Characterization of Free Tropospheric Layers and Double Tropopauses with Spire Radio Occultation (RO) Data and PAZ Polarimetric-RO Data

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Background/Motivation

- The lowest 1-2 km is the Planetary Boundary Layer has been well characterized by Radio Occultation (RO) (e.g. von Engeln et al., 2005; Kalmus et al. 2022) and PBL top height variability versus low-level clouds from RO and MODIS/MISR [Kubar et al. 2020; Kubar et al. 2024 (under review)]
- In the free troposphere where convective activity dominates, the convective layer ends at the height that caps the top of convective clouds and, especially in the tropics, water vapor mixing ratios become low enough such that CO, CO_2 and O_3 dominate radiative heating
- This intermediate layer, called the Tropical Tropopause Layer (TTL), often is marked by detraining clouds near its base to the tropopause at the top – in the tropics this is usually the Cold Point Tropopause (CPT). However, when heating by O_3 is largely absent in the stratosphere in the winter high latitudes, the CPT may be discerned at 20-30 km above the surface.
- Polarimetric-RO (PRO) data, from the PAZ satellite launched in 2018, provide concurrent information about hydrometeor profiles and thermodynamics, shedding new insights about the vertical structure of clouds and stability

Data

- Spire-RO (UCAR) for global statistics of troposphere and tropopause metrics and TTL metrics
- Conventional RO from PAZ and Grace-D and Radiosonde (RS) data for several California case studies in 2023 *(PAZ is a Spanish satellite launched in 2018),* as well as Commerical Smallsat Data Acquisition (CSDA) Spire-RO data
- Polarimetric PAZ ROHP Data for Cloud Top Height (CTOP) and LRMAX Relationships (2018-2021; **>151,000 Profiles) (ROHP: Radio Occultations through Heavy Precipitation)**
- For the sensitivity analysis in an attempt to both assess and possibly refine the threshold above which we consider Δϕ to represent a cloud **(for which we nominally assume the uppermost bin for which Δϕ>1mm)**, we also utilize IMERG/GPM precipitation and brightness temperature (T_b) data in order to make appropriate comparisons with PAZ-PRO CTOP for clouds which both datasets suggest contain precipitation.

Objectives of This Study

1. **Use both RO and PRO to capture the relationship between tropospheric layers above the PBL to the CPT representing layers of vertical mixing/convection**
2. **Calculate the modified CPT, the height corresponding to the min of ∂LR/∂z, and demonstrate that it corresponds with the CPT in the tropics and generally the WMO lapse rate tropopause from the subtropics to high-latitudes.**
3. **Introduce a mid-latitude/subtropical case study showcasing a double tropopause case and an analysis of the origins of both the upper (tropical) and lower (mid-latitude) tropopauses**
4. **Calculate Statistics of the TTL Layers Based on Lapse Rate (LR) minima/maxima and characterize their importance to cloud top height (CTOP) from Polarimetric-RO (PRO) data from PAZ, using the phase difference between the horizontal and vertical components (Δϕ)**
5. **Assess the sensitivity of different thresholds for CTOP in the tropics and the relationships with LRMAX, exploring how changes in the threshold affect the correlation and slope between CTOP and LRMAX.**
6. **Compare histograms of CTOP-LRMAX offset versus $[\Delta\phi]_{max}$, in which [Δϕ] and finds a useful parameter in predicting the probability of heavy precipitation**

Visual Manifestation of the TTL

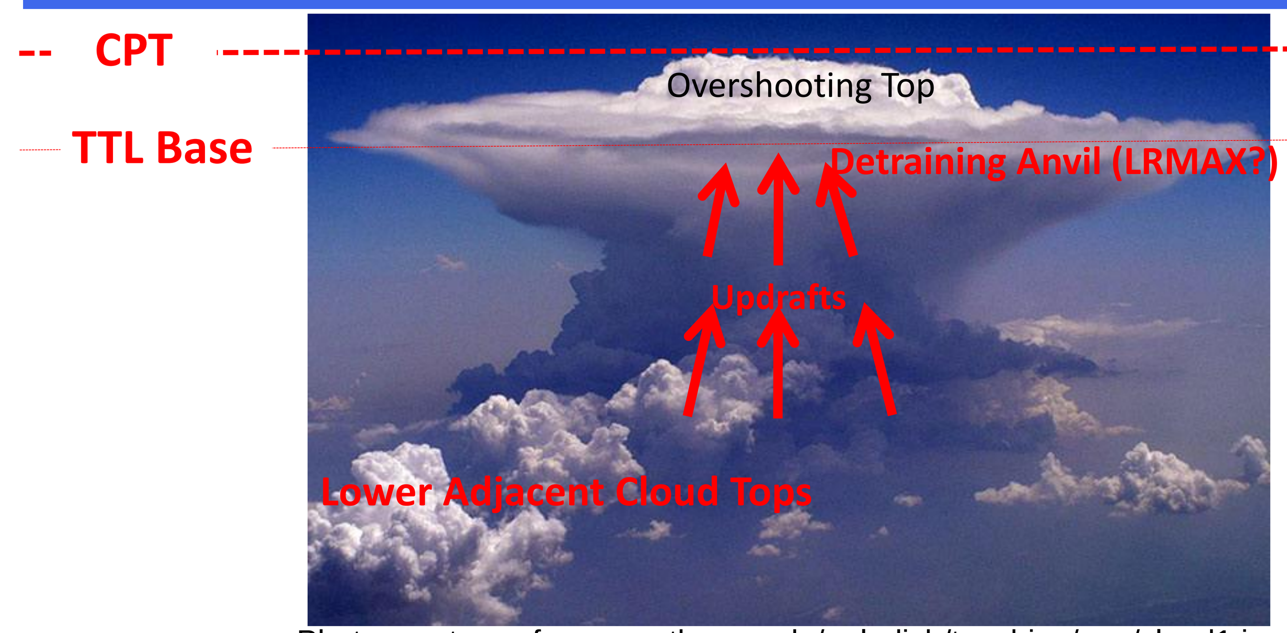
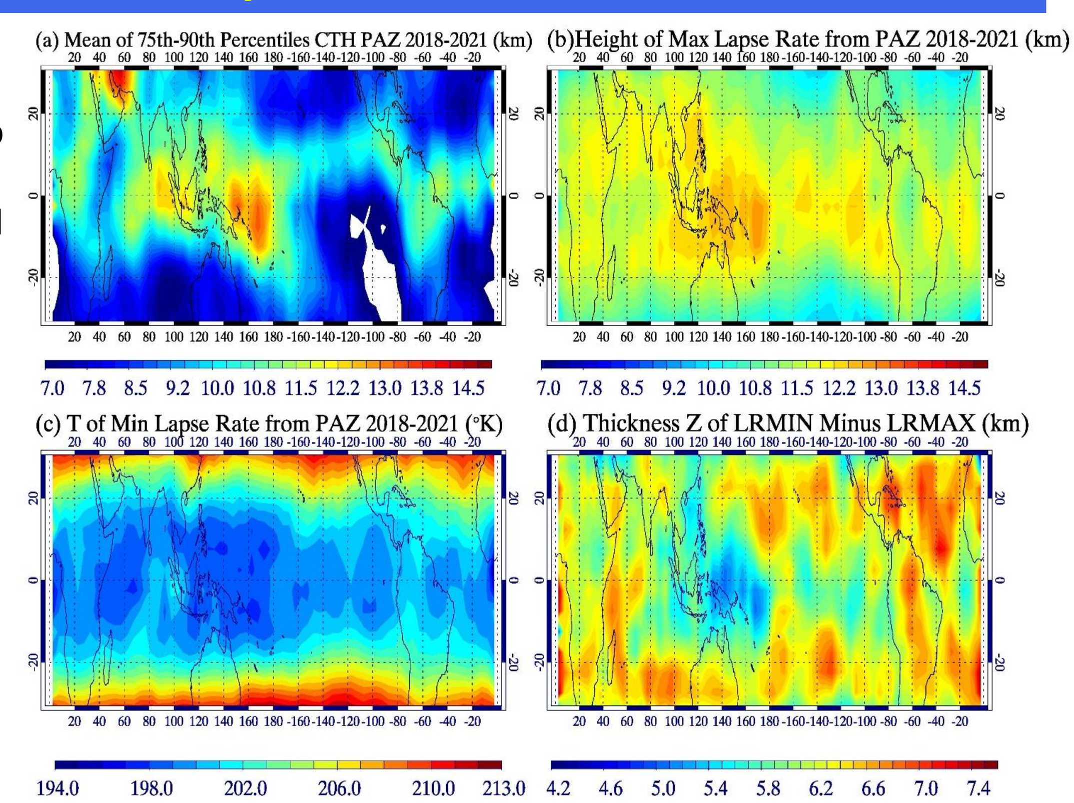


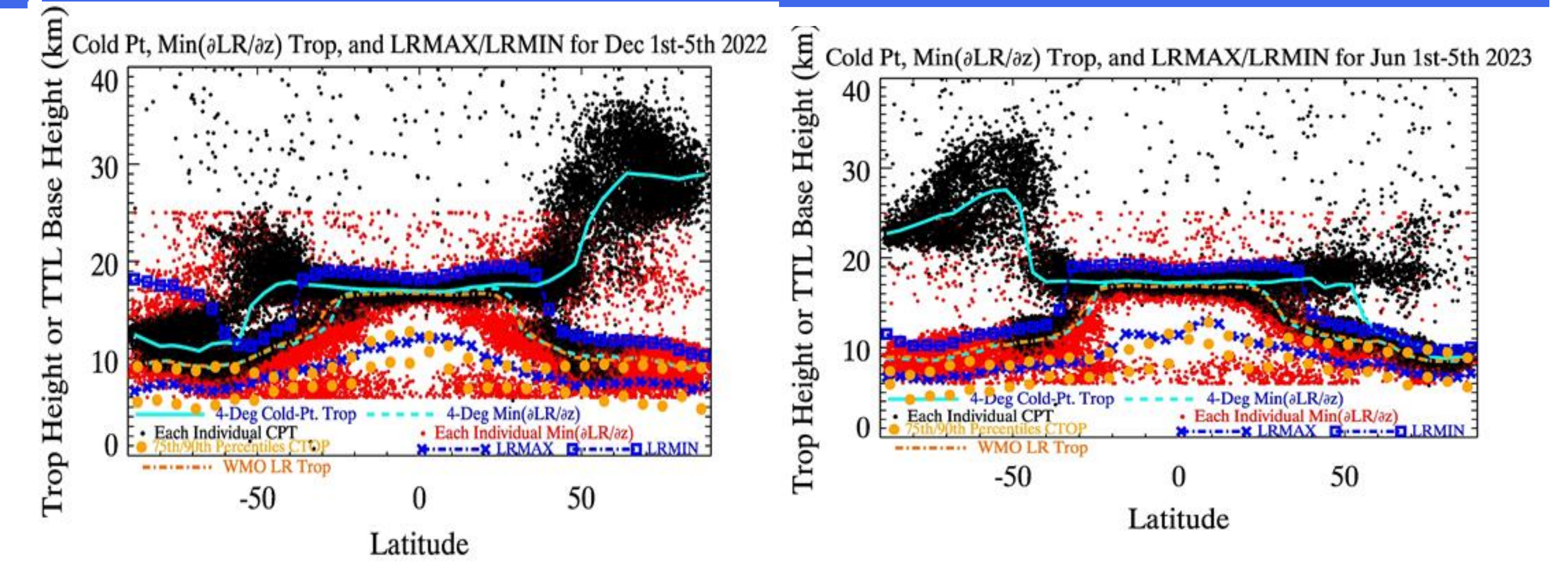
Photo courtesy of www.math.nyu.edu/~gladish/teaching/eao/cloud1.jpg

Tropical Tropopause Layer (TTL) Thickness as an Inverse Proxy for Deep Convection



- Mean of 75th-90th Percentiles of Cloud Top Height (CTH) estimates (top left) ranked in each 5°x5° box; the tropical warm pool is well-mapped and relatively well spatially correlated with LRMAX (top right)
- The temperature of LRMIN is coldest in the tropics, with the western Pacific the coldest
- [LRMIN – LRMAX] is inversely related to the depth of deep convection (e.g. min over Western Pacific Warm Pool) [right]

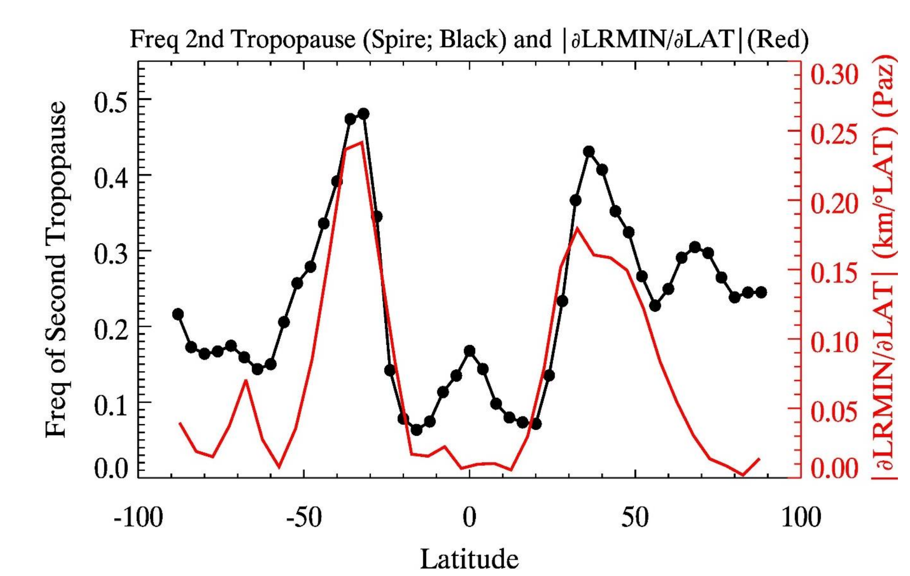
Global Tropopause, TTL, and Cloud Top Height Statistics



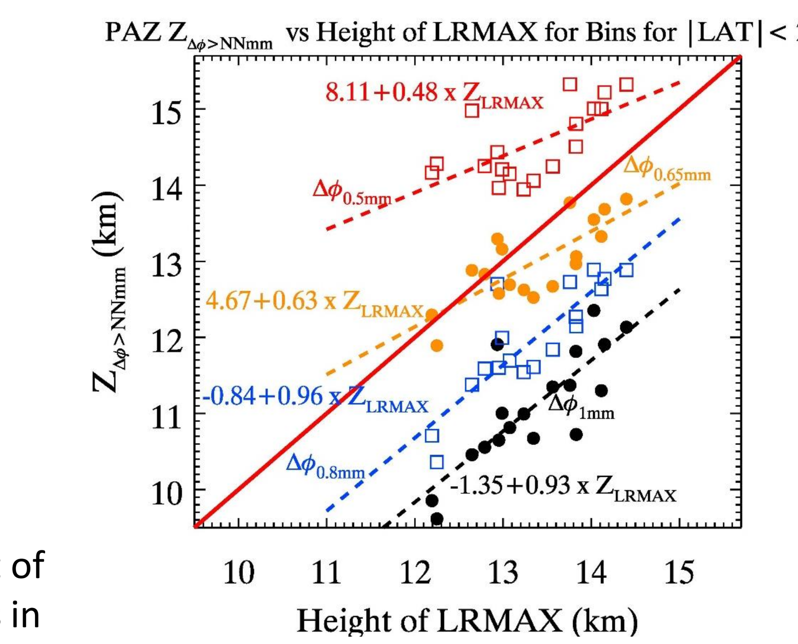
Left: Small black dots represent the coldest level of the atmosphere, and small red dots the height of $(\partial LR/\partial z)_{min}$, more related to the WMO LR tropopause (UCAR Spire Dec 2022). 75th/90th percentiles in 6-deg latitude bins from PAZ of CTOP from 2018-2020 December. **Right: Same except June 2023 Spire and 2018-2021 June for PAZ. Upper percentiles of cloud tops (orange dots) tend to overlap with LRMAX (x-symbols).**

Frequency of Two Tropopauses (UCAR Spire: Black) and |∂LRMIN/∂LAT| (Spire: Red)

The peak subtropical frequency of double tropopauses from |30°-35°| coincides with the location of the strongest horizontal gradient of the Tropopause Inversion Layer, or |∂LRMIN/∂LAT|. A secondary maximum of double tropopauses may exist over the northern high latitudes in which very high polar night tropopauses or much lower tropopauses are quite likely concurrently

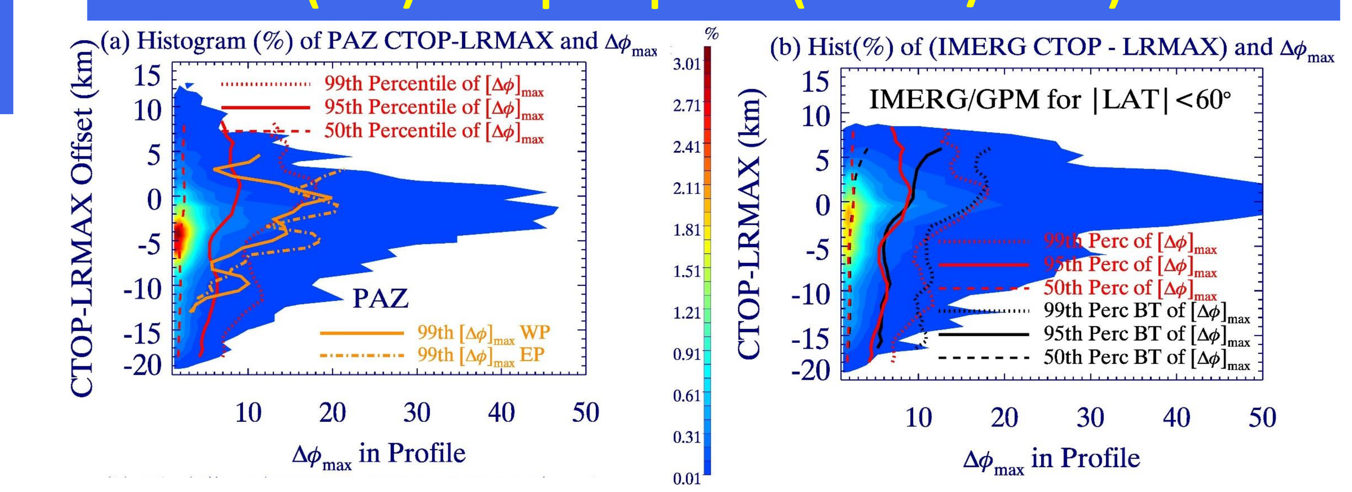


Tropical Raining [$\Delta\phi_{max}$>10mm] Cloud Top Height vs LRMAX Relationships



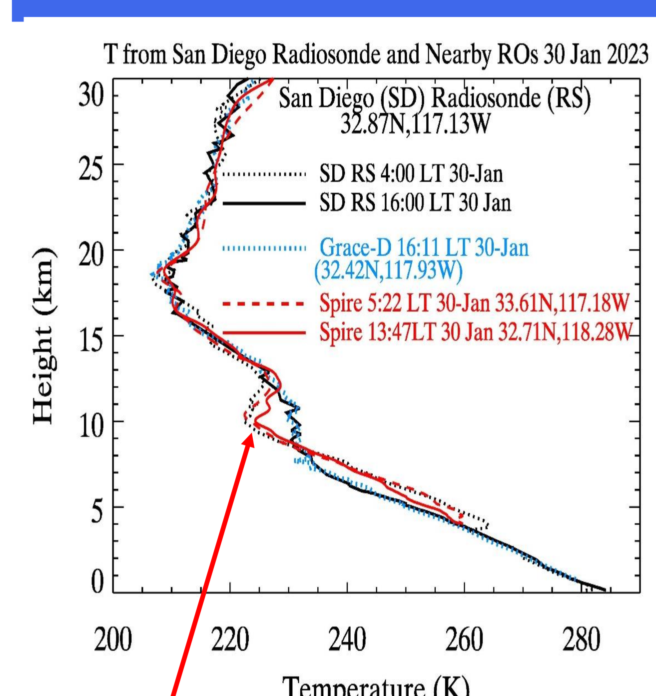
- CTOP is about 2 km below LRMAX (when a Δϕ>1mm threshold is used for CTOP) but there is a strong one-to-one relationship
- Reducing the Δϕ for CTOP to 0.65mm or lower improves the mean CTOP, but at the expense of the relationship with LRMAX (red/orange symbols/ dashed lines
- A threshold of Δϕ>0.8 mm reduces the LR-CTOP offset and may perform best overall

Joint Histograms of (CTOP-LRMAX)/[$\Delta\phi_{max}$] Globally (Paz) and |LAT|<60° (IMERG/GPM)



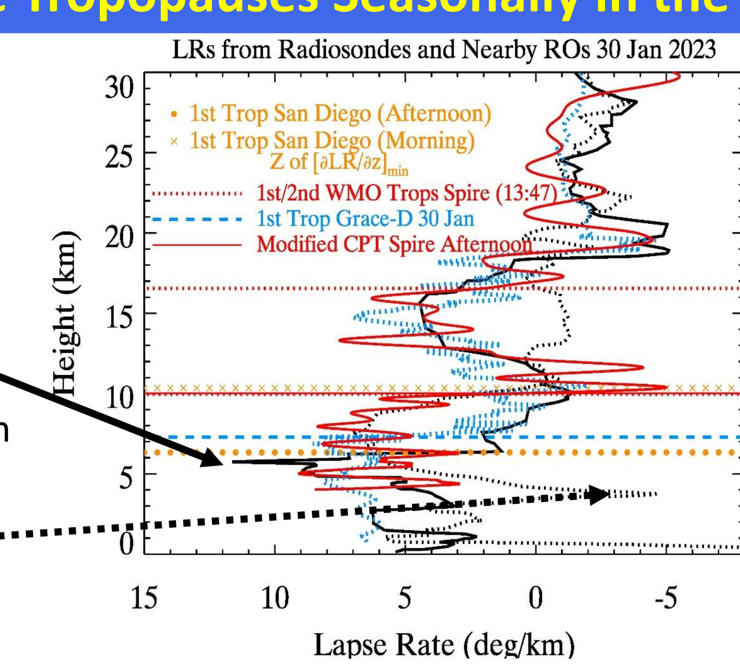
- The heaviest raining clouds (whether globally or over the tropics – WP and EP in the left panel stand for West Pacific [5°N-15°N; 120°E-160°E] and East Pacific [5°N-15°N; 150°W-100°W], respectively) are likely to reach LRMAX or just exceed it, though weakly or non-precipitating cloud tops are 5.4 km below LRMAX for Paz (left) and 4.3 km below LRMAX for IMERG/GPM (right).
- Histograms from either PAZ or GPM/IMERG qualitatively resemble each other, though even for heavily raining clouds, GPM/IMERG CTOPs are about 1 km higher than PAZ

Double Tropopause over San Diego Prior to and After a Frontal Passage on 30 Jan 2023 and the Larger-Scale Context Showing Propensity for Double Tropopauses Seasonally in the Subtropics and Mid-Latitudes

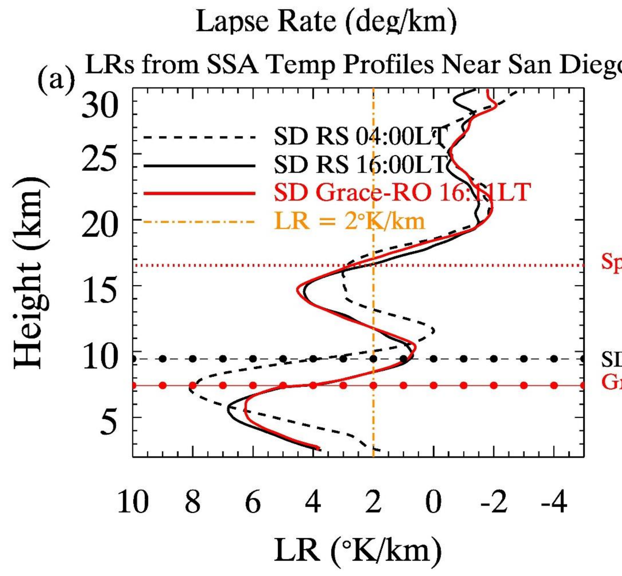


- Red Solid/Dashed (Spire Morning/Early Afternoon) and Black Dashed (Radiosonde Morning): Deeper First Tropopause (~10 km) *Prior to Approach of Front/Upper Level Trough*
- Black solid (Radiosonde)/Blue Dashed (Grace-D RO): Afternoon During Moderate Precipitation When Upper-Level Low is Overhead

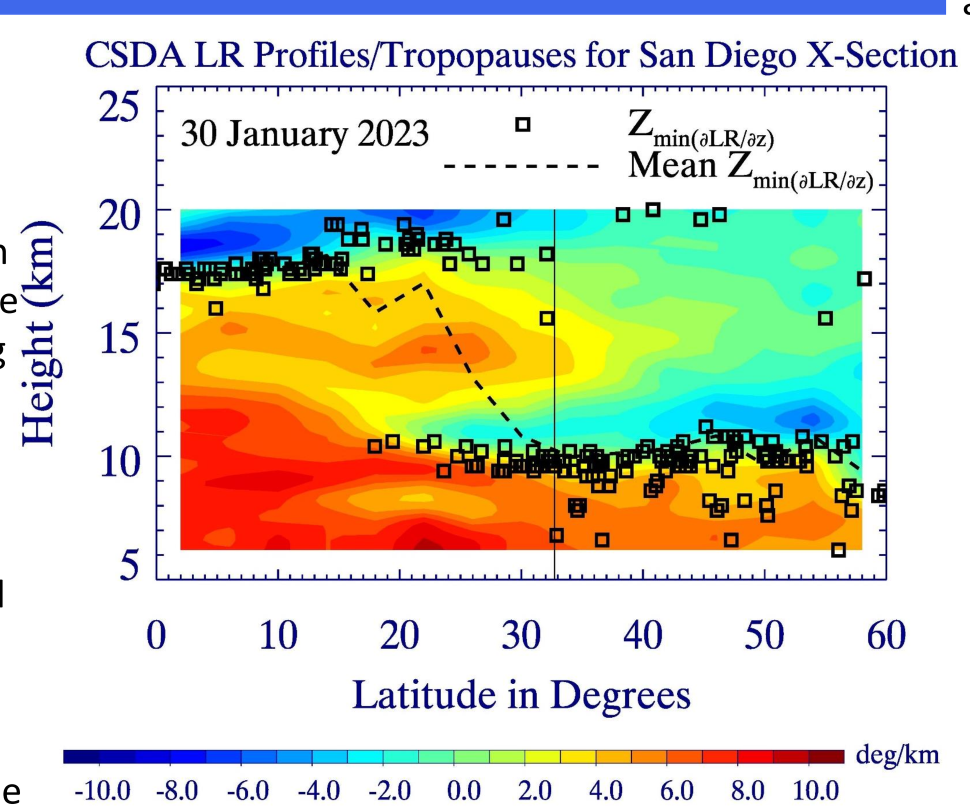
- Strong and relatively shallow LRMAX associated with the top of a moderate to strong precipitation layer by the afternoon
- Inversion around 4km corresponds with shallow echo tops around 4 a.m. LT



- Smoothed LRs (Using Singular Spectrum Analysis): Second relative LRMAX (around 14.5 km in the afternoon) but reduced in magnitude compared to primary LRMAX below 10 km – all have double tropopauses!



- The analysis on the right, performed with CSDA Spire data from 30 January 2023, presents lapse rate (LR) vertical profiles as a function of latitude with the longitude box anchored (+/-7.5°) along San Diego's longitude; San Diego's latitude (32.72°N) is indicated by a thin vertical line. The heights of the modified CPT are shown and highlight two modes – the tropical CPT which extends poleward to just north of 30°N, peaking in height in the subtropics ~20°N, and then the much shallower mid-latitude tropopauses with a mean height around 10km.



- The approaching upper-level trough shoals the first tropopause over San Diego (as shown in the profiles to the left as well).
- Overall, the latitude range at which the tropical CPT overlies the equatorward-moving mid-latitude tropopause is the window in which double tropopauses are most likely

Summary

- Polarimetric Δϕ provides a signature for cloud tops
- Δϕ cloud tops relate to the height of LRMAX, which has been proposed as the location of the TTL
- Global CPT, defined from the LRMIN, minus TTL bottom, from LRMAX, are used to estimate TTL thickness: The warm pool is well identified.
- The presence of double tropopauses is most likely seasonally in the subtropics and lower mid-latitudes where the very high tropical CPTs overlie much shallower mid-latitude tropopauses

References:
Kalmus, P., Ao, C. O., Wang, K.-N, Manzi, M. P., & Teixeira, J. (2022). A high-resolution planetary boundary layer height seasonal climatology from GNSS radio occultations. *Rem. Sens. Environment. 276,* https://doi.org/10.1016/j.rse.2022.113037
Kubar, T. L., Feiqin, X., Chi, A. O., & Loknath, A. (2020): An assessment of PBL heights and low cloud profiles in CAM5 and CAM5-CLUBB over the southeast Pacific using satellite observations. *Geophs. Res. Lett, 47*(2), https://doi.org/10.1029/2019gl084498
von Engeln, A., J. Teixeira, J. Wickert, and S. A. Buehler (2005), Using CHAMP radio occultation data to determine the top altitude of the planetary boundary layer, *Geophys. Res. Lett*, *32*, L06815, https://doi.org/10.1029/2004GL022168.

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