Variability of Chemical Constituents in the Tropical Tropopause Layer and their Radiative Impacts

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Introduction

The tropical tropopause layer (TTL) is the region of the atmosphere where air above the level of zero radiative heating (LZRH) is transported upward from the troposphere to the stratosphere. The TTL is unique because of its transitory nature, and it contains both elements of the troposphere—such as deep convection and associated latent heat release—and the stratosphere—such as signatures of the Quasi-Biennial Oscillation (QBO) and Brewer Dobson Circulation (BDC), ozone increases with height, and significant influences of radiation on the circulation. These mixed characteristics are due to the presence of the cold point tropopause (CPT), the coldest height in the atmosphere below the mesosphere, and the location where the lapse rate changes sign from negative (temperature decreasing with height in the troposphere) to positive (temperature increasing with height in the stratosphere). The chemical composition of the TTL determines the radiation balance there, while the composition itself is controlled by temperatures and dynamics which are balanced with the radiation. The intricate coupling between composition, temperatures, circulation, and radiation implies feedbacks in the TTL system, which have not been studied in depth. The radiative budget of the TTL which was initially determined by Gettelman et al. (2004) has not been updated since the advent of the Aura Microwave Limb Sounder (MLS) that contains a robust set of TTL data, spatially and temporally. In addition to these considerations, "abrupt drops" in TTL water vapor, temperature, and ozone were observed after 2001 by Randel et al. (2006). While the zonal mean structure in these variables was analyzed in part, and the horizontal structure of temperatures was analyzed by Rosenlof and Reid (2008), the full structure in space and time of these "abrupt drops" in composition and temperature (including the role of radiation) was not explored due to data limitations. Recently, another TTL abrupt drop in water vapor was observed in 2011-2012 (Dessler et al. 2013), which provides an excellent opportunity to study it in depth with MLS. This study uses MLS and MERRA data along with Community Atmosphere Model's offline radiative driver to study the relationships between composition, circulation, and radiation in the TTL, particularly during the 2011-2012 abrupt drop. Radiation changes could impact the potential intensity of tropical cyclones by modifying outflow temperatures (Emanuel et al. 2013).

It has also been shown that the recent "slow down" in global warming could be partially explained by reductions in water vapor through radiation changes (Solomon et al. 2010). Future work will focus on expanding the investigation of these temperature and composition relationships, updating TTL radiation climatology, and determining the radiative impacts of abrupt drop events on tropical cyclones and the rate of global warming.

The tropical tropopause layer

Data and Model

- Aura Microwave Limb Sounder (**MLS**), version 3.3
  - Water vapor (H_2O), Ozone (O_3) and Temperature measurements
  - Values from 2004 through 2013.
  - Data extends from 316.2 hPa – 0.02 hPa, with 39 vertical levels
  - Gridded onto a 2.5° x 2.5° horizontal resolution
  - Known dry biases in water vapor measurements at lower altitudes (~200 hPa) and higher latitudes, but matches multi-instrument means well through most of the stratosphere and the tropics (Hegglin et al. 2013)
- Modern-Era Retrospective Analysis for Research and Applications (**MERRA**)
  - Reanalysis of Temperatures, H_2O, and O_3
  - Values from 1979 through 2013, see climatology in Figure 1
  - Data extends from 316.2 hPa – 0.02 hPa, with 39 vertical levels
  - 0.5° x 0.66° horizontal resolution, 72 vertical levels from the surface to 0.01 hPa

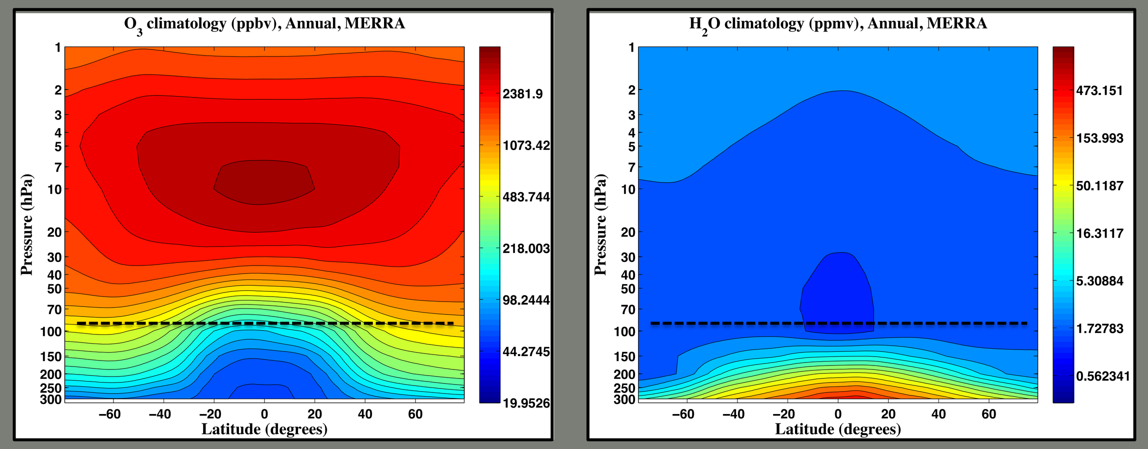

Figure 1: Zonal mean climatology of (left) Ozone and (right) Water Vapor from the full MERRA dataset. Values are averaged zonally from 300 hPa to 1 hPa, and 90S to 90N. The dotted line indicates the 82.5 hPa which is used most often in when studying the TTL and lowermost stratosphere.

- Parallel Offline Radiative Transfer (**PORT**) model as part of the Community Atmosphere Model (CAM) in the Community Earth System Model (CESM)
  - Detailed in Conley et al. (2013)
  - Uses a Fixed Dynamical Heating (FDH) assumption to compute diabatic heating rate changes and radiative forcing when the background CAM input is perturbed.
  - Run on coarse horizontal resolution for this study (10° x 15°)
  - Hybrid vertical coordinate that is approximately equal to pressure in the TTL
  - One-year simulations with 4 month spin-up time (16 months total)

TTL Variability

Vertical Velocity & Temperature

- Stratospheric wave drag drives a residual poleward circulation requiring TTL upwelling and polar downwelling to satisfy mass balance (the Brewer-Dobson Circulation, BDC).
- The BDC has a seasonal amplitude because of larger wave drag in northern hemisphere winters than summer hemisphere winters (Figure 2).
- The thermodynamic equation balancing anomalous temperature and vertical velocity in the TTL is, in the absence of the small horizontal advection term,

$$\frac{\partial T}{\partial t} = Q - wS \qquad (1)$$

where T is temperature, Q is the diabatic heating rate (dominated by radiation), w is upwelling, and S is the static stability.

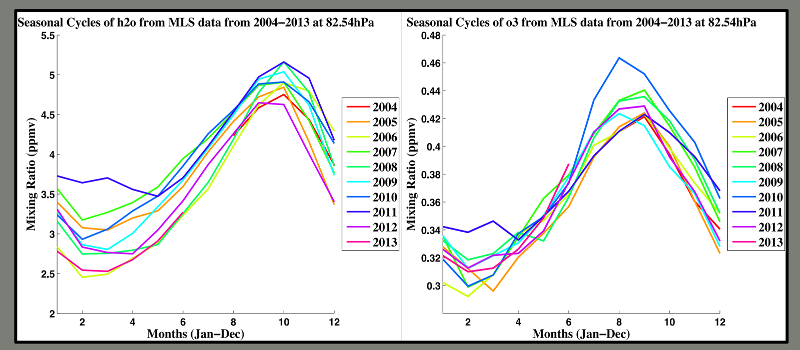

Figure 2: Seasonal cycles of MLS water vapor (left) and ozone (right) at 82.5 hPa from 2004 to mid-2013.

Water Vapor & Ozone

- Water vapor (H_2O) traversing the TTL is flash frozen out of air parcels as a function of the temperature due to Clausius-Clapeyron scaling near saturation, leading to small values of water vapor, due to cold temperatures in the TTL, that propagate upward seen in the iconic "tropical tape recorder" (Figure 3). Anomalous temperatures thus drive anomalous H_2O mixing ratios.
- Ozone (O_3) concentration anomalies in the TTL are primarily driven by anomalous vertical advection of ozone, as the vertical gradient of ozone in the TTL is positive and anomalous photochemical production of ozone is small.

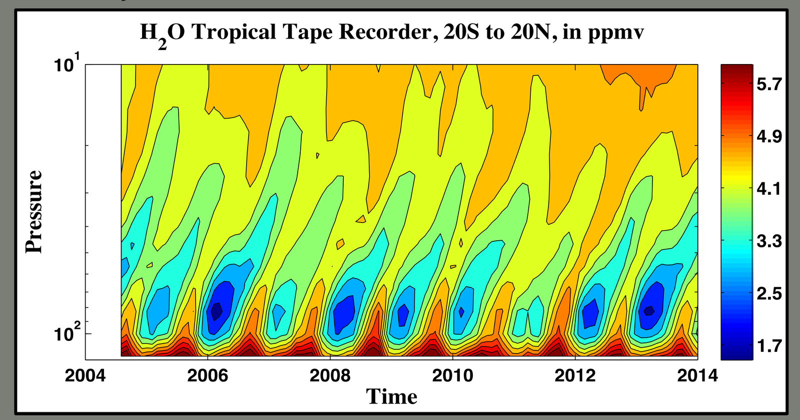

Figure 3: The tropical tape recorder. Zonal and meridionally averaged MLS water vapor from 20S to 20N and from 125 hPa to 1 hPa.

Ozone, Water Vapor, & Temperature during the 2011-2012 Abrupt Drop

Temporal Structure

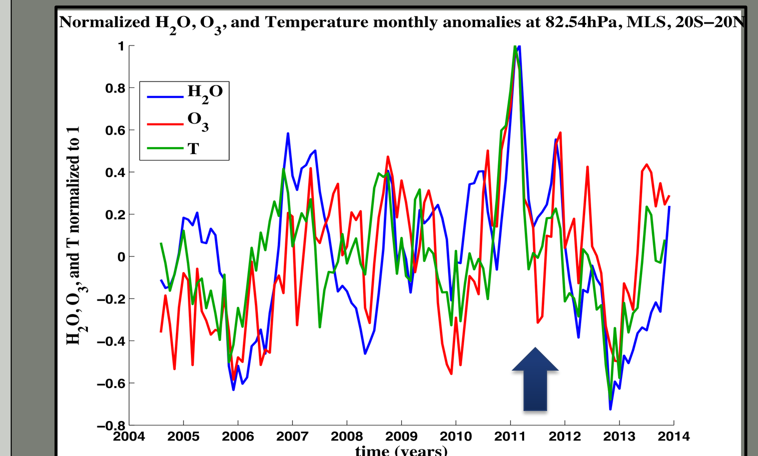

Figure 4: Normalized zonal mean time series of water vapor (H_2O), ozone (O_3), and temperature (T) from MLS data. Data is averaged meridionally from 20°S–20°N at 82.5 hPa. Arrow indicates the location of the abrupt drop event during 2011–2012.

The 2011-2012 abrupt drop event first noted by Dessler et al. (2013) allows an investigation into the timing and structure of these events with MLS (Figures 4-6).

- **Temperature, water vapor, and ozone appear to couple near the end of 2010 and become well correlated through 2013. They are likely related by anomalous upwelling.**
- **The influence of the Quasi-Biennial Oscillation is apparent in the time series with an approximately 26-month period.**
- **The 2011-2012 event is very similar to the 2001 abrupt drop event, with an initial large rise in variables followed by the abrupt drop.**

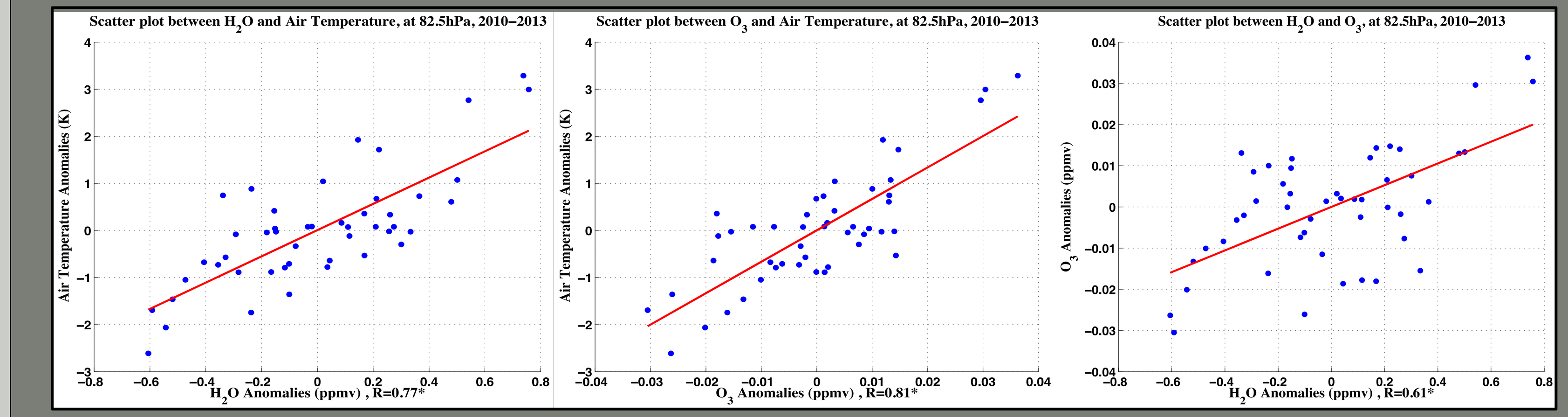

Figure 5: Scatter plots and linear fits between h2o/o3 (left), o3/T (middle), and h2o/T (right) at 82.5 hPa. Data is averaged meridionally from 20°S–20°N from MLS data during 2010–2013. The correlation coefficient, R, is shown in x-axis labels. All correlations are statistically significant.

- **Positive statistically significant correlations exist between temperatures, H_2O, and O_3 during the abrupt drop, suggesting that the same physically process could be responsible for the drop.**
- **Anomalously warm sea surface temperatures are also significantly correlated with drops in TTL air temperature, H_2O, and O_3 (not shown).**

Spatial Structure

- **Large reductions in water vapor and temperature are found over the Pacific Warm Pool region.**
- **Changes are larger and less noisy at the higher TTL level (82.5 hPa).**
- **Ozone results (not shown) show stronger decreases in the Warm Pool region at the 100 hPa level and a poleward (but still tropical) displacement of decreases at the 82.5 hPa level.**

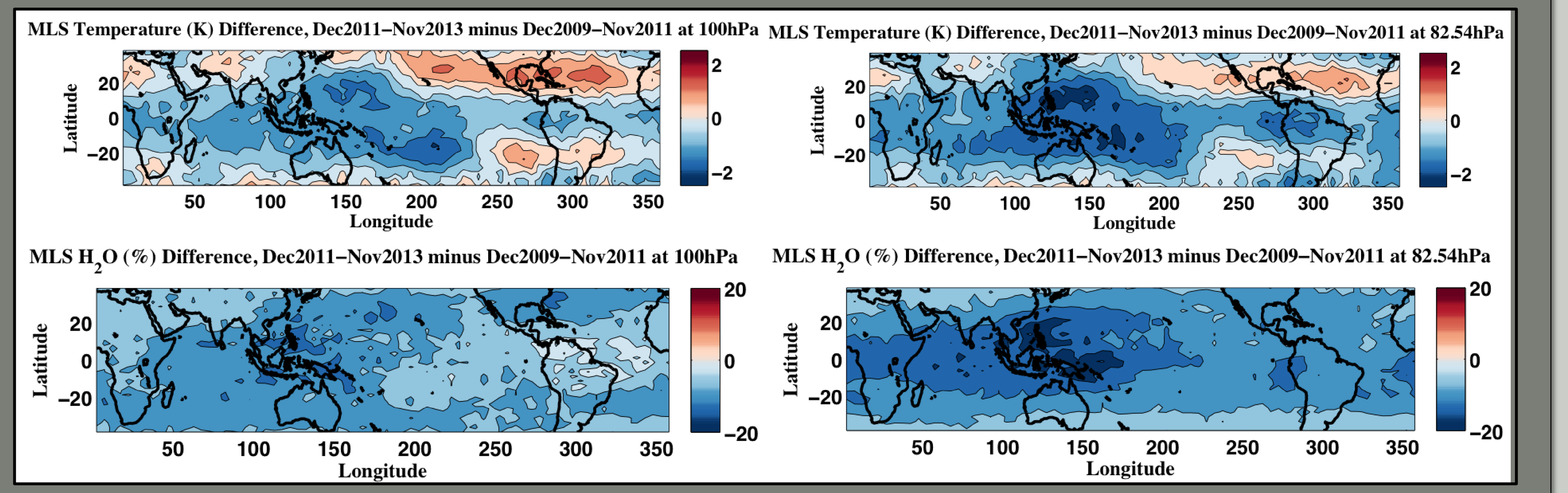

Figure 6: Spatial distribution of absolute temperature (top) and percentage water vapor (bottom) differences between the periods after the abrupt drop event (12/2011–11/2013) and before the abrupt drop event (12/2009–11/2011) using MLS observations. The TTL height structure of the differences is shown with the 100 hPa surface on the left and 82.5 hPa surface on the right. Contour levels are every 0.5K (temperature) and every 4% (water vapor).

Initial Radiation Calculations

Assuming a fixed-dynamical heating in the TTL (w is constant in Equation 1), Heating rates can be calculated by PORT using present day CAM input; the climatology is shown in Figure 7.

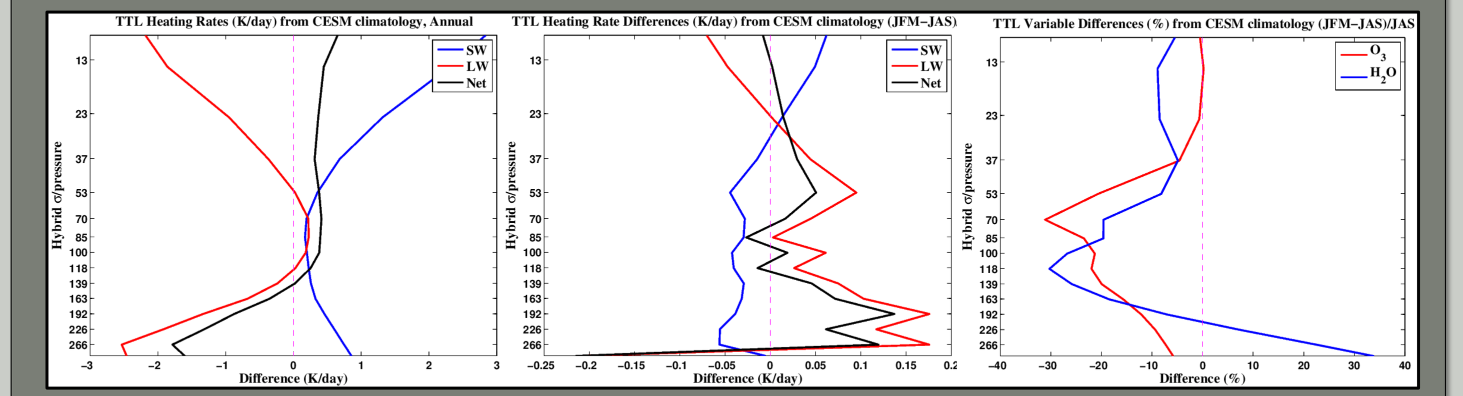

Figure 7: CAM TTL profiles of the radiative heating rate climatology (left) and differences (middle) between boreal winter (JFM) and summer (JAS). The percent changes in composition between JFM and JAS are also shown (right).

Radiative processes are nonlinear, therefore changing multiple constituents (as is done in the seasonal differences, Figure 7) complicates the changes in heating rates.

Applying the separate percent differences to ozone and water vapor in Figure 6 at a single TTL level (82.5 hPa), we determine the changes in heating rates in the TTL, stratosphere, and troposphere (Figure 8). Using a conservative Newtonian relaxation rate of 30 days, we estimate the heating rate impact on temperatures.

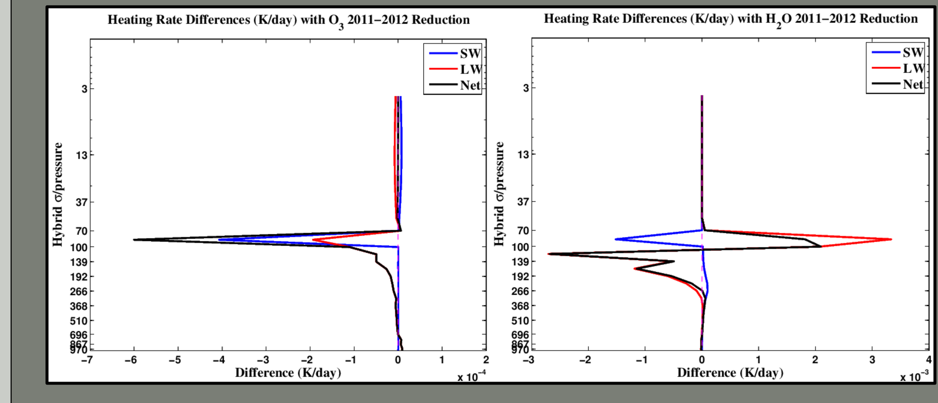

Figure 8: Atmospheric radiative heating rate changes under the climatological percent differences of ozone (left) and water vapor (right) during the 2011-2012 abrupt drop.

- **Reduction in ozone lead to a cooling in the TTL that extends into the upper troposphere. Temperature changes peak at ~ -0.018 K**
- **Water vapor reduction warms the lower stratosphere and cools the upper troposphere. Temperature changes in the TTL/troposphere peak at ~ +0.096 K/-0.081 K**

Summary & Future Plans

- **Temperatures, chemical composition, radiation, and circulation and intricately connected in the TTL.**
- **An abrupt drop similar to that of 2001 occurred in 2011-2012. Temperature, ozone, and water vapor in the TTL all fell dramatically during the abrupt drop and were significantly correlated. This suggests that there may be a specific consistent cause/event driving the abrupt drop.**
- **The horizontal structure of the 2011-2012 abrupt drop shows that the majority of the reductions in water vapor and temperature occurred over the region of the Pacific Warm Pool. This pattern agrees very well with the pattern of the 2001 TTL temperature drop shown by Rosenlof and Reid (2008), suggesting that the two events are similar in nature.**
- **PORT is able to simulate the observational climatology of the TTL radiation balance calculated by Gettelman et al. (2004).**
- **The 2011-2012 reduction in ozone leads to a cooling in the TTL that extends into the troposphere. There is a small associated warming at the surface.**
- **The 2011-2012 reduction in water vapor leads to a warming in the TTL/upper stratosphere and a cooling in the upper troposphere.**

In the future we will use Fast-Fourier Transforms and lag-lead relationships to determine the temporal structure of the abrupt drop events more fully. Spatial regression will be used to determine the three-dimensional structure relationship. Abrupt drop events in MERRA (several of which have been indentified) will similarly be analyzed. The structure of changes in TTL radiative balance due to these events (including feedbacks) will be determined more extensively. Relationships between these changes and tropical cyclone outflow temperatures and the rate of global warming will be explored.

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