STIPMEX-2024

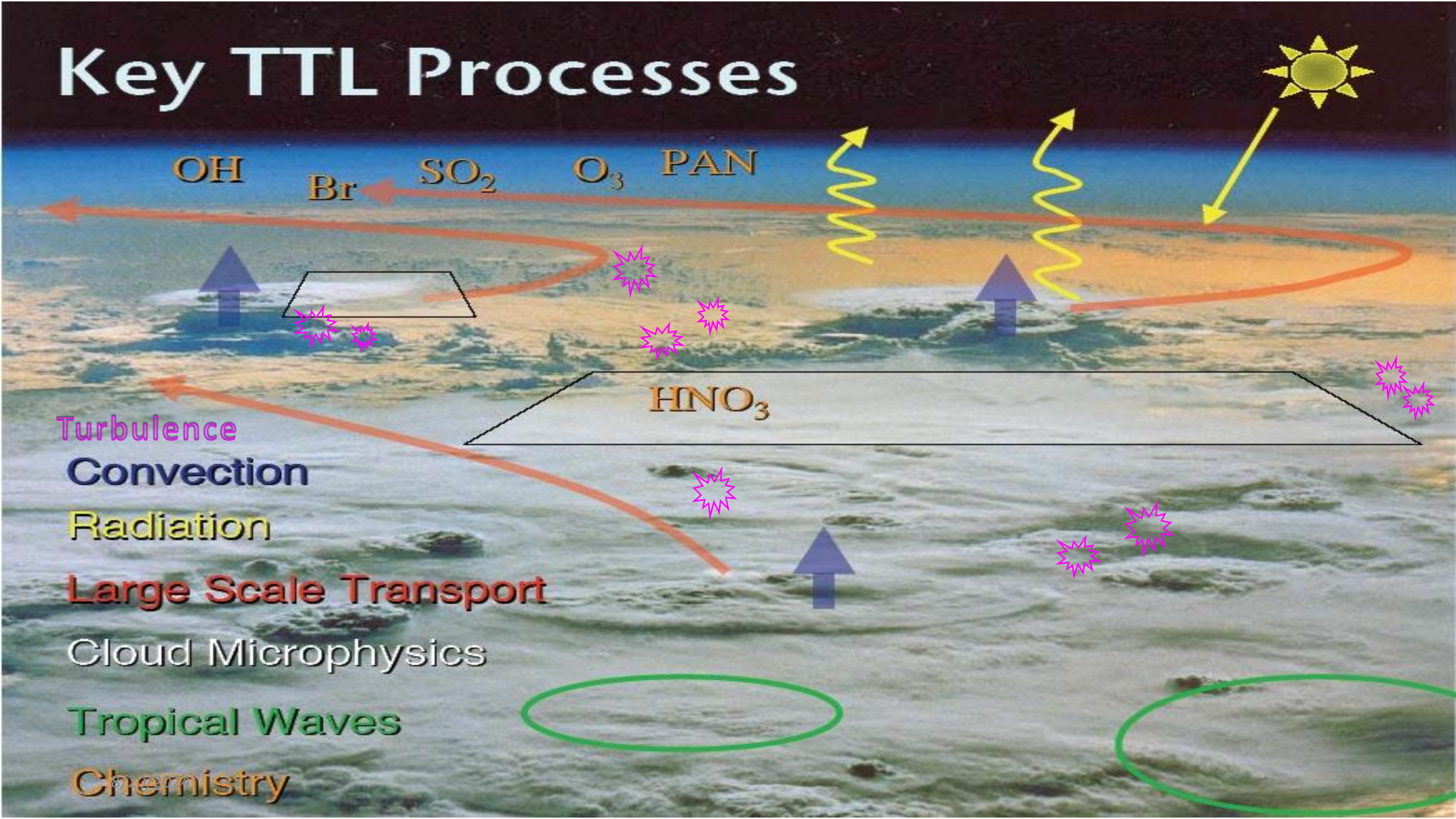
Insights from Tropical Tropopause Dynamics Experiments under GARNETS program over Indian monsoon region

GPS **A**ided **R**adiosonde **N**etwork **E**xperiments for **T**roposphere stratosphere **S**tudies (**GARNETS**)

S V Sunil Kumar (PI) & Team

Space Physics Laboratory (SPL), Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram

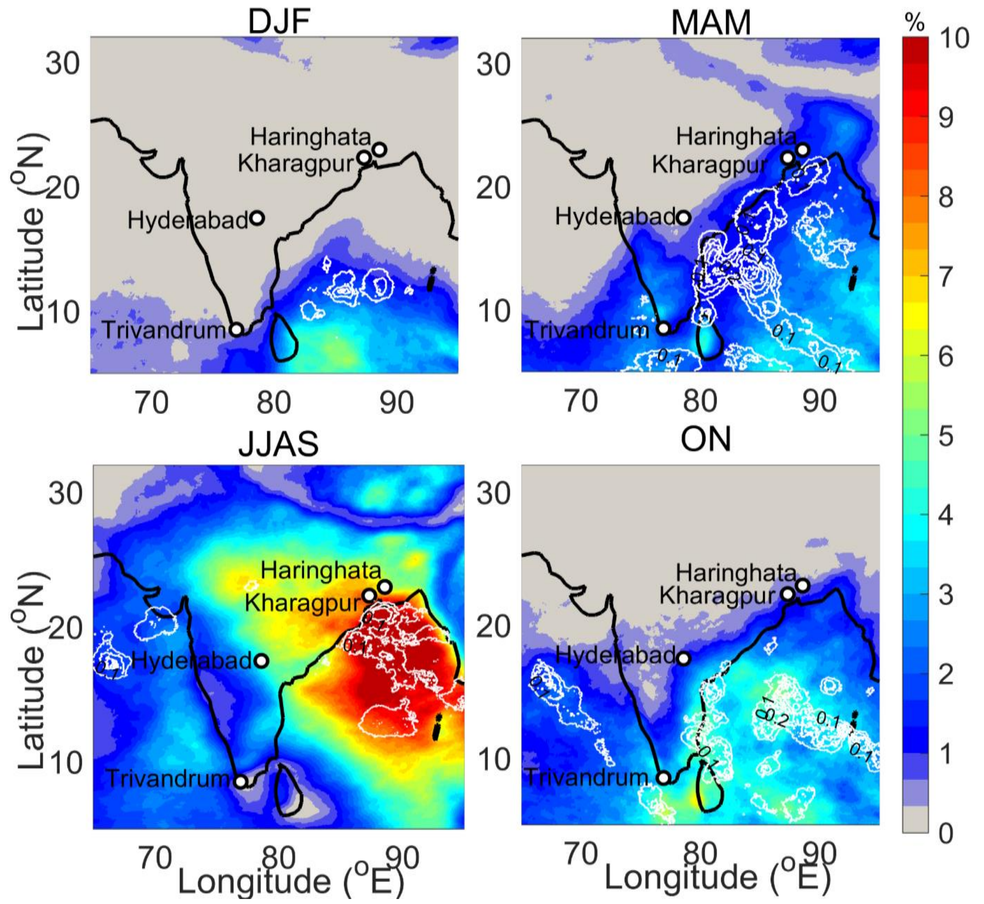
Email: sv_sunilkumar@vssc.gov.in


Key TTL Processes
OH
Br
SO_2
O_3
PAN
HNO_3
Turbulence
Convection
Radiation
Large Scale Transport
Cloud Microphysics
Tropical Waves
Chemistry

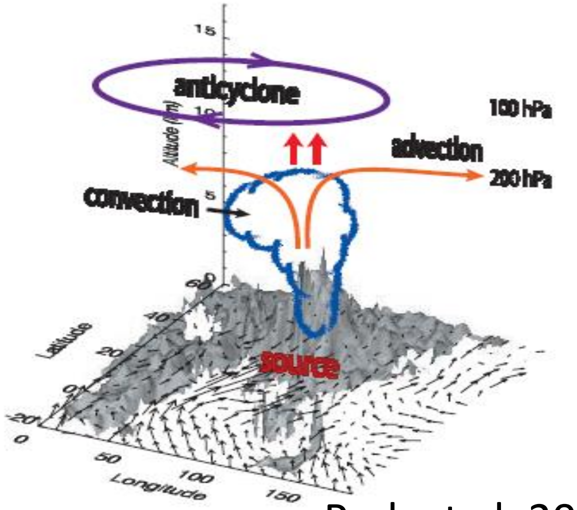
Uniqueness of Indian region in perspective of UTLS studies

- Large annual migration of **Inter Tropical Convergence Zone (ITCZ)**
- Monsoon dynamics
  - Deep convective clouds over Bay of Bengal
  - Strong Tropical Easterly Jet (TEJ)
  - Anticyclonic circulation
- Major source region for the lower stratospheric water vapour (Bannister et al., 2004; Lelieveld et al., 2007)
- Deep convective thunderstorms in Pre- and post monsoon

Frequency of Deep Convective Clouds > 12 km: KALPANA-1 observations (2011-2016)

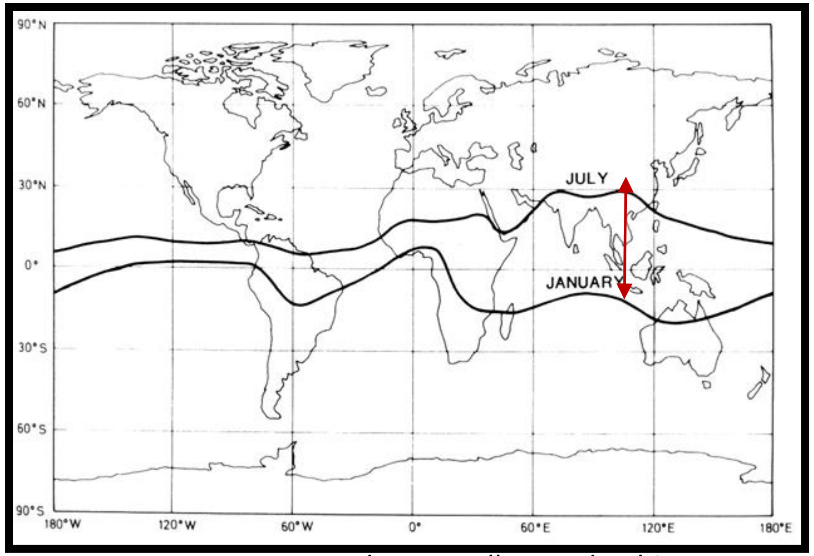


Emmanuel et al, 2020



Park et al, 2009

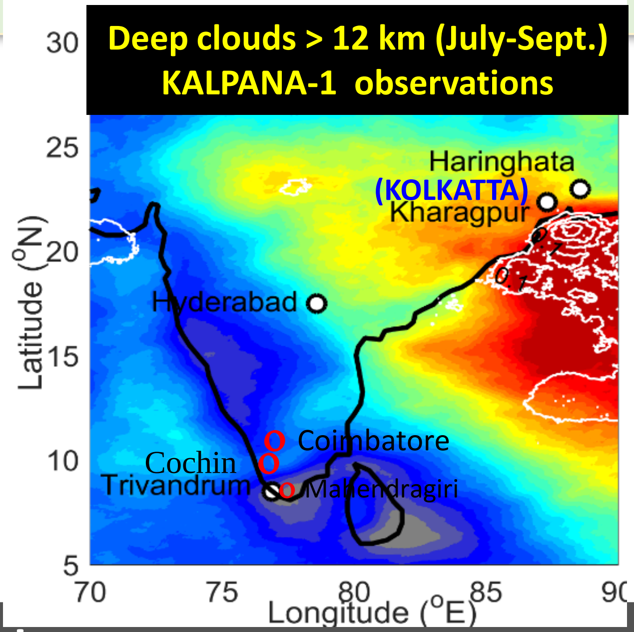
Annual migration of ITCZ



Henderson-Sellers and Robinson, 1991

GPS Aided Radiosonde Network Experiments for Troposphere stratosphere Studies

GARNETS



Scientific Objectives:

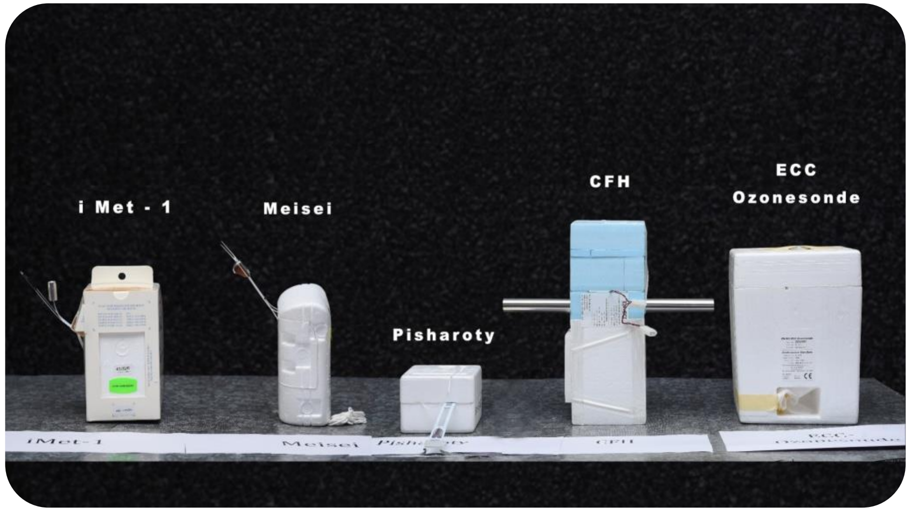
- Tracer variability in the UTLS & the role of dynamics over Indian region
- Impact of deep convection and monsoon dynamics on moisture budget in the UTLS and their consequences in cirrus formation and thermodynamics

❖ *Approach:* ***In situ*** **measurements of water vapour, Ozone,** temperature and winds at finer vertical resolution, using light-weight balloon-borne sensors**.**

❖**Systematic and regular experiments** over the **hotspots** (**deep convective outflow regions**) & non-hotspots regions of Indian region.

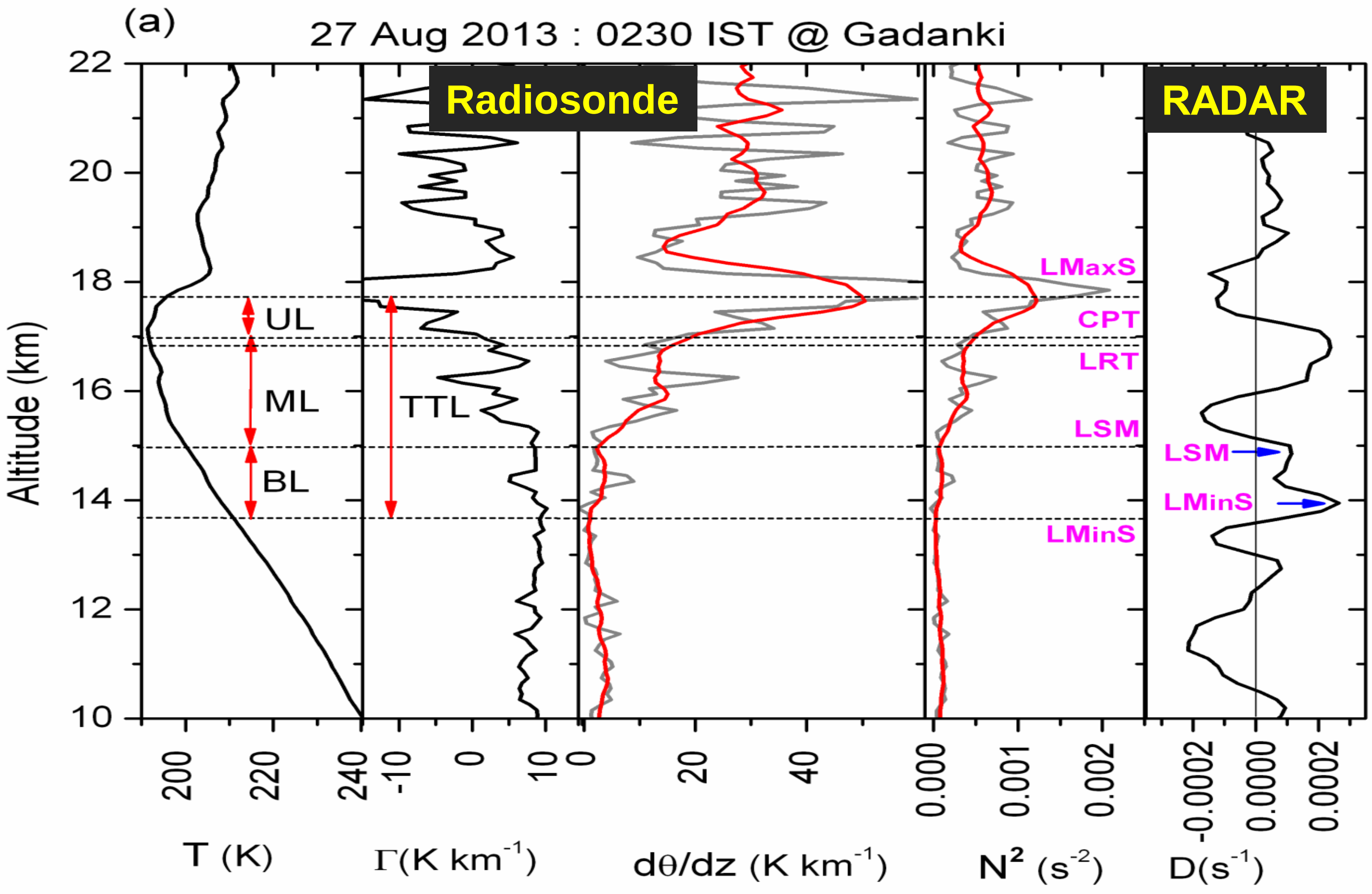
Balloon-borne sensors	Balloon Sounding Experiments						
	TRIVANDRUM [Since 2014]	HYDERABAD [2014-2017]	KOLKATTA [2016- 2019]	Indian Ocean [2018]	COIMBATORE [2014]	COCHIN [2014]	MAHENDRAGIRI [Since 2021]
Radiosonde	300	85	123	164	134	100	640
ECC Ozonesonde	125	53	22	17			12
Cryogenic Frost-point Hygrometer (CFH)	67	55	21	7			
	SPL/VSSC	TIFR	U. Of Calcutta IIT, Kharagpur	ORV Sagarkanya	Amrita Viswha Vidhyapeetham	CUSAT	IPRC/ISRO

Balloon Sounding Experiments



Light weight Balloon sensors

A new Perspective of TTL



- Boundaries of TTL using Static Stability profiles:
- **Re-defined the upper boundary of TTL** (the TTL-top) & is defined as level of Maximum stability (LMaxS)
- TTL-top is about 1 km above CPT

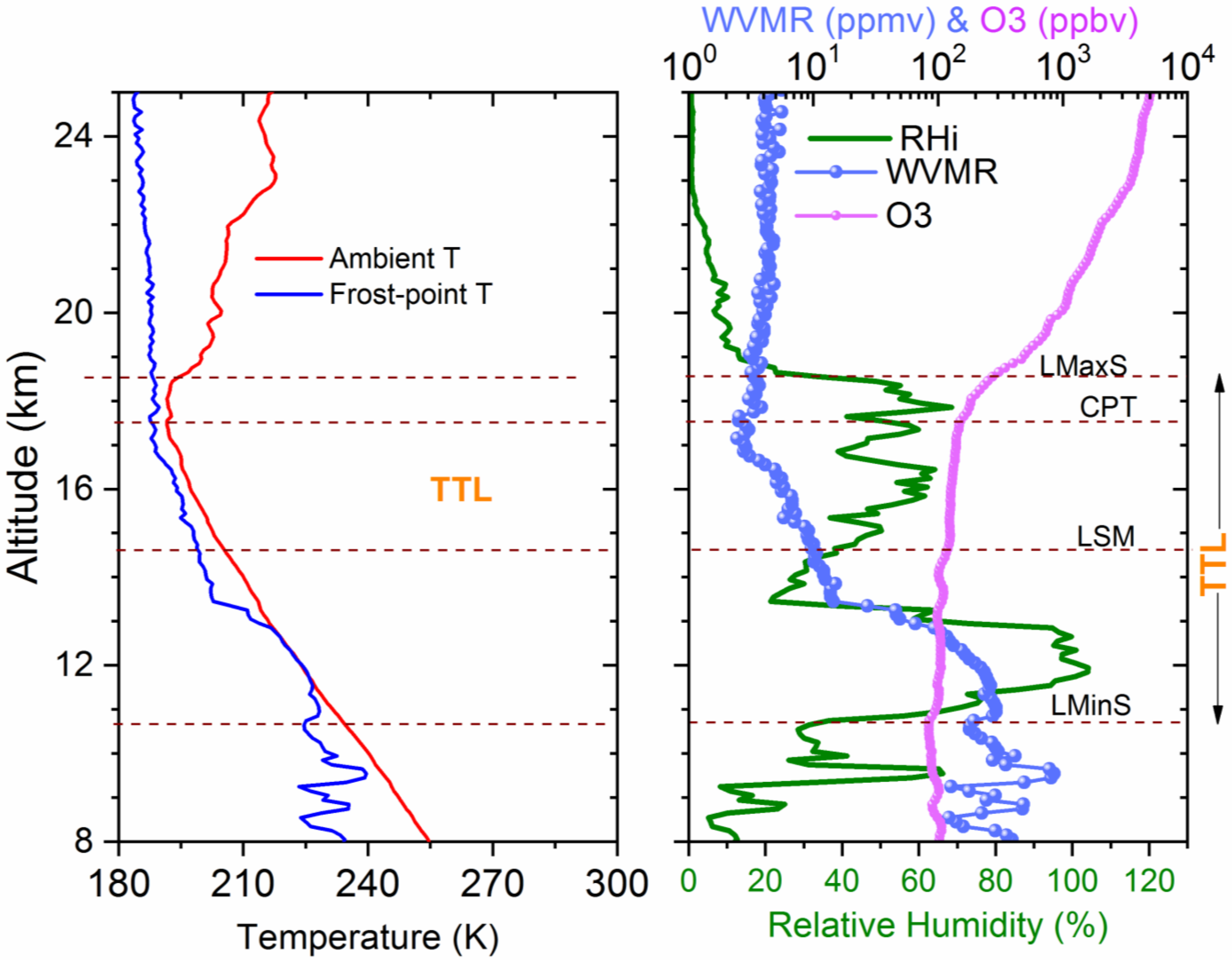
This study suggests that, the TTL can be treated as a composite of 3 sub-layers

Sunilkumar et al., JGR, 2017

Data: TTD [CAWSES –Phase-II & GARNETS]

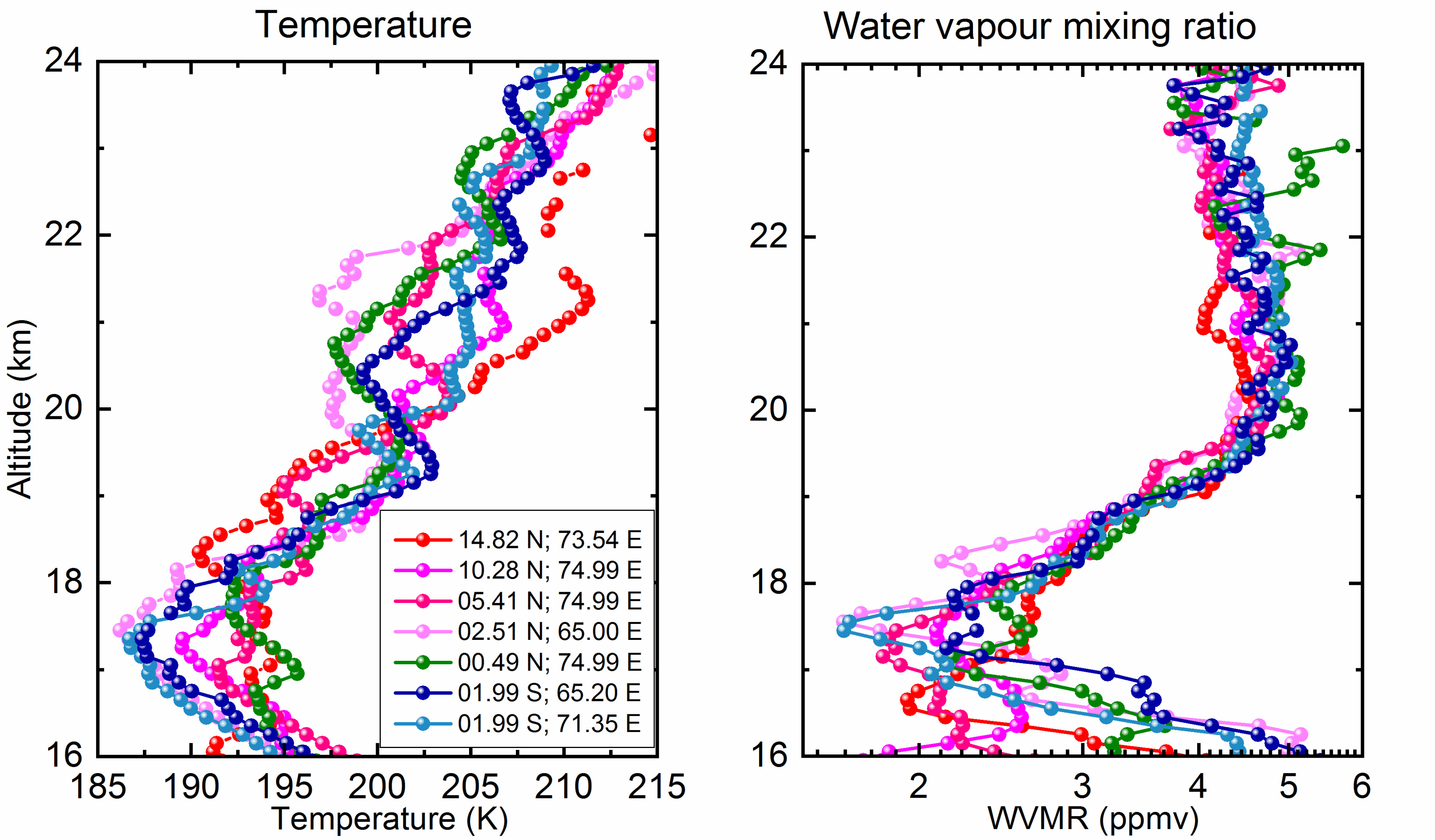
Observations from Light-weight Balloon-borne sensors
(Radiosonde, Cryogenic Frost-point Hygrometer, Ozonesonde)

Typical profiles @ Trivandrum (17 April 2014 @ 17:30 IST)

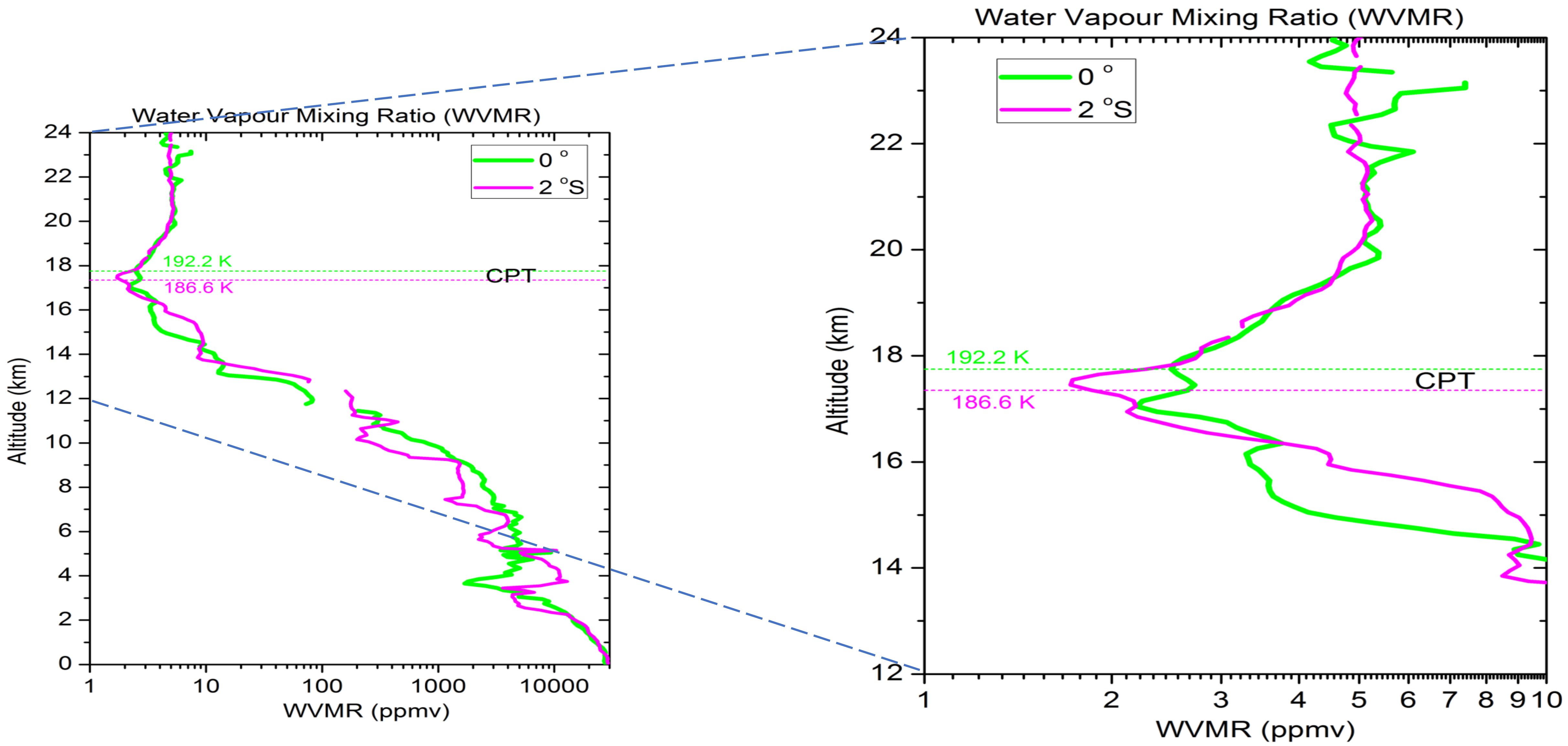


Sunilkumar et al., JGR, 2017

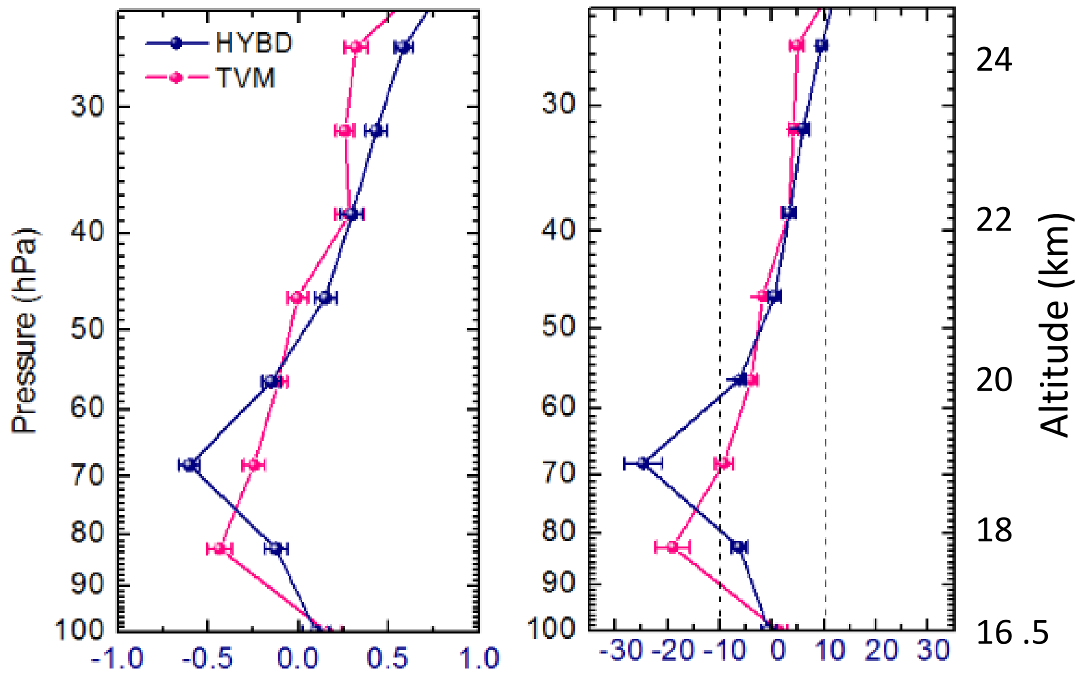
Cryogenic Frost-point Hygrometer (CFH) observations over Indian Ocean
-Typical Profiles over Equator (January 20218)



Cryogenic Frost-point Hygrometer (CFH) observations over Indian Ocean
-Typical Profiles over Equator (23 January 20218)



Water Vapour Mixing Ratio (WVMR): CFH vs MLS



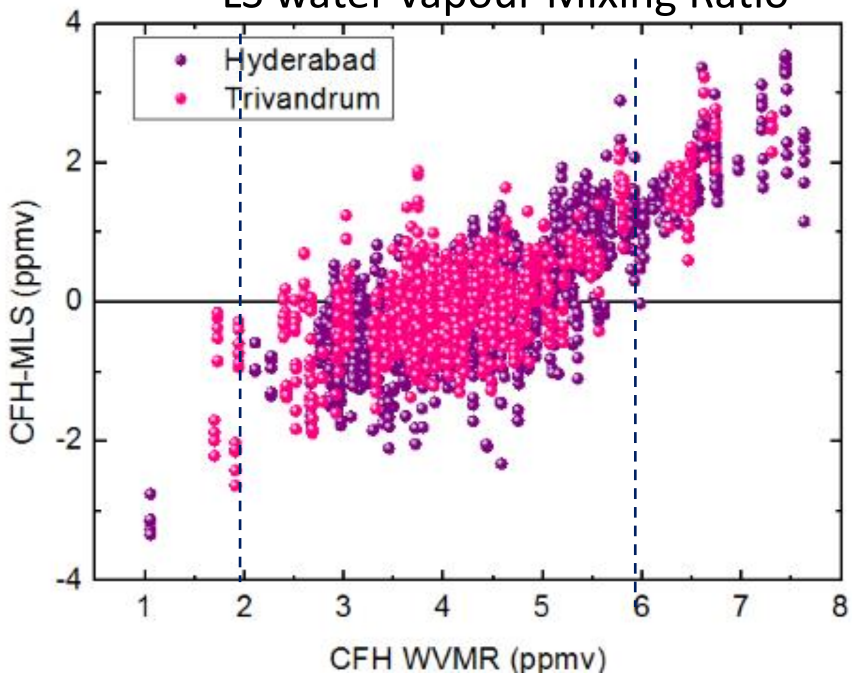
Δ WVMR

Δ WVMR in %

ΔWVMR = difference in WVMR (CFH – MLS)

Uncertainty in CFH derived WVMR is ~9-10% in the UTLS

LS water vapour Mixing Ratio

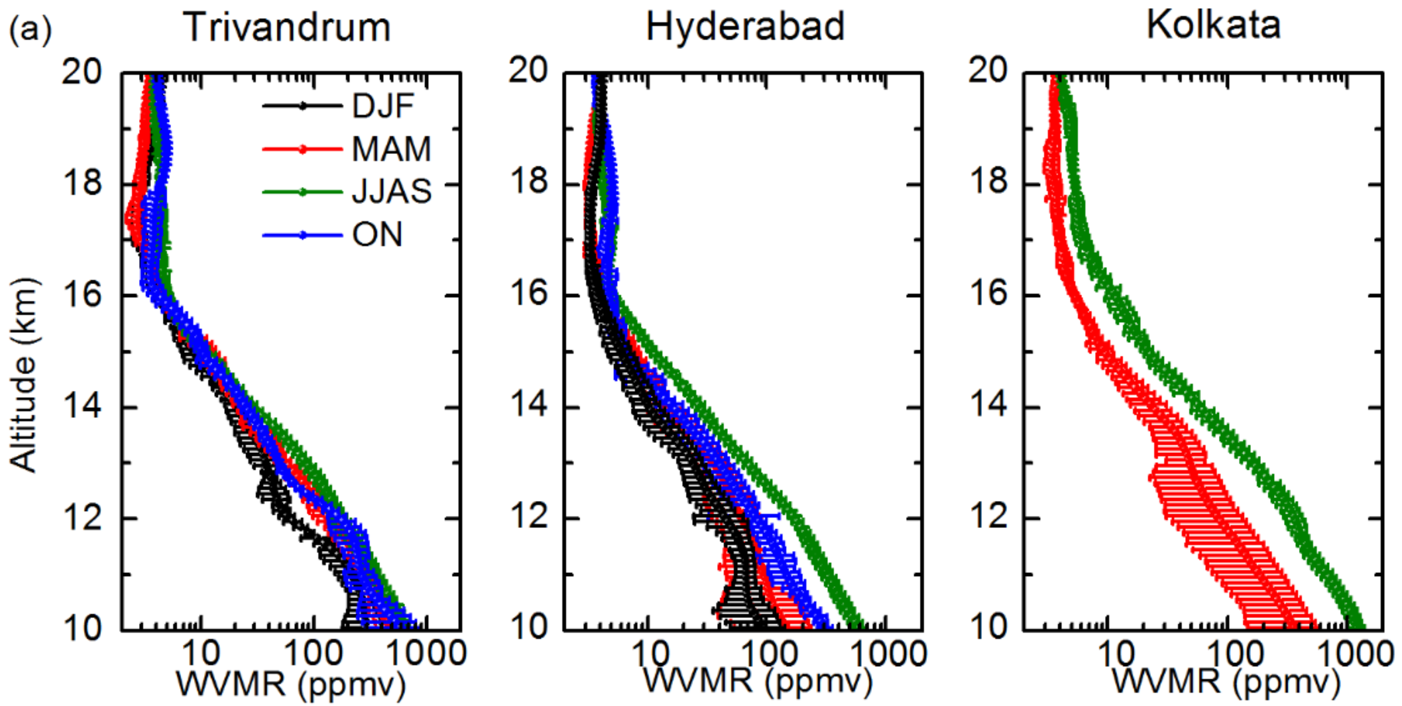


Period of observation: 2014-2017;
No of profiles : 66 [43-HYBD + 23 –TVM];

[Emmanuel et al., IEEE Trans. Geosci. Rem. Sens., 2018]

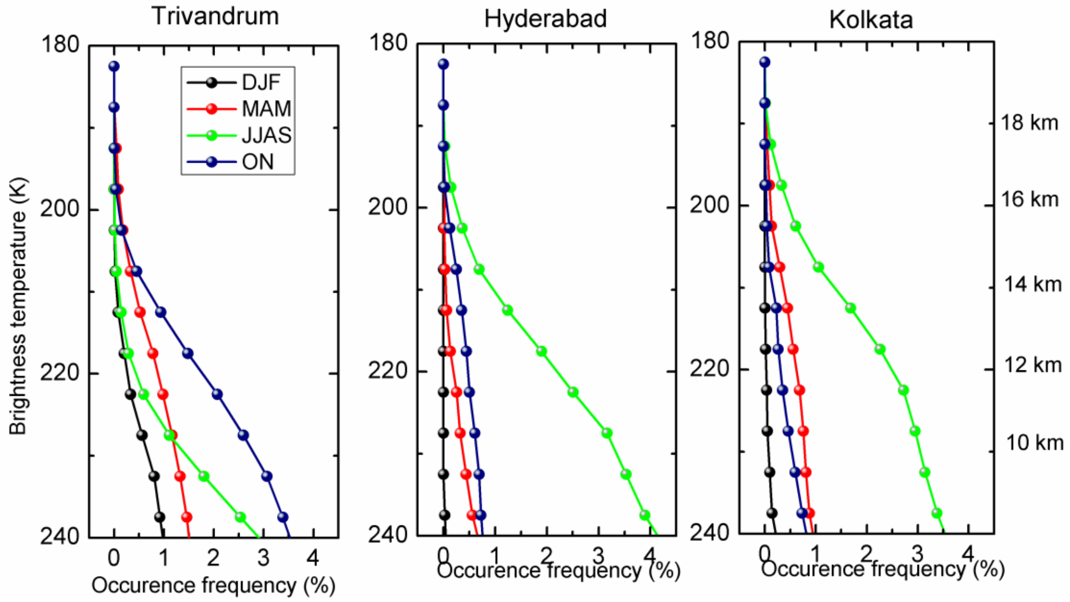
- For MLS, the mean difference shows a wet bias below 50hPa level and dry bias above that region.
- MLS over estimates when the CFH measured WVMR is <2 ppmv and underestimates when the CFH measured WVMR is > 6 ppmv

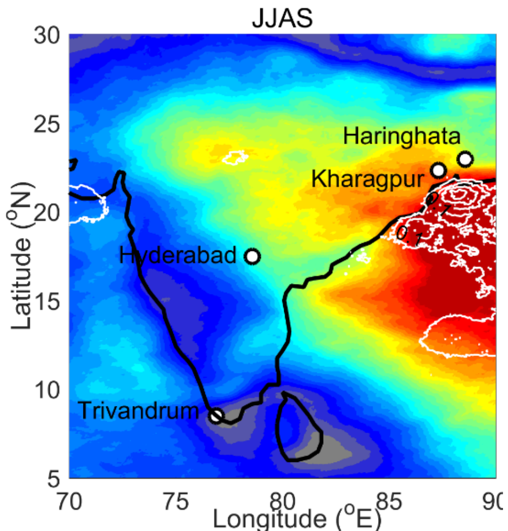
CFH measured water vapor in the UTLS: Seasonal Variation



Emmanuel et al., Atmos. Res., 2020

Frequency of deep convection from KALPANA

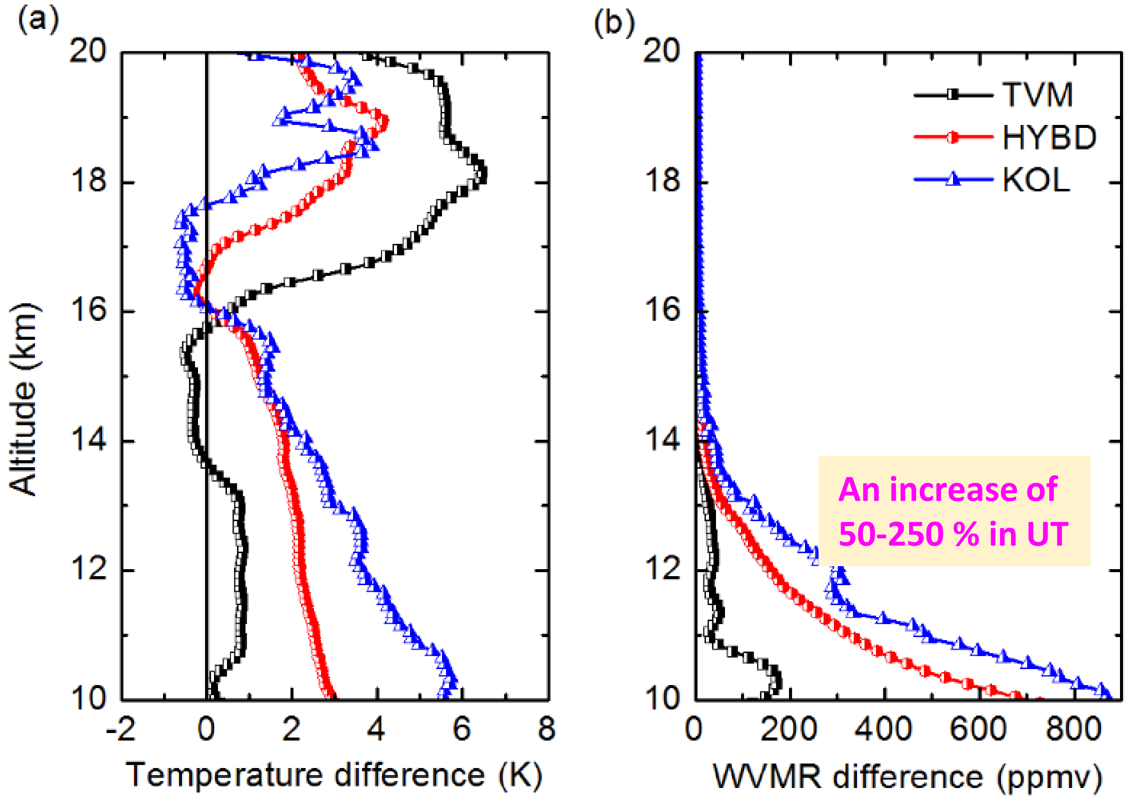


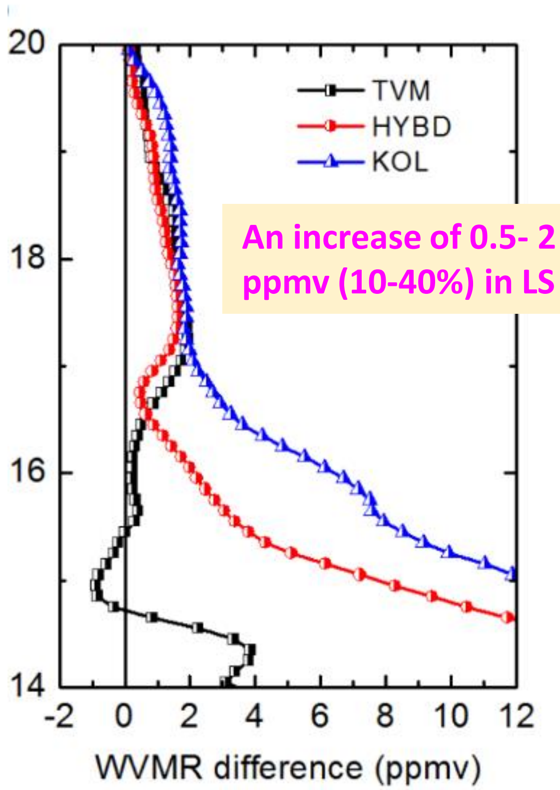


Deep clouds > 12 km (July-Sept.) from KALPANA-1 observations

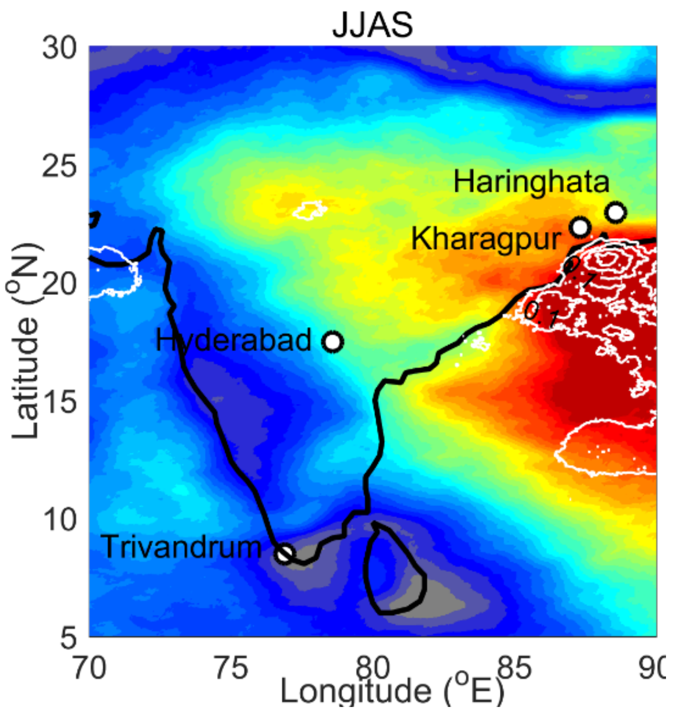
Enhancement of Water Vapour in UTLS during Asian Summer Monsoon (ASM) w.r.t pre-monsoon

How much amount of Water Vapour entered LS during ASM period?





Deep clouds > 12 km (July-Sept.)
KALPANA-1 observations

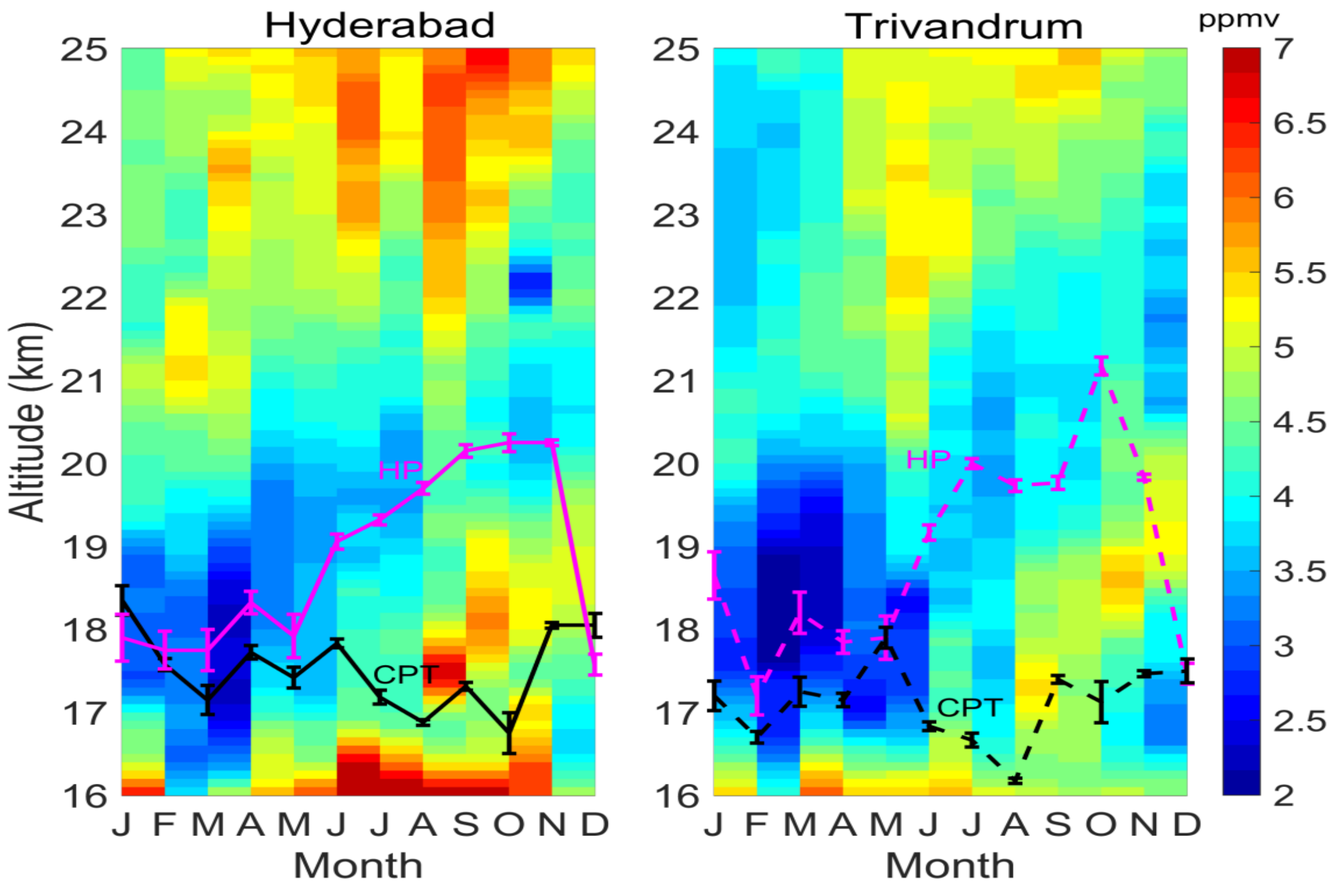


- ❖ Warmer Upper Troposphere (UT) and cooler Tropopause region in summer monsoon w.r.t to pre-monsoon
- ❖ In the UT region (10–16 km), water vapour shows an enhancement of ~40–60% at Trivandrum, 150–200% at Hyderabad and ~ 200–300% at Kolkata during the summer-monsoon with respect to the pre-monsoon season.

Emmanuel et al., Atmos. Res., 2020

Annual Cycle of Water Vapour in the UTLS region (CFH measurements)

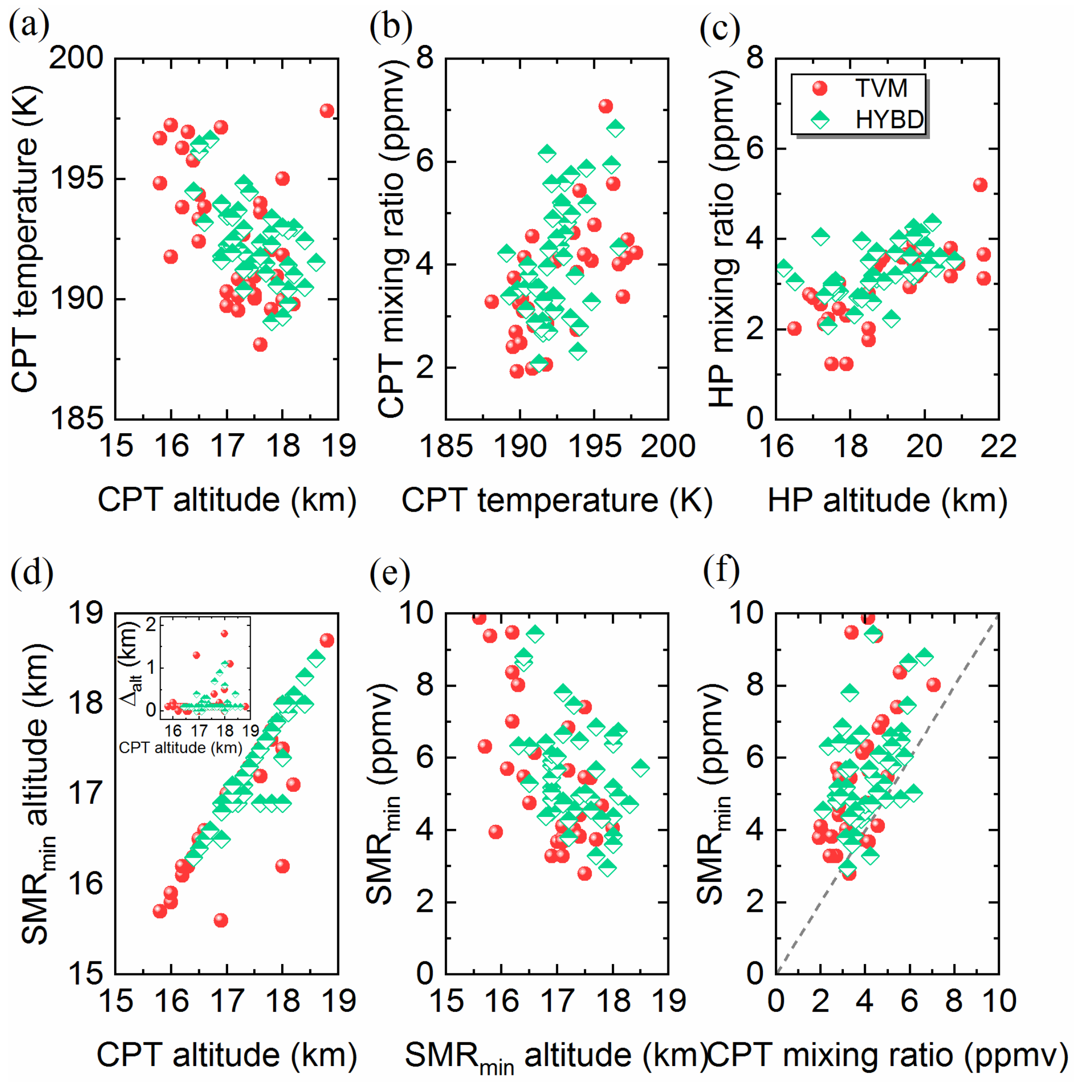
Tape Recorder Signal



- ❖ Tape recorder signal is highly disturbed in the region 16- 21 km.

Emmanuel et al., Climate Dynamics, 2023

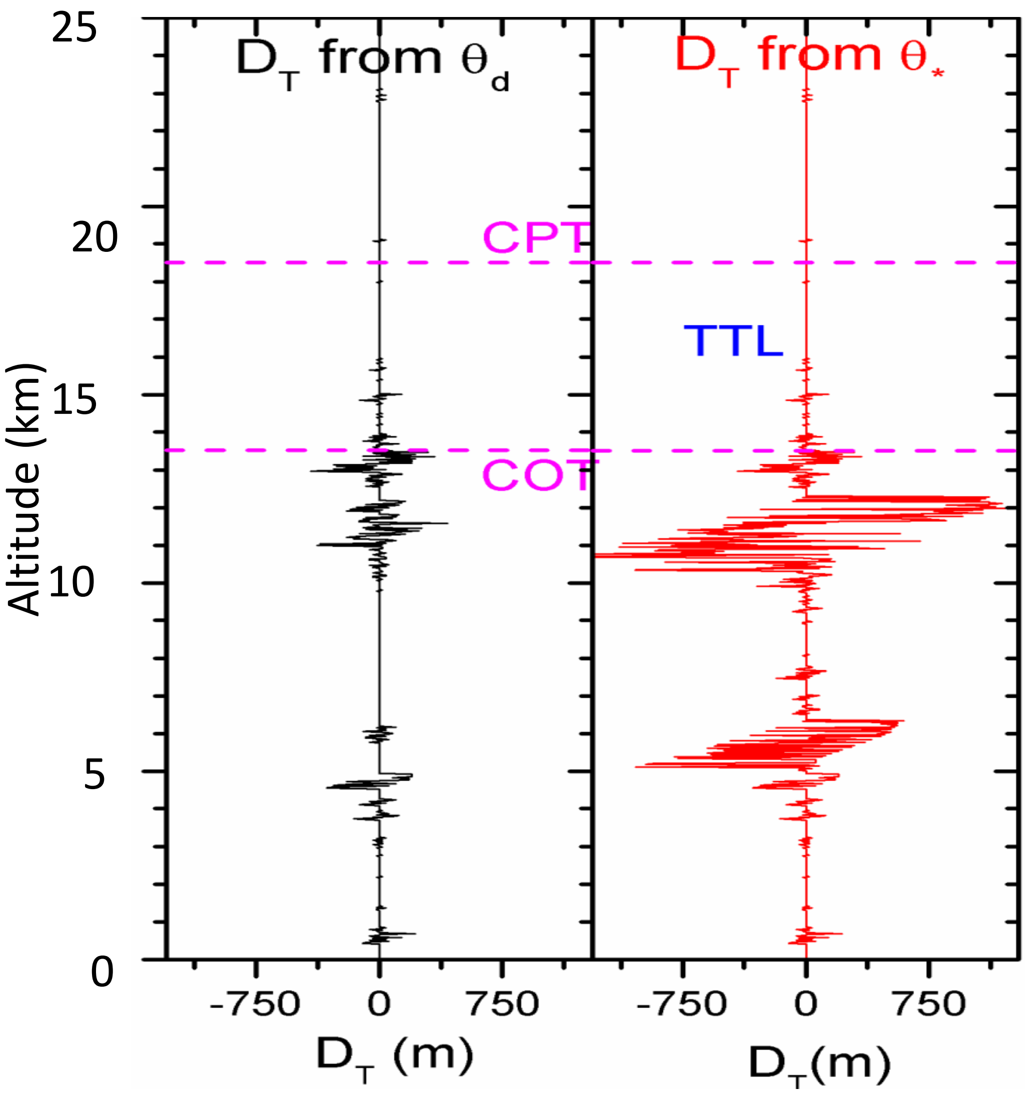
Effect of Tropopause dynamics



Emmanuel et al., Climate Dynamics, 2023

- CPT temperature & CPT altitude shows a moderate negative correlation coefficient (-0.4to -0.6)
- WVMR at CPT varies in the range ~2-5 ppmv and increases with increase in CPT temperature
- WVMR at hygropause increases with hygropause altitude.
- Minimum in Saturated Mixing Ratio (SMR_{min}) is situated below the Hygropause and CPT in summer profiles and above the Hygropause but below the CPT in winter profiles
- Altitude separation between CPT and SMR_{min} is smaller in summer profiles than that in winter.
- SMR_{min} altitude is usually lower than the CPT altitude.
- The SMRmin and SMRmin-altitude shows a negative correlation (Fig. 5e) similar to the CPT altitude and temperature
- Though the CPT WVMR increases with increase in SMR_{min}, it is mostly less than the corresponding SMR_{min} value, leading to the inference that freeze drying in the tropopause region is mainly controlled by the temperature itself (SMR is a function of temperature and ambient pressure).

Turbulence detection from Radiosonde data



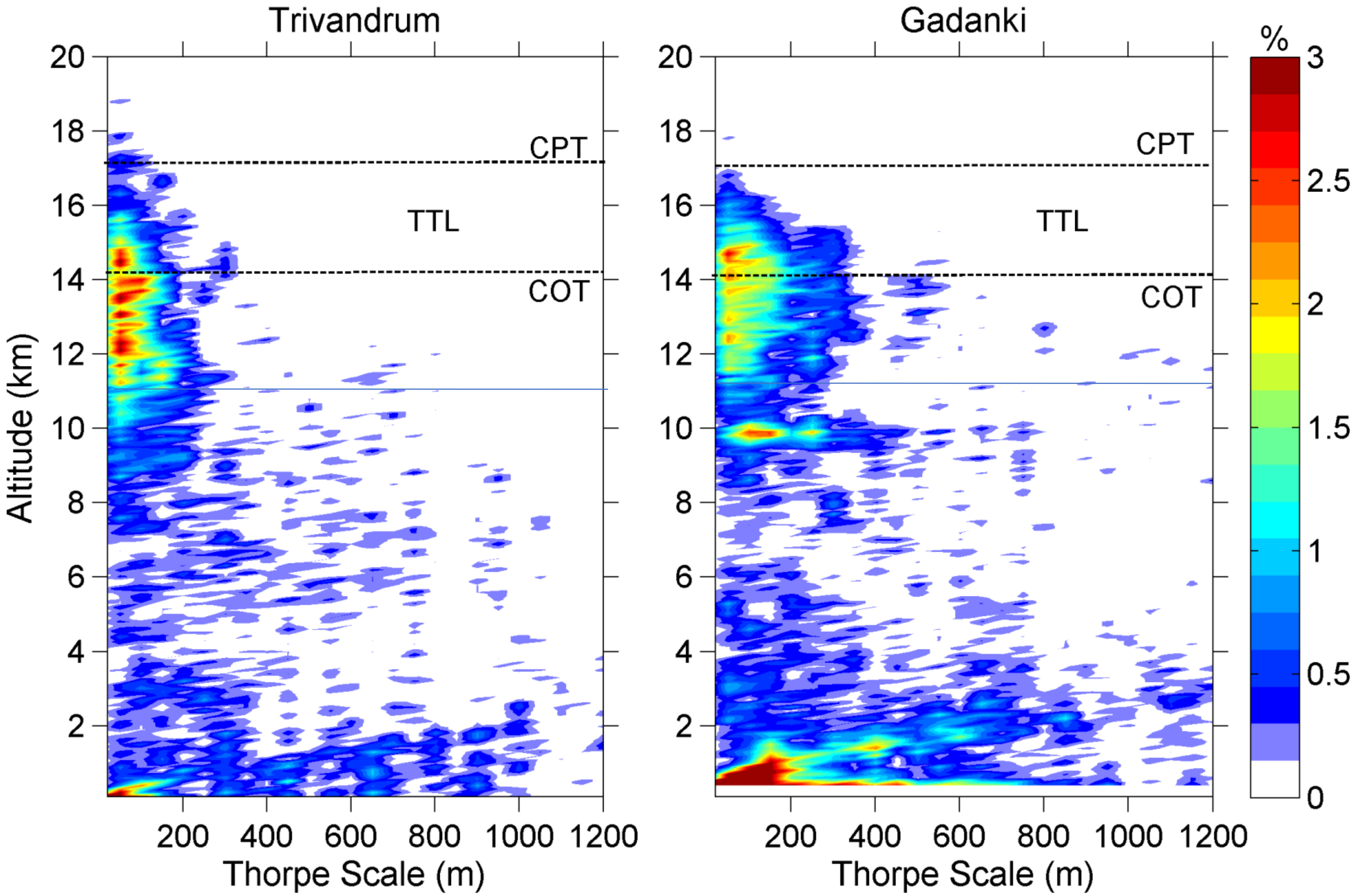
- ***Thorpe method*** ***(Thorpe, 1977; Clayson and Kantha, 2008)***
- ***Effect of Measurement Noise and moisture taken care***

Thorpe scale or Thorpe length $L_T = \langle D_T^2 \rangle^{1/2}$

D_T: Thorpe Displacement

Sunilkumar et al., JASTP, 2015

Turbulence: Radiosonde

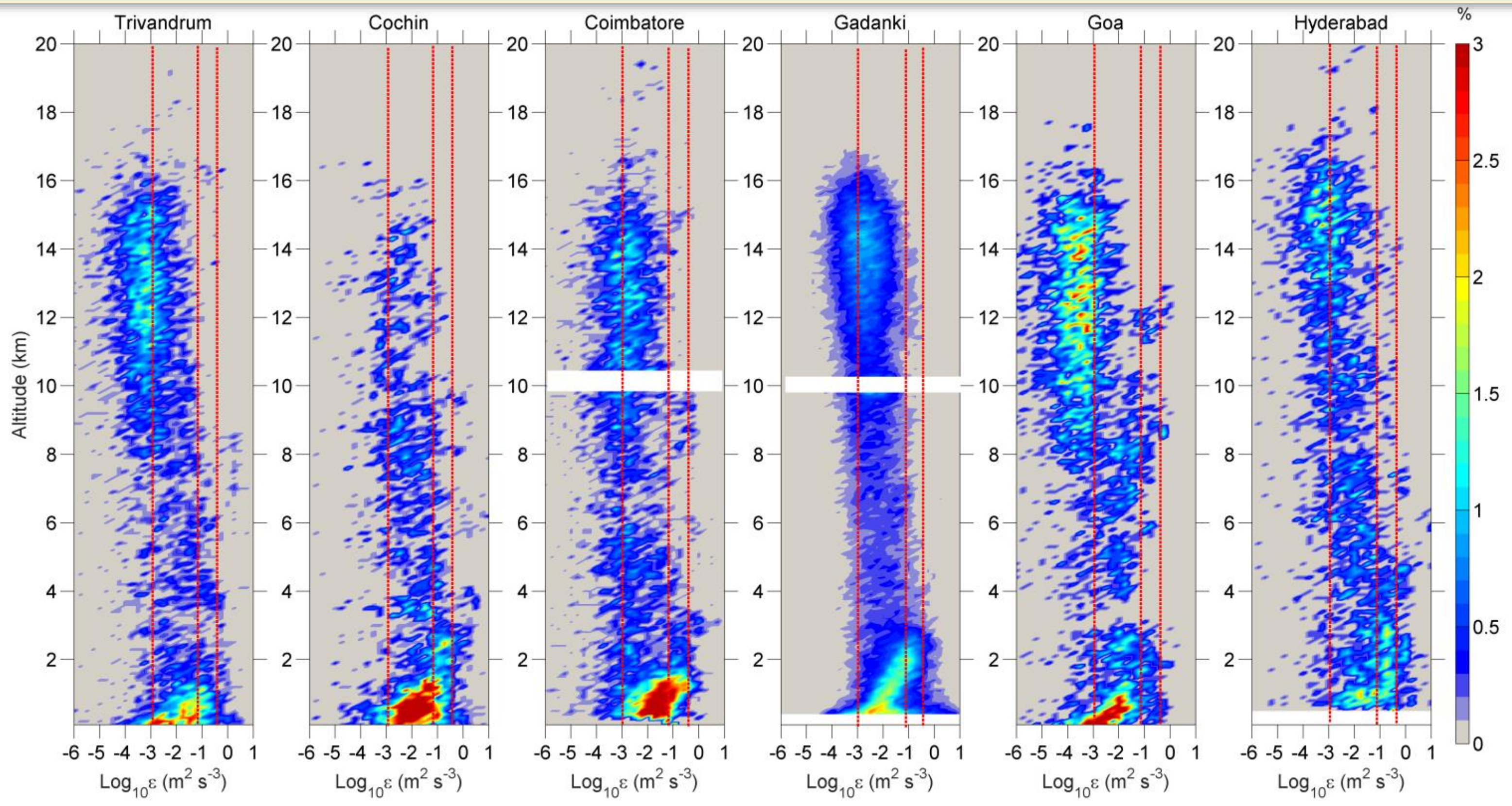


Thorpe Scale: a measure of turbulence length scale

Data: TTD [CAWSES –Phase-II] Sunilkumar et al., JASTP, 2015

Muhsin et al., Atmos Res., 2016

Contour Frequency Altitude Diagram(CFAD) of **Turbulent kinetic energy dissipation rate (ε)**



- In general, the turbulence occurrence frequency is relatively high in the lower troposphere and the 10–15 km altitude region and low in the3–8 km altitude region.
- In the altitude region 10-15 km, the occurrence of turbulence is less over Cochin compared to other stations.
- Over Cochin, even though the occurrence of turbulence is less in the altitude region of 10-15 km, the turbulence is strong in this region compared to other stations.

Muhsin et al., JASTP, 2020

Eddy dissipation rate (EDR) = $\varepsilon^{1/3}$

Percentage

Turbulence Intensity classification		TVM	CoN	CMB	Goa	HYD	GAD
No Turbulence	EDR < 0.1	53	23	35	69	41	31
Light	0.1 < EDR < 0.4	45	66	59	26	53	63
Moderate	0.4 < EDR < 0.7	1.5	9	4	4	4.5	5
Severe	EDR > 0.7	0.5	2	2	2	1.5	1

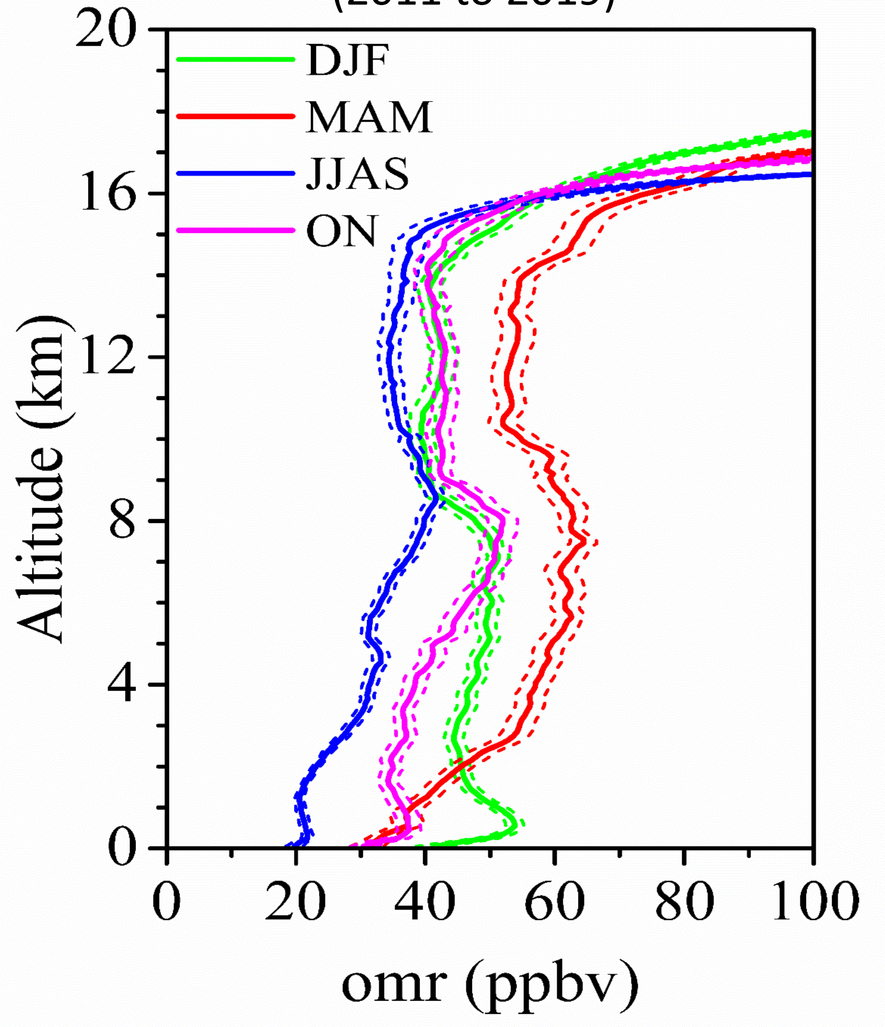
These observations have significant implications for the aviation industry.

(*ICAO*, 2007).

Variability of Ozone@ Trivandrum: Altitude and Seasonal distribution

Seasonal mean Ozone Mixing Ratio (OMR)

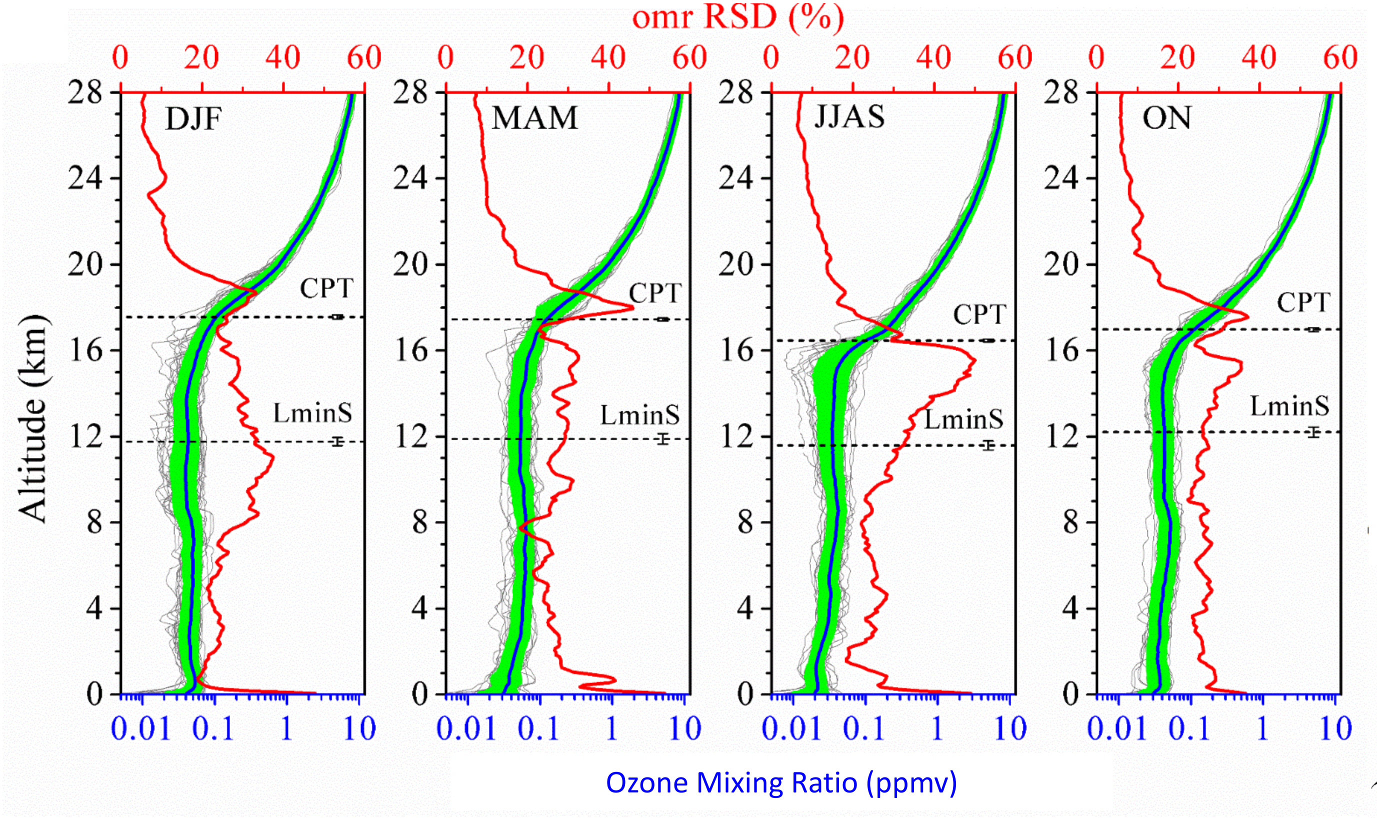
(2011 to 2019)



- ❖ Ozone concentration,
  - In the lower troposphere, highest in winter (~ 50 ppbv) and lowest in summer monsoon (~20 ppbv)
  - In the free troposphere, highest in pre-monsoon and lowest in monsoon
- ❖ Maximum difference (~30 ppbv) in the 3-10 km region

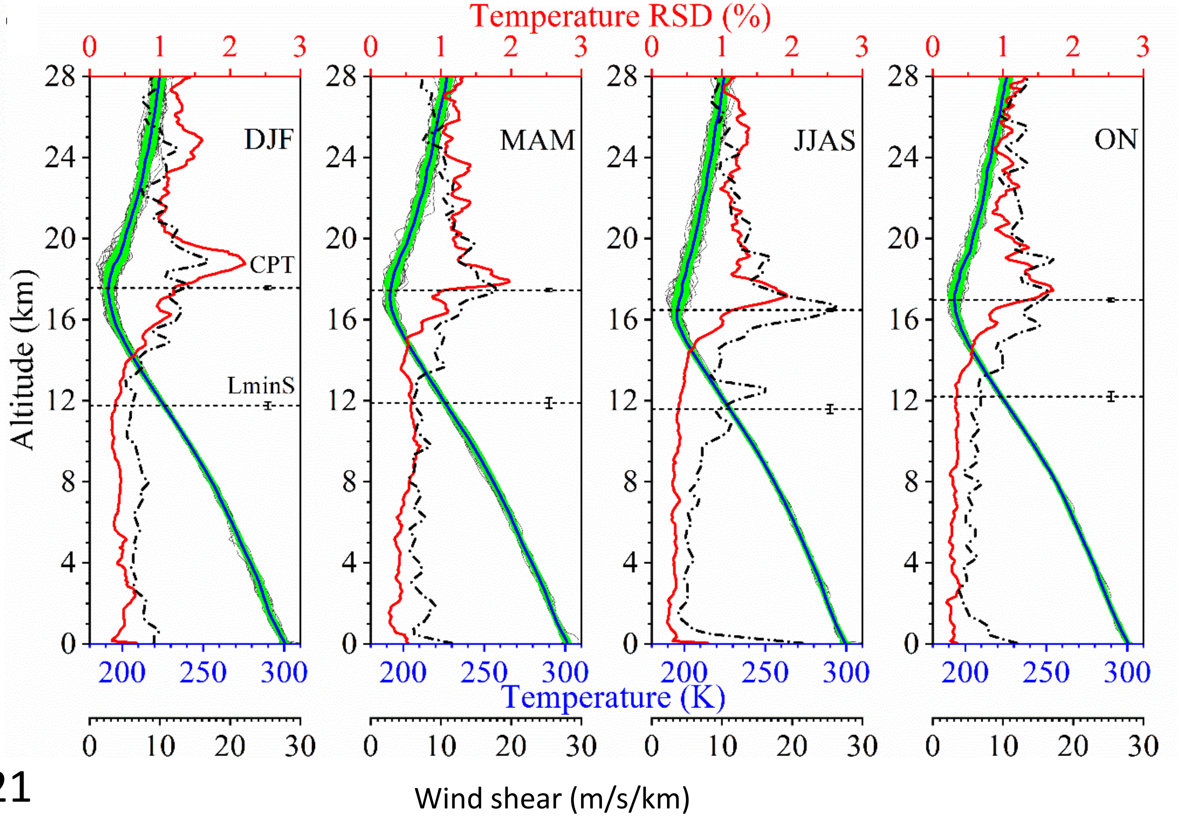
Satheesh Chandran et al., 2021

Seasonal mean ozone profiles



- Intra seasonal variability of ozone and temperature in the TTL
  - RSD peaks near the cold point tropopause (CPT).
  - O3 shows highest variability (RSD ~ 50%) in UT during summer monsoon
- Large variability observed concurrently in ozone and temperature just above the CPT could be associated with the shear induced turbulence

Seasonal mean temperature profiles

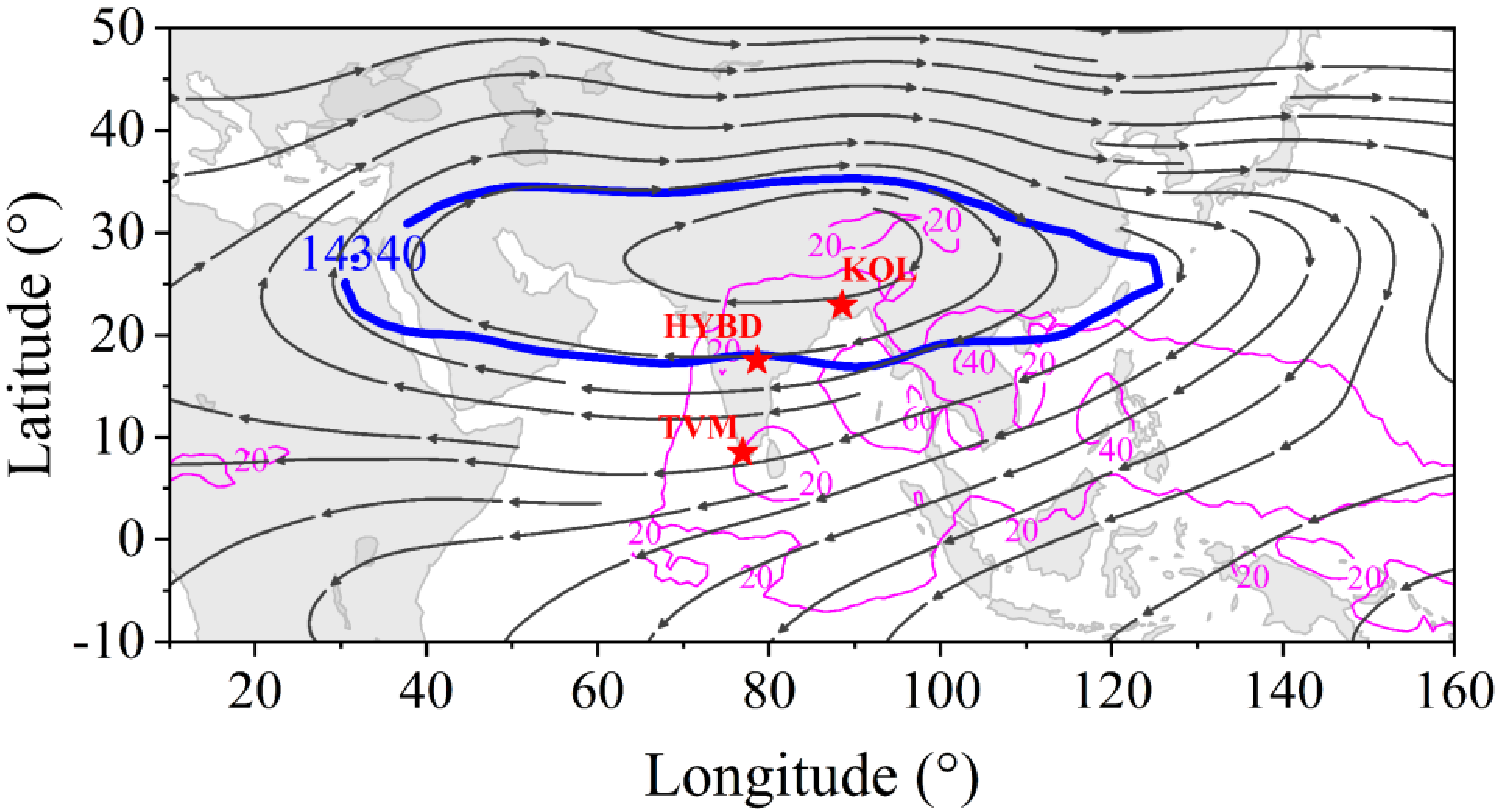


Thin gray lines – Individual profiles
Blue line –Seasonal mean profile
Green shade-Standard deviation of mean
Red line – Relative Standard Deviation (RSD) = *[(Std.dev / Mean)*100] %.*

Black dash dot line- vertical shear in horizontal wind

Satheesh Chandran et al., 2021

Variability of ozone in the UTLS across the Asian Summer monsoon region



Spatial map of seasonal mean horizontal wind at 150 hPa (streamlines) and boundary of ***Asian summer monsoon anticyclone (ASMA)*** *depicted by 14340 m geopotential height (GPH) contour (blue solid line). Ozonesonde launch stations are marked as red stars. The magenta contour indicates the occurrence frequency of outgoing longwave radiation (OLR)< 190 W/m2, representing the locations of deep convection.*

Effect of circulation change associated with El Niño and La Niña

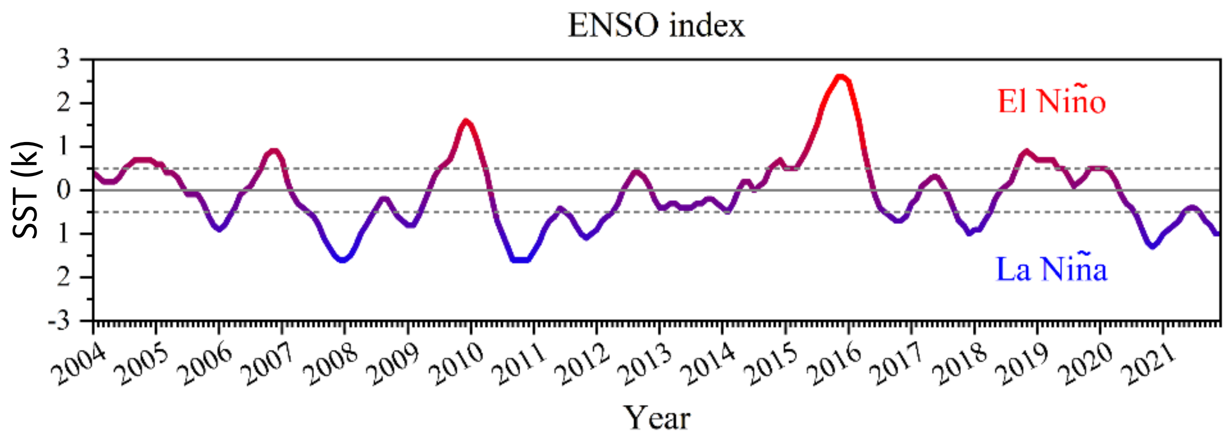
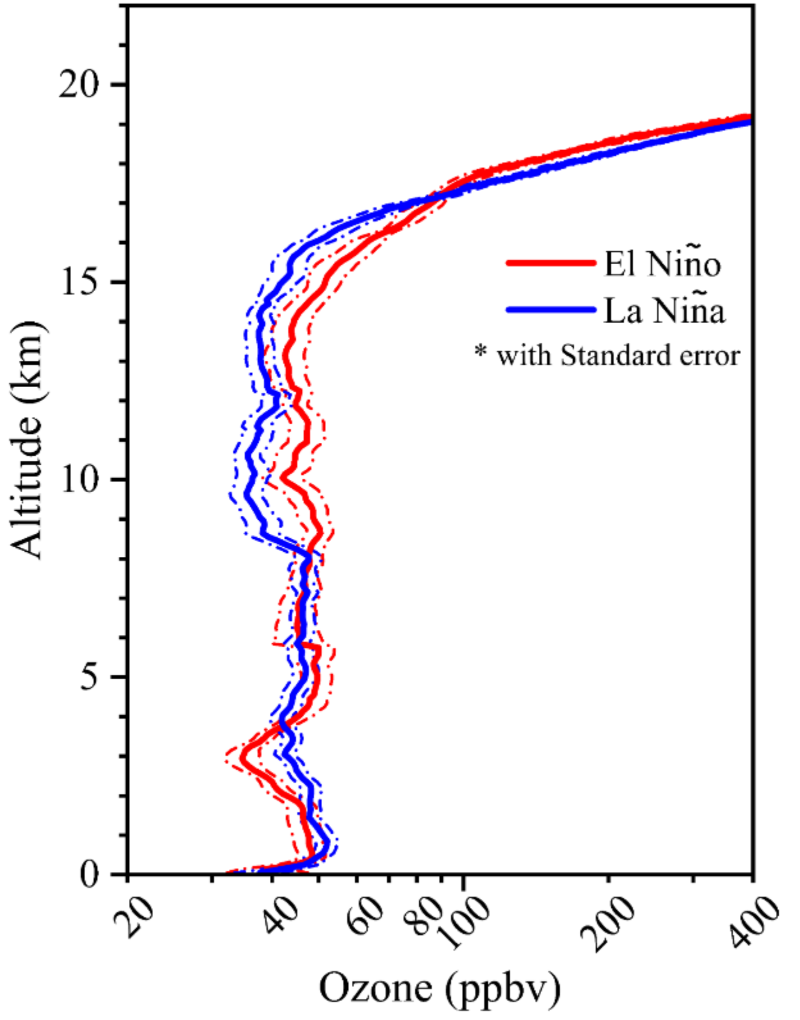


Figure 1: Time series of SST anomaly at Nino 3.4 region (> 0.5 K for El Niño and < 0.5 K for La Niña).

- In situ observations over Trivandrum (2011-2021) indicate a ~10 ppbv change in the upper tropospheric ozone.
- MLS observations over South Asian region shows significant ENSO response over the peninsular India, Bay of Bengal and southeast Asian sector in the UT (~5-15 ppbv). 30-40 ppbv change in ozone is observed in lower stratosphere



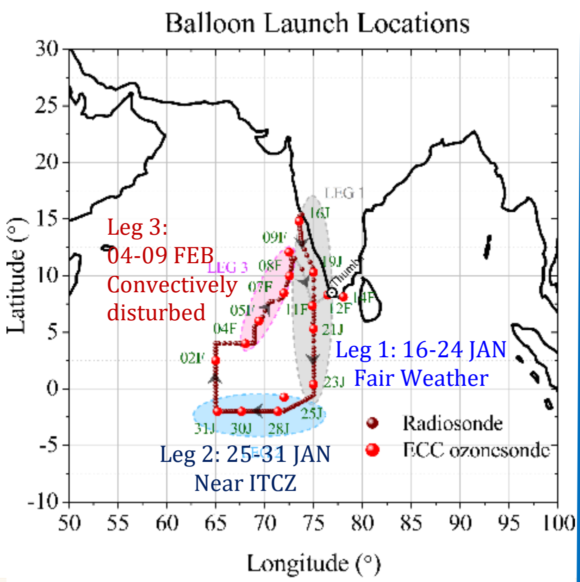
Mean ozone profiles with respective standard error during El Niño and La Niña winter over Thumba [period: 2011-2021].

Effect of Synoptic-scale dynamics on the vertical distribution of Tropospheric Ozone over the Arabian Sea and the Indian Ocean during the boreal winter of 2018

ICARB-2018 – Ship cruise

Onboard ORV Sagar Kanya

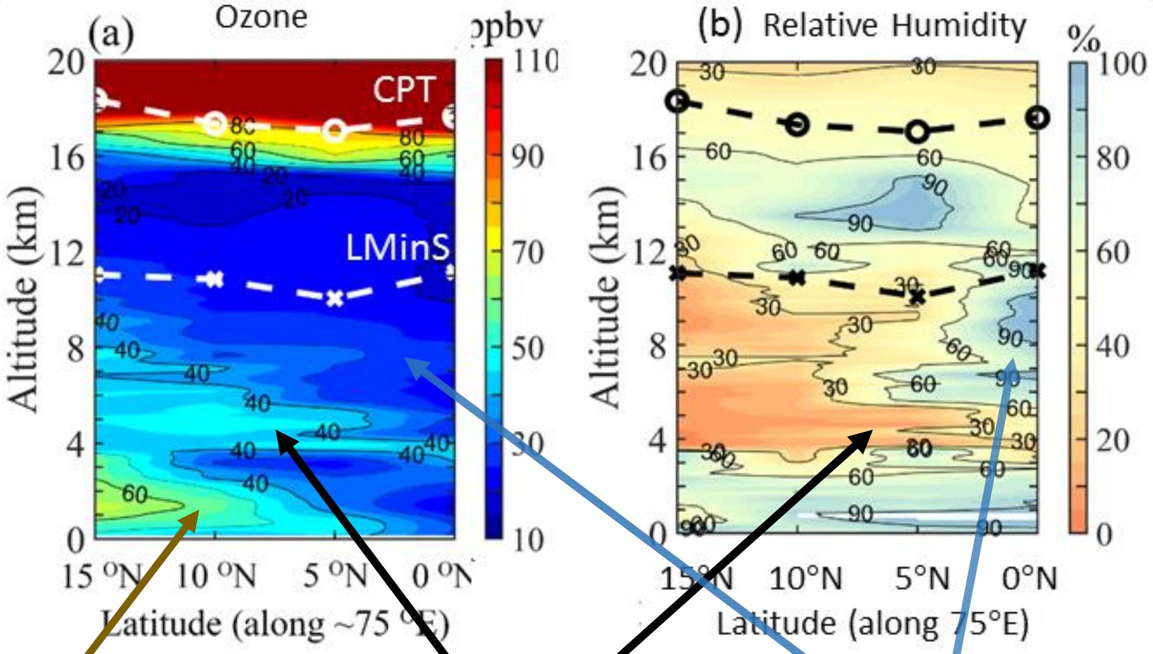
16 January-14 February 2018



Balloon Soundings Experiments

- 163 Radiosonde Flights
- 17 Ozonesonde Flights

Influence of atmospheric circulation on mid-tropospheric Ozone



Continental outflow of polluted air caused the ozone rich plume structure around 1–3 km over the pristine oceanic region

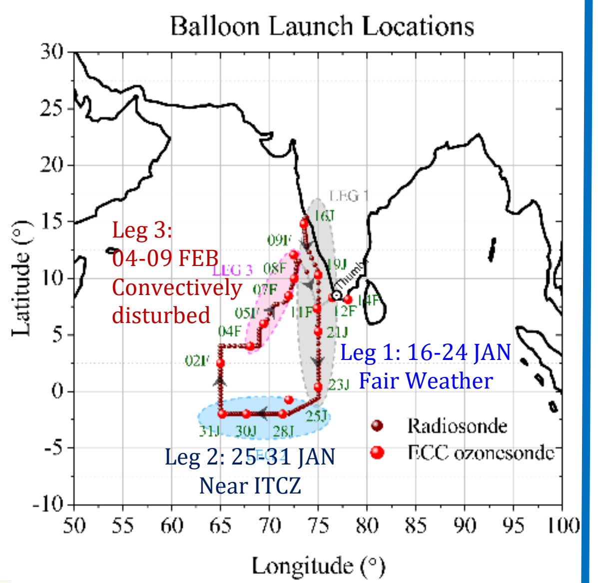
Mid-tropospheric (~ 4–5 km) tongue of ***High Ozone Low Water-vapour* (HOLW)** structure extending to the equator is hypothesized to be associated with the equatorward return flow of the Hadley circulation.

Low ozone (<20 ppbv) and high RH (>80%) are observed at the ascending limb of the Hadley circulation.

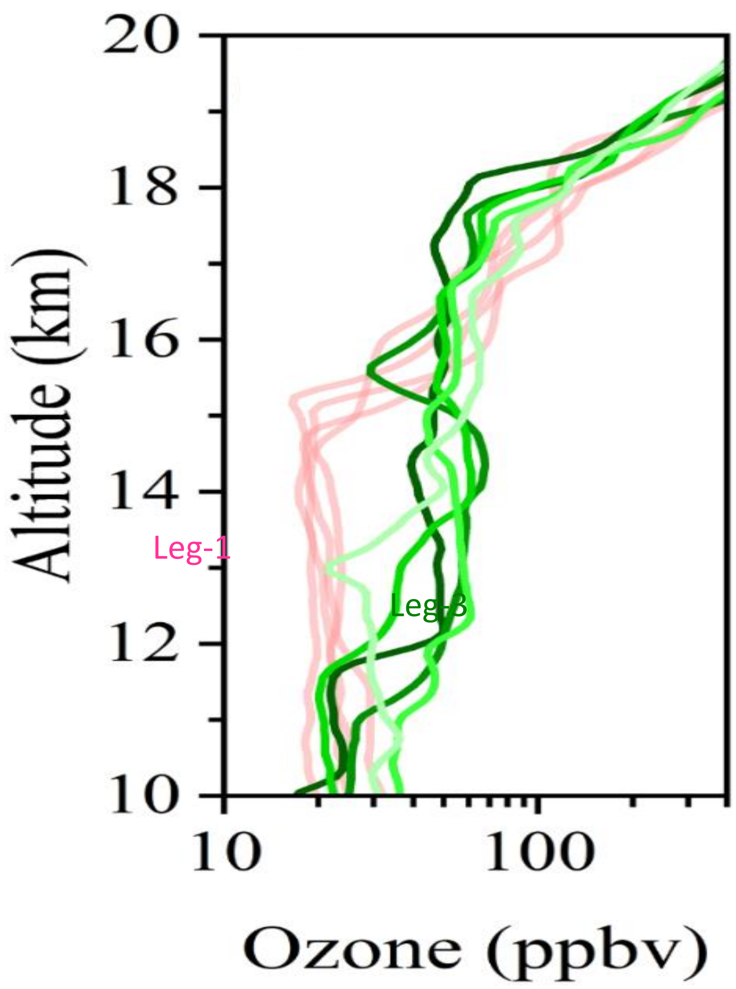
[Journal of Geophysical Research-Atmospheres, 10.1029/2021JD036412, 2022]

Effect of western disturbance on the upper tropospheric ozone

ICARB-2018 – Ship cruise
Onboard ORV Sagar Kanya
16 January-14 February 2018



Balloon Soundings Experiments
- 163 Radiosonde Flights
- 17 Ozonesonde Flights



Fair-weather conditions [Leg-1; 16-24 Jan 2018]
Western disturbance [Leg-3; 04-09 Feb 2018]

Enhancement of ozone (50–60 ppbv) in UT is due to Equator-ward intrusion of high PV and strong subsidence associated with western disturbance.

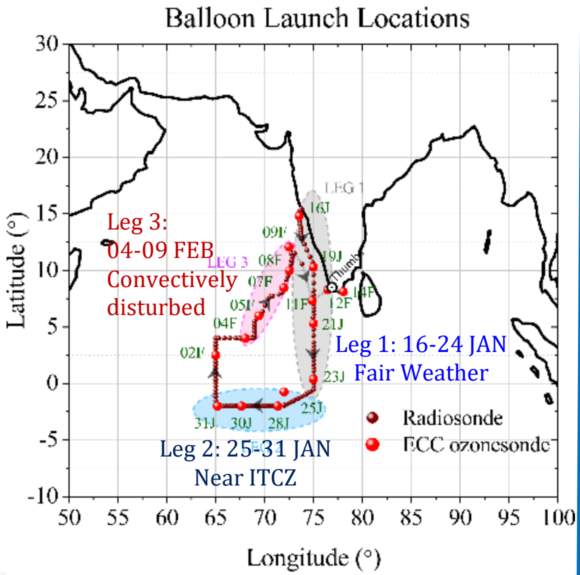
[Journal of Geophysical Research-Atmospheres, 10.1029/2021JD036412, 2022]

Upper Tropospheric Inversion (UTI) over the Indian Ocean during 2018 winter

ICARB-2018 – Ship cruise

Onboard ORV Sagar Kanya

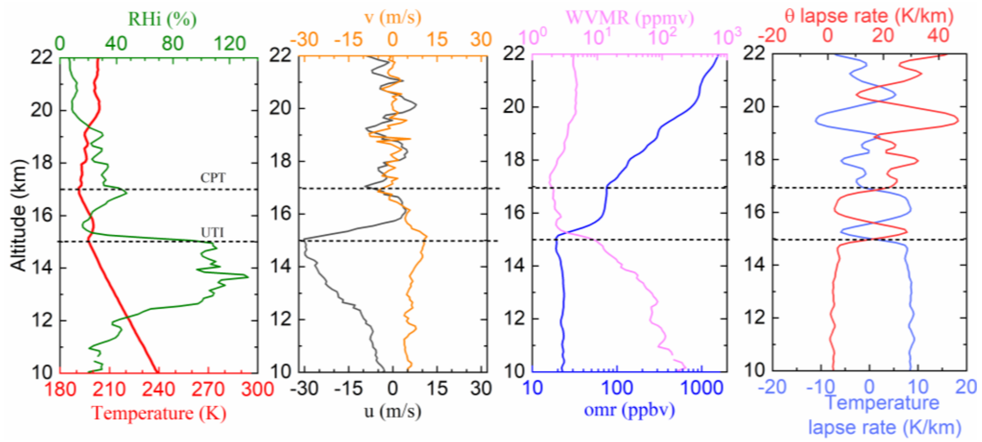
16 January-14 February 2018



Balloon Soundings Experiments

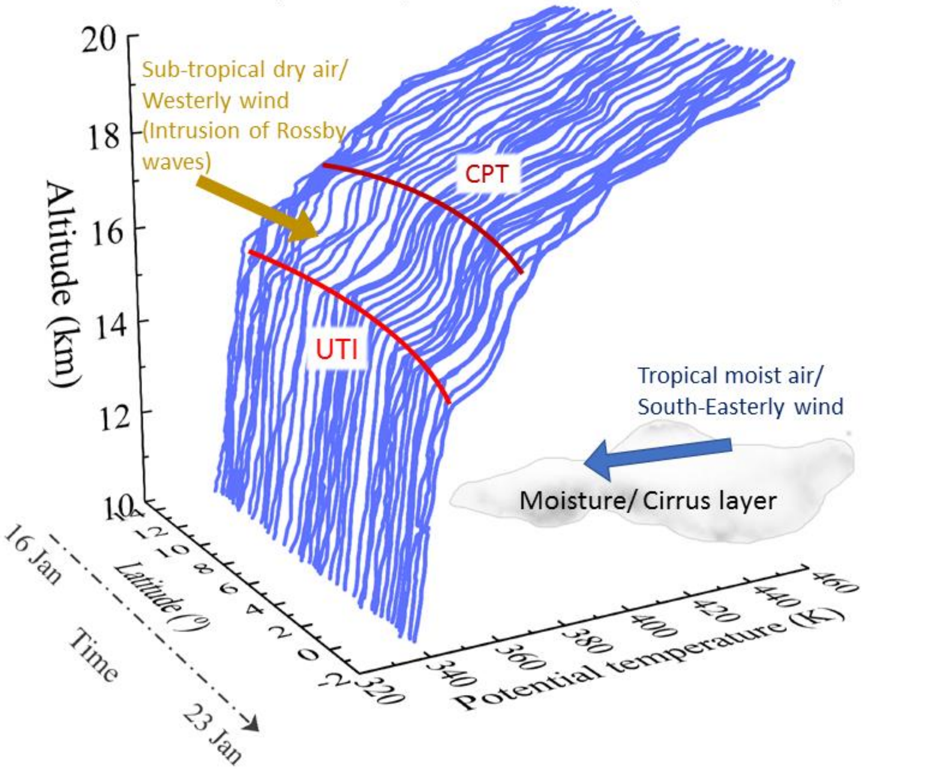
- 163 Radiosonde Flights
- 17 Ozonesonde Flights

Typical Profile



- Persistence of a sharp thermal inversion layer in the upper troposphere (UTI) in the latitude sector 12°N to 2°S over the Indian Ocean during winter 2018
- UTI layer having thickness of ~300 m around 15 km altitude (warming of about 2 K) is found to be situated on the top of a ~2 km thick moist layer.
- The study shows that the UTI magnitude is a result of the combined influence of radiative cooling due to the tropical moist air and the overlaying warm subtropical air.

Potential Temperature (14 °N-2 °S; ~75 °E) [16-23 January 2018]

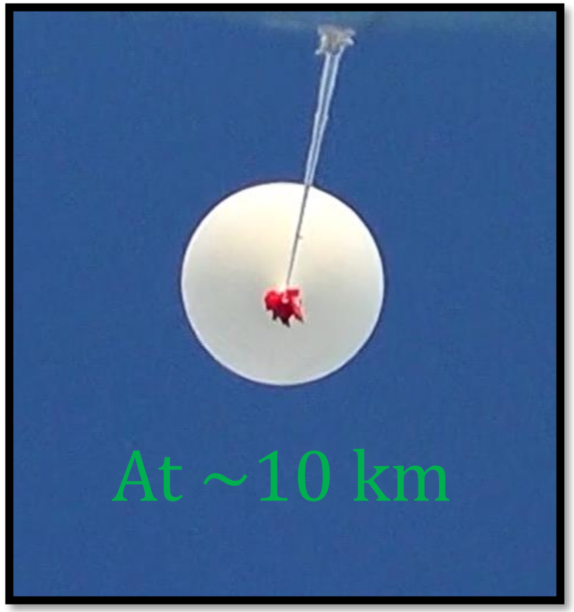


[Sunilkumar et al., Meteorology and Atmospheric Physics, 2023]

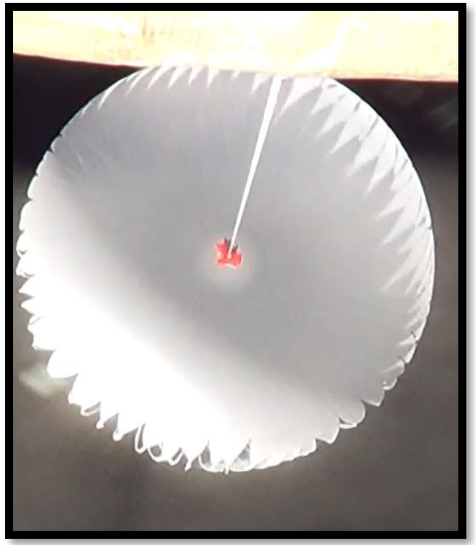
Conclusion

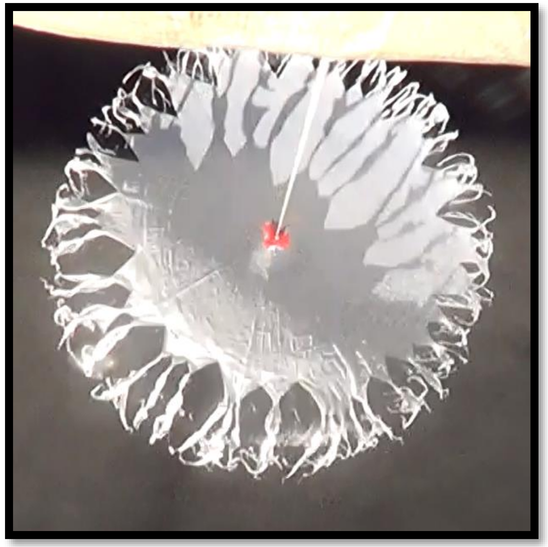
1) Investigations using GARNETS dataset has brought out quite a few interesting results and new insights in understanding the UTLS.
2) **Long term measurement of water vapour and ozone** : Direct measurements of atmospheric parameters in the UTLS region using balloon-borne sensors will be continued to address the scientific problems (Thematic campaign - Network of observations – Joint programs)
3) Further Investigations using in situ data along with models (e.g., **Lagrangian chemistry transport models**) &satellite /reanalysis dataset.

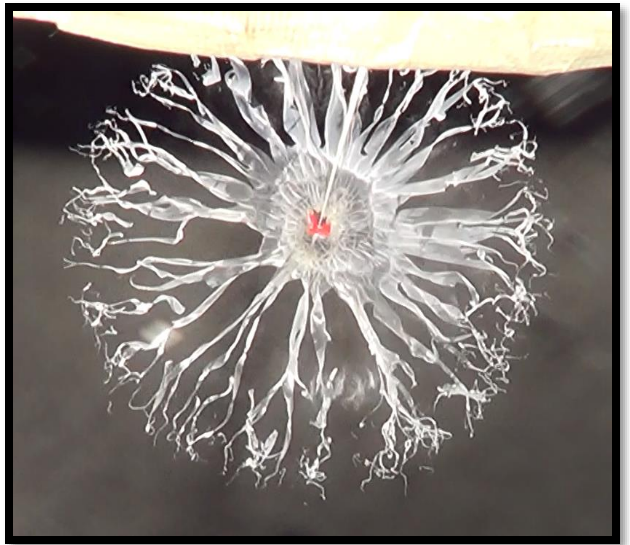
Journey of a balloon-from surface to the stratosphere (29 Oct 2015 over Hyderabad)

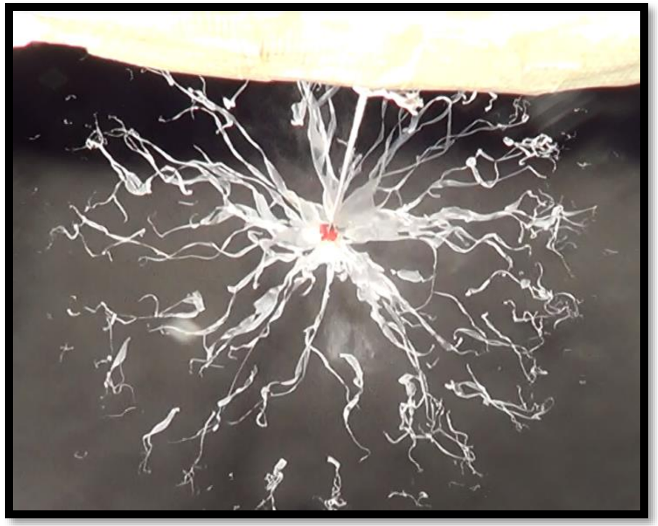


Balloon burst at ~29 km









Thank you