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Lapse Rate or Cold Point: The Tropical Tropopause Identified by In Situ Trace Gas Measurements

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Key Points:
- The tropical tropopause definitions are examined using airborne in situ measurements over the tropical western Pacific
- O_3 and H_2O relationship is used to identify the air mass change from the troposphere to the stratosphere
- The lapse rate definition is shown to more consistently identify the tropopause based on the tracer diagnostic

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Abstract Although the tropopause is a well-established concept, its definition and physical properties remain an active research topic. In the tropics, both the World Meteorological Organization established lapse rate tropopause definition and the minimum in the temperature profile (the cold point) are used to determine the tropopause height. We examine the differences produced by these two definitions using high-resolution airborne in situ measurements of temperature, water vapor, and ozone in the tropical tropopause layer from a recent experiment over the western Pacific using the National Aeronautics and Space Administration (NASA) Global Hawk unmanned aircraft system. When the two definitions do not produce the same tropopause height, which is in about half of the cases, the combined temperature and trace gas analysis shows that the lapse rate definition better identifies the transition from the troposphere to the stratosphere.

Plain Language Summary Discovered more than a century ago, the tropopause is known to mark the boundary of two dynamically and chemically distinct layers of atmosphere, the stratosphere, and the troposphere. In the tropics, the location, temperature, and physical/chemical gradients of the tropopause are important as part of the fundamental knowledge of the atmosphere and for regulating the amount of water vapor entering the stratosphere, which has a significant contribution to climate forcing. The tropopause over the tropical western Pacific, in particular, is known as the *decisive region* for determining the amount of stratospheric water vapor. High-resolution measurements for this region are rare because the region is remote and tropopause altitudes are difficult to access. An airborne experiment targeting this decisive region was conducted in 2014, using the National Aeronautics and Space Administration (NASA) Global Hawk unmanned aircraft system. These high-resolution temperature and trace gas data provided an unprecedented opportunity to examine the physical meaning of the two tropical tropopause definitions, known as the lapse-rate tropopause and the cold-point tropopause. In this work, we demonstrate how the relationship of two chemical tracers, ozone and water vapor, can unambiguously identify the transition from troposphere to stratosphere and therefore serve to diagnose the effectiveness of the different tropopause definitions.

1. Introduction

The tropopause is part of the fundamental structure of the atmosphere, separating the dynamically and chemically distinct troposphere and stratosphere. Although the tropopause is a century-old concept, its definitions are still frequently a topic of debate. Multiple tropopause definitions exist, and they often yield different tropopause heights. In the tropics, the World Meteorological Organization lapse rate tropopause (LRT; World Meteorological Organization, 1957) and the level of temperature minimum, that is, the cold point tropopause (CPT), are the most commonly used definitions (Highwood & Hoskins, 1998; Seidel et al., 2001). With the increasing interest in the mechanisms controlling stratospheric water vapor, it is becoming a prevalent view that the CPT is a more meaningful definition. The LRT is often considered not important (e.g., Highwood & Hoskins, 1998; Kim & Son, 2012; Randel et al., 2003). Additionally, it is not well understood how the temperature structure in the tropical upper troposphere is maintained, especially the separation of the cold point in the temperature profile from the top of convection and the fact that the lapse rate continues to be tropospheric above the convection (e.g., Folkins et al., 1999). The mixed influence from tropospheric and stratospheric processes in this layer is one of the key motivations for the concept of the tropical tropopause layer (TTL; Folkins, 2002; Fueglistaler et al., 2009; Gettelman & Forster, 2002, and references therein). Although the temperature structure of this layer is broadly described by the balance of radiative and convective equilibrium (Thuburn & Craig, 2002; Gettelman & Forster, 2002), a large number of processes, including dynamical, microphysical, and transport, contribute to the structure (e.g., Birner & Charlesworth, 2017; Kim & Alexander, 2015; Randel & Jensen, 2013, and references therein), which makes it challenging for global models to correctly reproduce (Gettelman et al., 2009; Randel & Jensen, 2013).

In this letter, we present the result of a tropical tropopause temperature structure analysis, connecting the two tropopause definitions to the transport characteristics revealed by chemical tracers. This analysis is afforded by recent high-resolution airborne observations of temperature (T), ozone (O_3), and water vapor (H_2O) during the Airborne Tropical Tropopause Experiment (ATTREX; Jensen, Pfister, et al., 2017). With this analysis, we aim to bring new insights into questions of whether the tropical tropopause is a meaningful air mass boundary, what the roles of the LRT or CPT are in representing this boundary, and the relationship between the boundary and the transition layer, that is, the TTL. The basic approach is to analyze high vertical resolution measurements of atmospheric composition across the LRT and CPT to identify the air mass discontinuity, which occurs at the air mass boundary if such boundary exists.

Prior to this work, a global climatology of the CPT and LRT relationship in the tropics was presented in Munchak and Pan (2014), using the global GPS temperature data. The results from that work show that the seasonally averaged altitude separation between the two levels is not zonally symmetric, and the spatial pattern of the separation shows a strong seasonal variation. These patterns and their seasonal variation clearly indicate that the CPT and LRT are not produced and maintained by the same mechanism. The results of their analysis also show that the region of large CPT-LRT separation on the seasonal scale is associated with the extratropical dynamics-driven upper troposphere, where the Rossby wave activity and quasi-horizontal flow create the separation. These large separation regions are not restricted to the vicinity of the subtropical jet, and they can extend into the deep tropics in the region of climatological westerly ducts (Waugh & Polvani, 2000; Webster & Holton, 1982). This result challenges the view that the CPT is generally a more relevant tropopause definition in the tropics and suggests that the CPT is only relevant to defining the tropopause and limiting the water vapor transport in the region of upwelling dominated UT. The tropical western Pacific (TWP) is the largest such region.

The TWP in the northern winter season has long been recognized as the most important upwelling region for troposphere-to-stratosphere transport (e.g., Bergman et al., 2012; Fueglistaler et al., 2004). It is also the region with the coldest tropopause, which leads to its dominant role in dehydrating the stratosphere. A number of trajectory-based analyses show that this region has the highest concentration of the *Lagrangian Cold Point* (LCP); that is, the coldest point air masses encounter on their way to entering the stratosphere through upwelling in the tropics (Fueglistaler et al., 2004; Krüger et al., 2008; Rex et al., 2014; Schoeberl & Dessler, 2011). The high vertical resolution, large spatial coverage and extensive profiling observations in the tropical tropopause region from the ATTREX provide the first opportunity to examine the questions of what defines the tropical tropopause and the respective roles of LRT and CPT in this convection-dominated tropical upwelling region.

2. The Experiment and Data

The ATTREX experiment was conducted using the National Aeronautics and Space Administration (NASA) Global Hawk unmanned aircraft system (UAS). The long range (16,000 km) and high-altitude (~19 km) capability of the UAS allowed an unprecedented horizontal coverage of the TTL over the TWP. The TWP phase of the experiment was conducted during January–March 2014 with flight operations from Guam (13.5°N, 144.8°E). The Global Hawk conducted six research flights with focused sampling of the TTL (14–19 km). The mission concept, flights, and payloads are described in the overview by Jensen, Pfister, et al. (2017). Figure 1 shows the flight tracks for the six research flights. The continuous vertical profiling between ~14.5- and 18.5-km altitude range during the flights is indicated by the variation in line thickness. Also shown are the locations of National Weather Service (NWS) stations where routine radiosondes are launched twice daily.

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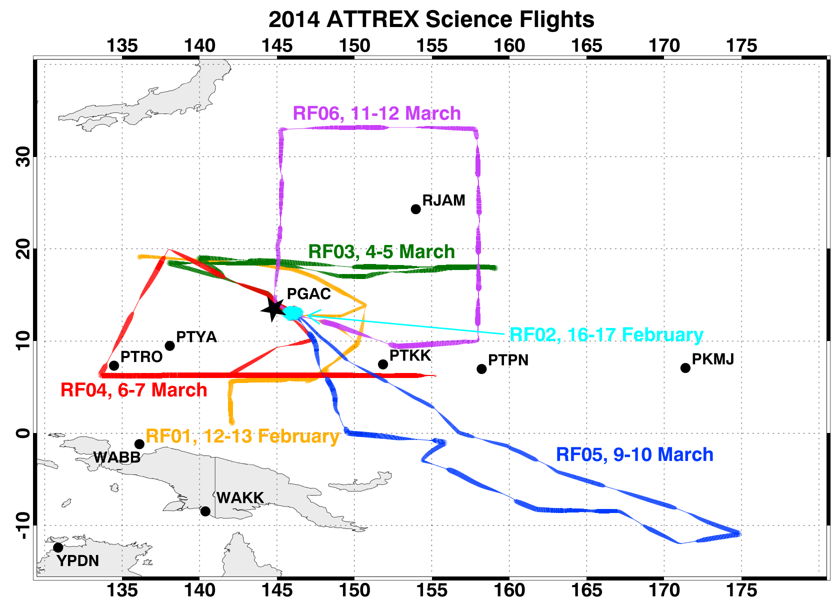

Figure 1. Flight tracks of the six Guam-based Global Hawk research flights during the 2014 deployment of Airborne Tropical Tropopause Experiment (ATTREX). The thickness of the lines is inversely scaled by the pressure level of the flight, highlighting the continued vertical profiling between approximately 14.5 and 18.5 km as the key feature of the flight pattern. Locations of the region's National Weather Service stations are shown by black dots with station ID.

The data used in this analysis are temperature, pressure, and altitudes measured by the Meteorological Measurement System (MMS; Scott et al., 1990); H_2O and ice water content measured by the NOAA-H2O instrument, a two-channel, internal-path tunable diode laser hygrometer (Thornberry et al., 2015); and O_3 from the NOAA Unmanned Aircraft Systems Chromatograph for Atmospheric Trace Species (UCATS) ozone instrument (partially described in Newton et al., 2018). Most data are reported at a 1-s rate with the exception of UCATS ozone data, which are reported at a slower rate (5–10 s). Further discussions of these data can be found in related works on the TTL humidity and cirrus clouds (Jensen, Thornberry, et al., 2017; Thornberry et al., 2017).

Since the flight ceiling during the first half of each flight was often too low to reach the tropical tropopause (~16–17 km) or allow a clear identification of the coldest point, we have used the nearest NWS radiosondes and satellite GPS temperature profile data to help verify the identifications by the in situ measurements. We have also used meteorological analysis data from NWS Global Forecast System model's final run (GFS/FNL), which provide the temperature and horizontal wind at the tropopause level.

3. The LRT and CPT in the Tracer-Tracer Space

In the upper troposphere and lower stratosphere (UTLS), H_2O and O_3 exhibit a demonstrated *L*-shaped relationship in the tracer-tracer space (Hegglin et al., 2009; Pan et al., 2007; Pan et al., 2014). Specifically, the compact relationship in the O_3-H_2O space shows the tropospheric data as a branch with a large range of water vapor variation and a relatively narrow range of ozone variation, while the lower stratospheric data appear as a branch of large ozone variation and a relatively narrow range of water vapor. The change between the two branches marks the transition in dynamics and chemistry, that is, from the vertical mixing dominated troposphere where water vapor is abundant to the horizontal mixing dominated stratosphere where ozone has its major source. This relationship has been used to diagnose the upper and lower boundaries of the TTL. The results indicate that the TTL has the level of minimum stability (LMS) and CPT as its lower and upper boundaries, respectively (Pan et al., 2014). In this study, we use the O_3-H_2O diagnostic to identify the location of the tropopause, that is, the critical level that best identifies the change from the tropospheric branch to the stratospheric branch in the tracer-tracer space.

Figure 2 provides an example vertical profile from the flight on 6 March 2014 where the CPT and LRT are both clearly identifiable in the temperature profile and show a large separation (>1 km). The L-shaped O_3-H_2O

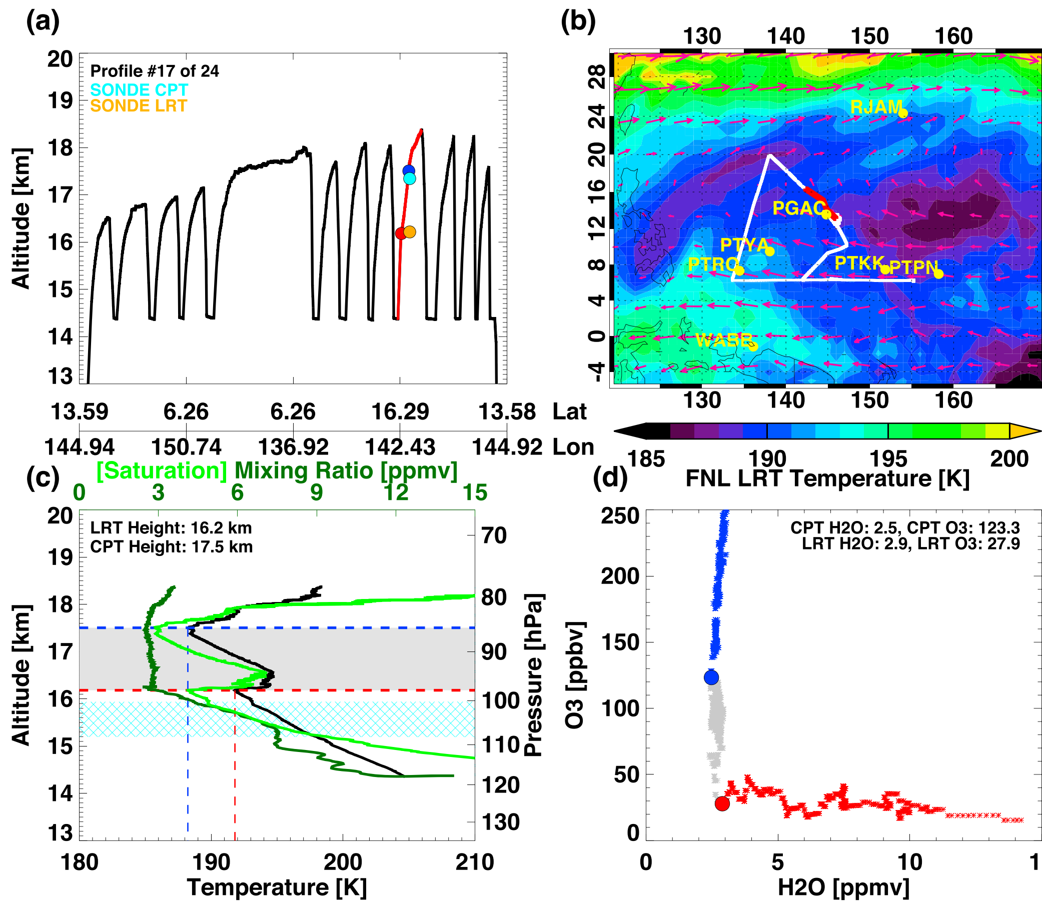

Figure 2. An example profile showing a large lapse rate tropopause-cold point tropopause (LRT-CPT) separation (profile #17 of RF04). (a) Time series of flight altitude (labeled by latitude/longitude). The selected profile is shown in red. The LRT and CPT identified in the profile are marked by red and blue dots, respectively. The light blue and orange dots mark the CPT and LRT levels, respectively, from the nearest NWS radiosonde profile. (b) The flight track (white) in plan view with temperature background from the Global Forecast System model's final run (GFS/FNL) analysis. The location of the selected profile is shown in red. Also included are the wind field (pink arrows) and the NWS stations in the region. (c) Profiles of temperature (black), in situ water vapor (dark green), and derived saturation vapor mixing ratios (light green). The dashed lines mark the levels of LRT (red) and CPT (blue) from the in situ temperature. The presence of cloud is indicated based on the ice water content (light blue shading). (d) LRT and CPT in the O_3-H_2O tracer-tracer space, using the same colors as in (c).

relationship clearly indicates that the LRT marks a sharp change from the troposphere to the stratosphere. The H_2O mixing ratio at the cold point in this case is a fraction of a ppmv (~0.4 ppmv) lower than that sampled at the LRT. This difference is much smaller than that between the saturation vapor mixing ratios derived from the temperature at the two critical levels (see the light green curve in Figure 2c). The smaller difference is largely contributed by the significant subsaturation at the LRT, indicating that the measurement is downwind from a colder region. Further discussion on this point will be presented in section 4. There is a noticeable increase in H_2O above the CPT, indicating the influence of warmer LCP in the air mass history.

Note that this example is representative in that the observed LRT most often is a local temperature minimum. It is therefore important to qualify that we use the term *coldpoint* or CPT to refer to the *coldest* point in the profile. Very often this determination needs to be supported by the nearby radiosonde or the GPS profiles. In this example, the CPT identified by the nearest radiosonde profile is marked in the figure (Figure 2a, the light blue dot), which supports the CPT identified by the airborne measurements. Also note that the identification of the LRT is made with criteria modified from the World Meteorological Organization (1957) definition because of the relatively low flight ceiling during the first part of each flight. Specifically, a level at which the lapse rate becomes less than 2 K/km and the average lapse rate is less than 2 K/km for

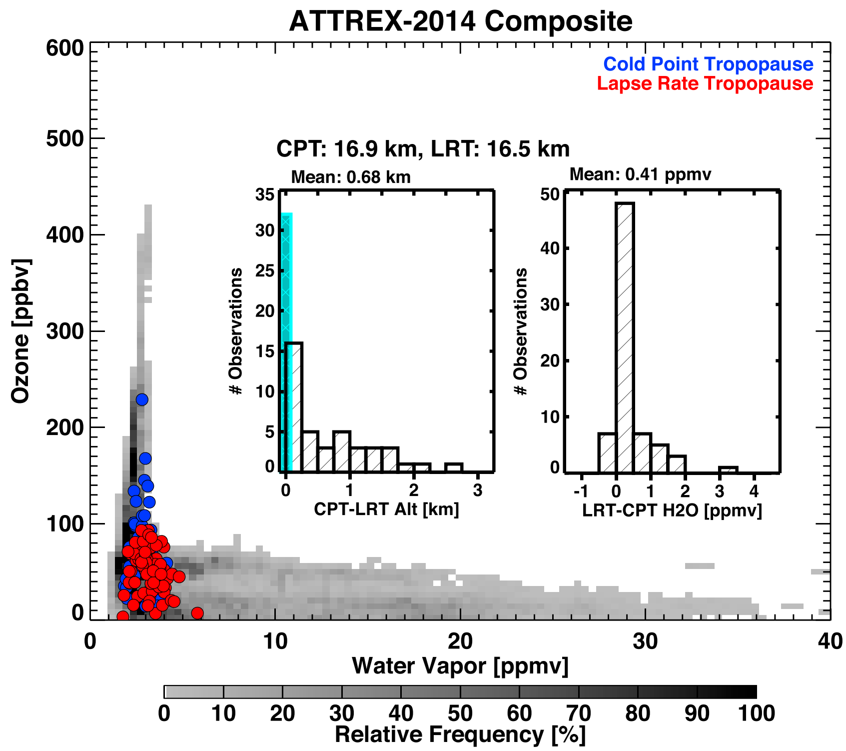

Figure 3. Relative frequency distributions for all samples during profiling in the latitude-longitude range (20°S–20°N, 120°E–180°E) and the positions of CPTs and LRTs in O_3-H_2O tracer-tracer space. Only the CPTs that are distinct from LRT are marked. The relative frequency is calculated in 6 ppbv versus 0.4 ppmv O_3 and H_2O bins, normalized by the highest sample number. The two inserts show histograms of the CPT-LRT separation in altitude and difference in their respective H_2O mixing ratios. The light blue shaded column indicates the number of co-located LRT and CPT.

0.5 km above this level is used, instead of the 2 km requirement in the original World Meteorological Organization definition.

Using all the TWP profiles, we have examined this behavior statistically, and the results are shown in Figure 3. The tracer-tracer space diagram is shown as the binned relative frequency of samples in 0.4 ppmv (H_2O) and 6.0 ppbv (O_3) bins. All profiles within 20°S to 20°N latitude range and 130°E to 180°E longitude range are used. Among the total of 152 profiles, a LRT is identified in 93 profiles, of which 73 also reached the CPT. Among these 73 profiles, 32 have co-located LRT and CPT, that is, the LRT is also the coldest point of the profile.

In the O_3-H_2O space, the locations of LRTs and CPTs have a large overlap and both cluster around the corner of the L. However, a significant number of CPTs is located away from the corner of L, spreading upward along the stratospheric branch, similar to the selected example (Figure 2d).

Also given in Figure 3 are the distributions of CPT-LRT altitude separation and water vapor difference. Although on average the separation of the LRT and CPT is small (0.68 km), the distribution shows values up to more than 2 km. This distribution is characteristically the same as the result from the GPS data analysis for the region (Figure 9, Munchak & Pan, 2014). The role of convectively generated tropical wave activity in producing these observed structures is discussed in Kim et al. (2016). The water vapor differences between these two critical levels show that in many cases the air is further dehydrated above the LRT, resulting in a 0.41 ppmv mean difference between CPT and LRT H_2O.

Although Figures 2 and 3 both point to the conclusion that the LRT provides a better identification of the tropopause, we present an additional analysis in Figure 4 to show which critical level delineates the discontinuity in the air masses. In this figure, distributions of H_2O, O_3 (chemical tracers) and potential temperature (a dynamical tracer) in layers relative to the two critical levels are compared. The result shows that the air

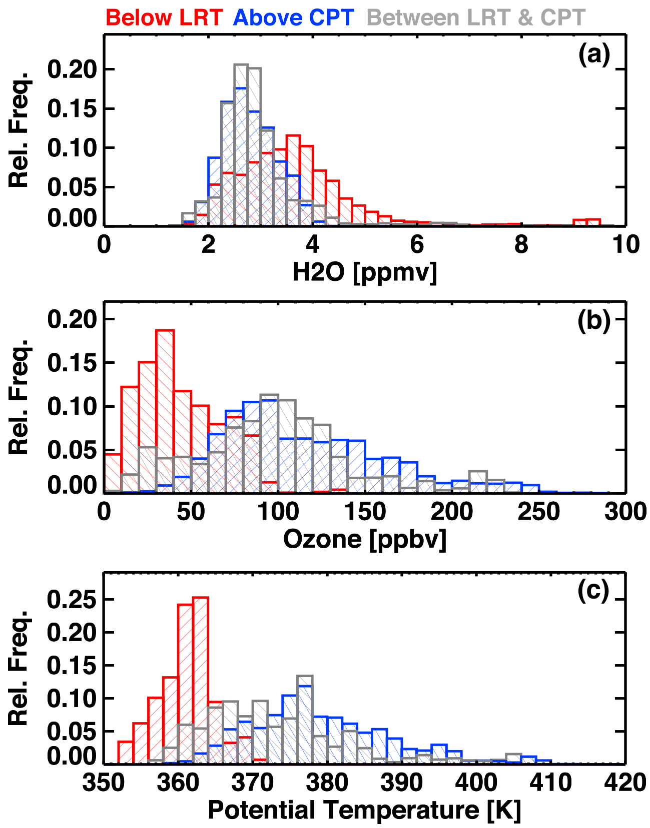

Figure 4. (a) H_2O, (b) O_3, and (c) potential temperature distributions for three layers relative to the LRT and CPT: 1-km layer below the LRT (red), 0.5-km layer above the CPT (blue), and the samples between the LRT and CPT (gray).

masses in the 1-km layers below the LRT and 0.5-km layer above the CPT, respectively, show distinct distributions in all three tracers, providing the characteristics of the upper troposphere in the layer below the LRT, and characteristics of the lower stratosphere in the layer above the CPT. In the layer between LRT and CPT, the distributions of all three tracers more closely resemble the stratospheric characteristics. This result further supports the conclusion that the LRT definition is more accurate in identifying the boundary between the stratosphere and troposphere. The distributions in the layer between the LRT and CPT, however, show some overlaps between the two layers above and below (especially the O_3 and the potential temperature distributions), which indicates that this layer is to some extent transitional between the layers above and below. This is consistent with prior analyses that identify the CPT as the upper boundary of the TTL (Gettelman & Forster, 2002; Pan et al., 2014).

4. Conclusions

Using the high resolution in situ trace gas measurements from ATTREX, we have examined two critical levels in the temperature profiles in association with the tracer distributions. The result can be summarized into the following three conclusions. First, the discontinuity in the tracer-tracer relationship and the tracers' vertical distributions both indicate that the LRT is a better identifier of the tropical tropopause over the TWP than the minimum temperature, in spite of this being a region of strong UT upwelling. Second, approximately half of the CPT and LRT are co-located in this region, and the distribution of the separation is similar to the statistical result of GPS data analyses (Figure 9, Munchak & Pan, 2014). In the cases the LRT is lower than the CPT, the air is drier on average at the CPT level. The CPT therefore remains an important determinant for water vapor transport to the stratosphere. Third, based on the significant air mass discontinuity across the LRT, the tropical tropopause appears to be a significant and meaningful air mass boundary. Conceptually, this can be understood as that the change in the lapse rate, therefore the static stability, at this level has dictated the change in transport characteristics locally, although controlling mechanisms for the lapse rate change are nonlocal, involving both stratospheric and tropospheric driven processes. In other words, this level appears to be an air mass boundary not due to any barrier effect locally, but it reflects the diminishing role of *bottom-up* convective driven transport and mixing.

The LRT and CPT are revealed by the tracer-tracer relationship to have different roles. While the air is statistically drier at the CPT level, the LRT marks the top of vertically mixed troposphere. This last point suggests that statistically the layer between the LRT and CPT is dominated by horizontal transport and mixing. This point is clearly supported by the selected profile shown in Figure 2. In this example, the H_2O profile, compared to the temperature and the saturation vapor mixing ratio profiles, does not support the local upwelling driven dehydration. On the other hand, Figure 2b shows that this profile is sampled in the region down-wind from a much colder region at the tropopause level. Both the undersaturation at the LRT level and the much colder CPT without co-located cirrus cloud layer support that the layer is dominated by horizontal transport from a colder region where the air mass encountered a colder LCP. This scenario is a major hypothesis behind the TTL concept (Hartmann et al., 2001; Holton & Gettelman, 2001) and the result of our analysis on this topic using the ATTREX data will be presented separately.

An important take home message from this work is that although the separation of LRT and CPT is small on average in this deep tropical region, the different roles of these two levels revealed by tracers shed new light on the different processes contributing to this temperature structure. This analysis also illustrates a point that the existence of multiple tropopause definitions does not imply the tropopause is a subjective level. If we look into the observations carefully, the differences the definitions produce often provide additional insights into the physical and chemical processes controlling this fundamental atmospheric structure.

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