Reply to anonymous Referee #1

General Comments:

To make this paper acceptable for publication, the authors need to do two things (as well as address the specific points below).

(1) As indicated above, the major result that the authors stress is the moistening of the TTL by convection. The authors need to be mindful (and point out clearly) that this is not new. What may be considered new is: (a) moistening in the central Pacific associated with El Nino (the Avery work is only a case study, so the general point is new); and (b) the method (regression) by which this result is arrived at. The authors need to clearly emphasize what is new and what is not.

Response: We have revised the introduction to clarify how our work fits into the previous literature. See page 2, lines 8-14 and lines 20-27.

(2) Explore the other implications of their regression analysis (see second paragraph above). The authors may want to save this for another paper, but ignoring most of the results of their regression analysis is simply unacceptable.

Response: In our opinion, the spatial patterns of the QBO and BDC coefficients are not interesting enough to warrant additional discussion. Thus, we have not added anything to the paper in response to this comment. We are open, however, to suggestions from the reviewer about what other implications are noteworthy.

Specific points:

Page 2, Line 10: How good is Dessler's model in evaluating the increase in water vapor in the UTLS due to convection for climate models? I would argue that we really can't simulate convection to the appropriate level of detail to get the effect of convective injection on UTLS water vapor in the current climate, so it is going to be difficult to make forecasts. Dessler's 2016 paper is one of the motivators to looking at this problem, but the statement is too strong. "a significant fraction of this increase may be due to the evaporation of lofted ice..." is more appropriate.

Response: This is covered in some detail in Dessler et al. (2016). Our assessment is that that analysis was able to unambiguously identify the influence of convective ice evaporation in the models. That said, we now note that this analysis only analyzed two models, so we've modified some text to make this clearer: "a significant fraction of this increase was found to be due to the evaporation of convective ice from convection in two chemistry-climate models (Dessler et al., 2016)" (Page 2, lines 16-18).

Page 7, lines 12-15: Look at the figure! The BDC coefficients change quite a bit over continental areas, so the statement is wrong. The statement that this is due to instant evaporation needs to be supported by some reasoning or evidence.

Response: We agree this was inartfully worded. We changed the statement to "The scatter plot of GEOSCCM vs. traj_ccm_ice BDC coefficients (Fig. 2k) shows larger scatter than the comparison without ice (Fig. 2i). The increase in scatter is likely the result of the crudeness of our microphysical assumptions, particularly the assumption that convective ice evaporates instantaneously. However, the comparison between the tropical average GEOSCCM BDC coefficient, -6.2 ppmv $(\mathrm{K\ day}^{-1})^{-1}$, and those from the trajectory models, -5.8 and -6.9 ppmv $(\mathrm{K\ day}^{-1})^{-1}$ without and with convective ice evaporation, respectively, is similar." (page 7, lines 23-28).

Page 7, lines 15-16: Systematic differences are reduced (comparing 4i to 4k), but scatter is much larger. For the BDC coefficient, the agreement (2i and 2k) is actually substantially worse. A region of negative coefficients appears over Indonesia in Figure 4j. I guess that is not statistically significant, but neither are any of the negative regions in figures 4g, 4j, and 4h that are emphasized in showing how convection moistens the central Pacific. There needs to be more discussion of these points.

Response: We have re-written this discussion to highlight that the scatter has visibly increased in the coefficient scatter plots when we add ice (page 7, lines 29-34).

Page 7, last paragraph: The contents of this paragraph should be moved to the conclusions section. The point about long-term trends of stratospheric water vapor (which this paper does not address at all) is speculation. Speculation is OK, but not in the results section.

Response: Done.

Page 7, line 33: How is it shown that a free running climate model GEOSCCM simulates TTL water vapor "over this period"? Since it is NOT a reanalysis, this needs to be explained.

Response: We have modified this statement and added some discussion (See page 3, lines 13-16 and page 9, lines 21-24).

Page 7, Line 4: I would use a study with a more detailed realistic model (e.g., Ueyama et al, 2015) to make this point.

Response: We have re-written this sentence as "In the last section, we hypothesized that this difference in the coefficients were due to evaporation of convective ice in the MLS data, a process not included in the trajectory model" (page 7, lines 14-16).

Minor comments:

line 7: ...as THE troposphere warms...

Response: Added.

Figure 3: Axes are mislabeled in (c) and (f)

Response: Corrected.

Figure 5 caption: magenta is negative, and black is positive temperature anomalies (reverse of what is in the caption). The black dots of significance are not always easy to see in the figures, suggest another color.

Response: We have removed the dots from the plot. We did this because what is important in the plots is not whether the coefficients are non-zero, but rather their overall spatial pattern. In its place, we've added a discussion about the significance of differences in the tropical average quantities (page 6, lines 16-20 and page 7, lines 13-14).

Reply to anonymous Referee #2

Specific comments:

The regression model, based on BDC, QBO and ΔT parameters, is an extension of Dessler et al., 2014 (D14). The accurate simulation of H_2O in the trajectory model is evidence that tropopause temperatures primarily control H_2O (as acknowledged here), and the regression model then accounts for variability of tropopause temperature. This is why the BDC accounts for most of the H_2O variance, as the BDC (heating rates) are closely proportional to temperature. The component of H_2O variance tied to tropospheric temperatures (ΔT) is relatively small in the regression model, with larger relative uncertainties (the corresponding H_2O variations for ΔT in Fig. 4 are < 0.1 ppmv, versus $\sim$ 0.5 ppmv for the BDC in Fig. 2). Time series of ΔT (Fig. 4 in D14) show that ΔT is mainly a proxy for ENSO variability, which explains the see-saw spatial structures in Fig. 4 (consistent with the patterns in Figs. 5-6). This ENSO spatial structure was discussed recently in Konopka et al., 2016, JGR, which should be referenced.

Response: The reference (Konopka et al., 2016) has been added (page 6, line 11 and page 9, line 1).

The key points of this paper relate to the small differences between the ΔT regression fits for MLS observations (or GEOSCCM model) and trajectory model results. To be convincing, the authors need to explain why the convection effect (persistent moistening) is associated with the ΔT (ENSO) regression, and demonstrate links to observed convection. Is there in fact more convection (in a global sense) when the troposphere is warm?

Response: To demonstrate the correlation between convection and the tropical warming, we added a scatter plot of tropical average convective cloud occurrence frequency at 370 K from observation and 500 hPa ΔT (Fig. 6a); it shows that that the convective cloud occurrence frequency in the TTL increases with ΔT.

This also occurs in the models. Dessler et al. (2016) (their Fig. 2) showed that convective ice in models' TTL increases in response to long-term warming. In this paper, we have also added a plot showing that IWC and net ice evaporation both increase with ΔT in response to interannual variability (Figs. 6b and 6c).

We also tested the correlation between convection and other regressors, i.e. BDC and QBO, and there is no apparent correlation like what found between convection and the tropical warming.

Overall, we view this as a reasonable assumption.

The ΔT regression differences (e.g. Fig. 4a vs. 4b) are likely within the uncertainty estimates of the regression fits, although this is not discussed.

Response: We have added a discussion about statistics testing of how confidently we can conclude that the tropical average coefficients are different (page 6, lines 16-20 and page 7, lines 13-14).

Furthermore, scatter plots (Figs. 4c,f,i) suggest an overall shift of the coefficients that is not dependent on location, and in particular the differences are not evidently related to regions of deep convection. Given these uncertainties, the argument that the differences are due to the neglected effects of deep convection are unconvincing.

Response: The reviewer makes a good point. While the hydration due to convection is localized, the impact is indeed spread throughout the tropics. That was not clear in the previous version and we have made changes throughout the paper to better reflect this.

My suggestion for revising the paper: 1) The authors could keep the present analysis, but provide more convincing discussion regarding the physical relationship between convection and ΔT, and in addition demonstrate statistical significance of the ΔT regression differences, and show clear physical links to observed convection.

Response: As discussed above, we have added new figures to connect ΔT and convective ice in observations and models (Figs. 6b and 6c). We also show that the ice evaporation rate in the GEOSCCM also increases with ΔT (Fig. 6c). While somewhat circumstantial, we feel the case we've made is nonetheless convincing.

2) A more convincing argument could be made by systematically analyzing the differences between observations and trajectory model results, and demonstrating that these differences are consistent with convective influence (e.g. using their spatial and temporal characteristics, and links with observed convection).

Response: This is not a new idea. One of us (AED) tried to do something like this about 10 years ago and it just didn't work. We know that other groups (such as one at JPL) also tried doing this. The main problem is that the TTL is relatively close to saturation, so any individual convective event doesn't add that much water. As a result, it's hard to pull the signal of that out of the background noise, which is considerable due to trajectory uncertainty and noise in the individual MLS measurements. Because of this prior experience, we do not judge this is a profitable course of research.

Effects of ~~tropical deep convection~~ convective ice evaporation on interannual variability of tropical tropopause layer water vapor

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Abstract.

Water vapor interannual variability in the tropical tropopause layer (TTL) is investigated using satellite observations and model simulations. We breakdown the influences of the Brewer-Dobson circulation (BDC), the quasi-biennial oscillation (QBO), and the tropospheric temperature (ΔT) on TTL water vapor as a function of latitude and longitude using a 2-dimensional multivariable linear regression. This allows us to examine the spatial distribution of the impact on TTL water vapor from these physical processes. In agreement with expectation, we find that the impacts from the BDC and QBO act on TTL water vapor by changing TTL temperature. For ΔT, we find that TTL temperatures alone cannot explain the influence. We hypothesize a moistening role for the evaporation of convective ice from increased deep convection as the troposphere warms. Tests ~~with simulations from GEOSCCM and a corresponding trajectory model~~using a chemistry-climate model, the GEOSCCM, support this hypothesis.

1 Introduction

Stratospheric water vapor plays an important role in both the chemistry (Stenke and Grewe, 2005) and radiative energy budget (Solomon et al., 2010; Dessler et al., 2013) of the atmosphere. Air enters the stratosphere from the tropical troposphere mainly through the tropical tropopause layer (TTL, ~15-18 km) (Sherwood and Dessler, 2000; Fueglistaler et al., 2009), which serves as a transition region between the troposphere and stratosphere. It is generally recognized that the coldest ~~temperature~~ temperatures in the TTL ~~acts~~ act like a "cold trap" that provides primary control on the amount of water vapor entering the lower stratosphere (Mote et al., 1996; Holton and Gettelman, 2001). Large interannual variations of TTL water vapor have been observed and attributed to a set of physical processes that affect water vapor by varying TTL temperatures, such as the quasi-biennial oscillation (QBO) ~~(Geller et al., 2002; Fueglistaler and Haynes, 2005; Dessler et al., 2013)~~ (Geller et al., 2002; Fueglistaler and H the Brewer-Dobson circulation (BDC) ~~(Randel et al., 2006; Calvo et al., 2010)~~(Randel et al., 2006; Calvo et al., 2010; Dessler et al., 2013,

Another important process is the deep convection that reaches the TTL. ~~Such convection can moisten the tropical lower stratosphere by evaporation of injected ice particles (Corti et al., 2008)~~Clouds comprised of convective ice can have important impacts on planetary energy balance (Lee et al., 2009; Zhou et al., 2014), and their evaporation can moisten the TTL (Corti et al., 2008; Wa The efficiency of ~~this process~~ cloud evaporation is strongly related to ambient relative humidity (Dessler and Sherwood, 2004; Wright et al., 2009) because high relative humidity inhibits evaporation. Recent aircraft measurements (Anderson et al., 2012;

Herman et al., 2017) and satellite observations (Dessler and Sherwood, 2004; Schwartz et al., 2013; Sun and Huang, 2015) confirm that the deep convection enhances lower stratospheric water vapor over the North American summer monsoon region, where relative humidity is very low.

In the tropics, the influence of convection on observed water vapor amounts is less clear. It seems certain that convective ice evaporation at least occasionally moistens the stratosphere ~~(Khaykin et al., 2009; Hassim and Lane, 2010; Carminati et al., 2014; Frey et al~~ but the impact of convection there is muted because the relative humidity of the TTL is high, suppressing evaporation, and only convection reaching above the cold point ~~will~~ is likely to significantly impact the humidity of the stratosphere (Dessler et al., 2007). ~~This makes identifying convective impacts difficult, although a recent analysis~~

Several modeling studies have addressed this by adding convection moistening into the trajectory model simulation, through a convective probability scheme (Dessler et al., 2007; Schoeberl and Dessler, 2011) or a reanalysis-based anvil ice scheme (Schoeberl et al., 2014) or an observation-based convective cloud top scheme (Ueyama et al., 2014, 2015). All these model simulations are in agreement that the convective ice can moisten the TTL and lower stratosphere. Schoeberl et al. (2014) and Ueyama et al. (2015) estimated that convective ice evaporation increases TTL water vapor by 0.3 ppmv and 0.5 to 0.6 ppmv, respectively. In addition, a recent case study has shown that evaporation of convective ice could account for a significant part of the TTL water vapor response to the strong El Niño of 2015-2016 (Avery et al., 2017).

On longer time scales, ~~though,~~ the impact of ice evaporation on stratospheric water vapor could be much more important. Almost all climate models predict that the water vapor in the UTLS will increase over the next century(Gettelman et al., 2010), and a significant fraction of this increase ~~is~~ was found to be due to the evaporation of ~~lofted ice from deep convection~~ convective ice from convection in two chemistry-climate models (Dessler et al., 2016). This gives us ample motivation to look more closely at the impact of convective ice evaporation on TTL water vapor in the observations.

The purpose of this study is to investigate in more detail the physical processes controlling the interannual variations of water vapor in the TTL, particularly the influence of evaporation of convective ice. Previous work ~~(Dessler et al., 2013, 2014) has shown that the QBO, the strength of the BDC, and the tropical tropospheric temperature can explain most of the variance in the interannual variations in~~ ~~*tropical average*~~ ~~TTL water vapor~~ has mostly taken a "forward model" approach — where a model (usually a dynamical model coupled to a microphysical model) driven by observations of winds, temperatures, and convection, is used to make an explicit estimate of the convective influence. Our analysis takes a different approach — we use a statistical model to decompose the water vapor variability into the dominant physical processes known to drive water vapor. We do this in both observations and water vapor simulated by a trajectory model. Because the trajectory model does not include convection, differences in the results will be tied to the influence of convection. We verify the methodology by reproducing it in a chemistry-climate model with known convection. ~~In this paper, we extend this previous work by investigating whether these variables can also explain the spatial distribution of the interannual variability.~~

2 Data and Methods

2.1 MLS water vapor

The observations of TTL water vapor ~~used~~ are from the Earth Observing System (EOS) Aura Microwave Limb Sounder (MLS) (Lambert et al., 2007; Read et al., 2007). The MLS instrument has obtained continuous ~~high quality~~ high-quality global observations of water vapor in the upper troposphere and stratosphere since August 2004. The data is available from https://mls.jpl.nasa.gov/.

Here we use MLS version 4.2 level 2 water vapor retrievals from August 2004 to December 2016. The daily water vapor mixing ratio measurements are binned and averaged to produce monthly data on a 4° × 8° latitude and longitude grid with the quality control following the instruction in Livesey et al. (2017). We focus on the interannual anomalies of water vapor from 30°N to 30°S at 100 hPa. ~~The interannual anomaly of water vapor~~ Throughout this paper, the interannual anomalies at each grid point ~~is~~ are calculated by subtracting the average annual cycle at ~~this~~ that grid point.

2.2 GEOSCCM

We also use simulations of TTL water vapor from the Goddard Earth Observing System Chemistry Climate Model (GEOSCCM) in this study. The state-of-the-art GEOSCCM includes the GEOS-5 atmospheric general circulation model (Molod et al., 2012) with ~~detailed cloud microphysical schemes (Barahona et al., 2014) and the "Combo CTM" tropospheric/stratospheric chemical package (Duncan et al., 2007)~~a single-moment cloud microphysics scheme (Bacmeister et al., 2006; Barahona et al., 2014) and the StratChem stratospheric chemical mechanism (Pawson et al., 2008; Oman and Douglass, 2014). The GEOSCCM simulation provides long term simulations of temperature, water vapor, horizontal winds, diabatic heating rates, and convective ice with a resolution of 2° × 2.5° in latitude and longitude on 72 vertical model levels, up to 0.01 hPa.

In this study, we investigate the water vapor ~~simulation from~~ simulated by the GEOSCCM in the TTL during model years corresponding to the MLS period. As these simulations are from a free-running ~~GEOSCCM, it can only be used for statistical analysis and is not directly comparable to observed water vapor variations~~model, climate variability in the model is not synchronous with that in the observations, so the comparisons with MLS observations are done statistically — using regression models (discussed below).

2.3 Trajectory model

We also produce simulations of TTL water vapor using a domain-filling forward trajectory model, which ~~accurately reproduces~~ has been in previous work to reproduce water vapor, ozone, and carbon monoxide anomalies in the TTL and lower stratosphere (Schoeberl and Dessler, 2011; Schoeberl et al., 2012, 2013; Dessler et al., 2014; Wang et al., 2014).

This model uses Bowman's trajectory code (Bowman, 1993; Bowman and Carrie, 2002). The parcels are driven by 6-hourly horizontal winds and total diabatic heating rates from ~~reanalysis datasets and~~ either reanalysis datasets or from the GEOSCCM. When comparing to MLS data, we use trajectory runs driven by two reanalysis datasets: the European Centre for Medium-

Range Weather Forecasts (ECMWF) ERA-interim reanalysis (ERAi) (Dee et al., 2011) and the NASA's Modern-Era Retrospective-Analysis for Research and Applications Version-2 (MERRA-2) (Bosilovich et al., 2016). When comparing to GEOSCCM output, we drive the model with meteorological fields from the GEOSCCM.

In all simulations, 1350 parcels are initialized every day from January 2000 to December 2016 on an equal area grid from 60°N to 60°S. The parcels are released on the 370-K isentropic level, which is just above the zero net diabatic heating level over the tropics (∼355-360 K) but below the cold point (∼375-380 K). Each parcel travels forward following the horizontal winds and diabatic heating rate. Once a parcel has a pressure larger than 250 hPa, it is regarded as having descended back into the troposphere and is removed from the model.

Each parcel is initialized with a water vapor mixing ratio of 200 parts per million by volume (~~ppmv~~ppmv). Along the trajectory, a parcel will immediately be dehydrated to saturation once its water vapor mixing ratio exceeds a predetermined saturation threshold, 100% in this study. The saturated water vapor mixing ratio is obtained from the thermodynamic equation with respect to ice (Murphy and Koop, 2005) based on temperatures from reanalyses or the GEOSCCM. The production of water vapor from methane oxidation is also included in these trajectory model runs but it has very little effect on water vapor in the TTL (Dessler et al., 2014).

The water vapor mixing ratio from the trajectory model is gridded into 4°× 8° bins, just as the MLS data were. In the vertical, the trajectory output is binned by averaging the parcels in a pressure range around each MLS or GEOSCCM level. In comparisons to MLS, the gridded water vapor mixing ratio is then re-averaged using the MLS averaging kernels following the instruction from Livesey et al. (2017). When doing this kernel averaging, grid boxes with no trajectory parcels (mostly at low altitudes) are filled with monthly water vapor mixing ratios from the reanalyses (ERAi and MERRA-2). Sensitivity tests confirm that changing water vapor mixing ratio from the reananlyses has no impact on the spatial distribution of the interannual variability of TTL water vapor that is the focus of this paper.

2.4 Convection clouds

We also use estimates of convective cloud occurrence produced by combining geostationary infrared satellite imagery and ~~rainfall measurements (Pfister et al., 2001; Bergman et al., 2012; Ueyama et al., 2015)~~microwave rainfall measurements (Pfister et al., 200 The data have a horizontal resolution of 0.25°×0.25° and a temporal resolution of 3 hours and cover the period from 2005 to 2016. In this paper, we use the cloud-top height and cloud-top potential temperature to estimate the convective cloud occurrence frequency in the TTL, which we take to be an indicator of ~~the~~ convective influence on the TTL. These data are available from https://bocachica.arc.nasa.gov/~lpfister/cloudtop/.

3 Results

3.1 Influence of the BDC and QBO on TTL water vapor

Fig. 1 shows ~~the~~ monthly and tropical averaged 100-hPa H_2O anomalies from MLS observations and from trajectory model runs driven by meteorology from ERAi (traj_ERAi) and MERRA-2 (traj_MERRA2). Similar to the results in Dessler et al. (2013, 2014) at 82 hPa, there is ~~a~~ good agreement between the observations and trajectory models at 100 hPa.

Dessler et al. (2013, 2014) also showed that we can fit tropical average ~~values of 82-hPa~~ anomalies of 82 hPa H_2O ~~anomalies~~ with a simple linear model:

$$H_2O = a \cdot \mathrm{BDC} + b \cdot \mathrm{QBO} + c \cdot \Delta T + r, \tag{1}$$

where BDC, QBO, and ΔT are indices representing the strength of the Brewer-Dobson circulation, the phase of the QBO, and the tropospheric temperature anomalies of the tropical climate system, respectively. ~~We can also fit the 100 hPa H_2O with the same model based on the regressors from ERAi and MERRA-2, with R^2 of 0.78 and 0.58, respectively~~Smalley et al. (2017) verified this approach is also valid in chemistry-climate models.

To ~~help us~~ gain additional physical insight into that result, in this paper we perform a similar multivariable regression, but at individual grid points in the TTL:

$$H_2O(x_i, y_j) = a(x_i, y_j) \cdot \mathrm{BDC} + b(x_i, y_j) \cdot \mathrm{QBO} + c(x_i, y_j) \cdot \Delta T + r(x_i, y_j). \tag{2}$$

Here, $H_2O(x_i, y_j)$ represents the H_2O anomaly time series at 100 hPa in a grid-box centered at longitude x_i and latitude y_j. The coefficients a, b, and c, as well as the residual term r, are also functions of latitude and longitude.

The regressors in Eq. 2 are the same tropical average time series used in Dessler et al. (2013, 2014): ~~ΔT is tropical averaged tropospheric temperature anomaly at 500 hPa, with units of degrees .~~ BDC is a Brewer-Dobson circulation index — here we use the tropical averaged diabatic heating rate anomaly at ~~82-hPa as a surrogate~~82 hPa, with units of $\mathrm{K\ day^{-1}}$. QBO is a quasi-biennial oscillation index and here we use standardized monthly and zonally averaged equatorial zonal winds anomaly at ~~50-hPa.~~ 50 hPa, with units of $\mathrm{m\ s^{-1}}$. ΔT is tropical averaged tropospheric temperature anomaly at 500 hPa, with units of degrees K. Because these regressors are tropical average values, they do not vary with location. The QBO index is lagged by 2 months in the regression because the phase of the QBO takes time to impact TTL temperature and then the water vapor at ~~100 hPa~~ 100-hPa (Dessler et al., 2013). There is no lag for the BDC and ΔT indices in this study.

We first analyze MLS H_2O observations. We run the regression on these observations twice: once using BDC and ΔT regressors from the ERAi reanalysis and again using regressors from the MERRA-2 reanalysis. The QBO index is the same in both regressions (we use ~~NCEP~~ observations downloaded from http://www.cpc.ncep.noaa.gov/data/indices/qbo.u50.index).

The BDC coefficients (Figs. 2a and 2d) are negative over the tropics, consistent with the idea that an enhanced Brewer-Dobson Circulation cools the TTL (Yulaeva et al., 1994; Randel et al., 2006) and reduces water vapor (Dhomse et al., 2008). The QBO coefficients (Figs. 3a and 3d) are positive over almost all of the tropics, as the positive phase of QBO tends to decrease the upwelling in TTL, thereby warming it (Plumb and Bell, 1982; Davis et al., 2013).

We also run the regression on H_2O simulated by the trajectory model. We use BDC and ΔT regressors from the same reanalysis used to drive each trajectory model (i.e., we use ERAi regressors to analyze the ERAi-driven trajectory model); the QBO index is always from the NCEP observations.

The BDC coefficients from regression of the trajectory models (Figs. 2b and 2e) agree well with the coefficients from the regressions of the MLS observations. The gridpoint-by-gridpoint scatter plots (MLS vs. trajectory; Figs. 2c and 2f) demonstrate this agreement in more detail. The only clear difference is that the regression of the MLS data using MERRA-2 regressors produces BDC coefficients that tend to be more negative than those from the trajectory model driven by MERRA-2 meteorology. This stems from what appear to be problems in the MERRA-2 heating rates. These heating rates disagree significantly with those from both ERAi as well as the original MERRA. While this has a minor effect on water vapor predicted by the trajectory model, it does have a large impact on regressions that use heating rates as a regressor.

The QBO coefficients from the regressions of the trajectory models are shown in Figs. 3b and 3e with gridpoint-by-gridpoint scatter plots in Figs. 3c and 3f. As with the BDC comparison, the trajectory models do a good job reproducing the regressions of the MLS data.

~~Dotted regions in Figs 2 and 3 indicate where the coefficients are statistically different from zero at a 95% significance level with a t-test. When testing the significance of coefficients, the autocorrelation in the time series is accounted for following Santer et al. (2000) by reducing the number of degrees of freedom from the lag-1 autocorrelation of the residual time series.~~

Overall, we conclude that the trajectory model accurately captures the impact of the BDC and QBO on TTL water vapor — for both the tropical average and the spatial distribution. This supports the hypothesis that these processes mainly influence TTL water vapor by varying large-scale TTL temperatures ~~(Giorgetta and Bengtsson, 1999; Randel et al., 2000; Geller et al., 2002; Randel et al.~~ transport (Giorgetta and Bengtsson, 1999; Randel et al., 2000; Geller et al., 2002; Randel et al., 2006; Dhomse et al., 2008; Liang et al., 20 which we expect the trajectory model to reproduce~~well~~.

3.2 Influence of tropospheric temperature ~~(ΔT)~~ on TTL water

Coefficients of ΔT from the MLS regressions are mostly positive, with large increases over the Tropical Warm Pool region (TWP) and Indian Ocean (Figs. 4a and 4e), indicating that warming of the tropical troposphere increases ~~the 100 hPa~~ TTL water vapor mixing ratio there. Over the Central Equatorial Pacific (CEP), however, a warming troposphere ~~decreases~~ *decreases* water vapor.

The decrease in water vapor in the CEP is not entirely unexpected. TTL temperatures are usually coldest — and water vapor a minimum — above the convection maximum in the TWP. As ΔT increases in response to an El Niño event, ~~convection shifts~~ this convective maximum, and its associated TTL cold pool, shifts eastward from the TWP to the CEP ~~. As this occurs, the cold pool moves to the CEP, so the CEP cools and the TWP warms (Davis et al., 2013; Hu et al., 2016; Avery et al., 2017)~~(corresponding to a shift from Figs. 5a and 5b) (Davis et al., 2013; Hu et al., 2016; Konopka et al., 2016; Avery et al., 2017). Changes in TTL H_2O are expected to mirror this, with increases in water vapor in the TWP and decreases in the CEP as ΔT increases. ~~The trajectory models, in which temperature is the only regulator, clearly~~

Both the MLS and trajectory model regressions show this dipole pattern. However, the MLS regressions yield ΔT coefficients that are systematically higher than those found in the trajectory regressions throughout the tropics (Figs. 4~~b and 4e).~~

~~The fits to the MLSdata (Figs. 4a and 4d)show~~ c and 4f). For the MLS/ERAi comparison (Fig. 4c), the average coefficients are 0.43 ppmv K^{-1} and 0.28 ppmv K^{-1}; for the MLS/MERRA-2 comparison (Fig. 4f), the average coefficients are 0.20 ppmv K^{-1} and 0.05 ppmv K^{-1}. We have also done regressions using tropical average values (using Eq. 1, similar to what was done in Dessler et al. (2013, 2014)) and find that the ΔT ~~coefficients in the TWP similar to those seen in the trajectory models. In the CEP, however, both MLS regressions show less negative coefficients than those found in the trajectory regressions (Figs. 4c and 4f).~~ coefficients from MLS and trajectory models are statistically different with probabilities of 85% and 70% for ERAi and MERRA-2, respectively. This probability is the chance that the two ΔT coefficient probability distributions from MLS and trajectory models are not the same.

We hypothesize that the evaporation of convective ice accounts for the difference between the ΔT coefficients in the MLS and trajectory-model regressions. As convection moves eastward during an El Niño event (Figs. 5a and 5b), there is an ~~increase~~ accompanying increase in convective ice in ~~ice injected into the TTL in the CEP~~ the TTL (Avery et al., 2017), where it evaporates and hydrates the TTL~~(Ueyama et al., 2015; Schoeberl et al., 2014). This evaporation partially offsets reductions in H_2O due to local cooling of the TTL. As a result, the net decrease in H_2O in the CEP in response to changes in ΔT is smaller in the observations than in the~~. The moistening from evaporation spreads throughout the tropics and increases the water vapor everywhere. The trajectory model, which ~~only includes the changes in TTL temperature.~~

~~Support for this hypothesis can be found in Figs~~does not include this process, simulates a smaller increase in water vapor, leading to smaller ΔT coefficients (Figs. 4c and 4f). ~~5a and 5b, which shows the temperature anomalies at 100 hPa (T_{100})in the two ENSO phases. The T_{100} anomalies clearly show the zonal shift of negative anomalies from the TWP during La Niña to the CEP during El Niño. The figure also shows observed cloud occurrence anomaly above the 365-K potential temperature level during El Niño and La Niña phases. These data~~

In support of this, in Fig. 6a we show that the ~~deep convective clouds shift from the TWP eastward to the CEP as well. This confirms CALIPSO observations of increased ice in the CEP during the exceptional El Niño event in 2015-2016 (Avery et al., 2017).~~

~~Thus, observations of convective clouds are~~ tropical averaged convective cloud occurrence frequency anomalies at 370 K increase with ΔT. This is consistent with the hypothesis that~~evaporation of ice in the CEP during El Niño events adds water vapor that mostly cancels the influence of the decrease in temperature of the region~~, as ΔT increases, we should also see an increase in evaporation of cloud ice.

3.3 Tests with a climate model

~~To more quantitatively test~~

To gain additional confidence in our hypothesis that evaporation of convective ice plays a role in the TTL water budget, we perform a parallel analysis with the GEOSCCM~~. We run the~~ , a model where evaporation of convective ice is known to add water to the TTL (Dessler et al., 2016). To do this, we run regression on the GEOSCCM ~~100 hPa~~ 100-hPa H_2O fields as well as on H_2O simulated by a trajectory model driven by the GEOSCCM meteorology. ~~Dessler et al. (2016) demonstrated the utility of this comparison in showing that convective ice evaporation plays an important role in the long-term trend in stratospheric water in this model.~~

Figs. 2g and 2h show the spatial distribution of the BDC coefficients from the GEOSCCM and the corresponding trajectory model. This comparison is analogous to the comparison of the regressions on the MLS data and trajectory models driven by reanalyses. The coefficients are similar to each other and ~~similar~~ to the MLS regressions, suggesting that the GEOSCCM is accurately simulating the impact of BDC changes on TTL water vapor. The influence of the QBO in the version of the GEOSCCM analyzed here does not ~~include a QBO, so there is~~ extend into the TTL, so we have not included a QBO term in the regression and there are consequently no GEOSCCM QBO ~~coefficient~~ coefficients in Fig. 3.

Before we discuss the ΔT coefficients, it is worth pointing out that the GEOSCCM has realistic ~~interannual variability in T_{100}~~ ENSO variability in TTL temperatures and convective ice. Figs. 5c and 5d show that the monthly convective cloud ice water content (IWC) anomalies at 118 hPa ~~from GEOSCCM during ENSO-like warm and cold phases, respectively. It shows positive convective ice anomalies~~ and cold anomalies at 100 hPa in the GEOSCCM shift eastward as the ΔT warms from a cold phase (Fig. 5~~d~~c) to a warm phase (Fig. 5~~c), with a similar zonal shift in temperature anomalies at 100 hPa. These compare well with the observations (Fig~~d), just as they did in observations (Figs. 5a and 5b).

The ΔT coefficient fields from the GEOSCCM and associated trajectory regressions (~~Fig~~Figs. 4g and 4h) show the same structural differences as do the ΔT coefficients from the MLS and accompanying ~~trajectory model~~ trajectory-model regressions — that the ΔT coefficient ~~in the CEP is less negative~~ is larger in the GEOSCCM regression than in the ~~trajectory regression. Since previous analysis of the GEOSCCM demonstrated that evaporation of convective ice from convection increases TTL water vapor (Dessler et al., 2016), it may be possible to demonstrate that~~ trajectory-model regression; the tropical average ΔT coefficients from GEOSCCM and trajectory model are significantly different at the 85% confidence level. In the last section, we hypothesized that this difference in the coefficients was due to evaporation of convective ice ~~is responsible for this difference~~in the MLS data, a process not included in the trajectory model.

To directly test this hypothesis in the GEOSCCM, we run a second version of the ~~traj_ccm~~ trajectory model that includes the evaporation of convective ice from GEOSCCM, referred to hereafter as traj_ccm_ice. ~~In thistrajectory model run~~To do this, we use the 6-hourly three-dimensional convective cloud IWC ~~fields~~ field from GEOSCCM and linearly interpolate it to each parcel's position at every time step. We then assume instantaneous and complete evaporation of this ice into the parcel by adding the IWC to the parcel's water vapor, although we do not let parcels exceed 100% relative humidity with respect to ice. This is the same procedure used to simulate convective ice evaporation by Dessler et al. (2016) .

We then run the regression on the traj_ccm_ice's H_2O field~~with the BDC and ΔT terms from GEOSCCM. The BDC coefficients change little in the CEP~~. The scatter plot of GEOSCCM vs. traj_ccm_ice BDC coefficients (Fig. 2~~j) when including the evaporation of convective ice . The point-by-point scatter plot in~~ k) shows larger scatter than the comparison without ice (Fig. 2~~k shows more scatter after we add ice evaporation, a likely~~ i). The increase in scatter is likely the result of the crudeness of our ~~instant evaporation assumption . That said, the addition of evaporationof convective ice~~ microphysical assumptions, particularly the assumption that convective ice evaporates instantaneously. However, the comparison between the tropical average GEOSCCM BDC coefficient, -6.2 ppmv $(\mathrm{K\ day}^{-1})^{-1}$, and those from the trajectory models, -5.8 and -6.9 ppmv $(\mathrm{K\ day}^{-1})^{-1}$ without and with convective ice evaporation, respectively, is similar.

The scatter plot of GEOSCCM vs. traj_ccm_ice ΔT coefficients (Fig. 4k) similarly shows larger scatter than the comparison without ice (Fig. 4i). Adding ice does, however, increase the average ΔT coefficient (seen by comparing Figs 4i to 4k), from 0.16 ppmv K^{-1} to ~~the model eliminates most of the negative coefficients in the CEP and brings the trajectory model into closer agreement with the GEOSCCM (seen by comparing Figs 4g to 4j).~~ 0.32 ppmv K^{-1}, bringing the trajectory model into closer agreement with the GEOSCCM, which has a corresponding value of 0.31 ppmv K^{-1}. There are also some interesting changes in the spatial pattern of the traj_ccm_ice (Fig. 4j). For example, negative ΔT coefficients appear in the TWP and Indonesia in the traj_ccm_ice regression; The cause of this is unknown, but also is likely linked to the trajectory model's ice evaporation assumption.

~~To better understand this result,~~ We showed in the previous section that the convective cloud occurrence frequency in the TTL increased as ΔT increased (Fig. 6a) and we also see that the GEOSCCM simulates a similar correlation between convective cloud IWC and ΔT (Fig. 6b). While these are not exactly the same quantity, they show a consistency that provides confidence that the behavior of the model is realistic.

Finally, to quantify convective ice evaporation, we calculate the evaporation rate of convective ice at 100 hPa in the trajectory model. To do this, we save the amount of water added to each parcel by ice evaporation in every time step. We then bin and average the amount evaporated to come up with the distribution of the amount evaporated per day~~between 109 and 93 hPa~~. Note that much of this water added will be lost in subsequent dehydration events, so this does not represent net water added to the stratosphere.

Fig. 6c shows that the tropical average evaporation rate of convective ice also increases with ΔT, which provides further evidence that the difference in ΔT coefficients between the GEOSCCM and the trajectory model is due to evaporation of convective ice. Fig. ~~6~~ 7 shows the distribution of monthly averaged evaporation rate ~~anomalies during the~~ during ENSO-like warm and cold phases in the GEOSCCM.

We see that, as ΔT increases and we ~~transit~~ transition from a cold to ~~a warm phase , the TTL convective cloud evaporation rate increases in the CEP and Latin America areas and decreases in the~~ warm phase of variability, the location of ice evaporation shifts from the TWP and Indian Ocean ~~areas. This confirms that ice evaporation increases TTL water vapor in the CEPand cancels out the drying effect of decreasing temperatures there in the GEOSCCM.~~ to the CEP. This is consistent with the analysis of Avery et al. (2017).

~~To conclude, our hypothesis that evaporation of convective ice moistens the TTL in the CEP is supported qualitatively by observations showing that clouds in the CEP increase with ΔT (Fig. 5; also Avery et al., 2017). It is also supported quantitatively by the GEOSCCM, which shows variations of TTL water vapor similar to the observations and that convective ice plays a key role in those variations. Given how accurately the GEOSCCM simulates water vapor in the TTL, we view this as support for our hypothesis.~~

4 Conclusions

~~Our work should not be taken as opposing previous work (Randel et al., 2006; Schiller et al., 2009; Wright et al., 2011; Randel and Jensen,~~ ~~concludes most of the variance in~~ Previous work has shown that TTL water vapor ~~over the last few decades is due to TTL temperature . We concur that the impact of convective ice only is a relatively minor contributor to TTL water vapor variability over the period spanned by the MLS data. But the GEOSCCM, which does an excellent job simulating TTL water vapor over this period, suggests that convective ice may play an important role in long-term trends of stratospheric water vapor (Dessler et al., 2016).~~

~~Previous work has shown that tropical average TTL water vapor variations can be attributed to physical processes correlated with three regressors: the tropical tropospheric temperature (ΔT), the~~ variability is mainly controlled by TTL temperature variability (Mote et al., 1996; Holton and Gettelman, 2001; Fueglistaler et al., 2009). In particular, variations in the Brewer-Dobson circulation (BDC) ~~,~~ and the quasi-biennial oscillation (QBO) ~~(Dessler et al., 2013, 2014). We extend these previous analyses and focus on the physical processes controlling~~ play key roles (Fueglistaler and Haynes, 2005; Geller et al., 2002; Liang et al., 201 It has been suggested by many previous investigators that evaporation of convective ice may also contribute water to the TTL (Khaykin et al., 2009; Hassim and Lane, 2010; Carminati et al., 2014; Frey et al., 2015; Virts and Houze Jr, 2015; Schoeberl and Dessler, In this paper, we analyze the spatial distribution of TTL water vapor and conclude that, indeed, convection makes a small contribution to the interannual variability over the MLS period.

To do that, we use a linear regression model on TTL water vapor at individual grid points over the tropics to investigate the spatial distribution of the impact of the BDC, QBO, and tropospheric temperature (ΔT~~indices.~~). We run this linear regression model on MLS observations of TTL water vapor anomalies and on water vapor anomalies simulated by a trajectory model that only includes the effects of TTL temperatures on water vapor.

The spatial pattern and magnitude of the BDC and QBO coefficients agree well between MLS observations and associated trajectory model simulations. This suggests that, consistent with expectations, these processes affect TTL water vapor mainly by changing TTL temperatures ~~(Randel et al., 2000; Geller et al., 2002; Randel et al., 2006; Dhomse et al., 2008; Liang et al., 2011; Dessle~~ ~~The GEOSCCM also produces similar coefficient fields, building confidence in that model's ability to simulate TTL water.~~ (Randel et al., 2000; Geller et al., 2002; Randel et al., 2006; Dhomse et al., 2008; Liang et al., 2011; Davis et al., 2013; Dessler et al., 201

The spatial distribution of ΔT coefficients has an obvious dipole structure ~~with~~ associated with the ENSO (Konopka et al., 2016): negative values in the Central Equatorial Pacific (CEP), where temperatures decrease as the troposphere warms, and positive values in the Tropical Warm Pool (TWP), where the opposite occurs. ~~The trajectory model analyses produce more negative values in the CEP, consistent with the strong cooling there as the troposphere warms. The MLS analysis, however, does not do this.~~

~~We hypothesized that an increase of deep convection as the troposphere warms increases~~

We also find that ΔT coefficients from the MLS observations are larger throughout the tropics than in the trajectory model. We hypothesize that changes in convection as ΔT increases leads to increases in evaporation of convective ice in the ~~CEP.~~

~~This ice evaporates, offsetting the reduction in water vapor there due to the decreasing temperatures~~TTL. This increases the ΔT coefficient in the MLS analysis, but not in the trajectory model, which does not have convective ice evaporation in it. We see ~~evidence of increases in convective clouds reaching the TTL in the CEP~~ support for this in the observations of increased convective cloud occurrence frequency in the TTL as ΔT increases~~in observations, in agreement with previous work (Avery et al., 2017). Tests of~~ . This result is also in agreement with the case study in Avery et al. (2017) as well as the model analysis in Schoeberl and Dessler (2011), Schoeberl et al. (2014), and Ueyama et al. (2014, 2015).

To gain additional confidence in our hypothesis that evaporation of convective ice is responsible for the difference in ΔT coefficients, we test the methodology in a parallel analysis with the GEOSCCM, a model where evaporation of convective ice is known to add water to the TTL (Dessler et al., 2016). We find that the results of this analysis show the same difference — that the ~~GEOSCCM model show that this process is occurring in that model~~ΔT coefficients from the regression of the GEOSCCM's water vapor field are larger than the coefficients from a trajectory model driven by GEOSCCM meteorology.

We confirm this is due to evaporation of convective ice by running a second version of the trajectory model, which includes convective ice evaporation. We find that the ΔT coefficient from the regression of this version of the trajectory model is in agreement with that from the GEOSCCM regression.

~~Thus~~Putting all of these together, we conclude that variability in the evaporation of convective ice ~~likely~~ plays a role in ~~setting the distribution of water vapor~~ water vapor variability in the TTL. ~~However, this effect is minor on interannual time scales;~~ Our work should not be taken as opposing previous research (Randel et al., 2006; Schiller et al., 2009; Wright et al., 2011; Randel and Jensen, 2 concluded most of the variance in TTL water vapor over the last few decades is due to ~~other processes that change~~ TTL temperatures. ~~However, it~~ We concur that the impact of convective ice only is a minor contributor to TTL water vapor variability over the period spanned by the MLS data. But for GEOSCCM, which does an excellent job simulating TTL water vapor over the comparable period, suggests that convective ice may play a much larger role in long-term trends of TTL and stratospheric water vapor (Dessler et al., 2016), so more research on this phenomenon is clearly warranted.

Competing interests. The authors declare that they have no conflict of interests.

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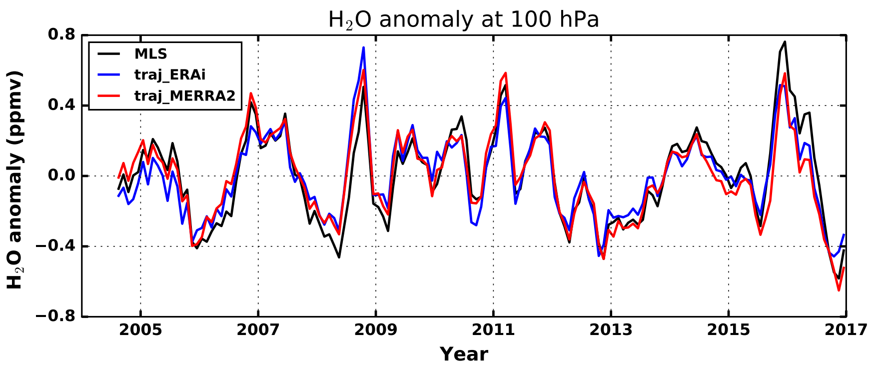

Figure 1. Tropical (30°N-30°S) monthly water vapor anomalies at 100 hPa from MLS observations (black line) and from trajectory model runs driven by ERAi (blue line) and MERRA-2 (red line) from August 2004 through 2016. Anomalies are calculated by subtracting the mean annual cycle from the observations.

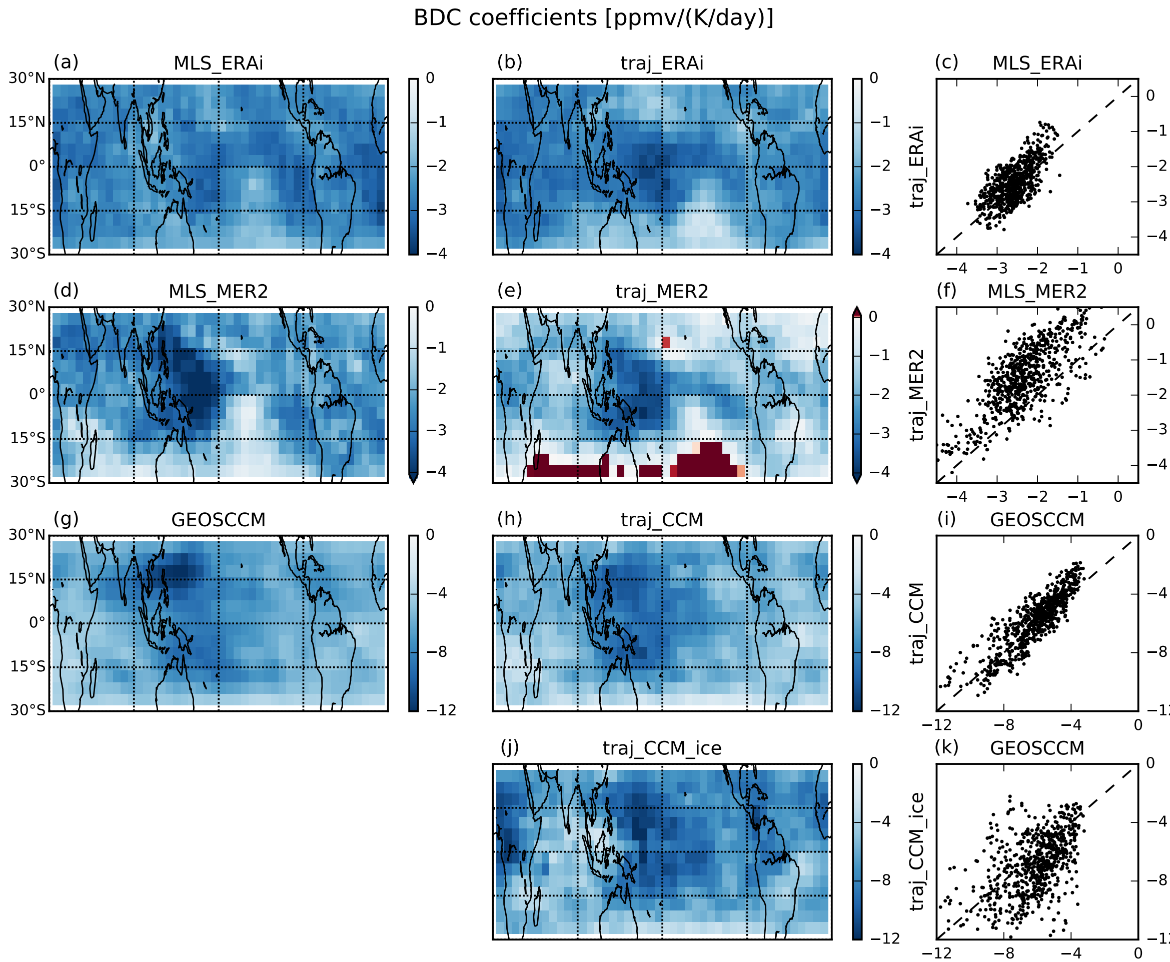

Figure 2. Multivariate linear regression coefficients of the BDC regressor from MLS and GEOSCCM H_2O fields (left column), as well as the coefficients from regression of the associated trajectory model fields (middle column). Scatter plots of MLS/GEOSCCM regressions vs. trajectory model regressions indicate the similarity of the fields (right column). The MLS and associated trajectory regressions cover the period August 2004 to December 2016 between 30°N and 30°S. The GEOSCCM and associated trajectory run cover 2005-2016 model years. The bottom row shows coefficients from regressions of a run of the trajectory model driven by GEOSCCM meteorology that includes evaporation of convective ice. ~~The black dots in the first two columns indicate where coefficients are non-zero with a significance level of 95%.~~

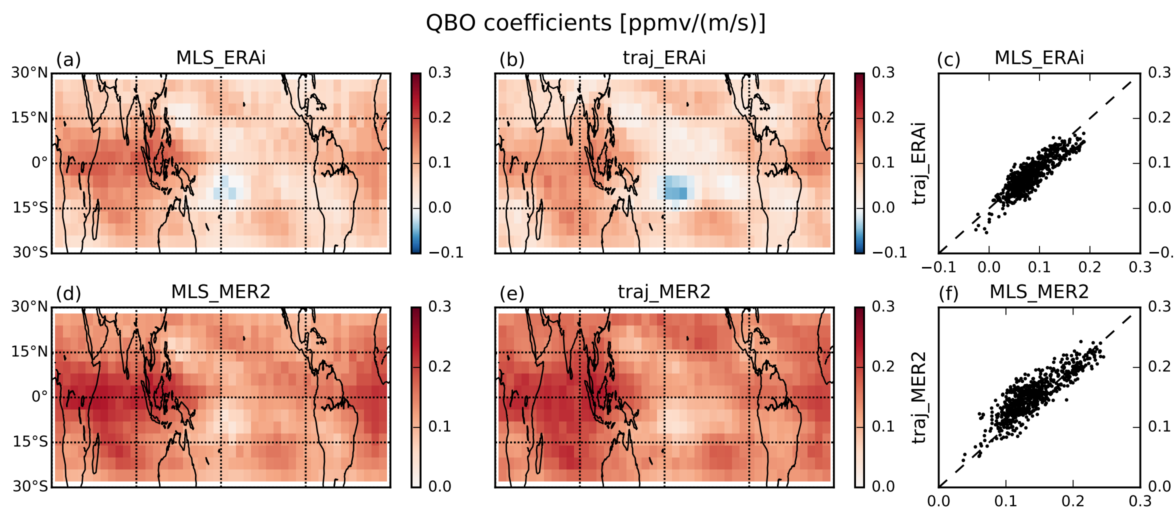

Figure 3. Same as Fig. ~~2~~2, but for coefficients of the QBO regressor. ~~This GEOSCCM run does not simulate a QBO, so it has been omitted.~~

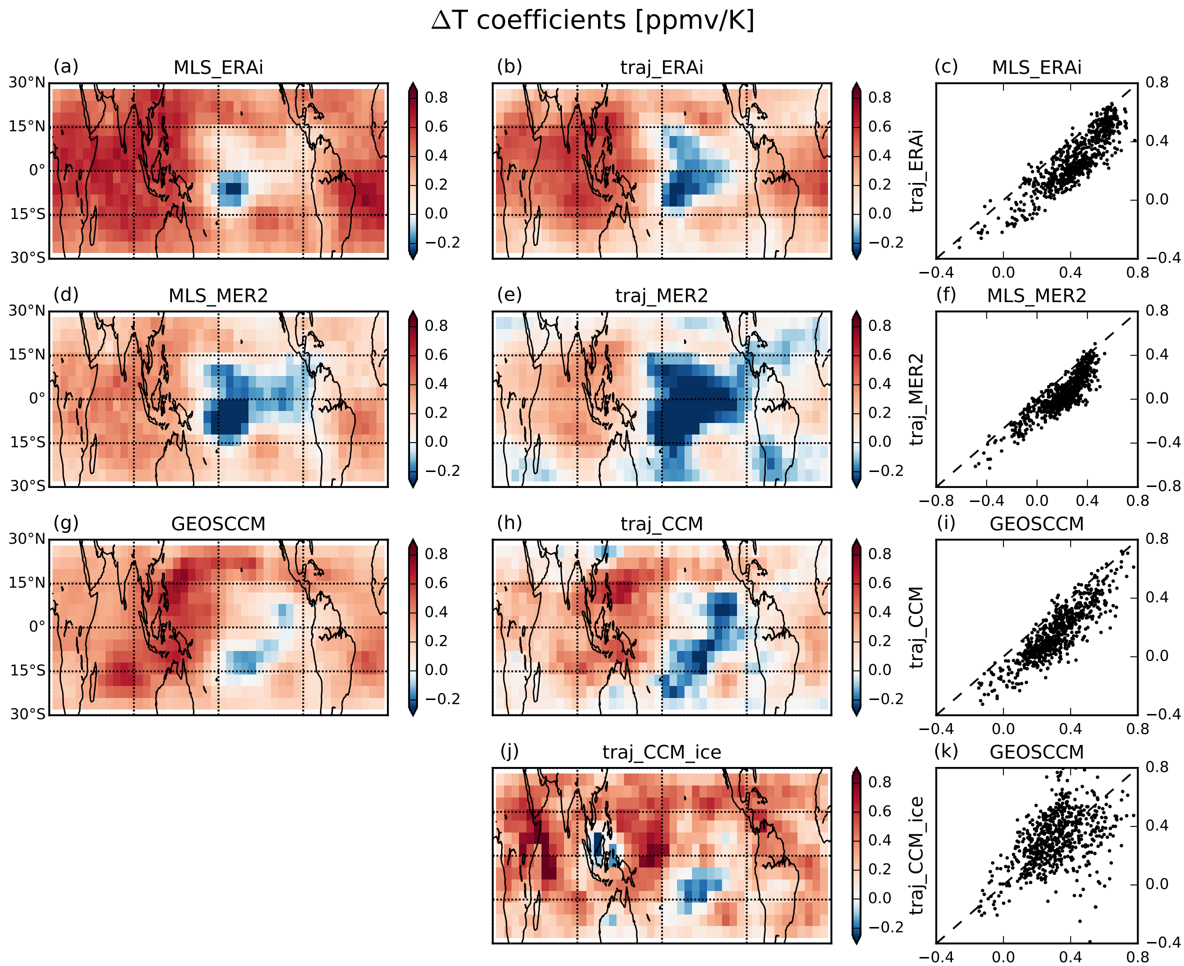

Figure 4. Same as Fig. ~~2~~ 2, but for the coefficient of the ΔT regressor.

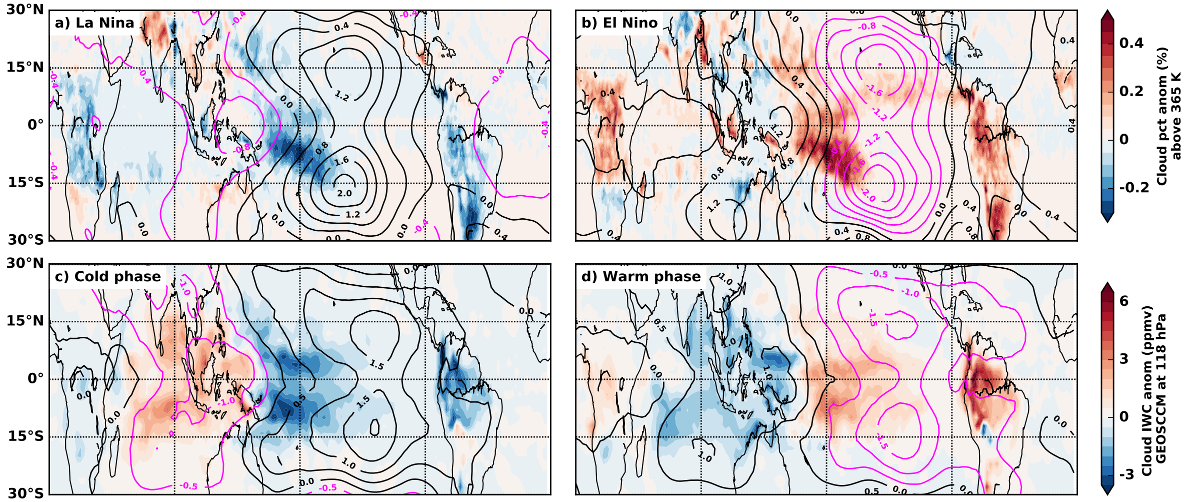

Figure 5. Averaged monthly cloud occurrence frequency anomalies above 365 K during (a) ~~El~~ La Niñ~~o~~a and (b) ~~La~~ El Niñ~~a~~o months from 2005 to 2016~~with averaged ERAi~~; also shown as contours are temperature anomalies at 100 hPa~~shown as contours~~. ~~El~~ La Niñ~~o~~a and ~~La~~ El Niñ~~a~~o months are based on the NOAA Oceanic Niño Index (ONI) in the Niño 3.4 region (5°S to 5°N; 170°W to 120°W). Averaged monthly GEOSCCM convective cloud ice water content (IWC) anomalies (ppmv) at 118 hPa during (c) ~~warm~~ cold and (d) ~~cold~~ warm GEOSCCM phases from model years 2005 to 2016 with averaged temperature anomalies at 100 hPa shown as contours. The ~~warm and~~ cold and warm phases are defined to be GEOSCCM surface temperature anomaly (departures from the mean annual cycle) of +0.5 K and -0.5 K, respectively, in the Niño 3.4 region (same as ONI). ~~In all panels, magenta and black contours show positive and negative temperature anomalies, respectively.~~

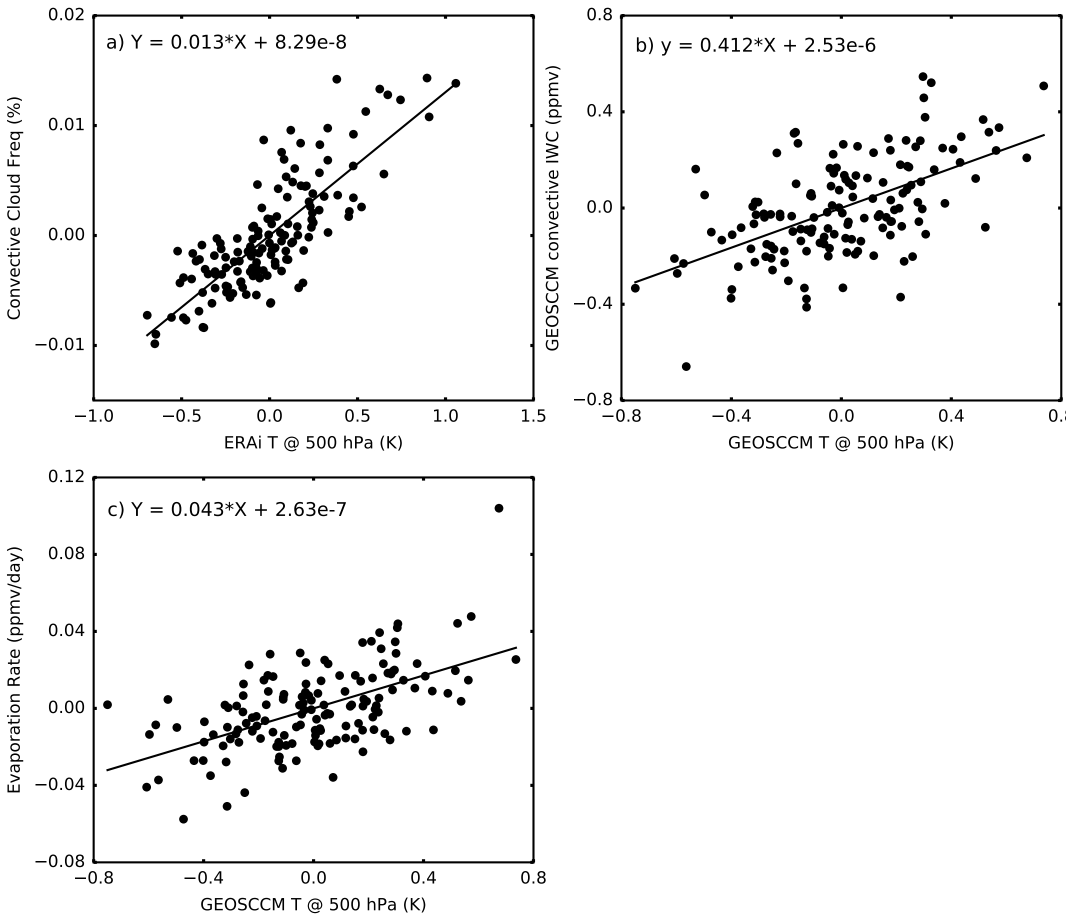

Figure 6. ~~Averaged monthly GEOSCCM~~ (a) Observed convective cloud ~~evaporation rate~~ occurrence frequency anomalies at ~~100 hPa during~~ 370 K and 500-hPa ΔT from ERAi. (~~a~~b) ~~warm~~ Convective IWC anomalies at 118 hPa and ΔT from GEOSCCM. (~~b~~c) ~~cold~~ GEOSCCM ~~phases from 2005 to 2016. Also shown are averaged horizontal wind anomaly vectors~~ convective cloud evaporation rate anomalies at 100 hPa and ΔT. All the data is monthly and tropical averaged from 30°S to 30°N.

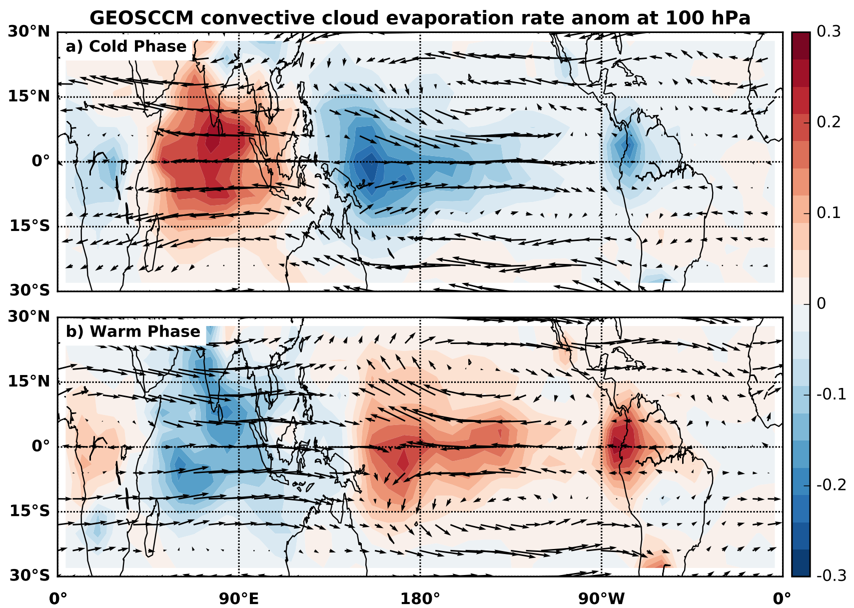

Figure 7. Averaged monthly GEOSCCM convective cloud evaporation rate anomalies at 100 hPa during (a) warm and (b) cold GEOSCCM phases from 2005 to 2016. Also shown are averaged horizontal wind anomaly vectors at 100 hPa.