

# A Unified View of the Tropical Tropopause Layer over India from Long-Term Radiosonde and Ozonesonde Observations

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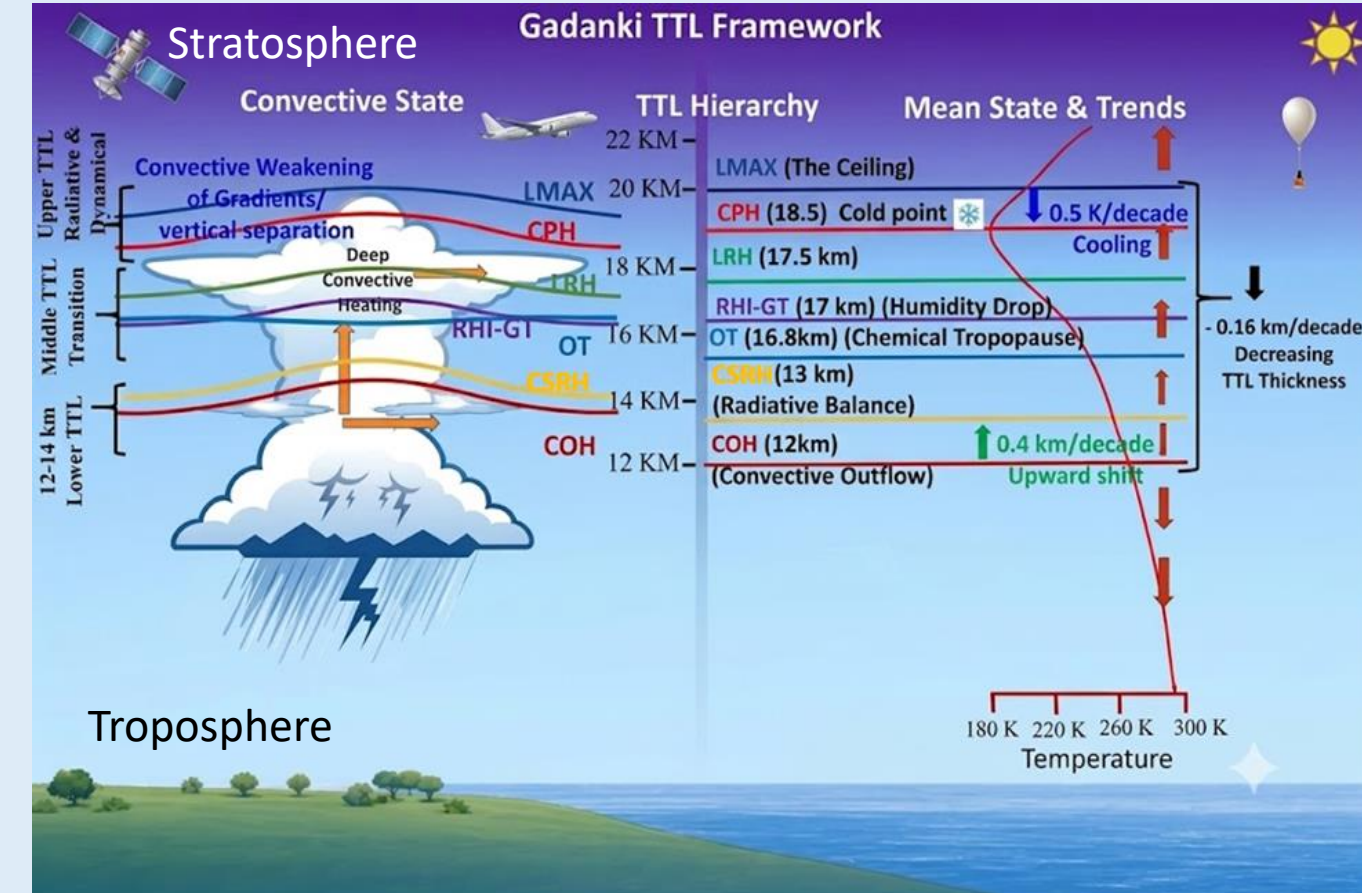


**Abstract** The Tropical Tropopause Layer (TTL) controls troposphere-stratosphere exchange, but its long-term structure is poorly constrained by in situ data. Using ~20 years (2006–2025) of radiosonde and ozonesonde observations over Gadanki (13.5°N, 79.2°E), multiple complementary diagnostics are applied to identify thermal, radiative, chemical, humidity and stability-based tropopause definitions into one framework. The TTL appears as a vertically ordered transition zone, not a single level. Seasonal variability far exceeds diurnal variability. Monsoon convection modulates the lower and middle TTL, while the upper boundary stays stable. Long-term changes include upward shifts of the lower boundaries, lower-stratospheric ozone decline, and a tightening moisture gradient. Deep convection weakens the gradients and reduces agreement among tropopause definitions.

## 1 Introduction & Motivation

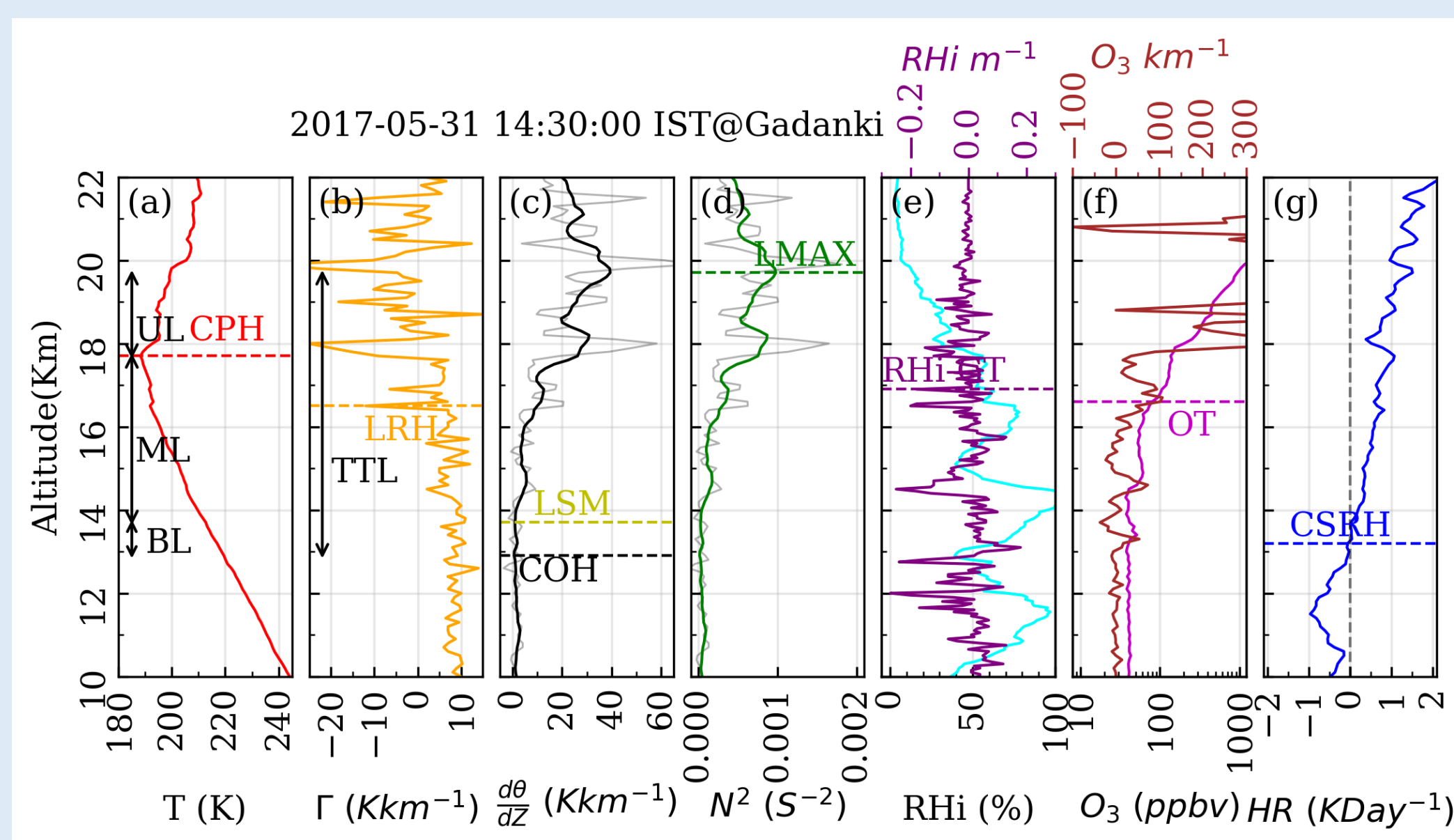
- The TTL is a complex transition region rather than a single, well-defined layer. Its structure reflects the interplay of dynamical, radiative, thermodynamic and chemical processes, with thermal, radiative and chemical tropopauses often occurring at different altitudes.

- This lack of a unique tropopause height challenges conventional descriptions of the tropical tropopause and limits our ability to understand its variability and role in STE exchange. Resolving this complexity provides the central motivation for the present study.



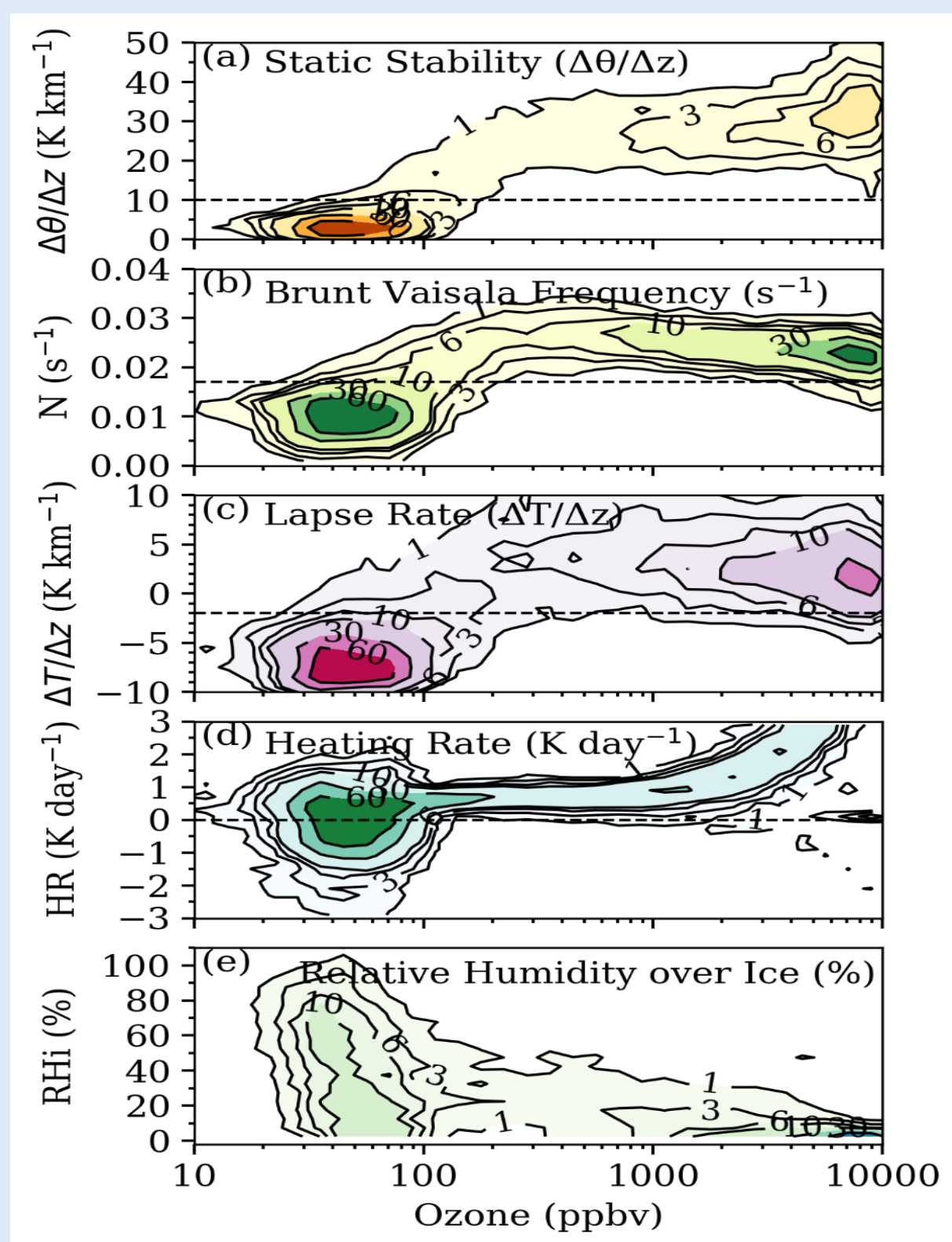
**Motivation:** Over Indian region, a comprehensive multi-diagnostic characterisation of TTL hierarchy, sub-layer thickness, and long-term trends under strong monsoon influence are studied using a 20-year collocated radiosonde–ozonesonde dataset over Gadanki.

## 3 Methodology



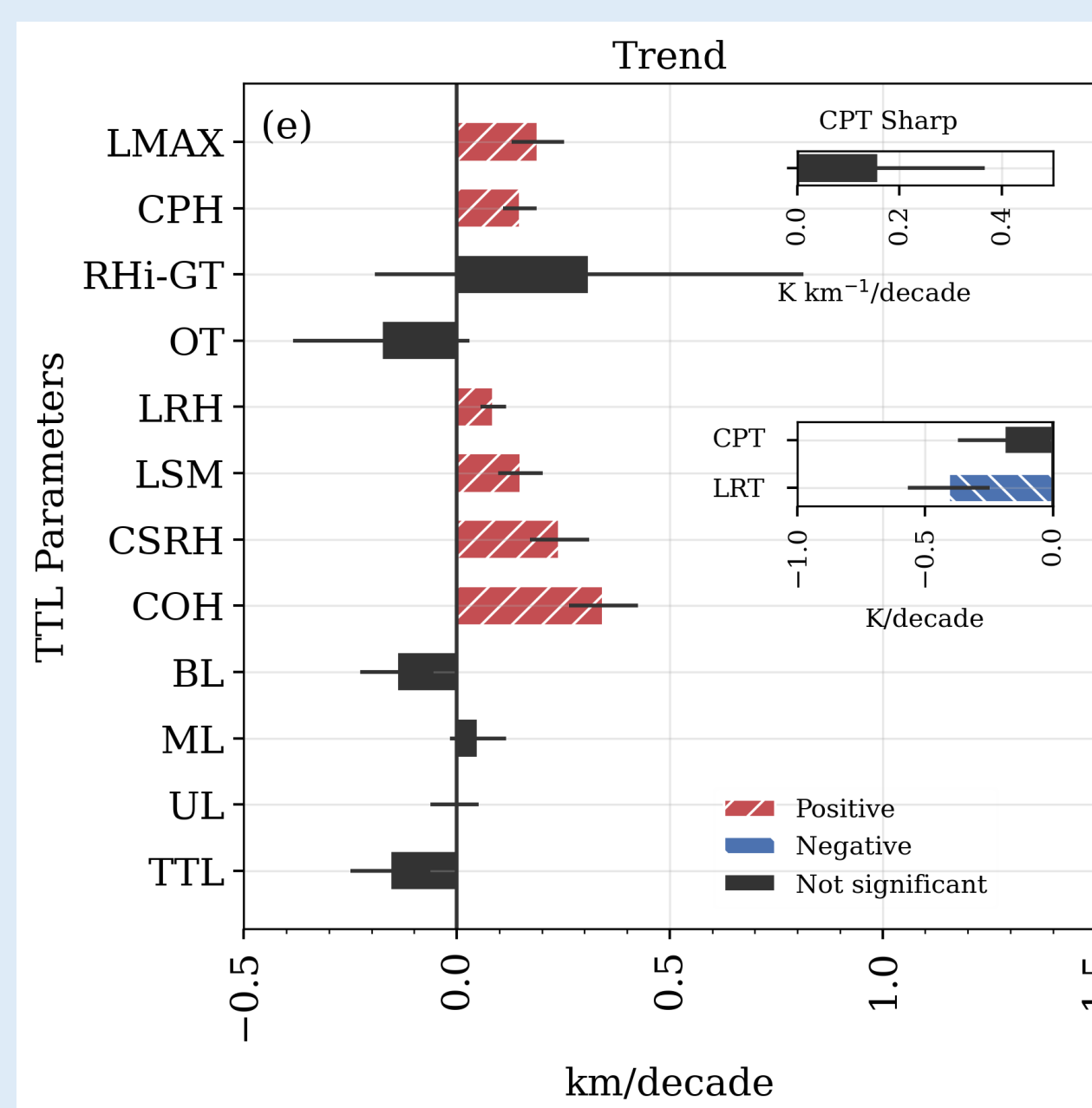
- Thermal tropopause** → temperature (T), potential temperature ( $\theta$ ), and squared Brunt-Väisälä frequency ( $N^2$ )
- Humidity (RHi-GT):** RHi > 10% &  $\partial \text{RHi} / \partial z < -0.15 \text{ \% m}^{-1}$  (sharp moisture drop)
- Chemical (OT):**  $\text{O}_3 > \sim 75 \text{ ppbv}$  &  $\partial \text{O}_3 / \partial z > \sim 55 \text{ ppbv km}^{-1}$  (rapid  $\text{O}_3$  rise)
- Radiative (CSRT):** clear-sky net heating changes sign (cooling → heating)

## 4.2 Ozone Relations with TTL Structure



- $\text{O}_3$ –stability shifts from weak and low- $\text{O}_3$  to strong stability with higher  $\text{O}_3$ , which supports tropopause as a transition zone, not a single level
- With increasing  $\text{O}_3$ , the lapse rate weakens and inverts, and RHi drops sharply from high values in moist, low- $\text{O}_3$  air, which is clear evidence of dehydration

## 4.3 Long-term Trends



- CPH altitude exhibits a significant increasing trend ↑
- Decrease in  $\text{O}_3$  is observed in lower stratosphere ↓
- TTL thickness decreases (monsoon influence)

## 2 Objectives

- Characterize the climatology and seasonal variability of TTL boundaries (thermal, chemical, radiative, humidity- and stability-based) over Gadanki.
- Ozone relations with stability, heating rate and Rhi.
- Quantify long-term trends in TTL boundaries, CPT temperature, ozone and layer thickness.
- Convective modulation of the tropopauses (pre-/post-convection categories).

## Data sets



**Radiosonde:** RS11G / IMS-100 / iMet, Apr 2006-Aug 2025 (5,266 launches). Balloons typically reach 30-35 km at an ascent rate of  $\sim 5\text{--}6 \text{ m s}^{-1}$ , and profiles are interpolated to 100 m. Launches are at 17:30 IST.



**Ozonesonde:** EN-SCI ECC, Oct 2011-Dec 2024, flown with Meisei/iMet radiosondes.

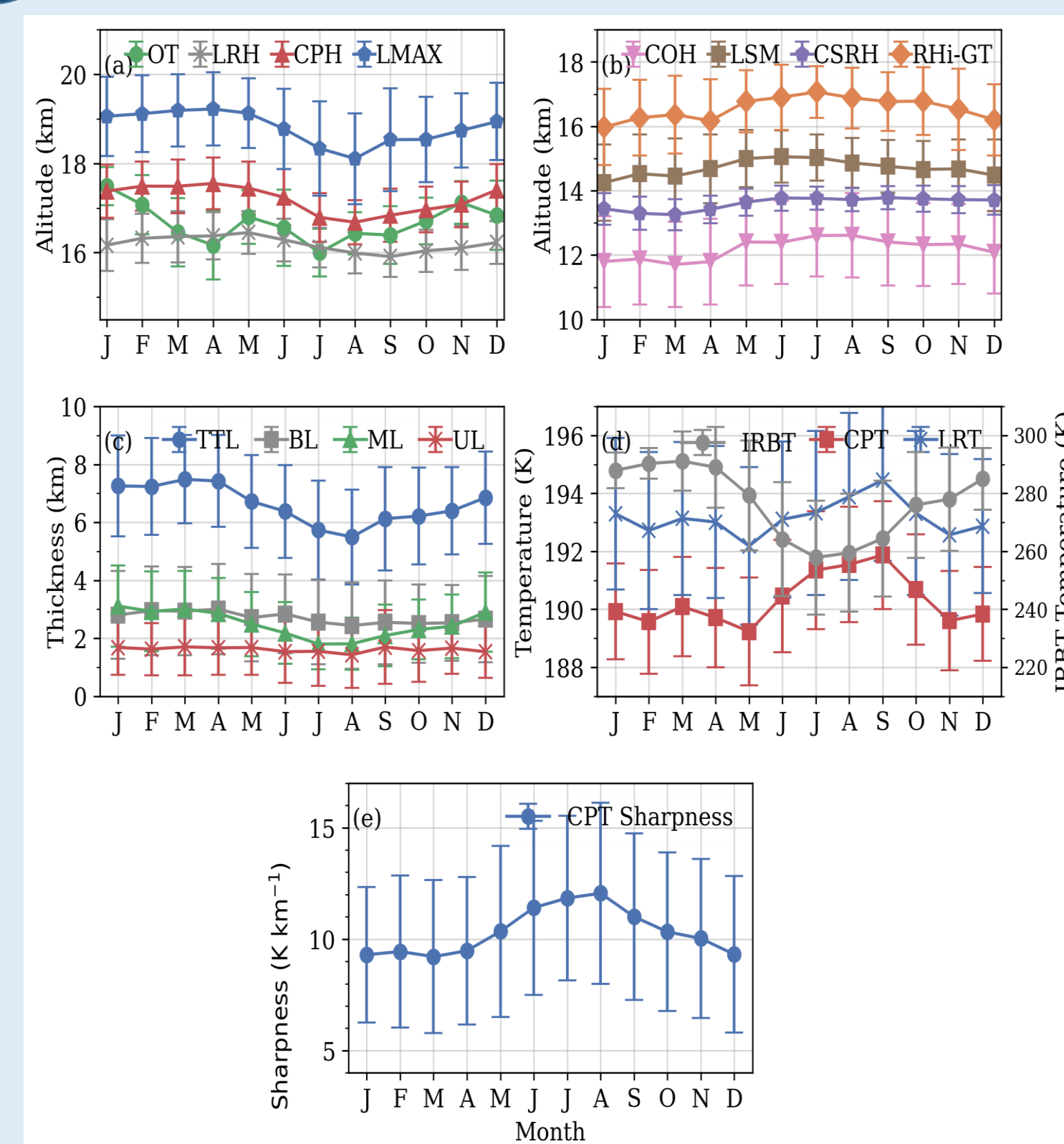


**Infrared Brightness Temperature (IRBT):** NCEP/CPC L3 (GPM\_MERGIR V1), hourly,  $0.04^\circ$  ( $11\text{--}15^\circ\text{N}$ ,  $78\text{--}81^\circ\text{E}$ ), used to classify convective categories ( $\pm 3 \text{ h}$  of launch).



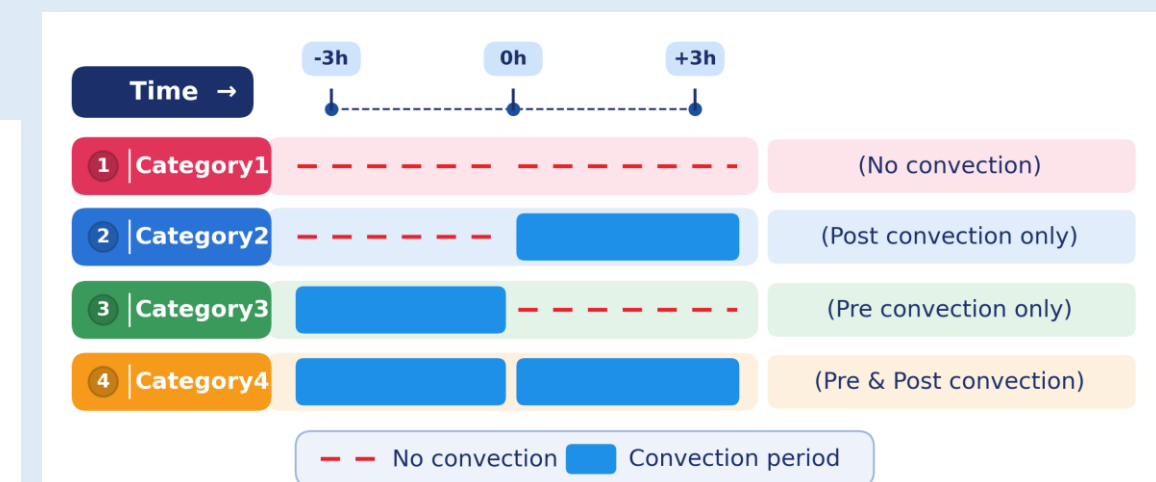
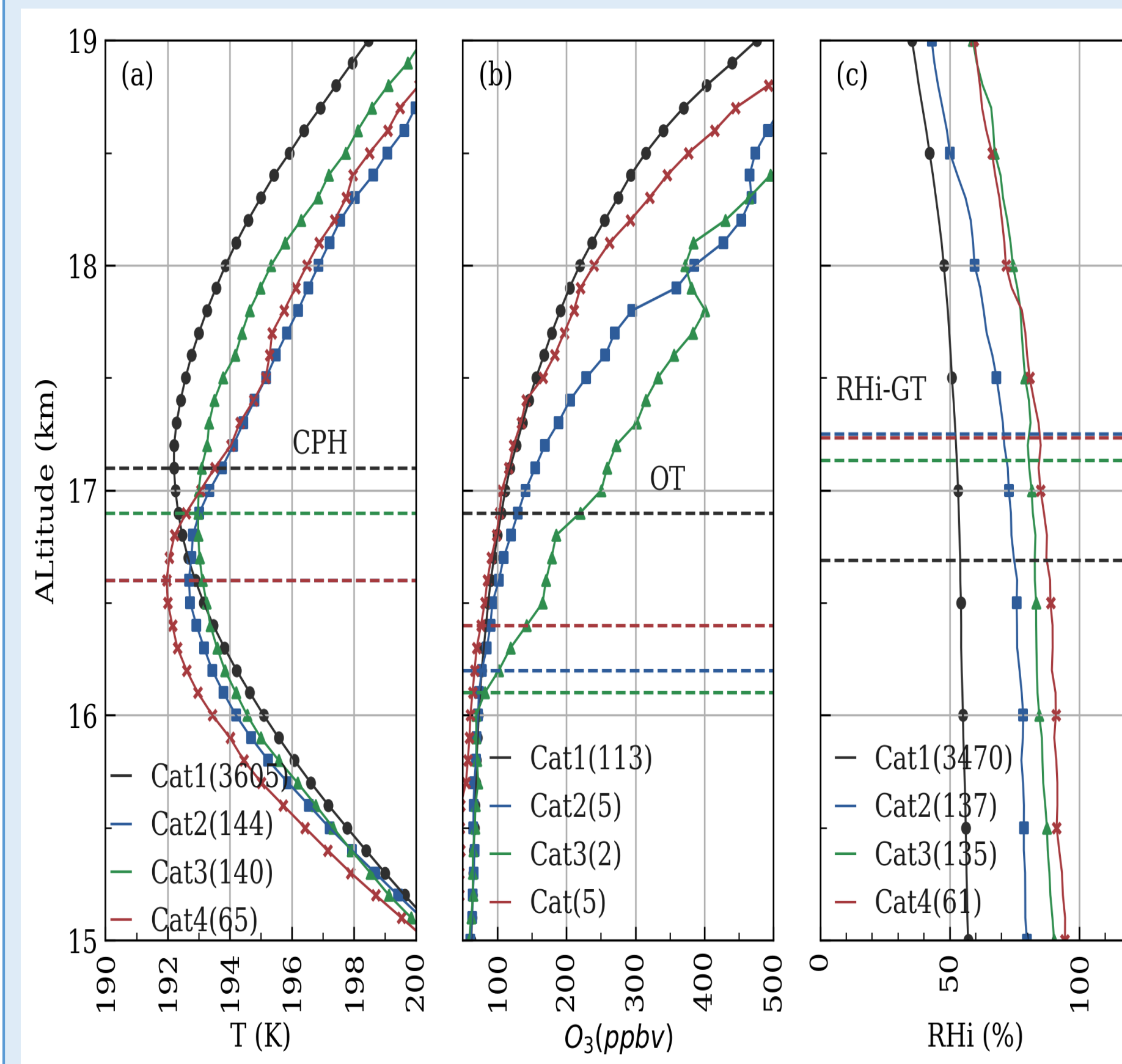
**TTD campaign:** 3-hourly launches, 3 days/month, Dec 2010-Mar 2014.

## 4 Results: 4.1 TTL thickness & seasonal variability



- Lower (COH & LSM) and intermediate boundaries vary by  $\sim 0.15\text{--}1.5 \text{ km}$ , rising in winter/pre-monsoon and lowering during the monsoon due to convective influence
- TTL thickness peaks in pre-monsoon and winter ( $\sim 7\text{--}8 \text{ km}$ ) and is smallest during the monsoon ( $\sim 5\text{--}6 \text{ km}$ )
- CPT/LRT is coldest in winter/pre-monsoon and warmest during the monsoon and IRBT reflects convective cloud-top effects

## 4.4 Convective Influence on the TTL



- Cat1 vs cat4: warmer, lower cold point - enhanced mixing and diabatic heating from UTLS
- Cat4: lower  $\text{O}_3$  values and a lower OT, indicating tropospheric air injection and chemical tropopause erosion
- Cat3 & Cat4: Elevated RHi and the RHi-GT shifts, implying TTL moistening by lofted ice and vapor followed by dehydration near the cold point

## 5 Conclusions

- ✓ Convective, radiative, humidity, thermal, and chemical diagnostics form a coherent vertical hierarchy, confirming the TTL as an extended transition zone rather than a single level
- ✓ Diurnal variations in TTL boundaries, thickness and temperature are modest compared to the strong seasonal modulation
- ✓  $\text{O}_3$ –stability,  $\text{O}_3$ –temperature, and  $\text{O}_3$ –humidity relations jointly show a gradual troposphere to stratosphere transition with increasing stability, lapse-rate inversion, and sharp drying with rising  $\text{O}_3$
- ✓ Long-term trends include cooling at the CPT and ozone-based transition levels, increasing middle-layer thickness, and a tightening moisture gradient across the TTL
- ✓ CPT cooling ( $\sim 0.5 \text{ K decade}^{-1}$ ) suggests a strengthening tropical cold trap and more efficient dehydration, with implications for stratospheric water vapor entry.
- ✓ Deep convection significantly lowers tropopause altitude and modifies UTLS thermal, chemical, and moisture structure over Gadanki
- ✓ **Convection, radiative balance, and dehydration jointly regulate TTL depth and stratosphere to troposphere exchange, offering new constraints for climate models**



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## Acknowledgement

The authors are grateful to ARTG technical staff for launching radiosonde, ozonesonde over Gadanki and to NARL for continuous support.