Large anomalies in lower stratospheric water vapor and ice during the 2015-2016 El Niño

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Abstract

The strong and unusual El Niño of 2015-2016 produced a remarkable perturbation to the hydrologic budget of the tropical tropopause layer (14-19 km). This region regulates stratospheric water vapor, which has a direct radiative impact on surface temperatures. To first order, the coldest tropical tropopause temperature regulates the amount of water vapor entering the stratosphere by controlling the amount of dehydration in the rising air. Here we show that tropical convective cloud ice and associated cirrus evaporting at unusually high altitudes might also have a role in stratospheric hydration. The 2015-2016 El Niño produced decadal record water vapor amounts in the tropical Western Pacific, coincident with warm tropopause temperature anomalies. In the

Central Pacific, convective cloud ice was observed 2 km above the anomalously cold tropopause. A trajectory-based dehydration model based on two reanalysis temperature and wind fields can account for only about 0.5-0.6 ppmv of the ~0.9 ppmv tropical lower stratospheric moistening observed during this event. This suggests that unresolved convective dynamics and/or associated sublimation of lofted ice particles also contributed to lower stratospheric moistening. These observations suggest that convective moistening could contribute to future climate change-induced stratospheric water vapor increases.

Main Text

Stratospheric water vapor has a direct impact on surface climate[1,2] and stratospheric ozone chemistry[3]. To first order, the amount of water vapor entering the stratosphere is regulated by the coldest temperatures experienced by air parcels ascending through the tropical tropopause layer (TTL)[4-6]. This simple mechanism postulates that as air slowly rises through the cold tropopause region, dehydration occurs when clouds are formed and water vapor deposits onto ice particles that subsequently precipitate out. In this view, the humidity of air entering the stratosphere in the tropics is therefore effectively controlled by the coldest temperature encountered by the rising air[7]. The tropical cold-point tropopause (CPT) is typically near or just above the WMO-defined tropical lapse rate tropopause, at an altitude of about 17 km[8], with temperatures coldest during boreal winter in the Tropical Warm Pool region (TWP)[9,10,12]. A simplified dehydration trajectory modeling framework where the amount of water vapor remaining in an air parcel is determined by the coldest temperature experienced by that parcel has been shown to capture much of the seasonal and year-to-year variations in the amount of water entering the tropical lower stratosphere[7,11-14].

Convective Moistening

In addition to the synoptic-scale temperature field in the TTL, small-scale wave-induced temperature perturbations[15], microphysical processes[16] and convective moistening[17,18] may also effect the entry value of stratospheric water vapor. Convective moistening of the lower stratosphere is of particular interest, as it has been proposed as a mechanism for directly injecting sublimating ice and associated water vapor above the local CPT. Sublimation of convective ice in adiabatically adjusting vertically ascending air at and just above cold deep convective cloud tops[29] could provide a direct route for air to bypass dehydration in the tropical cold trap, and has been suggested as a significant source of stratospheric moistening in climate models[19,20]. Ice injected above the CPT has been observed locally by aircraft[21] and balloon[22] measurements. Ice injection also provides a mechanism for explaining the isotopically heavy water vapor found in the stratosphere[23], but is difficult to measure globally because current satellite-based temperature and water vapor sensors do not have the vertical or horizontal spatial resolution to resolve local convectively perturbed CPT temperature or water vapor profiles.

The Unusual 2015-2016 El Niño

The unusual strength of the most recent El Niño event provides an opportunity to observe the impact of convectice ice lofting on the humidity of the lower stratosphere.

The 2015-2016 El Niño was one of the three strongest occurring since 1950, based on a ranking of the ERSST v4 El Niño Southern Oscillation (ENSO) 3.4 region sea surface temperature anomaly[24]. The 2015 El Niño developed Central Pacific SST and convection anomalies in the 2015 boreal summer[25], earlier and much farther west than the last record 1997-98 El Niño[24]. This recent event also produced very different extratropical teleconnections and stratospheric circulation impacts when compared to previous El Niños[26], with tropical circulation changes outside the range of modern observations. The dramatic relocation of deep convection and the associated CPT temperature minimum from the tropical Western Pacific to the Central Pacific potentially inhibited the Walker circulation[27] and disrupted the quasi-biennial oscillation (QBO) in the tropical stratospheric winds[25,26,28,29].

In this study we explore the connection between observed 2015 ENSO-related convection, TTL cloud ice mass, and lower stratospheric water vapor. For cloud observations, we examine the Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP) data record. Fig. 1a shows that high clouds occur primarily in the Western Pacific in the 2006-2014 December monthly average of cloud ice integrated above the MERRA-2 CPT. Fig. 1b shows that December 2015 is striking in both the absence of high clouds in the TWP (orange boxes, Fig. 1a/b) and the large amount of ice above the CPT in the Central/Eastern Pacific region (CEP, red boxes, Fig. 1a/b). Fig. 1c shows the lower stratospheric water vapor anomaly structure, with high values in the TWP region, and weak easterly winds above the region of high ice content. Fig. 1d shows the associated MERRA-2 CPT temperature field and climatology.

While unusual in timing and magnitude, the shift of convective high clouds from TWP to CEP is consistent with earlier analyses of TTL temperature and cloud occurrence frequency[30,31]. There is a distinct ENSO-related dipole pattern consisting of cold anomalies accompanied with increased cloudiness in the CEP sector and warm anomalies accompanied with decreased cloudiness in the TWP sector during El Niño. During La Niña, the pattern is reversed. However, it is worth noting that this earlier work focused only on cloud occurrence frequency, which gives equal weight to thin clouds that form in the TTL and thicker convective clouds. Also, they considered clouds occurring at altitudes well below the local CPT, which do not have the potential to hydrate the stratosphere by bypassing the cold trap[23]. Our observations of enhanced ice water content (IWC) above the CPT suggest that there was enhanced potential for ice transport into the stratosphere during this recent El Niño event.

Cold-Point Tropopause Temperature Changes

Given the well known importance of CPT temperature on the entry value of stratospheric water vapor, we consider the state of the CPT during this event. December 2015 had a strikingly warm CPT in the TWP (Fig. 1d), where the coldest temperatures and most extensive dehydration typically occur. The minimum in the CPT field was shifted eastward from its climatological position (Figs. 1d and S01b-d), towards the cloud ice maxima in the CEP. Thus, the ENSO-related eastward shift in convection also caused a strong shift in the coldest temperatures at the end of 2015, a pattern previously associated with the warm phase of ENSO[32, 33].

In December 2015, the geographical location and patterns of TTL cloud ice, temperature, and wind fields are indicative of a strong anomaly of convection in the Central Pacific, just to the East of the dateline. First, this region contains diverging winds in the vicinity at 85 and 100 hPa, near the tropopause, consistent with large-scale outflow from convection (Figs. 1cand S01a). Also, the location of the TTL cloud ice is co-located with the region of coldest tropopause temperatures (Fig. 1d), consistent with an adiabatic response to convective lofting[16,19]. This result is not reanalysis-dependent (the ERA-Interim analysis is shown in Fig. S01), and patterns of outgoing longwave radiation and precipitation (Fig. S02) confirm that convection was particularly active in this sector during December 2015.

Decadal Time Series

Next we consider how unusual the 2015-2016 El Niño event was in the context of the available satellite records. For cloud observations, we examine the Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP) data record. Area-averaged monthly mean time series of the quantities shown in Fig. 1 are plotted in Fig. 2, along with the Oceanic Niño Index (ONI). There are three El Niño events (ONI ≥ 0.5°C for 5 consecutive months[34]) within the CALIOP record, peaking in the boreal winters of 2006-2007, 2009-2010, and 2015-2016. During the peak of these El Niño events, the ice water path (IWP) time series indicates an increase in cloudiness above the CPT in the CEP region. CPT temperature anomalies in the CEP region were negative, differing significantly from the zonal mean during these El Niños. In contrast, in the TWP region during El Niño events, both water vapor anomalies and CPT temperature anomalies are positive and larger than those for the the zonal mean. Although limited to the three cases sampled, the difference between CEP and the zonal mean for IWP scales with the strength of the El Niño ONI, with the 2015-2016 event being the strongest, followed by 2009-2010, and lastly 2006-2007.

The time series of IWP shows clearly that at the end of 2015 cloud ice is injected above the CPT in the CEP region (Fig. 2a,b). To be confident that the IWP result does not depend on the location of the reanalysis CPT, the IWP calculation is repeated above a 17 km threshold, with this time series showing similar results (Fig. S03). The Aura Microwave Limb Sounder (MLS) water vapor anomaly at 82hPa is also a record (Fig. 2c); at 100 hPa the MLS water vapor anomaly was even larger (Figs S01a and S04). A convective cloud IWC profile time series in the CEP region (Figs 2b and S06b) demonstrates clearly that December 2015 was anomalous, with ice from relatively optically thick clouds observed up to 2 km above the environmental CPT. To our knowledge this had not been observed before the CALIOP observations became available.

The longer period of the merged SWOOSH satellite data record[35] also indicates this was a record-setting event after the occurrence of the precipitous drop in stratospheric water vapor at the end of the 1990's (Fig. S05). The satellite water vapor record in the tropics in the 1990's is highly uncertain given the sparse sampling and data quality impacts from elevated stratospheric aerosol loading related to Mt. Pinatubo, but there is some indication that the 1997-1998 El Niño may have had a similar magnitude impact on tropical lower stratospheric water vapor.

The record-setting lower stratospheric water vapor (Fig. 2c) occurs in the TWP where there is an absence of ice. This region is downwind and well to the west of the ice maxima. The maps in Fig. 1 imply that the anomalously warm TWP temperatures during December 2015 (see Fig. 2c) contributed to the record amount of lower stratospheric water vapor.

Trajectory Modeling

To check whether large-scale temperature and winds could explain the observations, we simulate the TTL using a forward domain-filling Lagrangian trajectory model[5]; the MLS water vapor averaging kernel has been applied to the model output to facilitate comparison. Fig. 3a shows that the trajectory model driven by the MERRA-2 and ERA-Interim reanalyses both reproduce the time series quite well, with the exception of a lag in ENSO response of 1-2 months by MERRA-2 . The phase of the QBO in combination with ENSO has been considered extensively in models with regard to top-down control of stratopheric water[27]. El Niño and QBO are accounted for in the trajectory model, to the extent that their impacts on the large-scale temperature and wind fields are accurately represented by the reanalyses. The phase of the QBO potentially impacts entry-level stratospheric water through changes in tropical tropopause temperatures. However, a simple regression of a 70 hPa shear-based QBO index with MLS water vapor data at 82 hPa shows that the QBO can account for only 0.1 ppmv of the observed zonal mean water vapor anomaly (Fig. S08). Differences in the magnitude of the modeled and observed water vapor anomalies are shown in Fig. 3b. In particular, the positive difference between MLS and both models of 0.3-0.4 ppmv at the ENSO peak in 2015-2016 shows that the simple temperature-based dehydration mechanism can not explain all of the record amount of observed water vapor during the 2015/2016 El Niño.

There are several potential explanations for why MLS observations show more water in the lower stratosphere than the trajectory model. One possibility is that convectively detrained ice sublimates into the subsaturated environment above a locally perturbed CPT, a process that is not included in the trajectory model. Indeed, CALIOP observations of significant ice above the CPT are consistent with this explanation. Other small-scale processes that are also unresolved by the trajectory model, such as clouds generated by turbulence or high-frequency gravity waves above deep convection, seem unlikely to produce the full amount of the observed difference. Clearly, this requires more detailed study.

Convection in a Warming World

We conclude that the dry bias of the trajectory model during the El Niño of 2015-2016 indicates that the simple dehydration model is missing physical processes that are associated with convection. The presence of substantial high-altitude ice at and above the local CPT indicates that hydration of the lower stratosphere by convectively detrained cloud ice is a plausible explanation for up to half of the observed +0.9 ppmv water vapor anomaly of the lower stratosphere, with the other half being due to anomalously warm CPT temperatures. Coupled cloud radiation feedback or biases in the reanalysis temperature/wind fields in the vicinity of deep convection also warrant further exploration. Nevertheless, the record amount of cloud ice observed above the

CPT, the wetter lower stratosphere during the peak of the 2015/2016 El Niño, as well as the unexpected changes in the stratospheric QBO highlight deficiencies in our understanding of impacts from ENSO-related enhancement in tropical convection. This was an unusual event in that the lower stratospheric ice as measured by the CALIOP instrument is the largest measured in the Central Pacific over its eleven years of operation. The 100 hPa zonal averaged water vapor anomaly estimated from MLS was also an instrument record (shown in Fig. S04); at 82 hPa, values were only matched on one other occasion (shown in Fig. 3). The observations reported here suggest that this was clearly an unusual event within our existing measurement time period, and that models do not accurately account for "bottom-up" strong convective processes. Because climate models predict higher tropical clouds and an increase in cloud ice at the tropical tropopause[19,20,36] with warming sea surface temperatures, accurate understanding of the stratospheric impact of changing patterns of tropical deep convection is critical in the context of a warming world[20,25,27,36].

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Author Contributions: Corresponding author MA provided gridded cloud ice water content from the CALIOP data record, integrated above the CPT altitude and 17 km.

Authors SD and KR analyzed the MLS water vapor observations and MERRA-2 temperature fields. HY and AD provided the trajectory model and model runs. All authors are responsible for the scientific interpretation of the data and for writing the text.

Competing financial interests

The authors declare that there are no competing financial interests.

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Figure Captions

Figure 1, Tropical Ice Water Path, Water Vapor and CPT Temperature Anomalies for December 2015: (a) Mean December 2006 – 2014 CALIOP-observed ice water path (IWP) above the MERRA-2 CPT. (b) IWP above the CPT for December, 2015. (c) The December 2015 82 hPa MLS water vapor anomaly (relative to 2006-2014), with the 9-year December average water vapor (yellow) and 85 hPa MERRA-2 wind vectors, (black). (d) December, 2015 MERRA-2 CPT temperature anomaly (filled contours), and December climatological (2006-2014) CPT temperature (lines). The analyzed domain is shown for the Tropical Western Pacific (TWP, orange box) and the Central and Eastern Pacific (CEP, red box).

Figure 2, Time series of IWP, Convective IWC, Water Vapor and Temperature Anomalies: a) A time series (June 2006 – November, 2016) of monthly average

CALIOP IWP from the CPT to 20km. The inset in a) shows a close-up of IWP in 2015 and 2016. The black lines show zonal averages between 15°S and 15°N latitudes, orange lines are for the TWP region, and red lines show the monthly averages for the CEP region. b) Convective (Cloud Optical Depth > ~3) cloud top IWC for the CEP region, with the MERRA-2 CPT height in red. c) MLS 82 hPa water vapor anomaly for the three regions and an ONI index (blue). d) Deseasonalized MERRA-2 CPT temperature anomaly.

Figure 3, MLS and Trajectory Modeled Water Vapor Anomaly Comparison: a) MLS water vapor anomaly at 82 hPa for the tropical zonal mean (black), with the 82 hPa water vapor anomaly calculated from a Lagrangian trajectory model (see text) using ERA-I wind and temperature fields (in purple), and MERRA-2 fields (in green). Panel b) shows the de-seasonalized difference between the measured (MLS) and modeled water vapor anomaly using both reanalysis data sets. Model results have been vertically averaged to match MLS. The MERRA-2 maximum difference appears to reflect a MERRA-2 failiure to capture the beginning of the 2015 El Nino.

Methods:

For a measure of the strength of ENSO, we use the NOAA Oceanic Niño Index (ONI, https://catalog.data.gov/dataset/climate-prediction-center-cpcoceanic-nino-index), which is a 3-month running mean of the Extended Reconstructed Sea Surface Temperature Version 4 (ERSST.v4) data in the Niño 3.4 region (5°S to 5N; 170°W to 120°W)[37].

Our analysis region for the tropical zonal mean is defined as all longitudes, and latitudes between 15 S and 15 N. Our CEP and TWP regions are defined to be of equal area, and are consistent for all data analyzed and labeled this way. We define the CEP as extending from 15 S – 15N and from 100 W – 180 W. The TWP is defined as 15 S – 15 N, from 80 E – 160 E.

We examine an eleven-year record of CALIOP ice water content (IWC) and ice water path (IWP) observations in the upper tropical troposphere and lower stratosphere, where the lidar is almost never fully attenuated[38]. Cloud and aerosol extinction is retrieved from CALIOP attenuated backscatter measurements using the method described in Young and Vaughan[39]. For this study we use CALIOP Version 3.01 – 3.30 (V3) retrieved extinctions, available in the Level 2 5km cloud profile data, to supply the eleven-year record. This data is available to the public in the NASA Langley ASDC archive https://eosweb.larc.nasa.gov/project/calipso/calipso_table. Only data from 1:30Z equatorial crossings (nighttime) is used for this analysis because it has a higher signal to noise ratio than daytime data. We feel that it is justified to ignore diurnal variability because we are primarily looking at maritime convection, where diurnal variability is low. CALIOP V3 IWC is parameterized from extinction as described in the V3 CALIPSO data products catalogue, available at https://www-calipso.larc.nasa.gov. V3 IWC is used at the native lidar resolution of 60 meters to produce the monthly-averaged all-sky IWC profiles shown in Figs. 2b and S06. We consider the valid range of IWC to be 10^{-5} – 10^{1} g/m^3, and have screened the data for valid extinction retrieval types of 0, 1, 2, 16 and 18, and have eliminated IWC produced from extinction error values of 99, as described in the data products catalogue. The V3 IWC shown in Figs. 2b and S06b is further screened to include only cloud extinction retrieval types 16 and 18, indicating that the extinction retrieval was successful for clouds that fully attenuate the lidar signal below the study region. CALIOP lidar attenuation by a cloud layer is an heuristic method to isolate convective clouds, useful for distinguishing observations of the tops of clouds with optical depths that are greater than 3-5. Clouds with optical depths larger than 3 are not likely to form "in situ" in the conditions found in the TTL. For comparison, we show the mean IWC profile time series for all cloud layers in Fig. S06a.

For the IWP calculations we have treated each profile individually, applying the Heymsfield 2014[40] temperature-dependent effective diameter IWC parameterization to V3 extinctions, and then integrating this IWC between an interpolated MERRA-2 CPT and 20.2 km to create an IWP. We note that the temperature-dependent IWC parameterization is most likely under-estimating convective cloud ice at the cold temperatures found in our study region, but is a reasonably accurate representation of IWC in cold thin TTL clouds[41]. Therefore our IWP calculated in this way is likey to be a lower limit, since the IWC in all cloudy bins is parameterized as if they contain only small ice particles.

The CPT is calculated by applying a zero-lapse rate definition[42] to the MERRA-2 reanalysis temperature field, using the 6-hourly native "model level" data (M2I6NVANA.5.12.4 subset, with 64 vertical levels or ~0.75 km near the tropopause, 0.5° longitude x 0.5° latitude). MERRA-2 is available at:

http://disc.sci.gsfc.nasa.gov/mdisc/. The altitude of the MERRA-2 CPT is located for each CALIOP profile by interpolation from the reanalysis grid to match each CALIPSO overpass location and time. To produce the time series, all-sky monthly averages of IWP above the CPT are calculated at 5° longitude x 2° latitude resolution. To show that our results do not depend on the exact location of the MERRA-2 CPT, the analysis is also repeated for a constant 17 km threshold for each profile. The IWP calculated above 17 km is shown in the Supplemental material, and gives similar results (Fig. S03).

Since we want to determine the impact of cloud ice on lower stratospheric water vapor, we use the Version 4.2 MLS water vapor (3 km vertical resolution) at the 82 hPa retrieval level, which mainly lies above the CPT. However, the 100 hPa MLS water vapor field is similar and is shown in the Supplemental material (S01a) for reference. The MLS data is available at: http://mls.jpl.nasa.gov/index-eos-mls.php. SWOOSH data[43] (doi: 10.7289/V5TD9VBX) is used in Fig. S05 to get a sense of the longer time series evolution of water vapor, and is available from https://www.esrl.noaa.gov/csd/groups/csd8/swoosh/.

Water vapor is also calculated using the Schoeberl-Dessler trajectory model[44,45], with results averaged vertically using the MLS averaging kernel to make the model results comparable the MLS observations. This data will be made available by contacting the authors directly.

Computer code used for data analysis was written using Interactive Data Language (IDL), and involved spatial and vertical binning, temporal averaging, and regression analysis. The IDL code used for our analysis is available upon request.

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