures by ~0.35 K. It is this reduction in cold-point temperature that is responsible for the reduction in H_2O entering the stratosphere.

Note that we included both GPS and MER-Twave datasets because they have their own advantages and limitations. GPS provides sparse sampling in the tropics (only ~800-1100 profiles per day), indicating a smaller horizontal variability in GPS than likely exists, but the mean temperatures are more accurate. In contrast, MER-Twave has better variability but not accurate mean, since it is designed to have similar temperature variability to radiosondes but with mean reserved to original MER-T. In summary, the mean temperature is closer to reality in GPS than in MER-T and MER-Twave, but the temperature variability is closer to reality in MER-Twave than in MER-T and GPS. In addition, the MER-Twave is a general technique that could be applied to situations where GPS temperatures are not available (e.g., reanalyses before 2006, climate models).

2.2.3 Interpolation scheme

In our studies, we use linear interpolation to estimate the temperature between the fixed levels of temperature data sets. However, some previous analyses have used higher order interpolations, such as cubic spline (e.g., Liu et al., 2010), to make assumptions about the strong curvature of temperature profiles around the cold-point tropopause. In order to determine which approach ~~if linear or cubic spline interpolation~~ is superior, we sample GPS tropical temperature profiles at MERRA vertical levels and then use the two interpolation schemes to reconstruct the full GPS resolution. Then we compare the minimum saturation mixing ratio from the recovered profiles to the minimum calculated from the full resolution GPS profiles.

Fig. 4a shows the probability distribution of the differences between the minimum saturation mixing ratio in the full-resolution GPS profile and in the two interpolation schemes. On average, the linear interpolation performs better (RMS difference is 0.18 and 0.25 ppmv for the linear and cubic spline, respectively). Fig. 4b shows the corresponding probability distribution of the difference of the pressure of this minimum, and the linear interpolation does better for this metric, too (RMS difference is 5.2 and 7.2 hPa for the linear and the cubic spline interpolation, respectively). We have also tested higher order spline interpolations and find that none produce lower RMS errors than linear interpolation. Overall, cubic spline interpolation tends to underestimate cold-point temperature ~~(sometimes unrealistically to as low as ~150 K)~~, making the implied H_2O too dry, as noted by Liu et al., (2010). Thus, in our studies we adopted linear interpolation scheme for three different trajectory integrations.

3. Trajectory Results

3.1 Dehydration patterns

The gridded GPS temperatures are available since July 2006, so for fair comparison we start all trajectory runs at that time and run them forward till the end of 2013. For each model run, we calculate statistics of the final dehydration points (FDP) for all parcels entering the stratosphere. We define "parcels entering the stratosphere" as parcels that underwent final dehydration between 45°N–45°S (thus ignoring polar dehydration) and that were already at altitudes higher (pressure lower) than 90 hPa for at least six months since the last time they were dehydrated (FDP) ~~after their FDP event~~. This guarantees that parcels already crossed the cold-point tropopause (~380 K or ~100-94 hPa) and has indeed experienced the coldest temperature along its ascending paths. Averaging over 7 years minimizes the effects of interannual variability.

Fig. 5a-c compares the FDP frequency (solid lines) and the FDP H_2O (dashed lines) in different seasons among three runs. As mentioned, the FDP H_2O can be understood as the stratosphere entry level of H_2O. In all cases, it is clear that dehydration occurs almost exclusively between 60 and 110 hPa. The ~~dashed lines represent the~~ average FDP H_2O~~, which~~ reaches a minimum at 85 hPa for all runs, meaning parcels dehydrated in its vicinity carry the smallest amount of H_2O into the stratosphere. The relatively high FDP-H_2O above 80 hPa (just above the entry level) comes from the parcels that avoided the tropical cold trap and experienced final dehydration at higher, warmer levels of the stratosphere. Out of ~1.3 millions of parcels in the stratosphere there are only ~0.3% bypassed the cold-point tropopause, and these parcels have little impact on the stratosphere water vapour.

The FDP frequency, however, shows large differences among three runs. The run using MERRA temperature (*traj.MER-T*) yields an annual bimodal FDP maxima distinctly at 98 and 84 hPa (Fig. 5a solid black lines), close to the MERRA model levels 100.5 and

85.4 hPa, respectively. The bimodal feature comes from averages between single, prominent peaks during DJF (December-January-February, Fig. 5a, blue) and JJA (June-July-August, Fig. 5a, red), when cold-point tropopause is close to a particular level (DJF to 85 hPa and JJA to 100 hPa) in MERRA (Fig. 5d-e black bars), as well as averages between bi-modal peaks during MAM (March-April-May, Fig. 5a, green) and SON (September-October-November, Fig. 5a, yellow), when tropopause temperature in real atmosphere fall in between the two MERRA levels (Fig. 5f red bars). ~~This occurs because the cold-point tropopause is constrained to be near these two levels due to limited vertical resolution in MERRA temperature, whereas in real atmosphere it may fall in between (see Fig. 7 below).~~ The dehydration profiles implied from using the other two datasets, however, experience smoothed changes due to gradual variations of cold-point altitudes in each season (red and blue bars in Fig. 5d-f). It is clear that more realistic dehydrations (Fig. 5b-c) occur with more variability in tropopause temperature (Fig. 5d-f red and blue bars).

Note that at FDP, the coldest temperature encountered could be either at MERRA model levels or in-between levels during that step of integration, depending on the trajectory integration intervals. Suppose our trajectory integration time step is as small as seconds, then at some time steps parcels would inevitably travel to each of the MERRA model levels, and therefore the encountered coldest temperatures would always be at either of the two levels in MERRA. In another word, the bimodal FDP distribution from MERRA run (Fig. 5a) could be even more peaked when choosing smaller integration step. Two reasons that we didn't choose such small time step: 1) the wind and temperature data are only available 6-hourly or even daily (GPS) so much smaller time step introduces more uncertainties with more interpolation; and 2) considering the balance between model running speed and computational resources.

Fig. 6 depicts the vertical distributions of normalized FDP in time (panel a-c) and longitude (panel d-f) sectors for the three different runs. We see that the MERRA coarse model levels do not capture the variations of cold-point tropopause well during MAM and SON, resulting in discontinuous transition of FDP from DJF to MAM, and from JJA to SON (panel a). When using GPS temperatures (panel b) and MERRA temperatures adjusted to recover wave-induced variability (panel c), the dehydration patterns show continuous variations throughout the year. The bimodal feature is more emphasized in the longitudinal-vertical view (panel d), where we can also see that throughout a year the most frequent dehydrations occur over the western tropical pacific region. ~~Take the SON for example, the longitudinal distribution of dehydration patterns emphasizes the bi-modal feature of using MERRA temperature (panel d), contradictory to contradicting the single mode feature of using GPS temperature (panel e) or MERRA temperature adjusted by waves (panel f), with enhancements centered at 85 and 98 hPa corresponding to the altitudes of most frequent cold-point tropopause during DJF and JJA, respectively.~~

~~The FDP seasonal changes follow exactly the variations of the cold-point tropopause represented differently by the three temperature records. During SON, for example, Fig. 7 shows that the cold-point tropopause in GPS temperatures (panel a, red) or MERRA temperature adjusted by waves (panel a, blue) can be found most frequently within 100-~~

~~85 hPa in this season. Trajectory runs therefore yield peak FDP occurring at the same level (panel b red and blue lines). However, due to lacking of levels between 100 and 85 hPa in MERRA temperatures, the cold-point tropopause is pushed to one of the two closest levels (panel a black bars), resulting in bimodal FDP distributions (panel b black line) and is therefore responsible for the discontinuity in FDP shown in Fig. 6a and 6d. The same argument applies to the MAM results, too. During DJF and JJA, however, the cold-point tropopause is close to a particular level (DJF to 85 hPa and JJA to 100 hPa, not shown here), generating a single, prominent dehydration peak.~~

3.2 Water Vapour (H_2O)

It is obvious that trajectory simulations using GPS temperatures (*traj.GPS-T*) and MERRA temperatures adjusted by waves (*traj.MER-Twave*) tend to yield more reasonable FDP patterns around the cold-point tropopause (Fig. 5 solid lines), although the parcels dehydrated at particular altitudes have similar amounts of H_2O in all three models (FDP H_2O, Fig. 5 dashed lines). A more interesting question is whether the different dehydration occurrences affect the stratospheric H_2O predicted by the trajectory model.

Fig. 7a shows ~~compare~~ the tropical (18°N–18°S) H_2O profile predicted from three trajectory runs compared with MLS observations. The vertical bars in MLS indicate the MLS vertical resolutions at each of the MLS retrieval pressure levels. Here, we see clearly that the H_2O in stratosphere reflects the different cold-point temperatures in three datasets. The differences induced more variability in temperatures are clearly shown in Fig. 7b, where we see slightly drier air expected in GPS run since GPS temperatures are at most ~0.4 K lower than that of MERRA around the tropopause (Fig. 2); whereas enhanced wave perturbations produce air 0.2-0.3 ppmv drier, in agreement with previous calculations (e.g., Jensen et al., 2004; Schoeberl et al., 2011).

Fig. 8c also shows that comparing to *traj.MER-T*, the dry biases from using GPS temperatures are largest in MAM and SON (0.14-0.21 ppmv on average), when the real cold-point tropopause cannot be resolved by the MERRA model levels. During DJF and JJA, when the cold point is near one of the two MERRA standard levels, the differences become smaller. Thus we conclude that using GPS temperatures decreases simulated stratospheric H_2O by an average of ~0.1 ppmv, accounting for ~2.5% given typical stratospheric H_2O abundances of ~4 ppmv.

It is important to point out that, despite these differences in the absolute value of H_2O, there is virtually no difference in the anomalies (remainder from the average annual cycle ~~remainder after the annual cycle has been subtracted~~). In Fig. 8a we compare the time series of H_2O anomalies at 83 hPa from the three different trajectory runs weighted by the MLS averaging kernels as well the MLS observations. Note that the interannual variations of approximately ±0.5 ppmv in H_2O are in good agreement with the ~~year-to-year~~ interannual changes of about ±1 K in cold-point tropopause temperatures (Fig. 8b) for all three different runs, further supporting ~~the knowledge~~ that the stratospheric entry level of H_2O and cold-point tropopause temperature ~~the two~~ are strongly coupled (e.g., Randel et al., 2004, 2006; Randel and Jensen, 2013). We also compared *traj.MER-T* and *traj.MER-Twave* over longer period (1985-2013) and it shows almost no differences in interannual variability, either. Clearly, for studying the interannual variability of H_2O, MERRA temperatures in coarse vertical resolution are as good as temperatures in higher vertical resolution.

4. Summary

~~The domain-filling, forward trajectory model is a useful tool in examining the regulation processes controlling the water vapour (H_2O) entering the stratosphereic. In the model,~~ The dehydration of air entering the stratosphere largely depends on the cold-point temperature around the tropopause. This ~~, which~~ may not be represented accurately by reanalyses due to ~~their~~ the relatively coarse vertical resolution with less variability in cold-point tropopause temperatures. To investigate ~~this~~ the impacts of ~~under-represented variability in cold-point temperatures~~ this, we compare trajectory results from using standard MERRA model level temperatures to those using temperature datasets in finer vertical resolution with enhanced variability. This includes GPS temperatures and ~~an~~ adjusted MERRA temperatures ~~dataset~~ with enhanced vertical variability induced by ~~that uses~~ wave scheme developed by Kim and Alexander (2013). ~~to reconstruct underrepresented vertical variability in MERRA temperatures.~~

Compared with ~~using~~ the standard MERRA ~~original~~ temperatures, we find that using higher resolution GPS temperatures dries the H_2O prediction ~~stratosphere~~ by ~0.1 ppmv, and using MERRA temperatures adjusted ~~with waves~~ by wave scheme dries the stratosphere by ~0.2-0.3 ppmv (Fig. 7a-b). This is consistent with previous analyses (e.g., Jensen et al., 2004; Schoeberl et al., 2011). Despite the small differences in H_2O

abundances, the interannual variability (the residual after subtracting from the mean annual cycle) exhibits virtually no differences, due to the strong coupling between stratospheric H_2O and tropical cold-point temperatures (Fig. 8). Therefore, in terms of studying the interannual changes of stratospheric H_2O, we argue that reanalysis temperatures are more useful due to its long-term availability.

Looking at the locations of FDP points, we find a bimodal distribution when using standard MERRA temperatures on model levels (Figs. 5-6). This is caused by the fact that the cold-point tropopause is constrained to be near the two MERRA model levels (100.5 and 85.4 hPa) that bracket the cold-point tropopause (Fig. 5d-f, black histograms). When using the temperatures fields with in higher vertical resolution with more variability, the resultant FDP patterns appear to be more physically reasonable (Figs. 5-6),

In this paper we perform linear interpolations for all trajectory runs. Other analyses have used cubic spline interpolation owing to the strong curvature of temperature profile around the cold-point tropopause. We investigate the performances of both schemes using GPS temperature profiles (Sect. 2.2.3) and find that while introducing new information due to its assumption in the temperature profile around the tropopause, cubic spline scheme tends to generate unrealistically low cold-point temperature due to cubic fitting. Therefore, the results are not necessarily realistic and on the other hand linear interpolation is overall more accurate (Fig. 4).

It is well known that TTL temperatures regulate stratospheric humidity. trajectory models can accurately simulate stratospheric humidity despite obvious arguments (e.g., vertical resolutions of temperatures, dehydration mechanisms, lack of convection, supersaturation, etc.). In this paper, we have investigated one issue in our understanding of TTL temperatures of these — the effect of finer vertical resolution that may have captured more variability in tropopause temperatures — and find that it is comparatively minor. This provides some confidence that the trajectory model driven by current modern reanalyses is good enough in depicting is capable of depicting the stratospheric water vapour accurately.

Acknowledgements

The authors thank Kenneth Bowman, Joan Alexander, and Eric Jensen for their helpful discussions and comments. This work was supported by NSF AGS-1261948, NASA grant NNX13AK25G and NNX14AF15G, and partially under the NASA Aura Science Program. This work was partially carried out during visits of Tao Wang funded by the Graduate Student Visitor Program under the Advanced Study Program (ASP) at the National Center for Atmospheric Research (NCAR), which is operated by the University Corporation for Atmospheric Research, under sponsorship of the National Science Foundation.

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Table

Table 1. Different temperature datasets used in trajectory model.

Temperature Datasets	Availability	Horizontal Resolution (Longitude x Latitude)	Vertical Resolution In TTL	Trajectory Runs Denoted
MERRA	Daily*	2/3 x 1/2	~1.2 km	*traj.MER-T*
GPS (gridded)	Daily	2.5 x 1.25	0.2 km	*traj.GPS-T*
MERRA w/ waves	Daily*	2/3 x 1/2	0.2 km	*traj.MER-Twave*

*These datasets are available 6-hourly. But for fair comparison with using GPS data, we used daily averages.

Figures

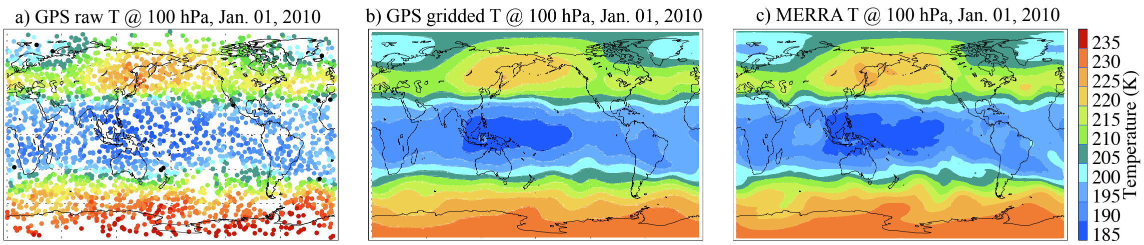

Fig. 1. (a) Comparison of temperatures from raw GPS (panel a), gridded GPS (panel b), and MERRA temperature (panel c) at 100 hPa on Jan. 1st, 2010.

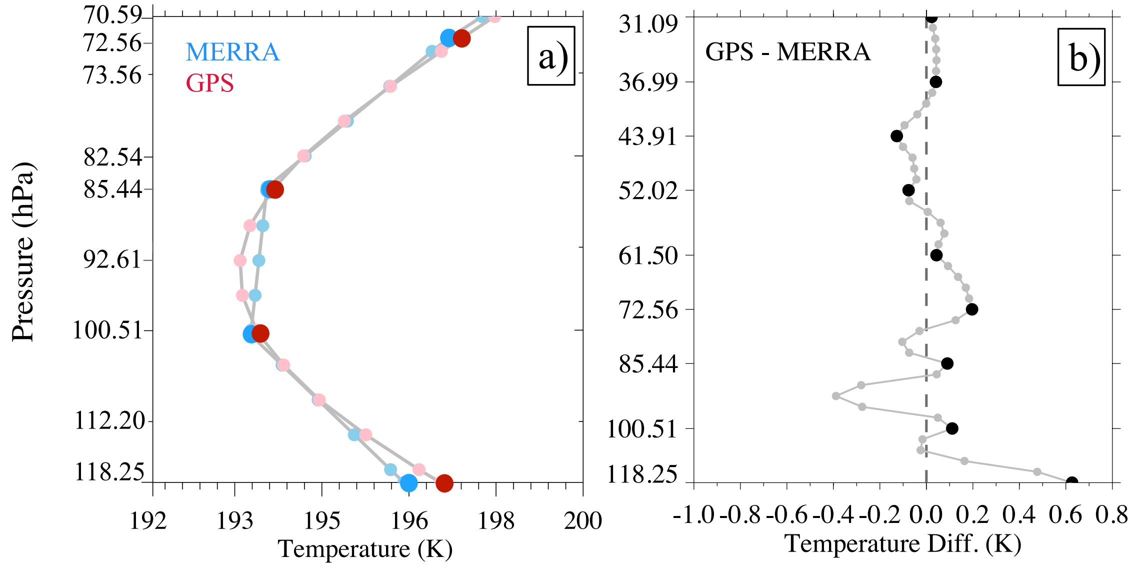

Fig. 2. (a) MERRA (blue) and GPS (red) mean temperature in TTL and (b) their differences (GPS – MERRA) extended to 31 hPa. All values are averaged over the deep tropics (18^{o}S–18^{o}N) in 2007-2013, with larger dots marking the MERRA model levels and small dots marking the MERRA in-between levels, where both GPS and MERRA temperatures are linearly interpolated to the same pressure levels. ~~Temperature differences between GPS and MERRA at MERRA model levels (black dots) and MERRA in-between levels, averaged over the deep tropics (18^{o}S–18^{o}N) in 2007-2013. Temperature in-between MERRA levels are obtained from linear interpolation.~~

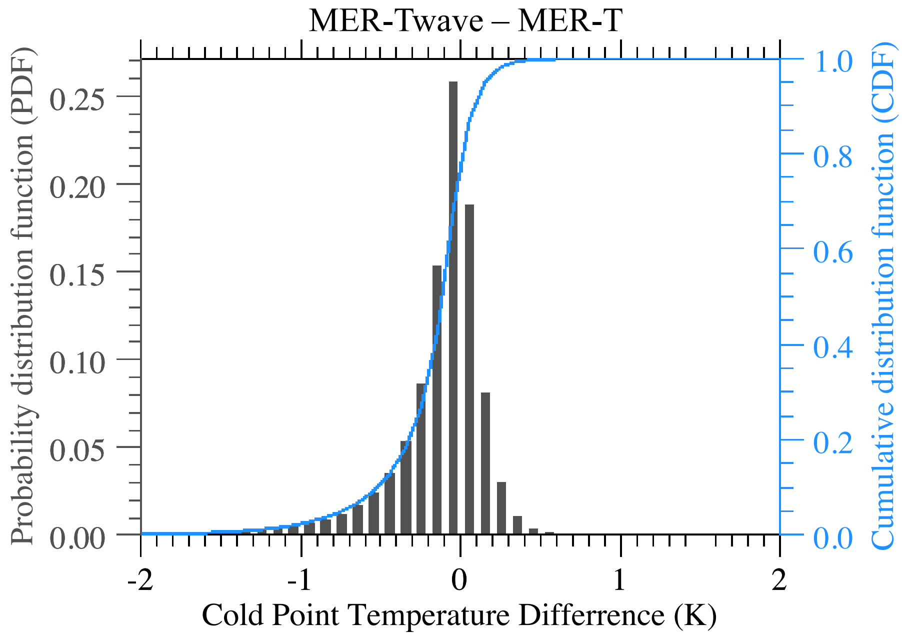

Fig. 3. Cold-Point temperature differences between MERRA adjusted by waves and MERRA (MER-Twave – MER-T) during 2007-2013. The PDF in black is plotted on left-y axis and CDF in blue on right-y axis.

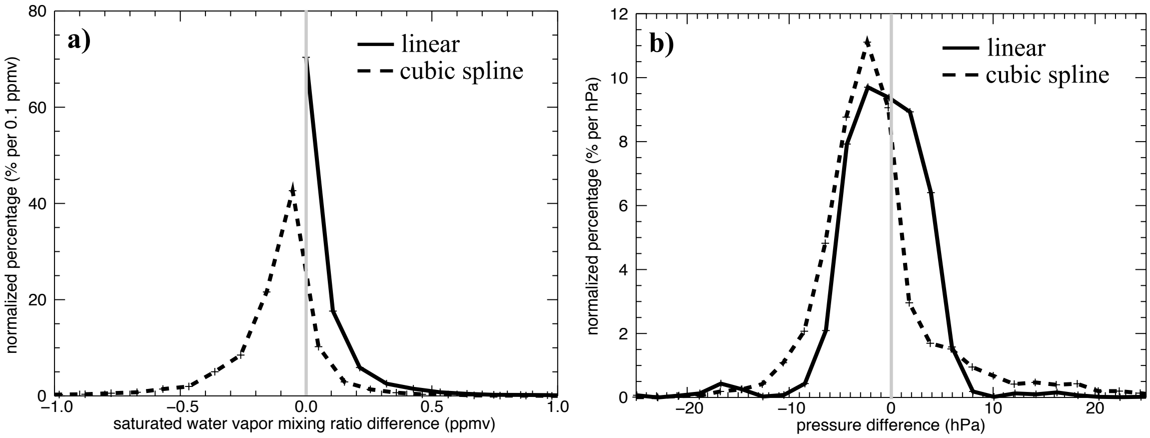

Fig. 4. PDFs of the differences between linear or cubic spline interpolations to the actual value form the GPS temperature profiles. (a) Minimum saturation mixing ratio of the profile (units are percent per 0.1 ppmv); (b) pressure of the saturation mixing ratio minimum (units are percent per hPa). The plus signs in each line mark the bin intervals.

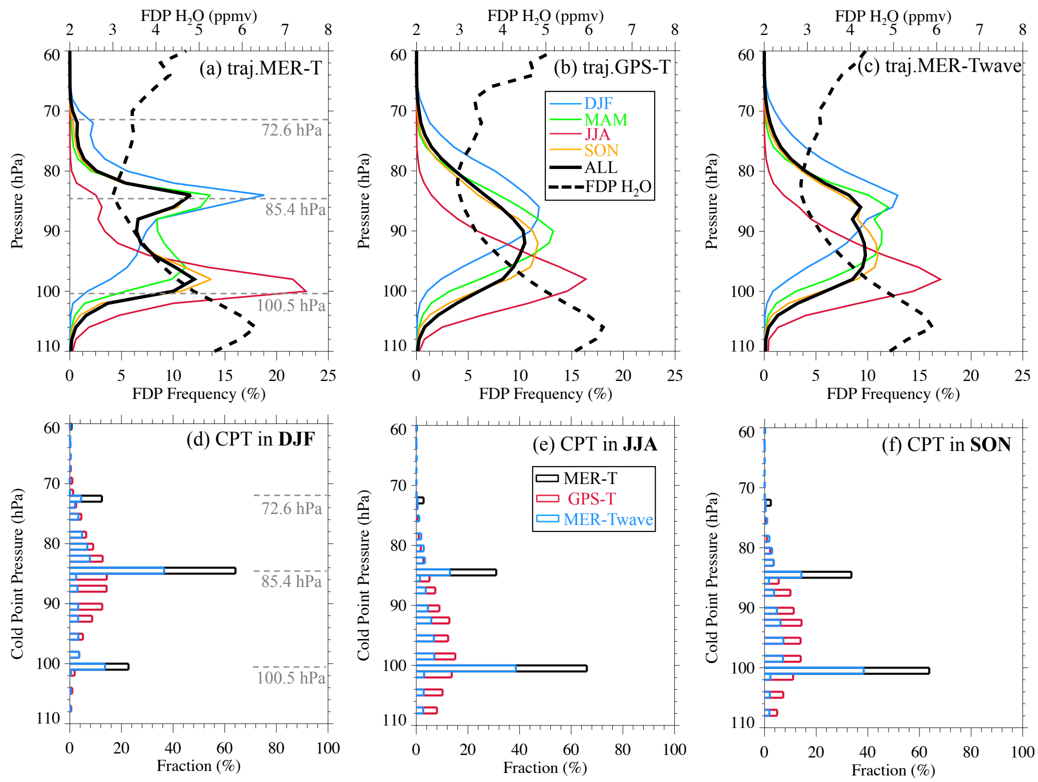

Fig. 5. Seasonal FDP vertical distributions (in %~~/hPa~~, solid lines, lower x axis) and FDP saturation mixing ratio (FDP-H_2O, i.e., the stratosphere entry level H_2O, ppmv, dashed lines, upper x axis) from trajectory simulations using (a) MERRA temperatures, (b) GPS temperatures, and MERRA temperatures adjusted by waves (c), compared to the cold point tropopause statistics during (d) DJF, (e) JJA, and (f) SON. The FDP frequency is normalized by total FDP events, so each solid curve adds up to 100%. The MERRA model levels are marked in panels a and d.

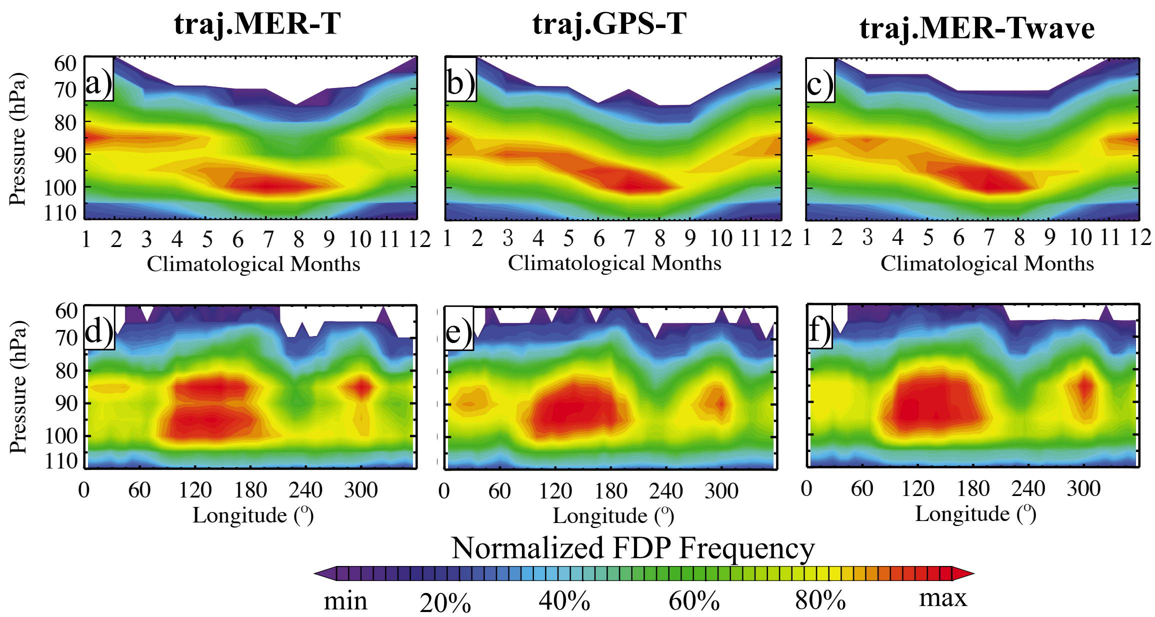

Fig. 6. Vertical distributions of normalized FDP events in time-evolutional (a-c) views among trajectory simulations by using a) MERRA temperature (*traj.MER-T*), b) GPS RO temperature (*traj.GPS-T*), and c) MERRA temperature adjusted by waves (*traj.MER-Twave*). The longitudinal variations of FDP ~~during SON~~ are highlighted in panel d-f to emphasize the FDP discontinuity in *traj.MER-T*. All panels are plotted in their own range and color-coded at the same percentiles (i.e., 0, 20%, 40%, …, 100%) to compare the patterns.

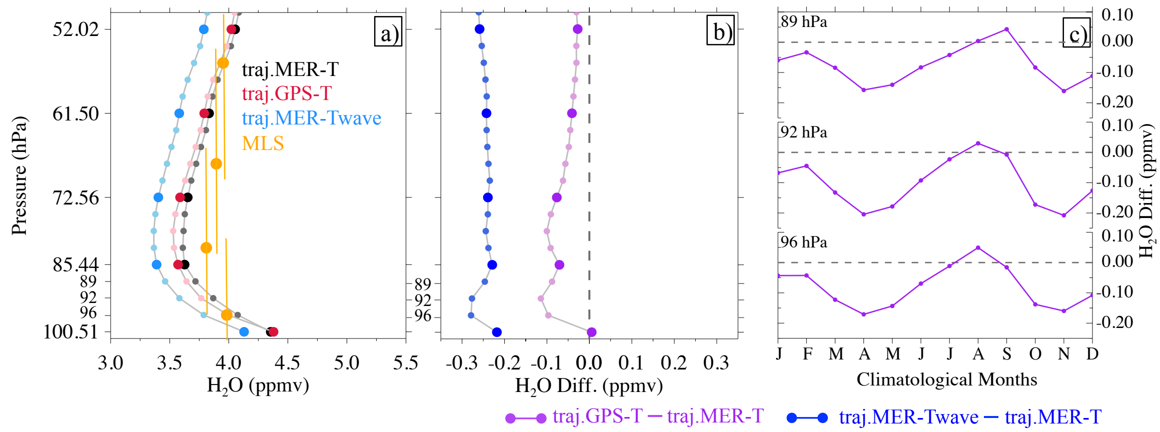

Fig. 7. (a) Trajectory predicted H_2O compared with MLS observations (the vertical bars in orange indicate the MLS vertical resolutions at each of the MLS retrieval pressure levels); (b) trajectory H_2O differences induced by waves (blue) and by using GPS temperatures (purple); (c) annual differences at 96, 92, and 89 hPa. All values are averaged over the deep tropics (18°S–18°N) in 2007-2013, with larger dots marking the MERRA model levels and small dots marking the MERRA in-between levels – those are the levels that the cold-point tropopause could have been found but not available in current MERRA vertical resolution.

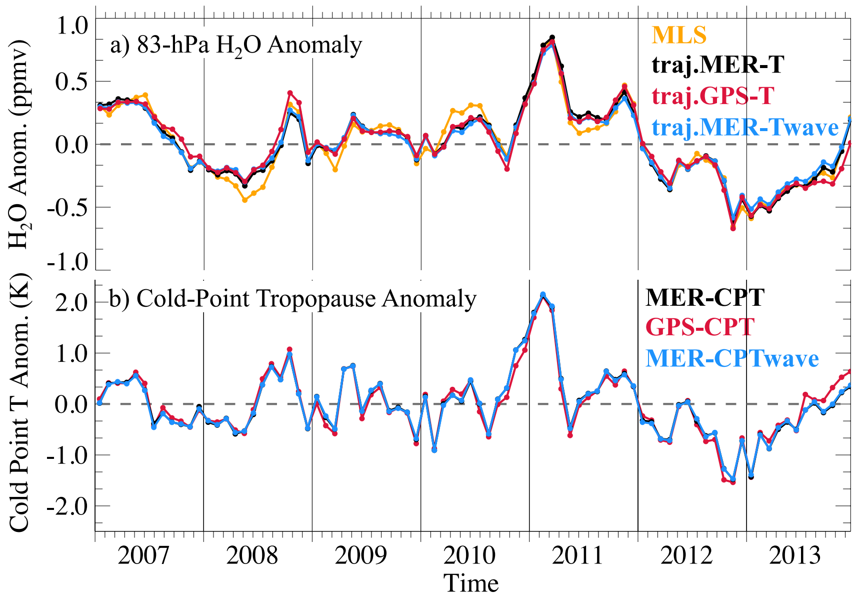

Fig. 8. (a) Trajectory simulated H_2O anomalies compared with the MLS observations; and (b) cold-point temperature anomalies from three temperature datasets. All time series are averaged over the deep tropics (18^{o}N-18^{o}S). All trajectory results in panel a are weighted by the MLS averaging kernels for far comparison.