

Balloon Measurements of Cirrus Clouds Observed over Hyderabad during the BATAL Campaign



BATAL: Balloon measurement campaigns of the Asian Tropopause Aerosol Layer



(July-August
2014-2019)

Gadanki, India

Hyderabad, India

Varanasi, India

Thuwal, Saudi Arabia



Acknowledgements

- NASA UARP/ACMAP, ISRO, NASA NPP, and NIA for the funding support.
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Outline

- Background
- Motivation & Objectives
- Instruments Used for Ice Measurements during BATAL
- Balloon Flight of 23rd August 2017: A Tropopause Cirrus Cloud Layer
- Optical & Microphysical properties
- Formation Mechanisms
- Summary

Cirrus Clouds & their Formation Mechanisms



Cirrus: Latin word meaning curl of hair.
(First named by Luke Howard in 1802).

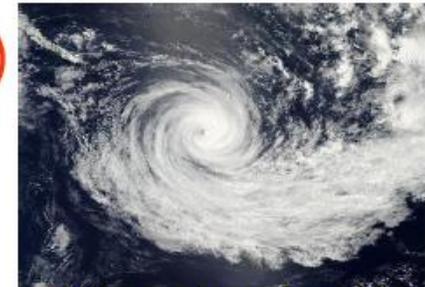
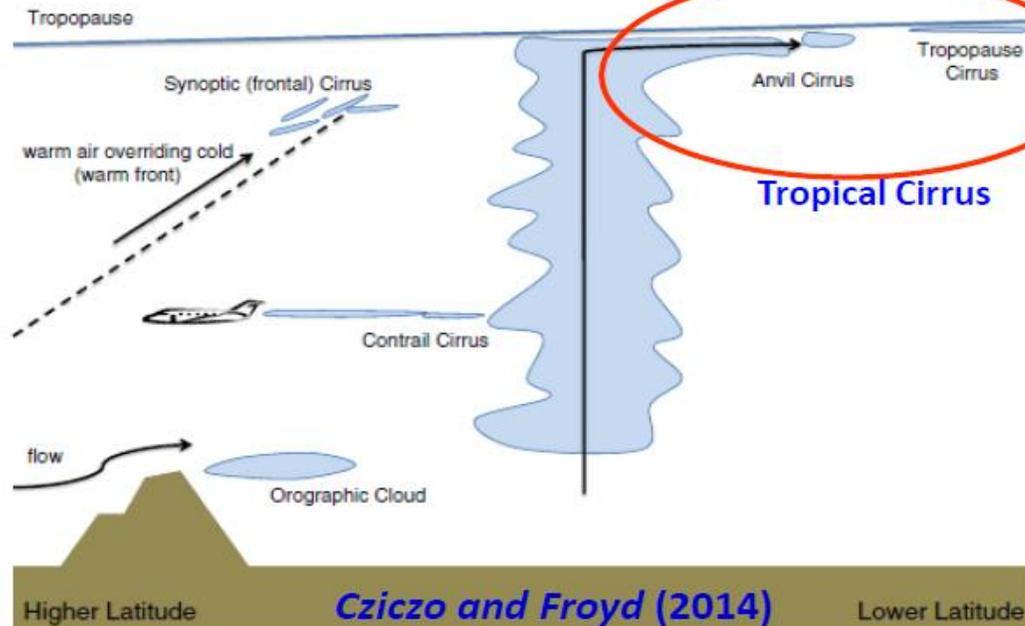
Property	Mean	Range
Altitude (km)	9.0	4.0 to 20.0
Temperature (°C)	-50	-20 to -80
Thickness (km)	1.5	0.1 to 8.0
Concentration (L ⁻¹)	30.0	10 ⁻⁴ to 10 ⁴
Ice content (gm ⁻³)	0.025	10 ⁻⁴ to 1.2
Crystal size (µm)	250	1 to 8000



<http://icons.wunderground.com/data/wximagenew/w/walcek/414-800.jpg>



<http://cosmicconvergence.org/wp-content/uploads/2013/09/plane.jpeg>



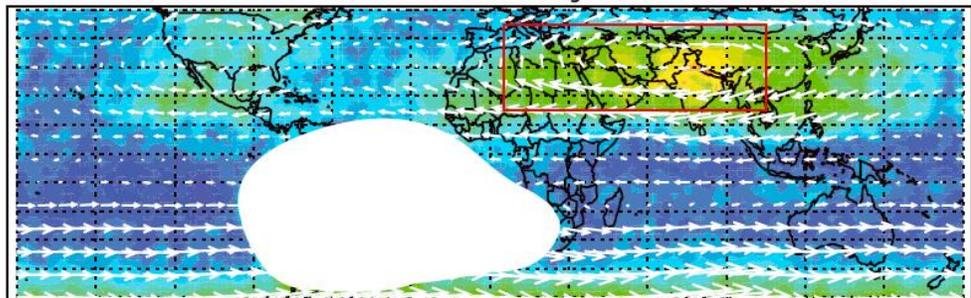
<http://images.scienceworldreport.com/data/images/full/296/tropical-cyclone-jasmine-seen-by-nasa-satellite.jpg?w=680>



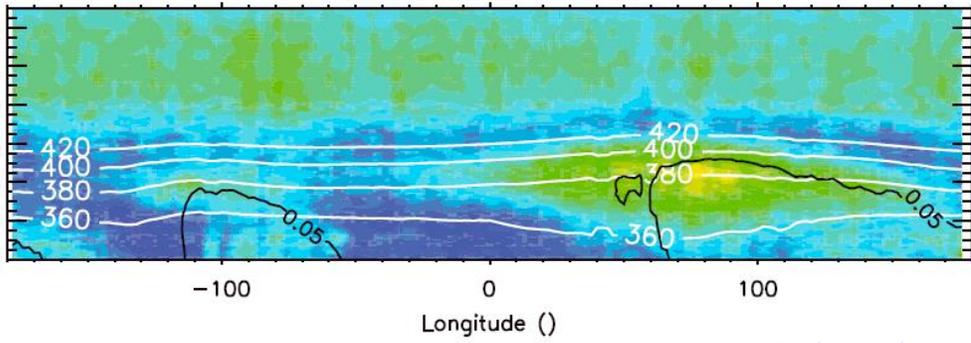
<http://i.stack.imgur.com/O2s15.jpg>

Background

b) CALIOP 15–17km Jul–Aug 2006–2013



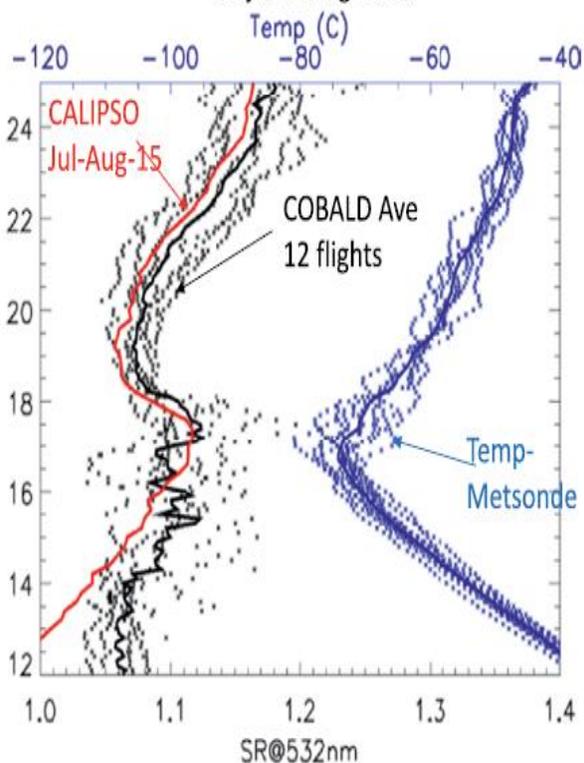
c) CALIOP Mean 15–45N



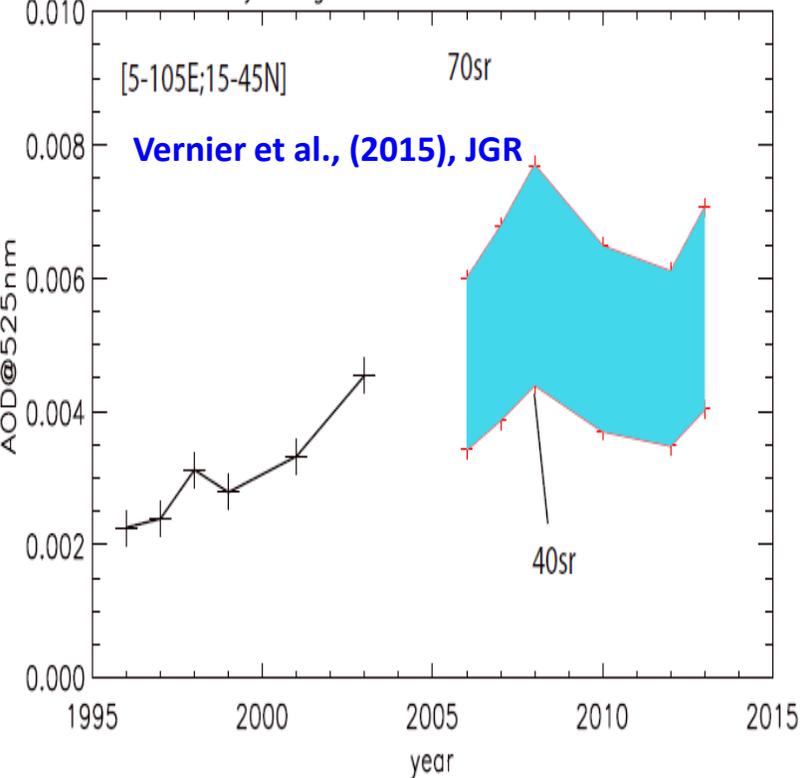
Vernier et al., (2015), JGR

SR@532nm

Gadanki-Hyderabad
17jul-13Aug 2015

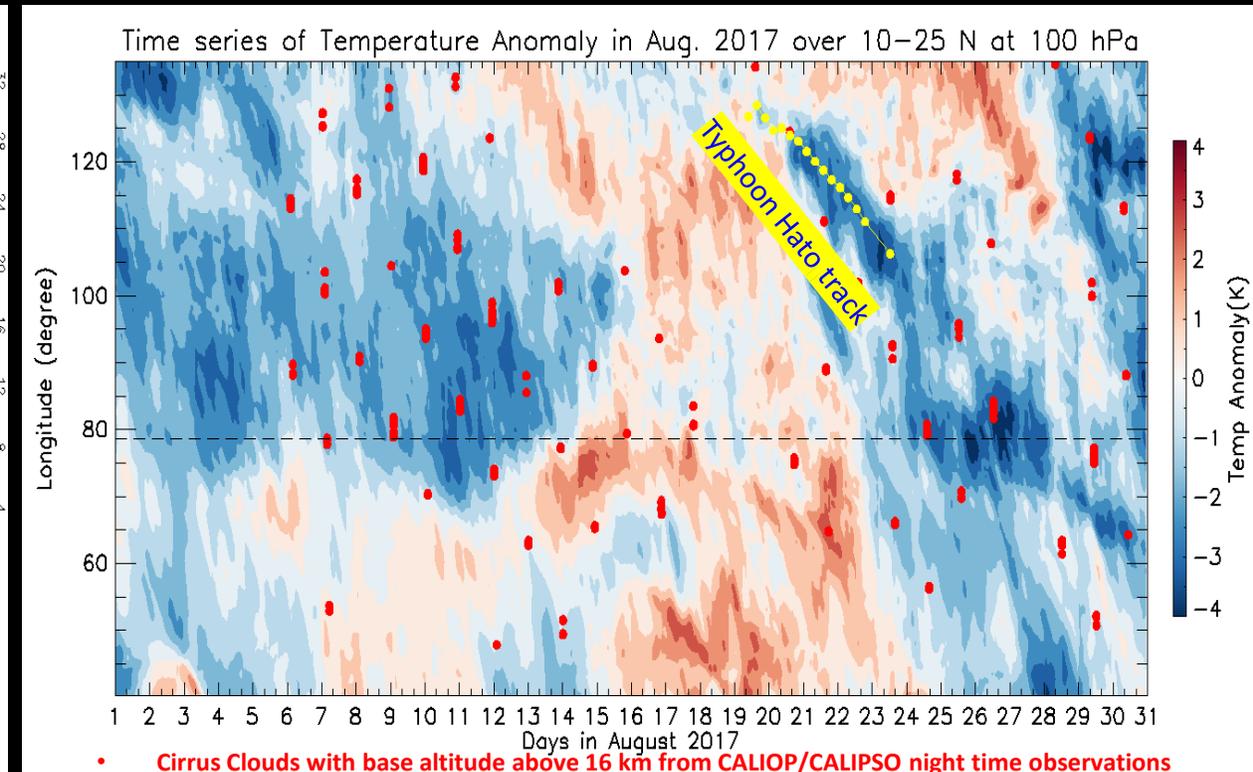
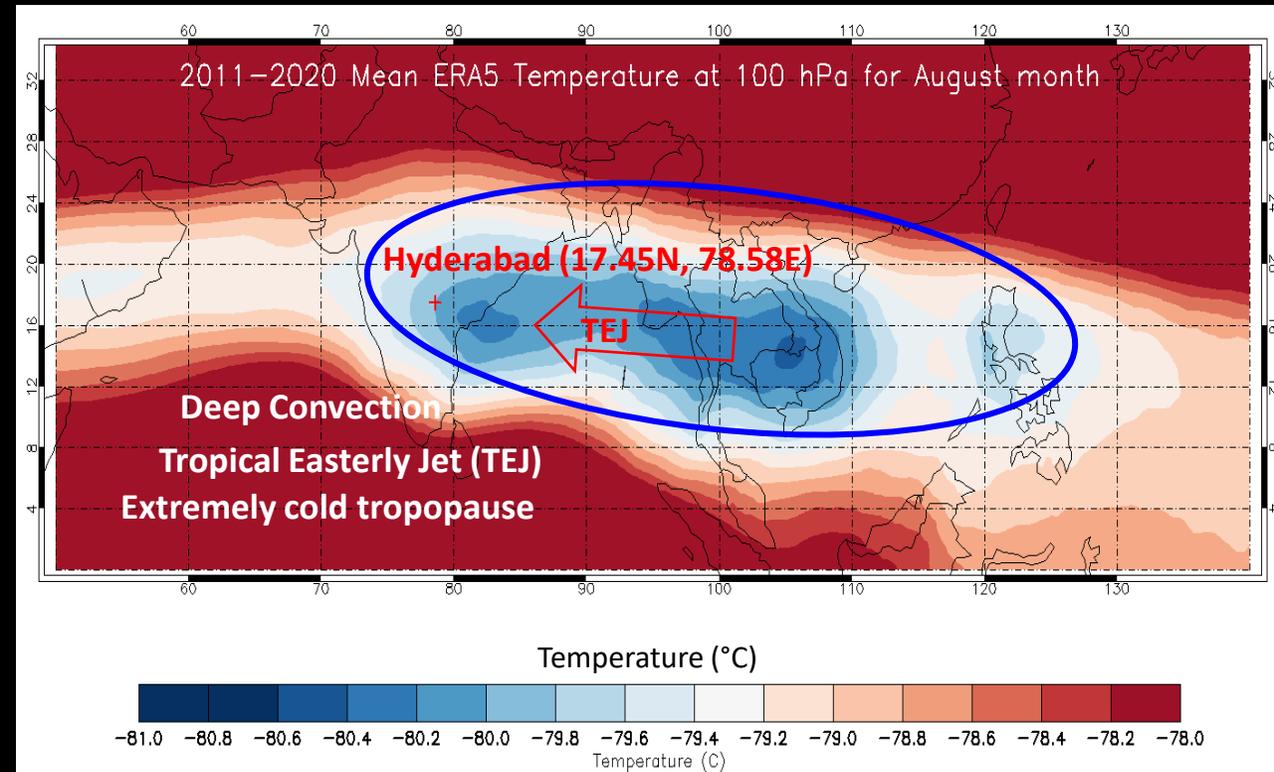


July–August AOD 13–18 km ATAL

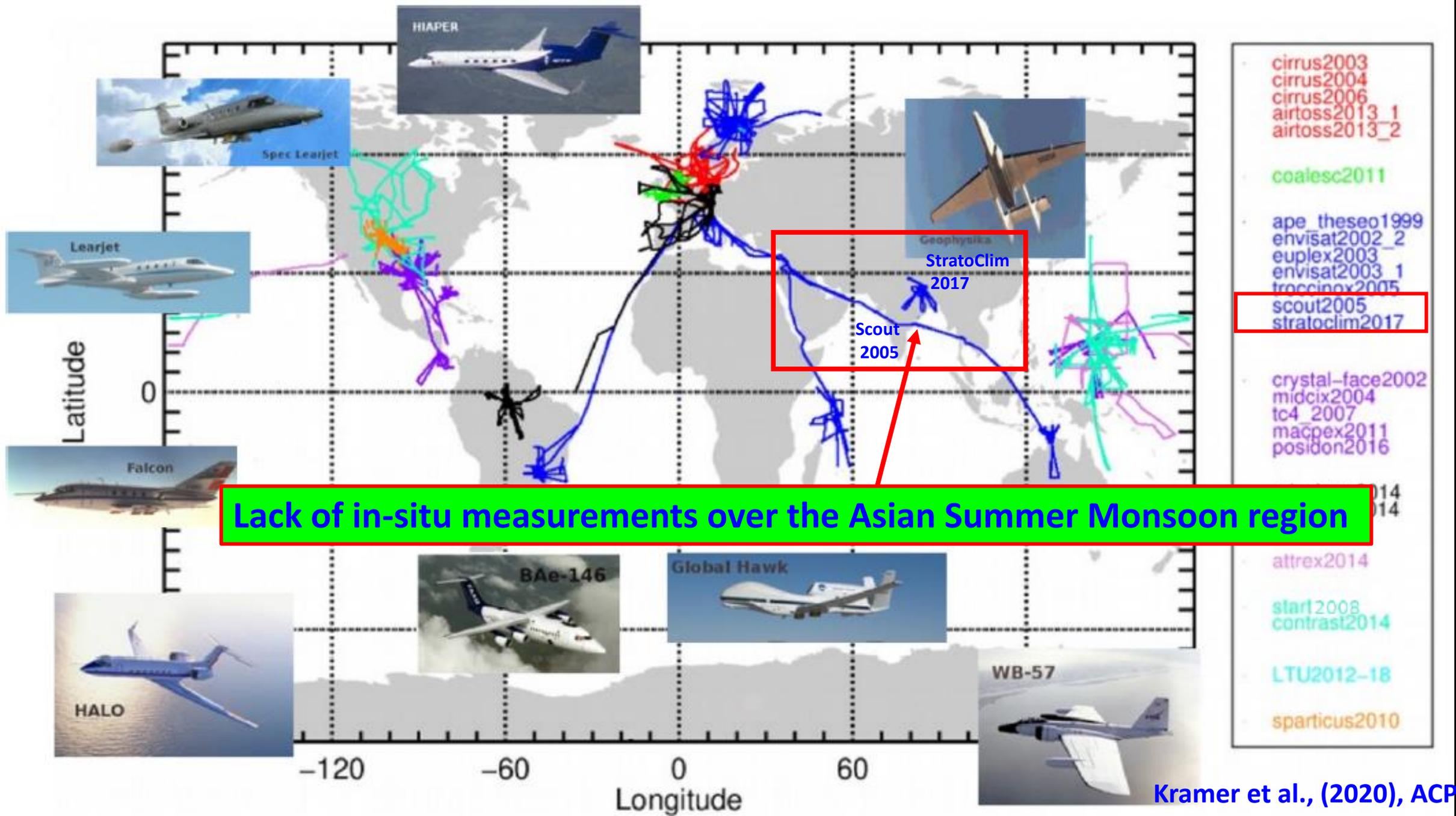


- Positive trends in the frequency of the occurrence of sub-visible cirrus cloud fraction observed by ground-based lidar in South India between 1998 and 2013 (Pandit et al., 2015) might be linked with the positive trends of aerosol optical depth over Asia during the same period (Vernier et al., 2015) and need to be further investigated.
- The discovery of ammonium nitrate within the ATAL region (Höpfner et al., 2019) during the StratoClim aircraft campaign yields new science questions regarding the interaction between ATAL and cirrus clouds in the UTLS. Recent cloud chamber studies suggest the potential of the rapid growth of ammonium nitrate aerosols nuclei at cirrus temperatures from ammonia and nitric acid droplets (Wang et al. 2019; Wagner et al., 2020).

Motivation and Objectives



- Number concentrations and shapes of ice-crystals smaller than 100 microns are uncertain (Heymsfield et al., 2017).
 - Past aircraft measurement results were influenced by shattering effects of ice-crystals.
 - Satellite derived (DARDAR) number concentrations are overestimated, and they do not represent thinnest cirrus clouds at cold temperatures (Krämer et al., 2020).
 - Lack of in-situ measurements of optical and microphysical properties of cirrus clouds over the Asian Summer Monsoon region.
- To obtain the in-situ measurements of cirrus cloud microphysical and optical properties over the Asian Summer Monsoon region using balloon borne sensors**



BATAL campaigns 2014-2019

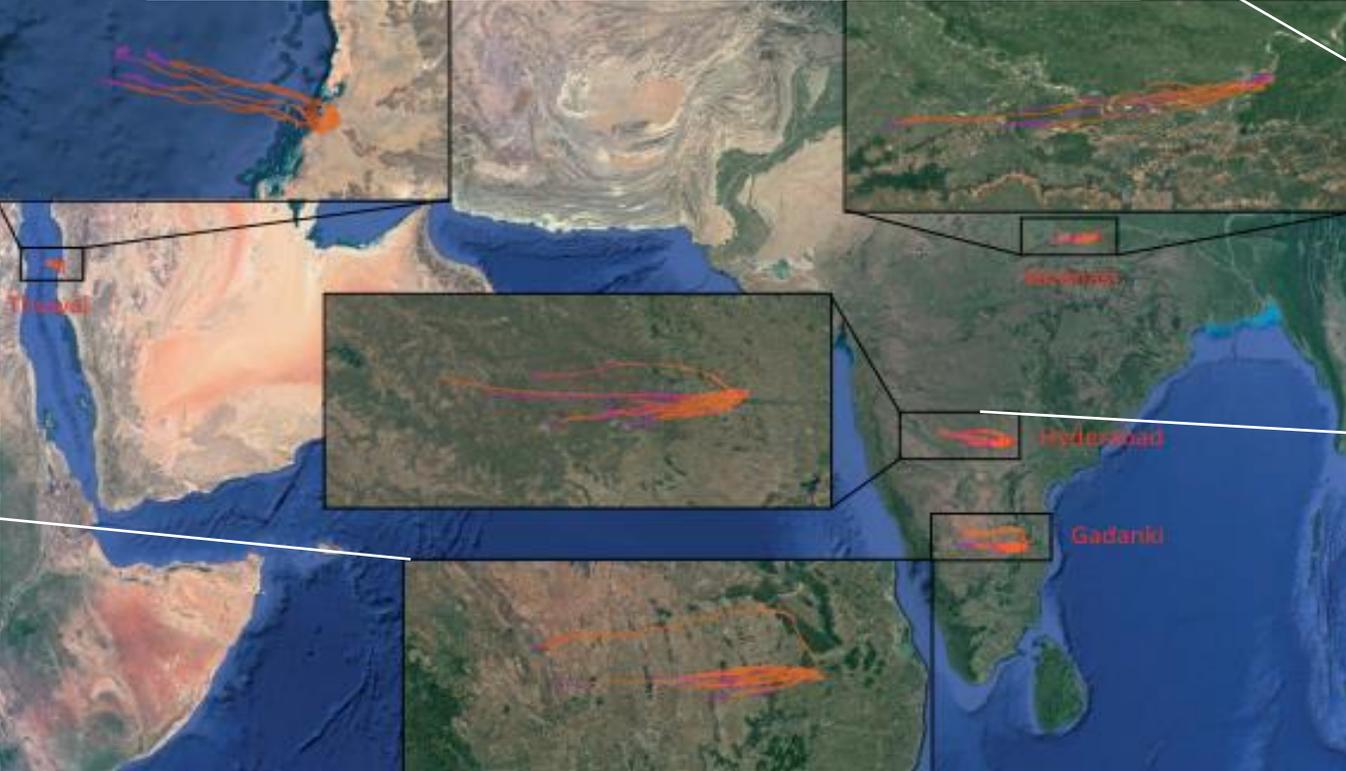
Balloon Trajectories: **Ascent**/**Descent** (2015)



King Abdullah University of Science and Technology (KAUST), Thuwal, Saudi Arabia



National Atmospheric Research Laboratory (NARL), Gadanki, India



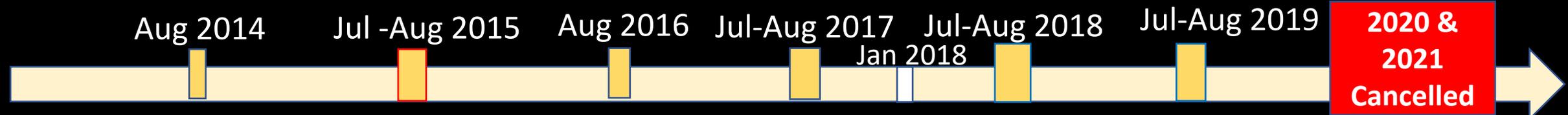
Banaras Hindu University (BHU), Varanasi, India



Tata Institute for Fundamental Research Balloon facility (TiFR)

- 6-year project 2014-2019
- 4 Launch locations (3 India, 1 Saudi Arabia)
- 12 Institutes Involved/ 6 Countries
- 101 Balloon Flights since 2014

Vernier et al., 2018, BAMS



Balloon-borne Instruments for Measuring Ice Crystals in Cirrus Clouds

iMet Radiosonde + COBALD (A Backscattersonde)



Meteorological parameters, GPS location, Backscatter ratio at 455 nm & 940 nm, and Color Ratio.

Boulder Counter- An Optical Particle Counter

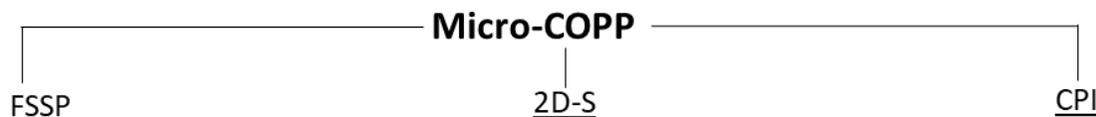


Particle counts @ 5, 10, 25, 40, 50 and 100 μm .
Flow at 28.3 LPM (1 CFM)
Sampling time: 5s

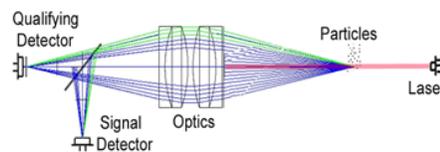
Micro-COPP



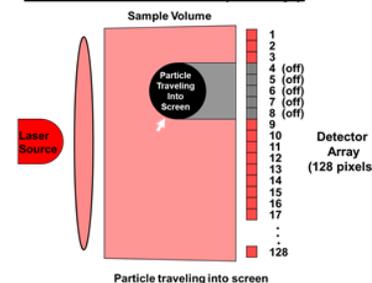
Micro-COPP: Heritage from Global Hawk payload used during ATTREX



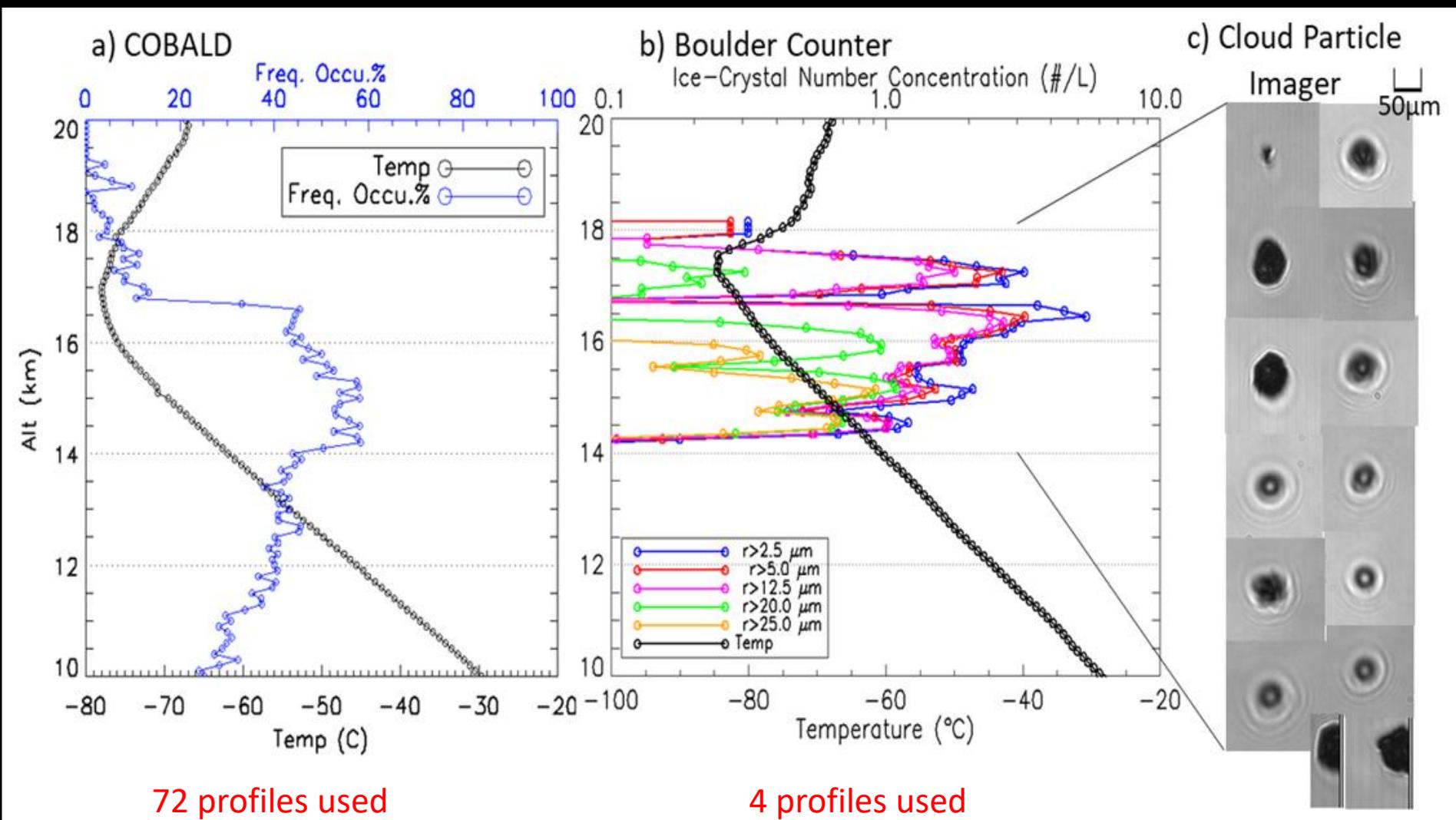
- FSSP**
 - Forward Scattering Spectrometer Probe
 - Size distribution and concentration of cloud particles
 - 1 to 50 μm over 20 bins
- 2D-S**
 - 2-Dimensional Optical Array Probe
 - size distribution, concentration, and area/extinction of cloud droplets, precipitation and ice crystals
 - Size range: 5 μm -1mm
 - 10 to 25 μm pixel resolution
- CPI**
 - Cloud Particle Imager
 - Digital camera
 - Up to 400 frames per second
 - Size range: 5 μm -1mm
 - Resolution 1 μm



128 - Detectors (Array)



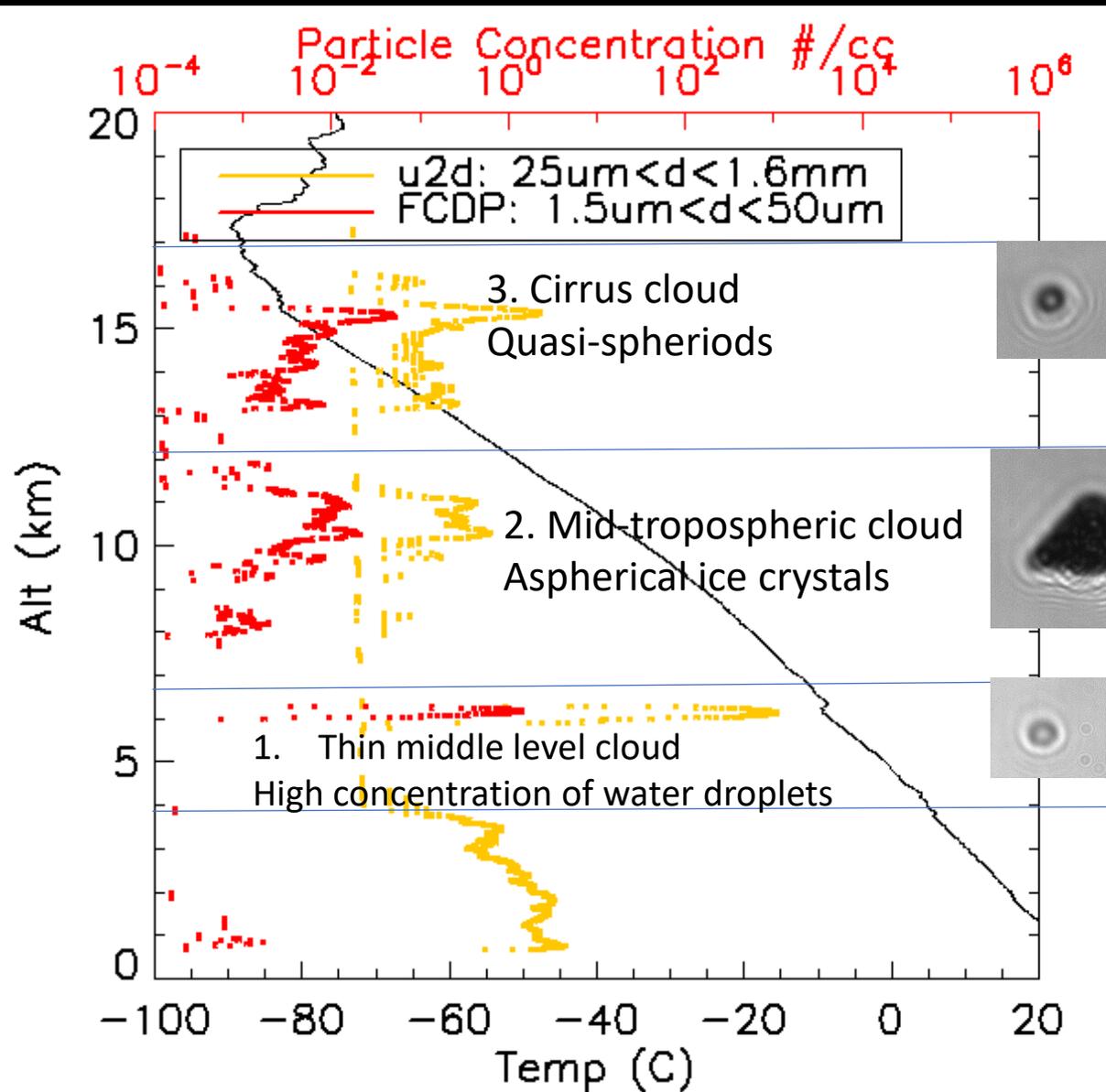
Occurrence Frequency, Number Concentration & Shape of Ice crystals



High occurrence of cirrus clouds near the cold-point tropopause (16-18 km) at extremely cold temperatures with quasi-spheroid ice-crystals smaller than 50 μm diameter.

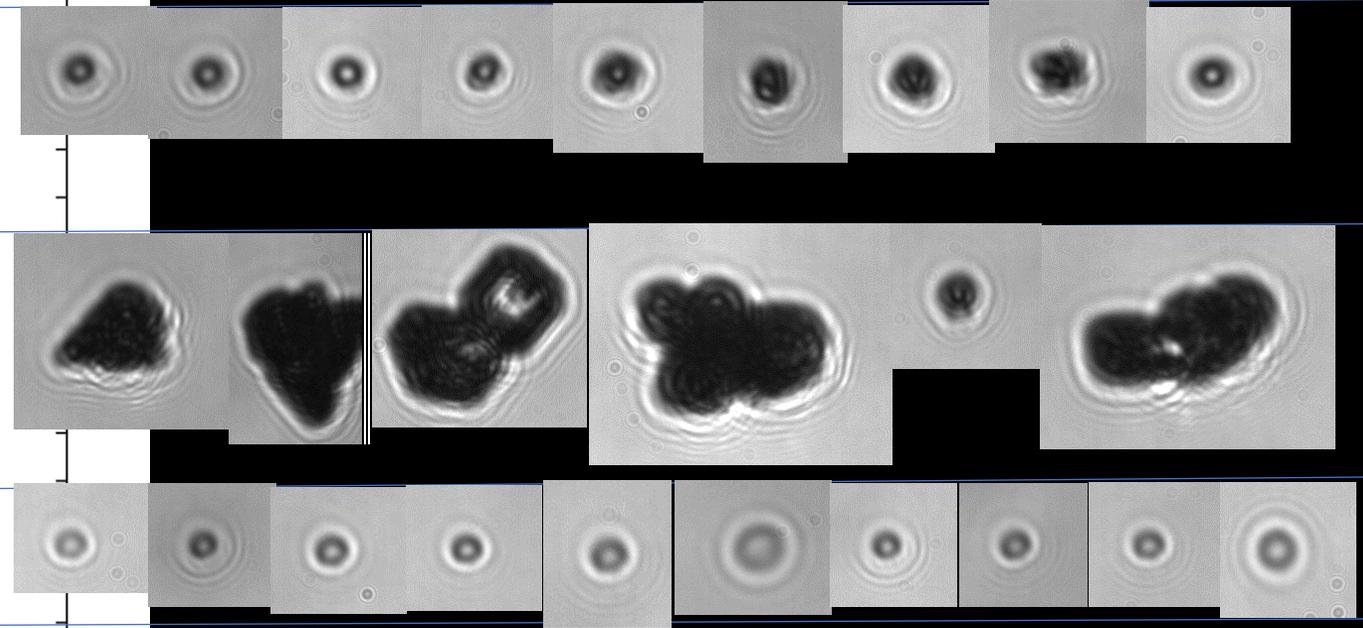
Micro-COPP Measurements on 29th August 2018

29th August 2018



Cloud Particle Imager (CPI)

200 μ m

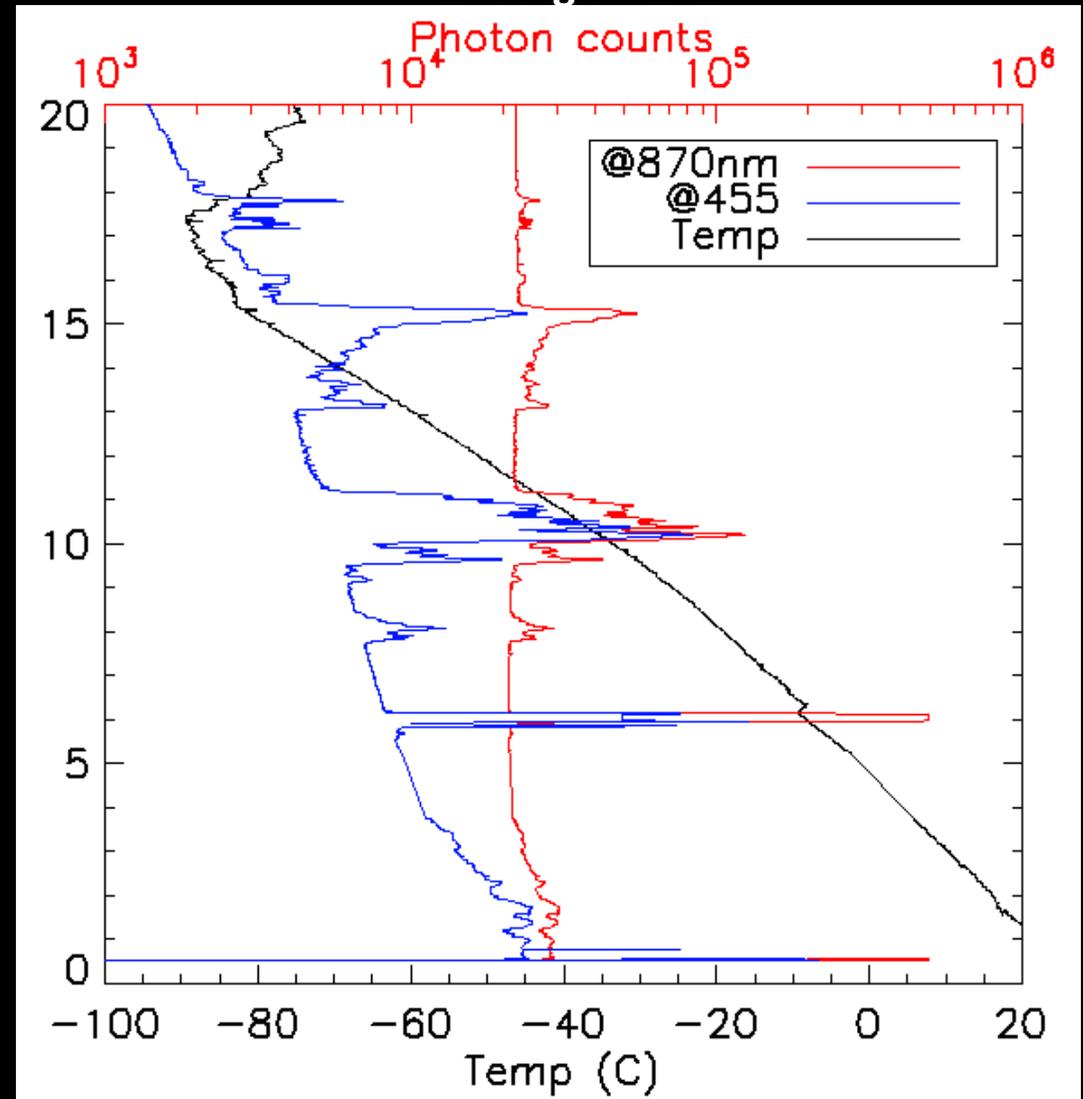
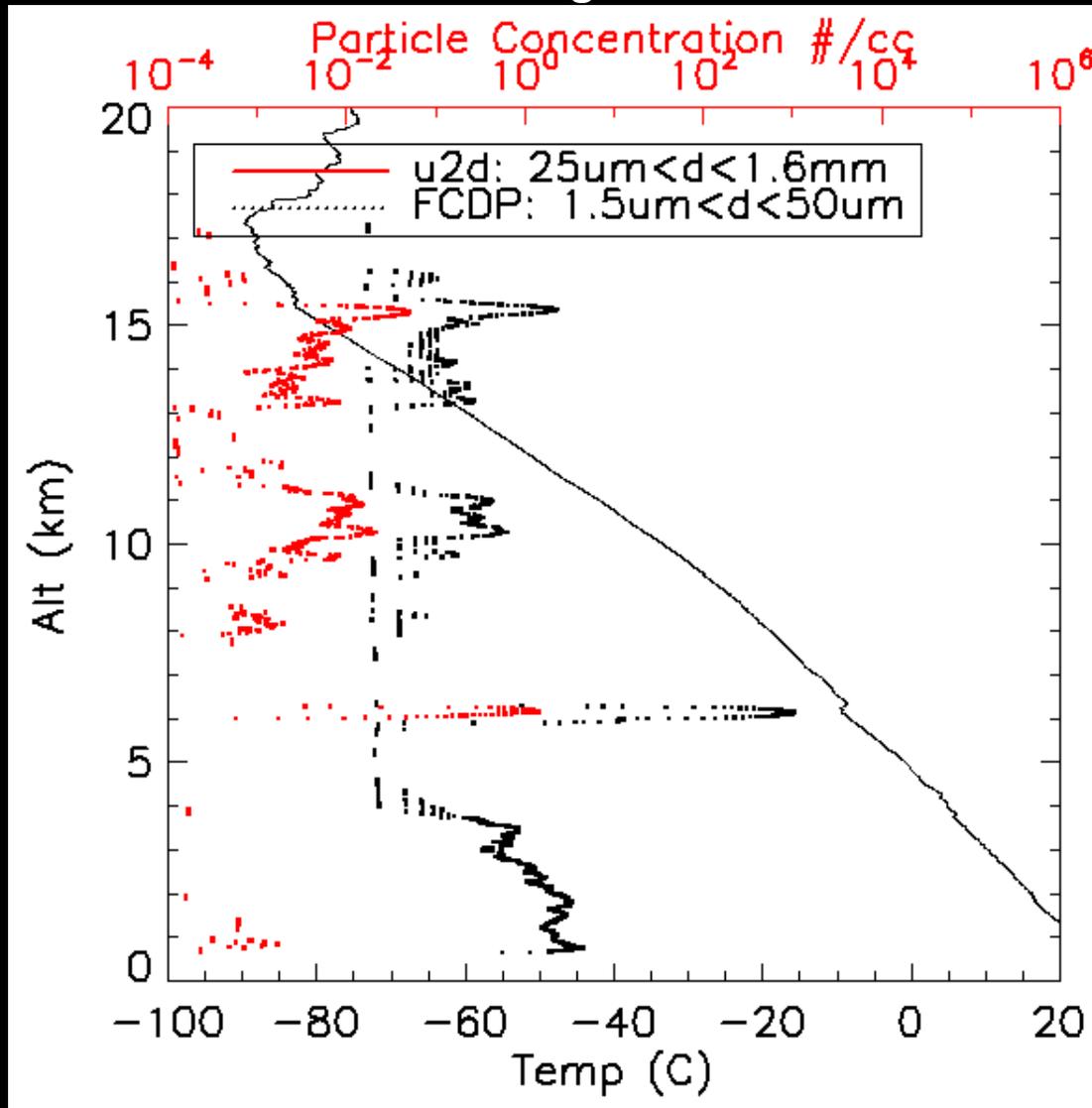


Balloon measurements unaffected by shattering

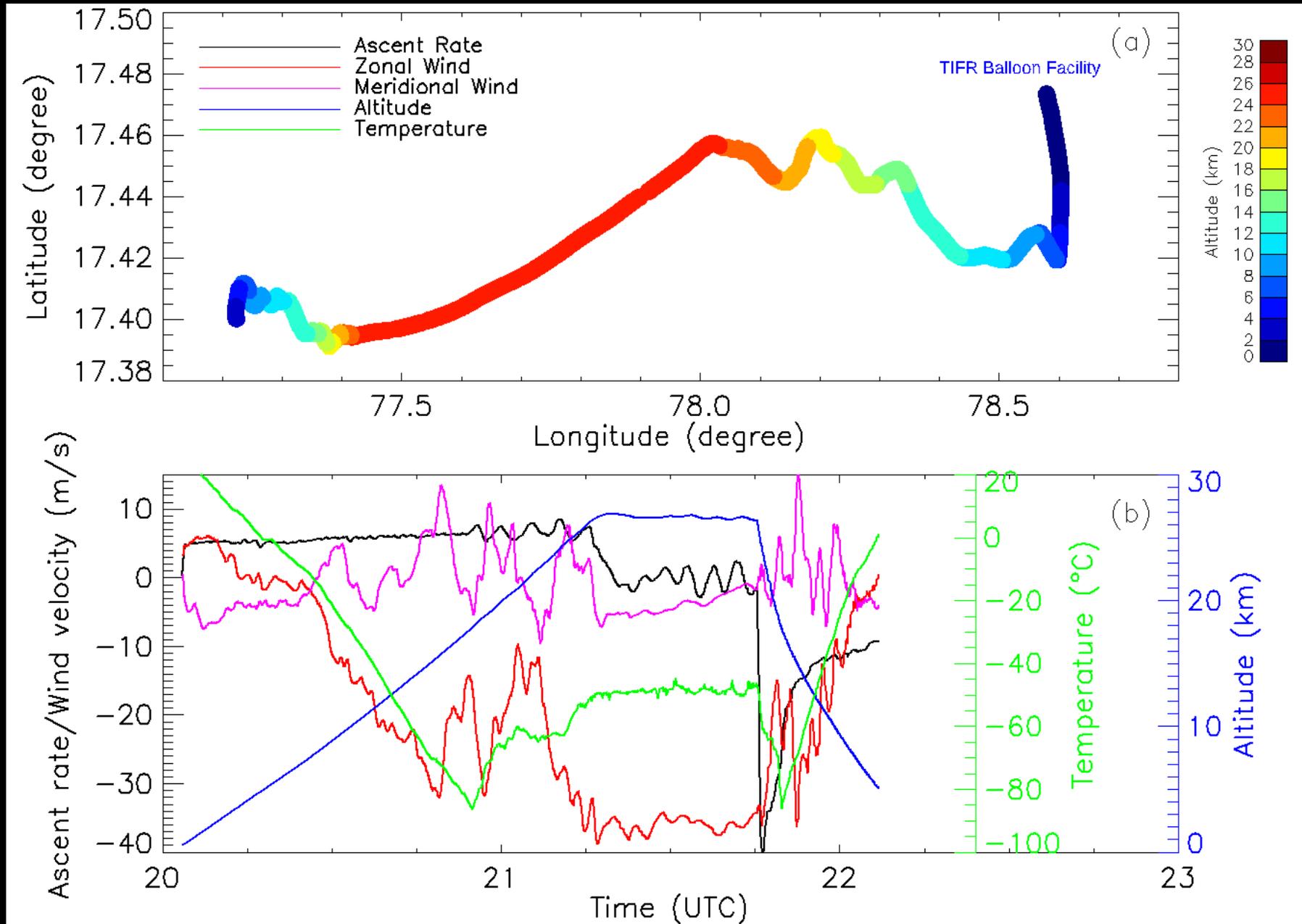
Micro-COPP Vs COBALD

29 August 2018

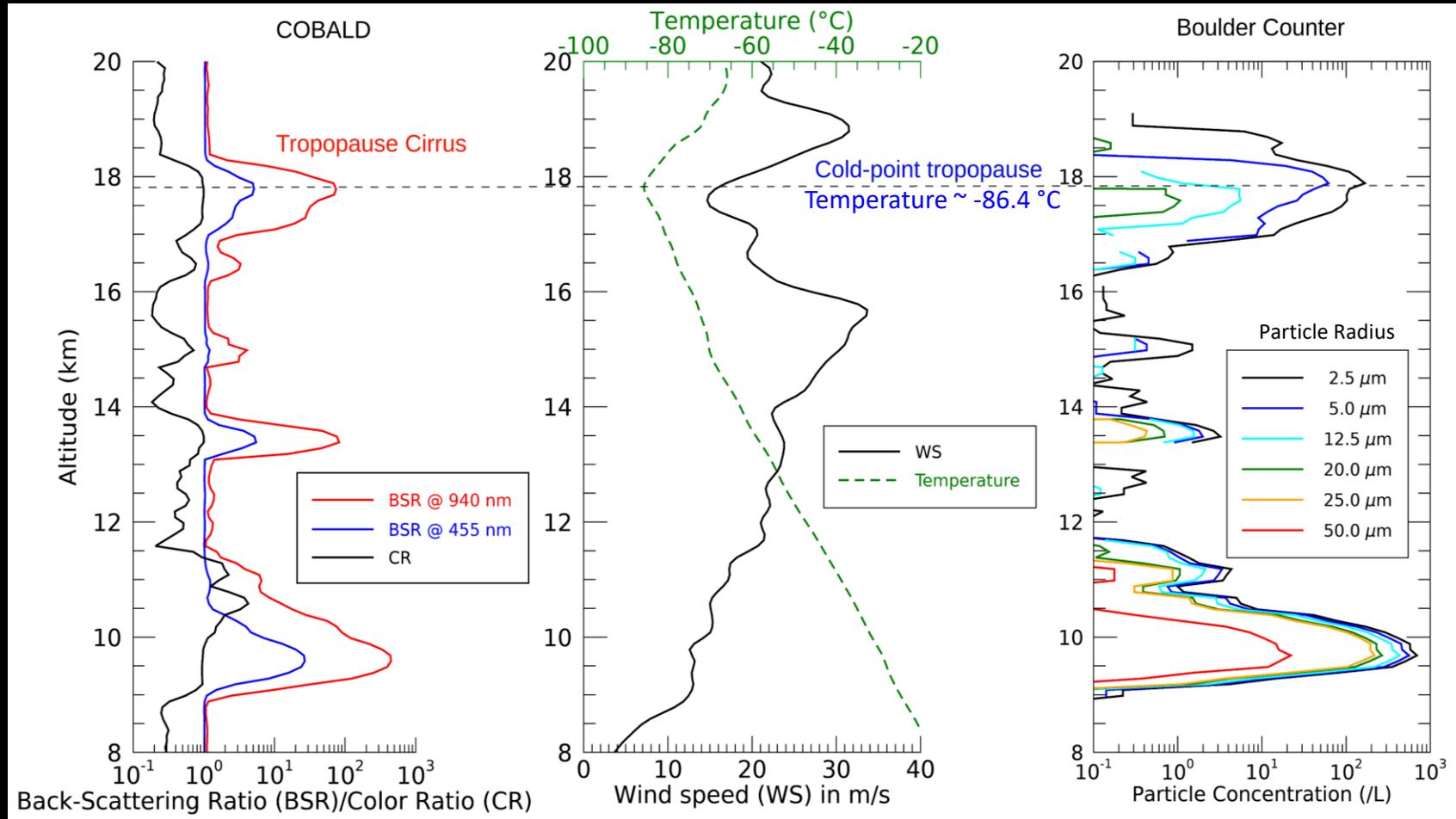
29 August 2018



Balloon flight on 23 August 2017 from TIFR Balloon Facility in Hyderabad



Balloon flight on 23 August 2017 from TIFR Balloon Facility in Hyderabad



- **Backscatter Ratio (BSR):** Ratio of total backscattering coefficient ($\beta = \beta_p + \beta_m$) to the molecular backscattering coefficient (β_m).

- **Color Index (CI) and Particulate Color Ratio (CR):** $CI = (BSR_{940} - 1) / (BSR_{455} - 1) = 18 \cdot \left(\frac{\beta_{p940}}{\beta_{p455}} \right) = 18 \cdot CR$

CR < 0.7 - Aerosol

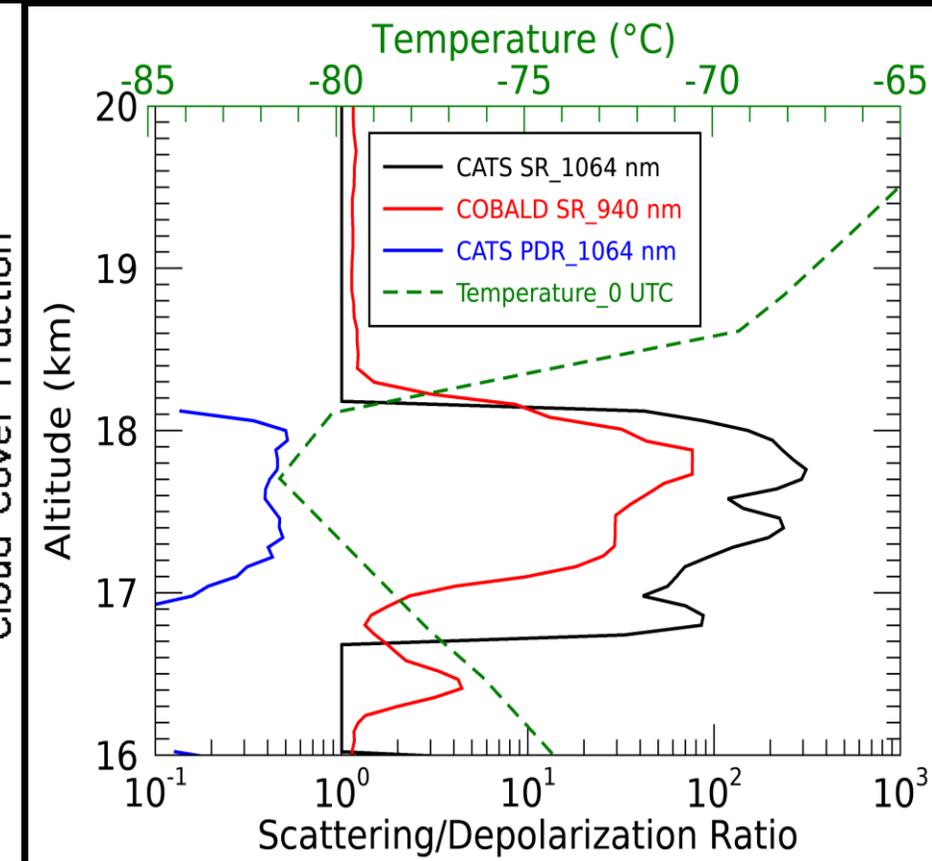
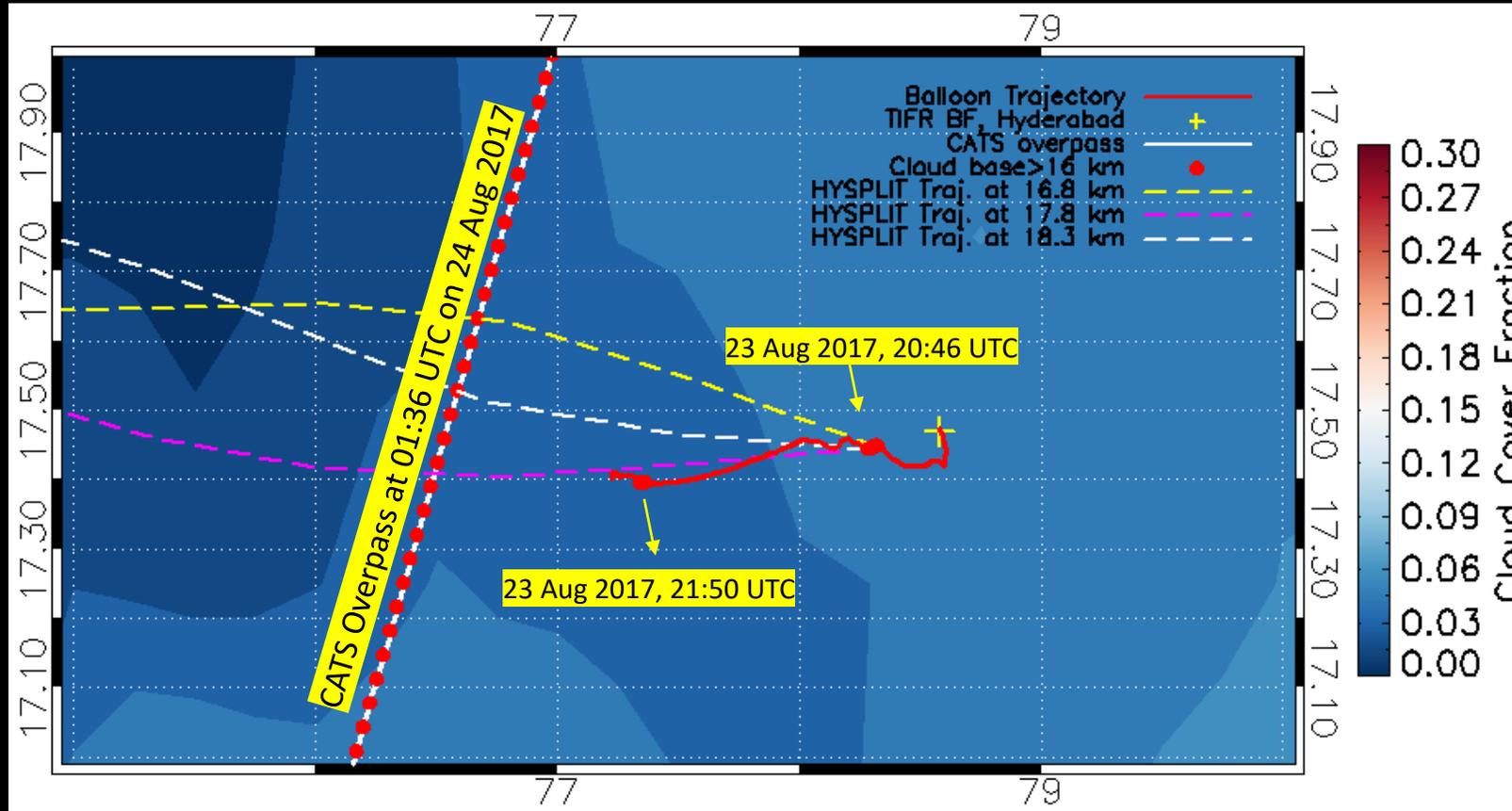
CR > 0.7 - Cloud

(Vernier et al., 2015; Brunamonti et al., 2018)

Validation of Balloon Measurements using CATS Lidar observations onboard ISS

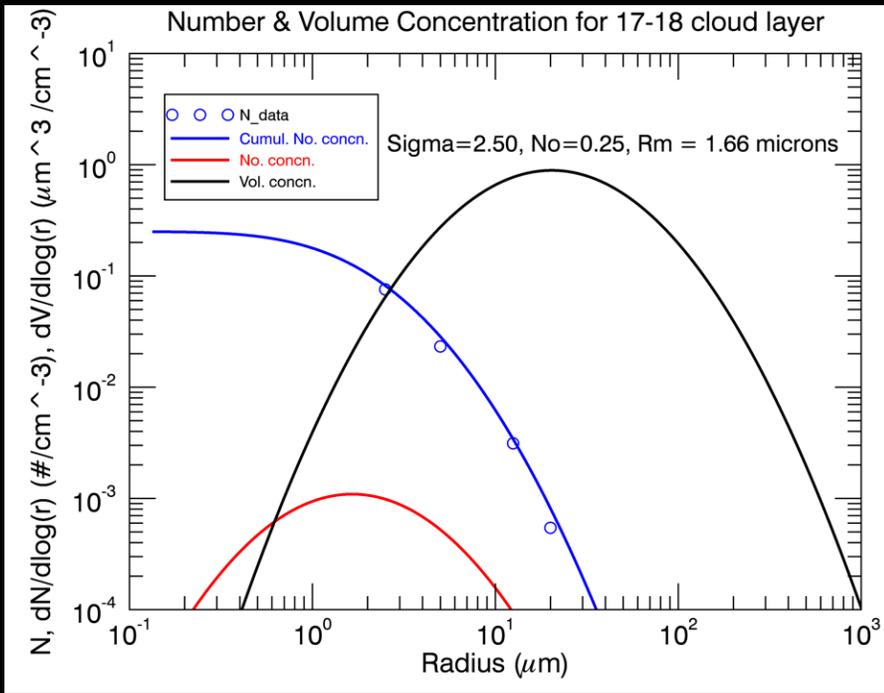
ERA5 Cloud cover Fraction at 100 hPa on 24 Aug 2017 between 1 & 2 UTC

CATS profiles averaged between 17.40 -17.65°N



Horizontal extent of tropopause cirrus is > 500 km along the CATS orbit track

Optical & Microphysical Properties of a Tropopause Cirrus on 23rd August 2017



Using the log-normal size distribution,

$$\frac{dN(r)}{d(r)} = N_0 \frac{\exp\left[-\frac{1}{2} \left\{ \frac{\ln^2\left(\frac{r}{r_m}\right)}{\ln^2\sigma} \right\}\right]}{r \ln\sigma \sqrt{2\pi}}$$

we can derive:

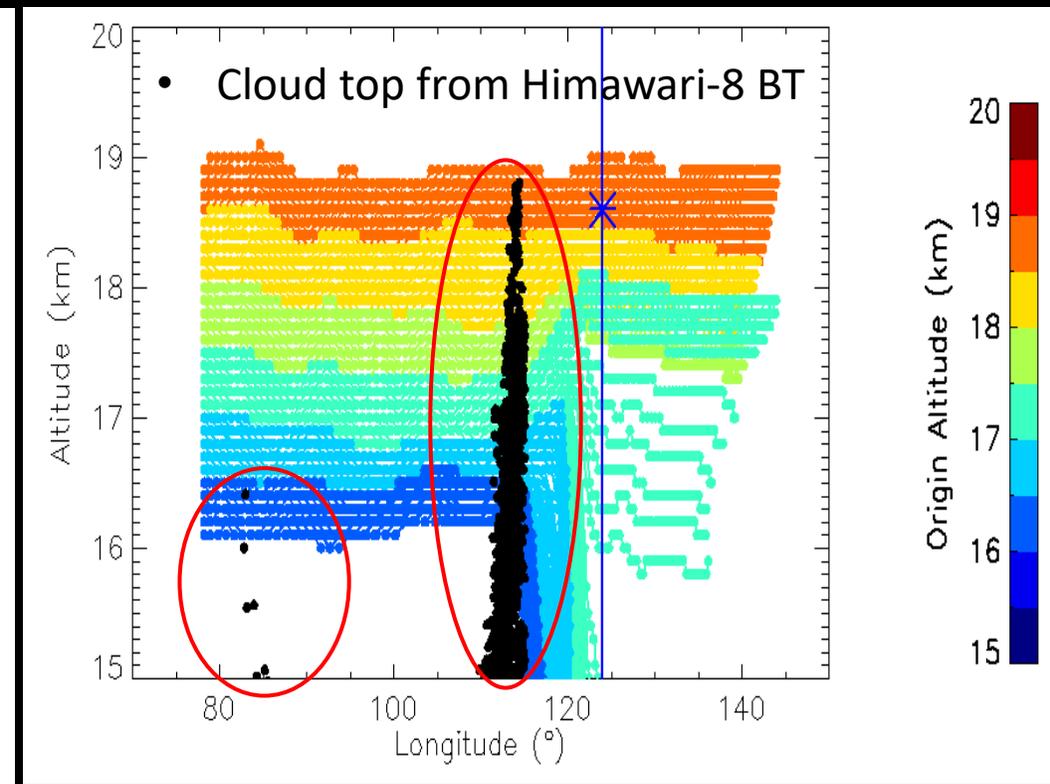
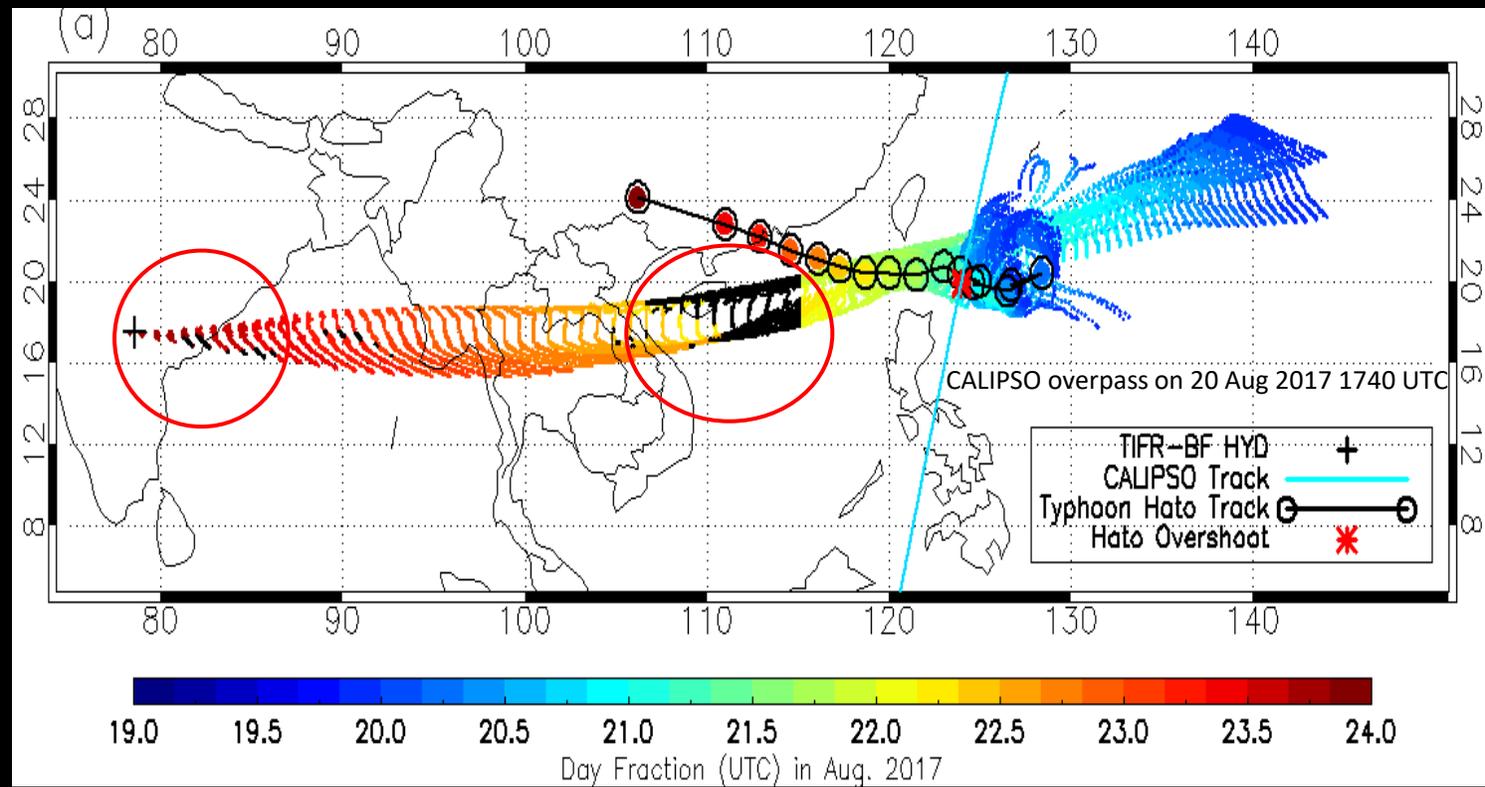
- Effective diameter (D_e), $D_e = 2 \cdot \frac{\int_0^r r^3 N(r) dr}{\int_0^r r^2 N(r) dr}$
- Extinction coefficient (σ_{ext}), $\sigma_{ext} = 2 \cdot \sum_j N_j \pi r_j^2$ (Geometric approximation)
- Ice-Water Content (IWC): IWC = Total volume x Ice Density (917 kg/m^3)

Altitude (km)	Temperature (°C)	Number concentration (#cm ⁻³)	Effective Diameter (μm)	Extinction coefficient (km ⁻¹)	Ice-Water Content (mgm ⁻³)	Lidar ratio (sr)
17.38	-82.19	0.06727	13.49	0.0144	0.06	23.47
17.48	-83.10	0.09337	17.22	0.0257	0.135	41.81
17.58	-83.95	0.09341	18.94	0.0284	0.164	35.08
17.68	-84.80	0.11418	28.67	0.0405	0.355	39.65
17.78	-85.61	0.10809	18.93	0.0261	0.151	14.54
Mean ± Std. Dev (COBALD)	-83.93 ± 1.35	0.0953 ± 0.0181	19.45 ± 5.61 (17.71 ± 0.38)	0.027 ± 0.009 (0.026 ± 0.010)	0.173 ± 0.109 (0.112)	30.9 ± 11.6 (CATS Ir: 28)

Satellite Observations, Lagrangian Back-trajectories and Reanalysis

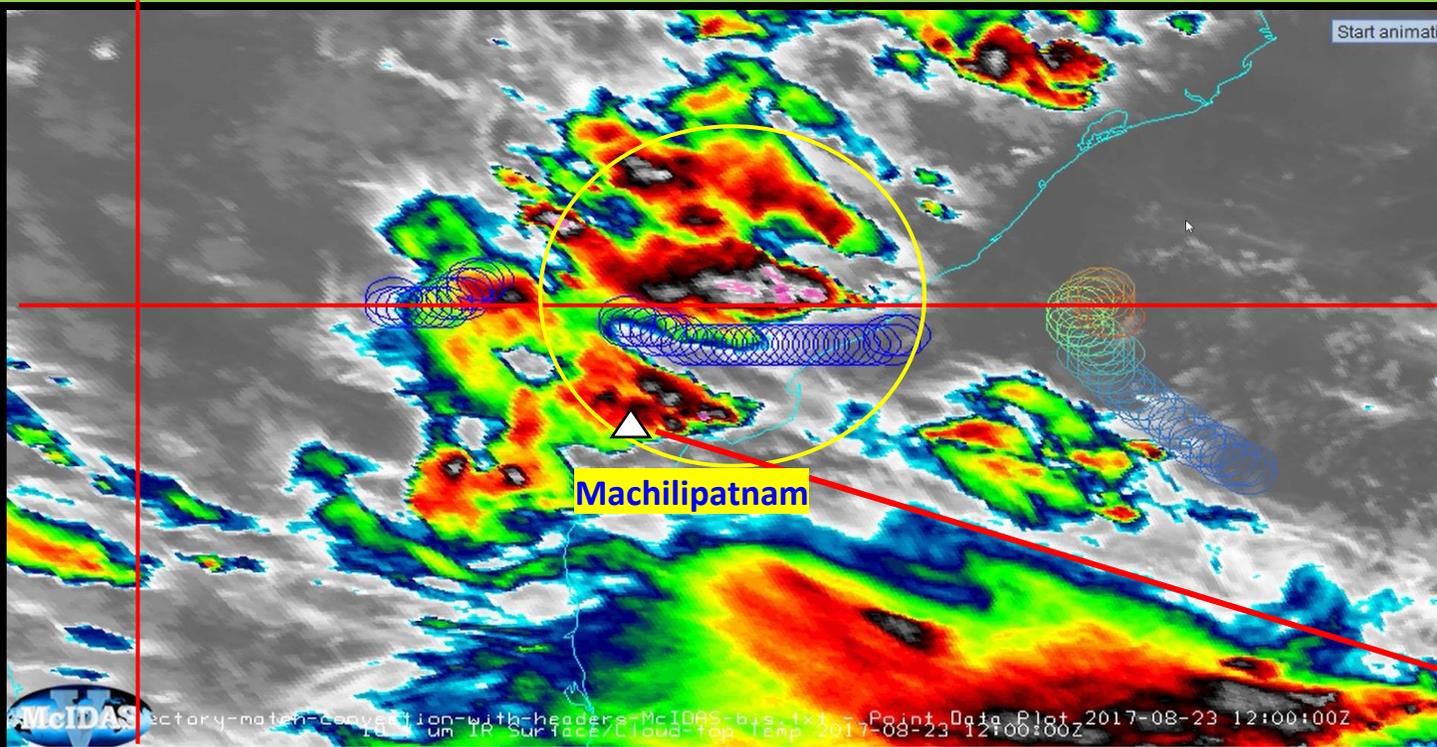
Satellite/Model	Resolution	Output Parameters
CALIOP/CALIPSO (L2 5km V4.2 Clay & Cpro products)	Vertical:60 m, Horizontal: 5km along the orbit track	532 nm backscatter ratio, cloud base and top heights
CATS/ISS (5km M7.2 Level 2, Version 3.0 Operational Layer (OL) and Profile (OP) products)	Vertical resolution: 60 m, Horizontal: 5km along the orbit track	1064 backscatter ratio, cloud base and top heights
Himawari-8	Horizontal: ~2 km for IR bands, Temporal: 10 min	10.4 μm cloud top brightness temperature
MLS/Aura (L2 V5.1)	Vertical: ~ 3km in UTLS, Horizontal:~200 x 7 km	Water vapor mixing ratio
GNSS-RO (L2 atmPrf) obtained from COSMIC-1, Metop A/B, GRACE, KOMPSAT-5, TSX, TDX	Vertical: 100 m	Temperature profiles, cold-point tropopause height
Daily 0 UTC radiosonde data (IMD stations near Hyderabad)	Not fixed	T, RH, u, v, wind speed and wind direction profiles.
ERA 5 Reanalysis (at 70 &100 hPa levels)	Horizontal:0.25° x 0.25°, Temporal: 1h	Temperature, relative humidity and cloud fraction
Langley Trajectory Model (LaTM)	Vertical: 100m,Temporal: 1 hour	3D back-trajectories using winds from NASA GMAO V5 GEOS-5 FP

Formation Mechanism: Back-trajectories and Convective Influence



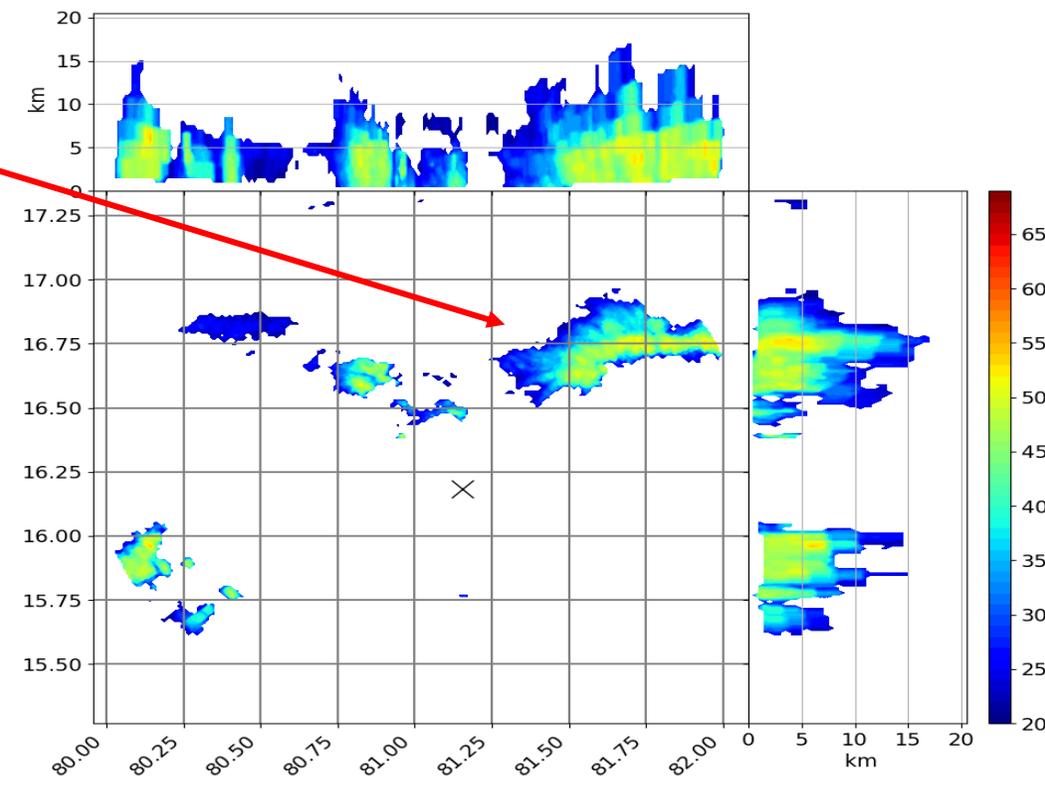
- Back-trajectories initialized from the tropopause cirrus site between 16-18 km are influenced by local and distant convection.
- Local convection: Late afternoon convection near the East coast India.
- Distant Convection: Typhoon Hato – a category-3 tropical cyclone.

Formation Mechanism: Local Convection

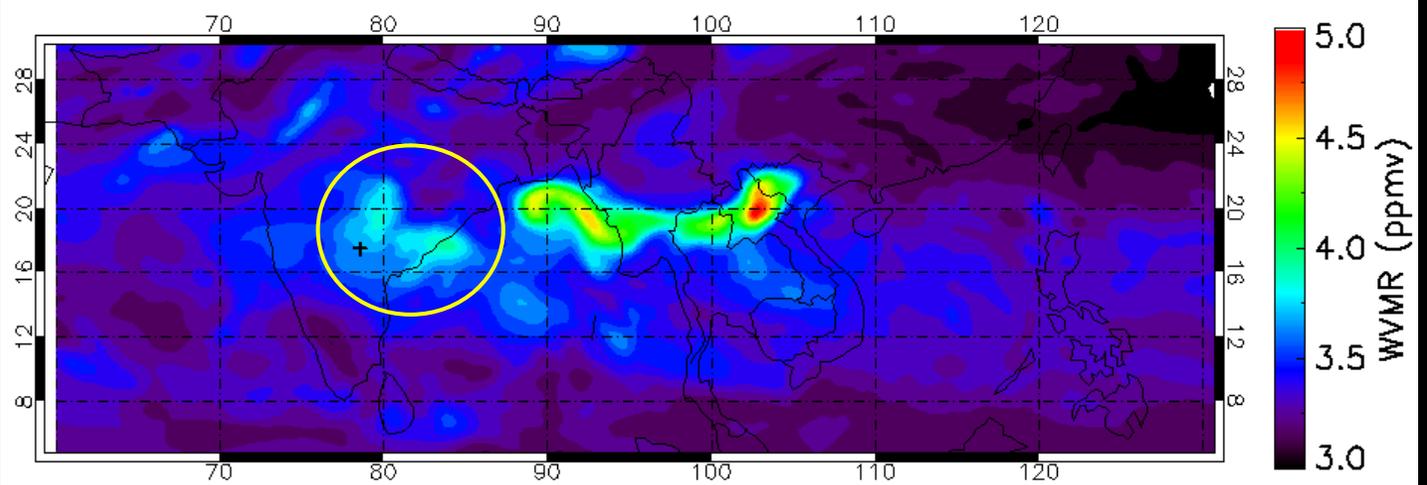


- No nearby CATS and CALIOP overpasses
- No MLS WVMR profiles

Machilipatnam Doppler Radar, 20170823, 1201 UTC



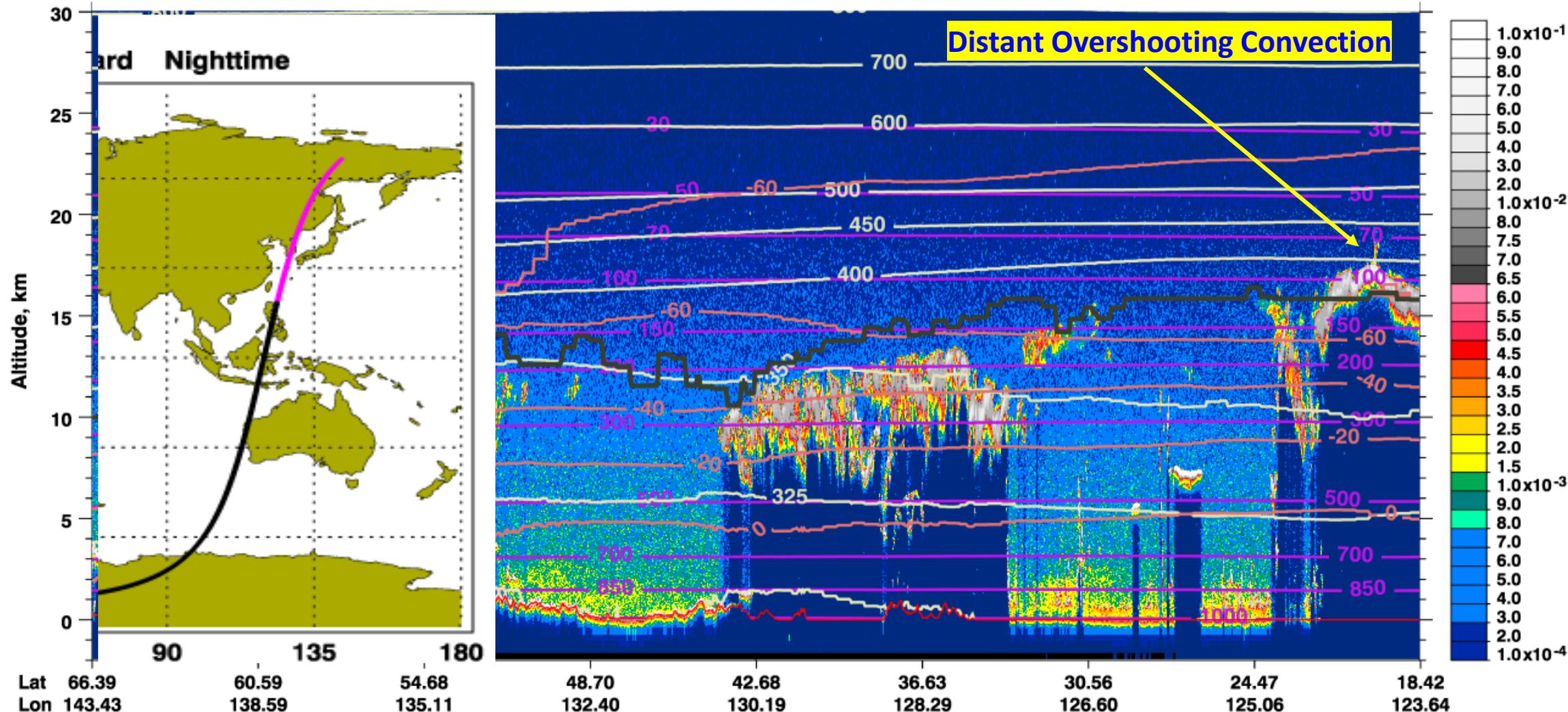
ERA5 WVMR at 70 hPa 2017-08-23 1200



Tropopause Temperature Variations on 23 August 2017 in and around Hyderabad

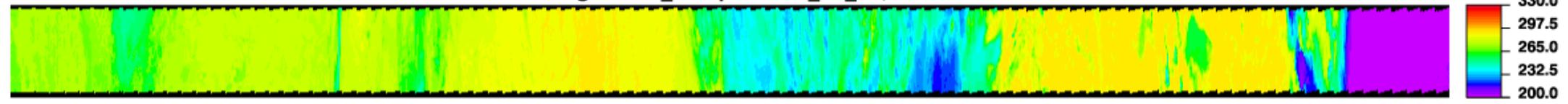
Date/Time	23 Aug 2017, 0UTC	23 Aug 2017, 14 UTC	23 Aug 2017, 2046 UTC	23 Aug 2017, 2150 UTC	24 Aug 2017, 0 UTC
Lat/Lon	~ 17.40, 78.46, 0UTC	18.449, 81.40, 14UTC	17.445N, 78.297, 20:54:59 UTC	17.396, 77.359, 21:49:46 UTC	~ 17.40, 78.46, 0UTC
Displacement from TIFR-BF (km)	~100	332	38.9	135.5	~100
CPT Altitude (km)	17.20	17.30	17.9	17.75	17.7
CPT Temp (°C)	-77.2	-82.5	-86.4	-86.1	-81.5

- Convection peaks in the late afternoon and early evening hours
- Convectively influenced tropopause cooling could have formed the tropopause cirrus cloud

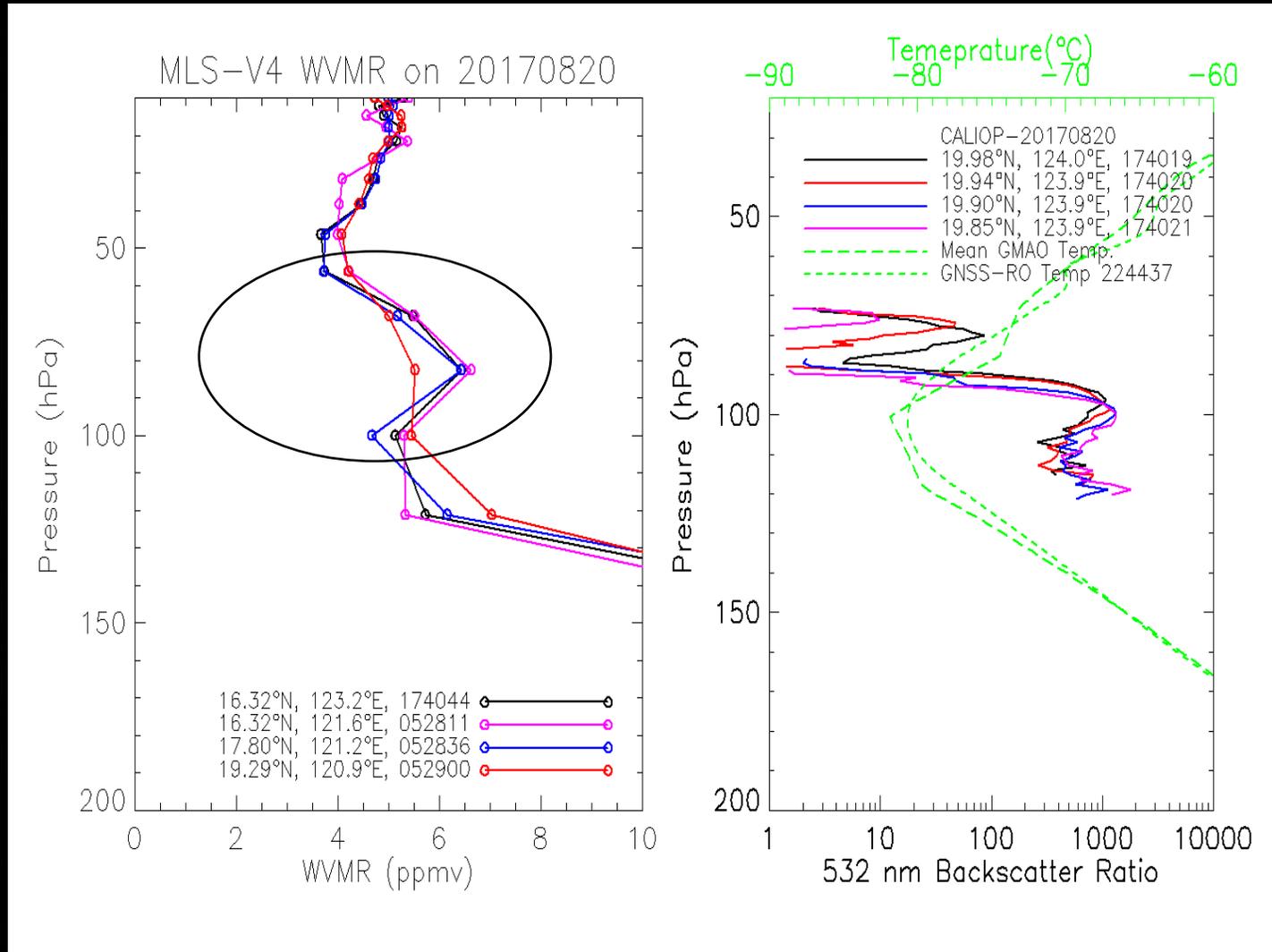
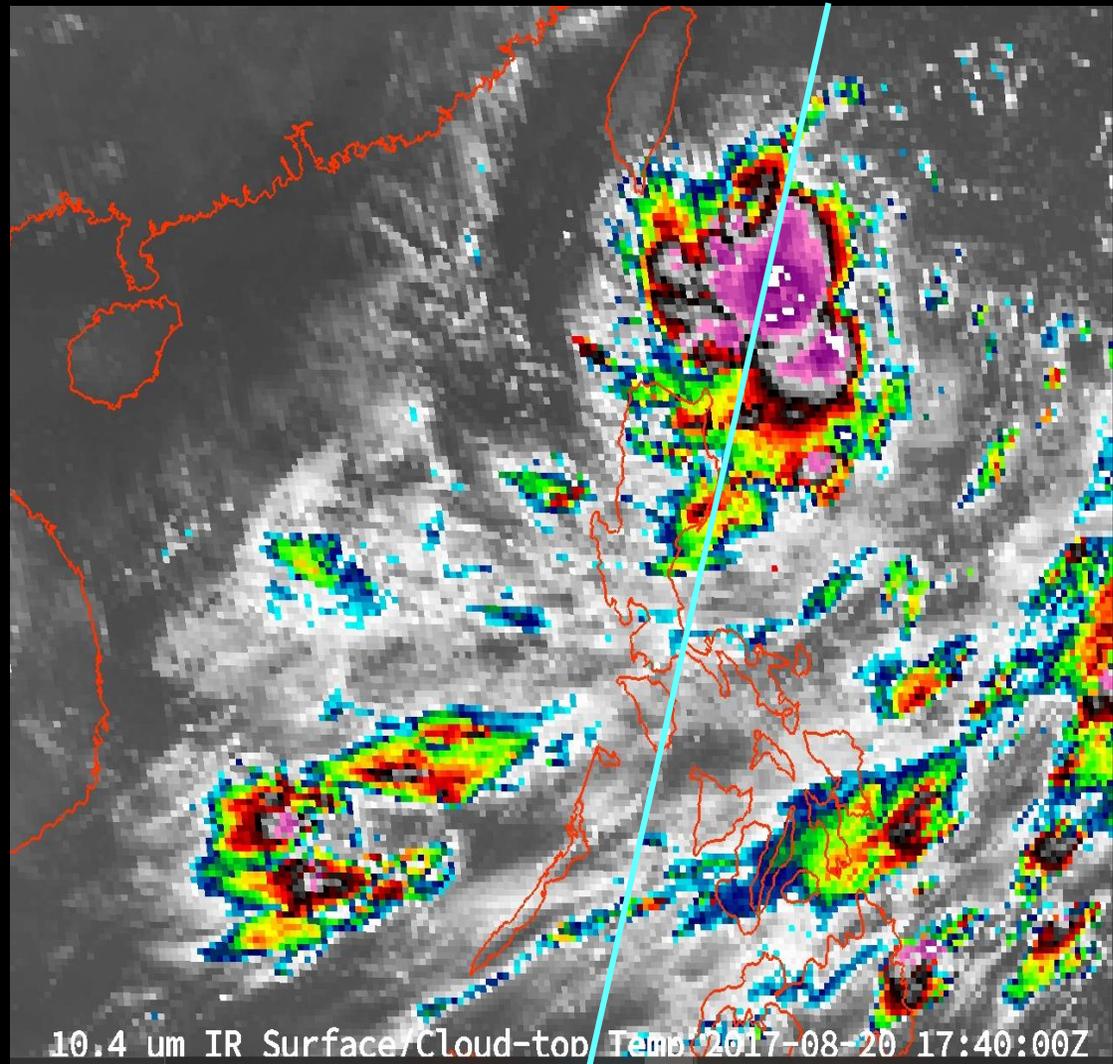


UTC: 2017-08-20 17:27:06.7 to 2017-08-20 17:40:36.0 Version: 4.20 Standard Nighttime

Brightness_Temperature_12_05, K

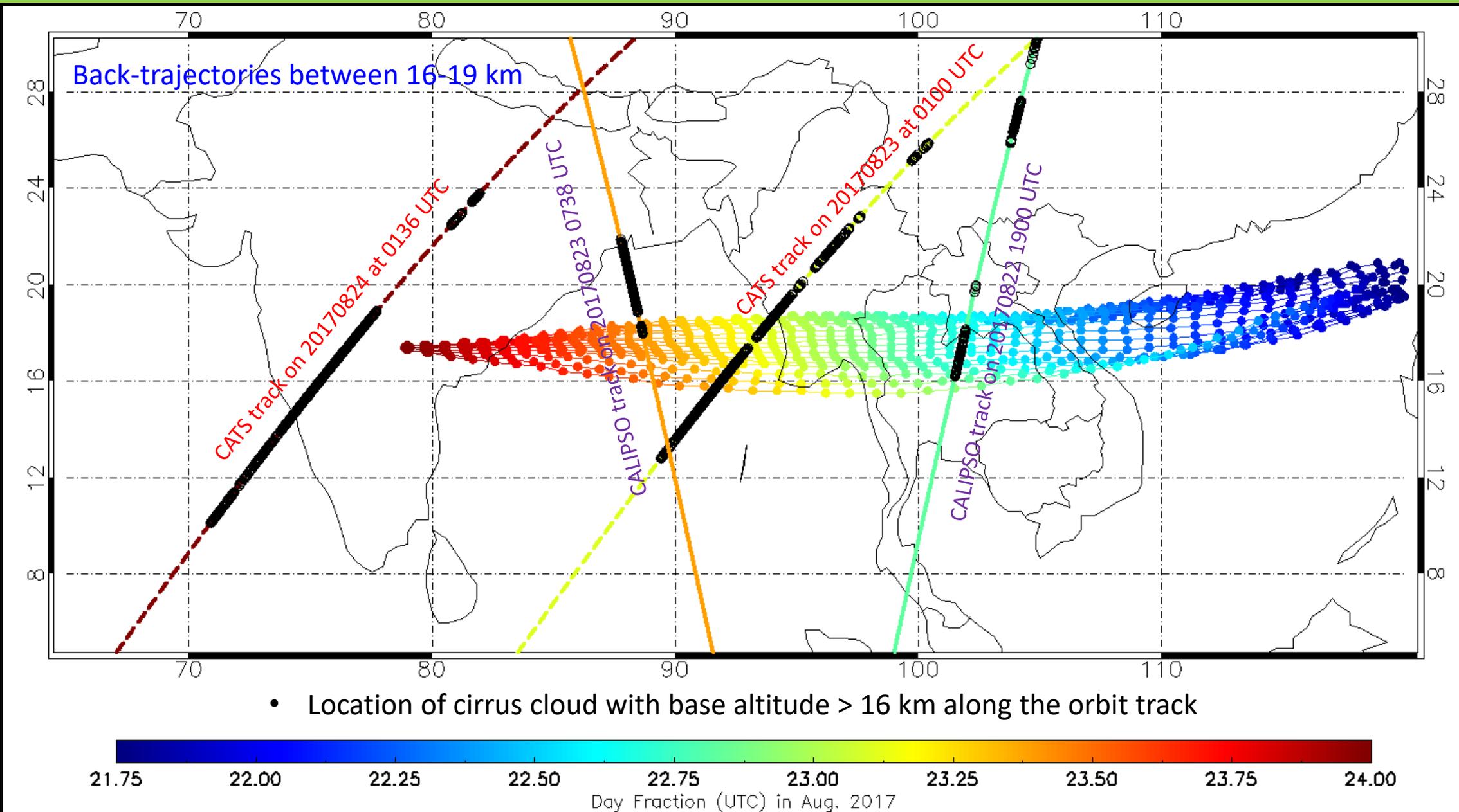


Lower Stratospheric Hydration due to Overshooting Convection on 20 Aug 2017

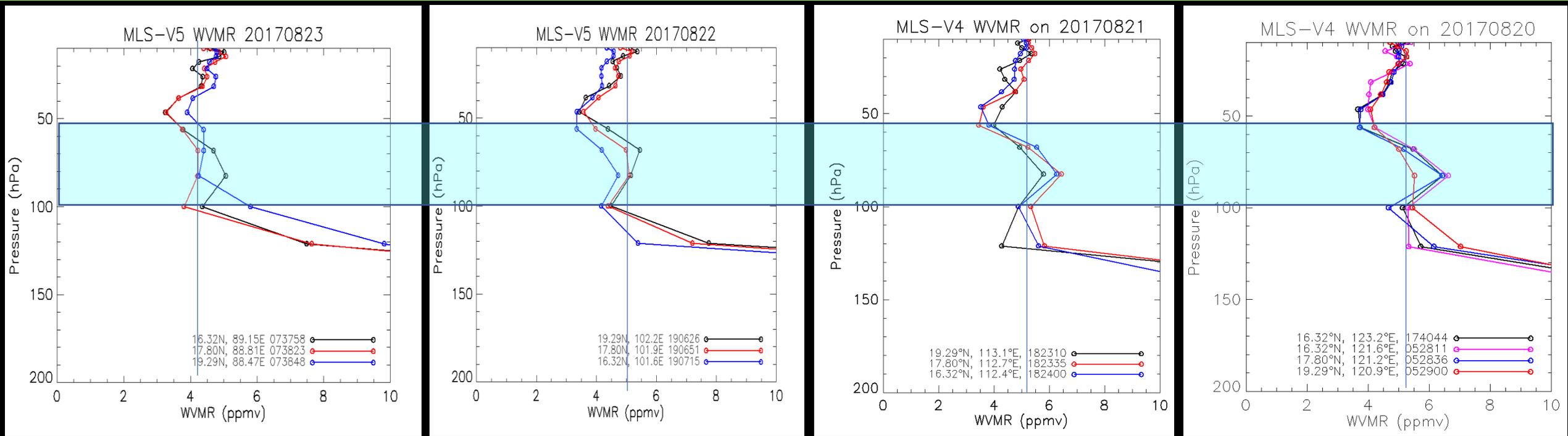


This hydration patch could have advected along the trajectories towards Hyderabad

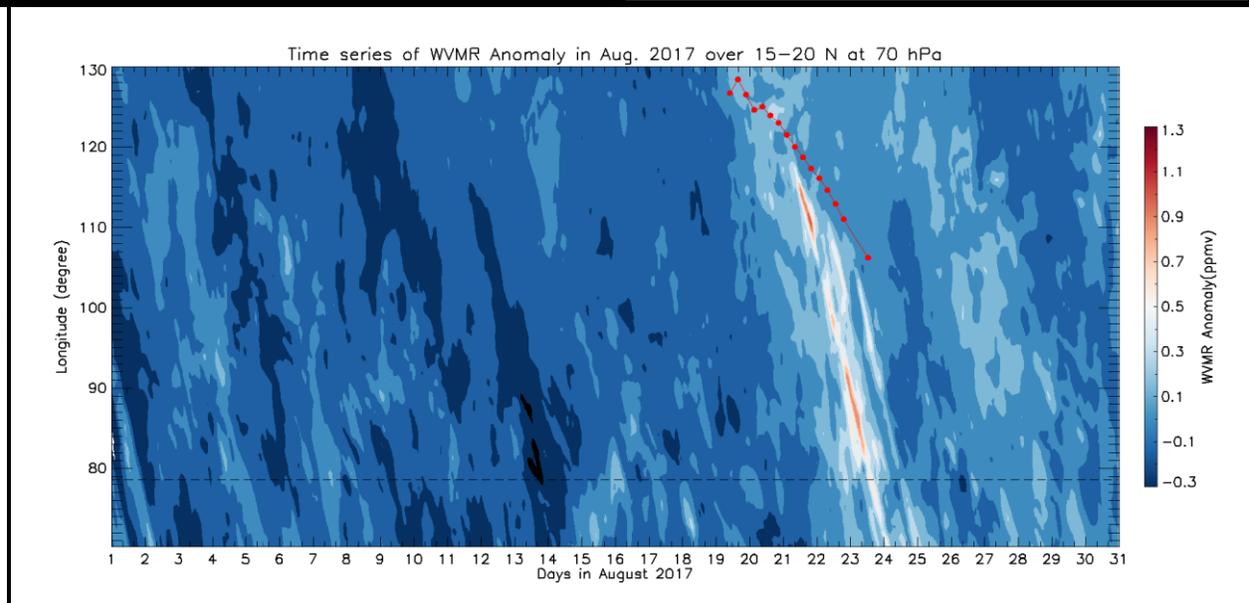
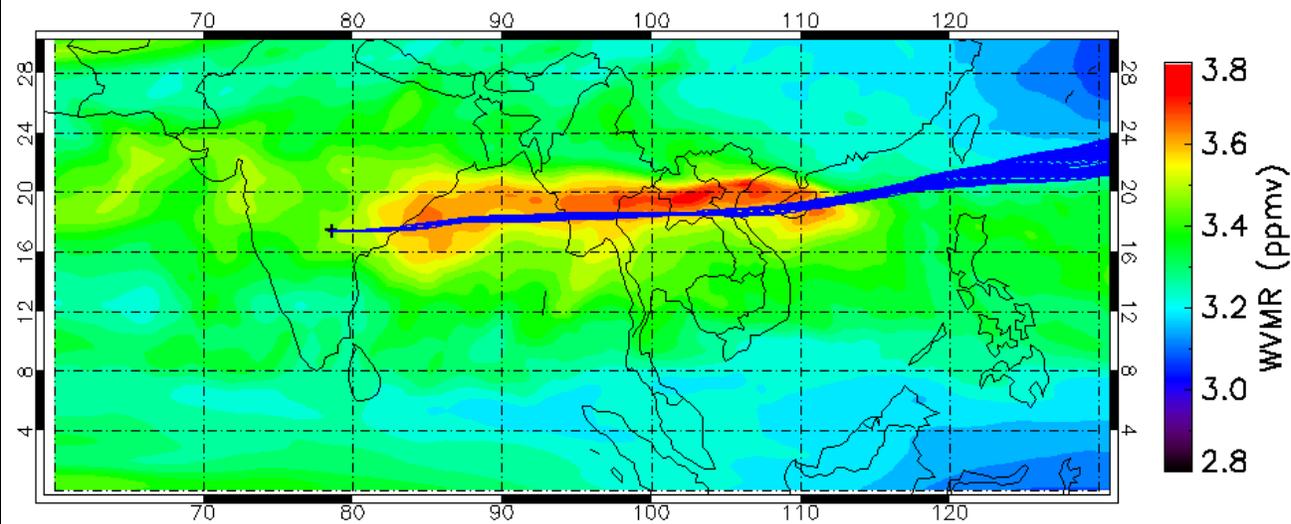
Time history of the Air parcels & Tropopause Cirrus Cloud Observations from CALIOP/CATS



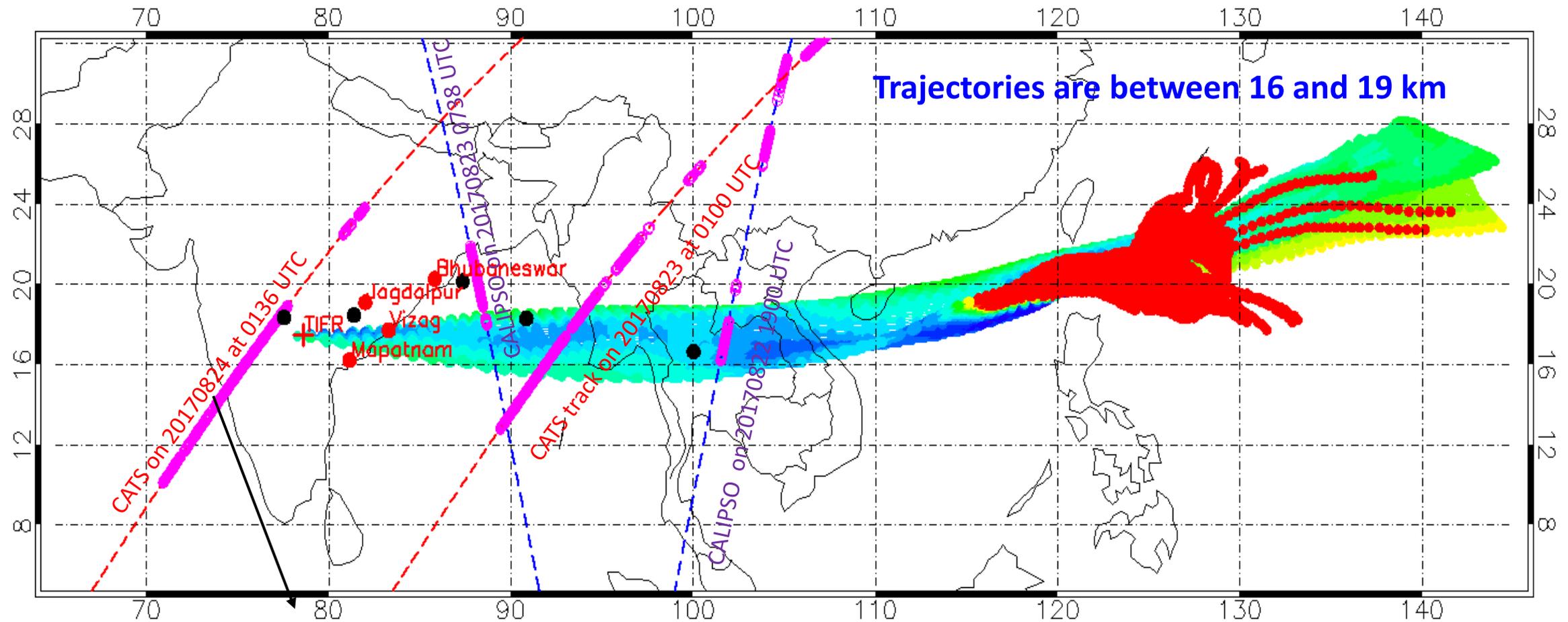
Advection of Hydration Patch by the ASM Anticyclone towards Hyderabad



Mean ERA5 WVMR at 70 hPa during 22–23 August 2017



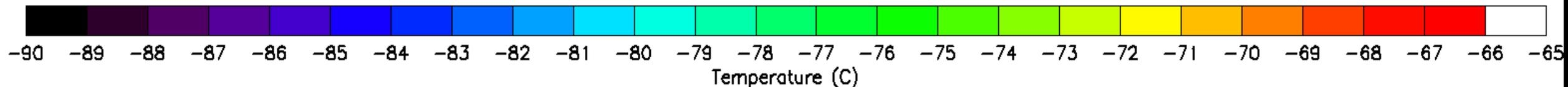
Temperature history of Air Parcels & CALIOP/CATS clouds



• Clouds with base altitude >16km (Laminar cirrus)

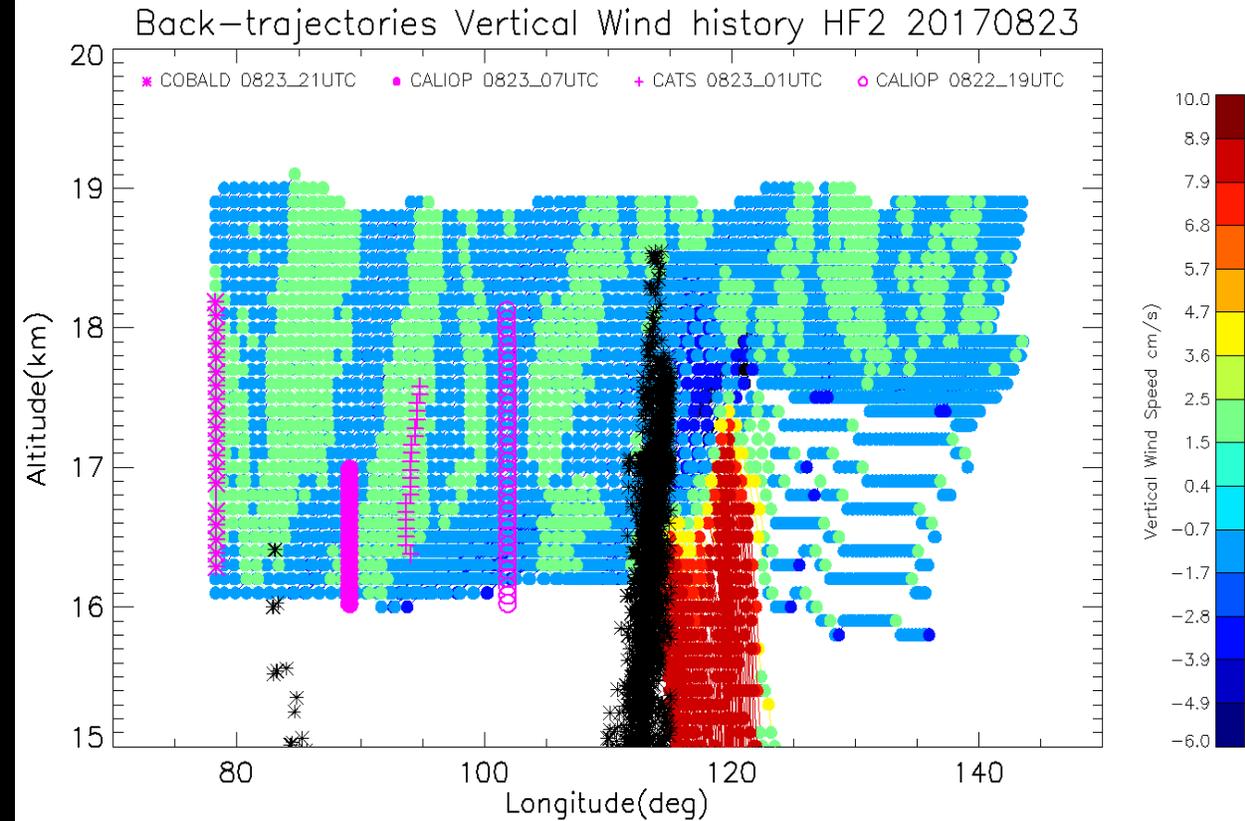
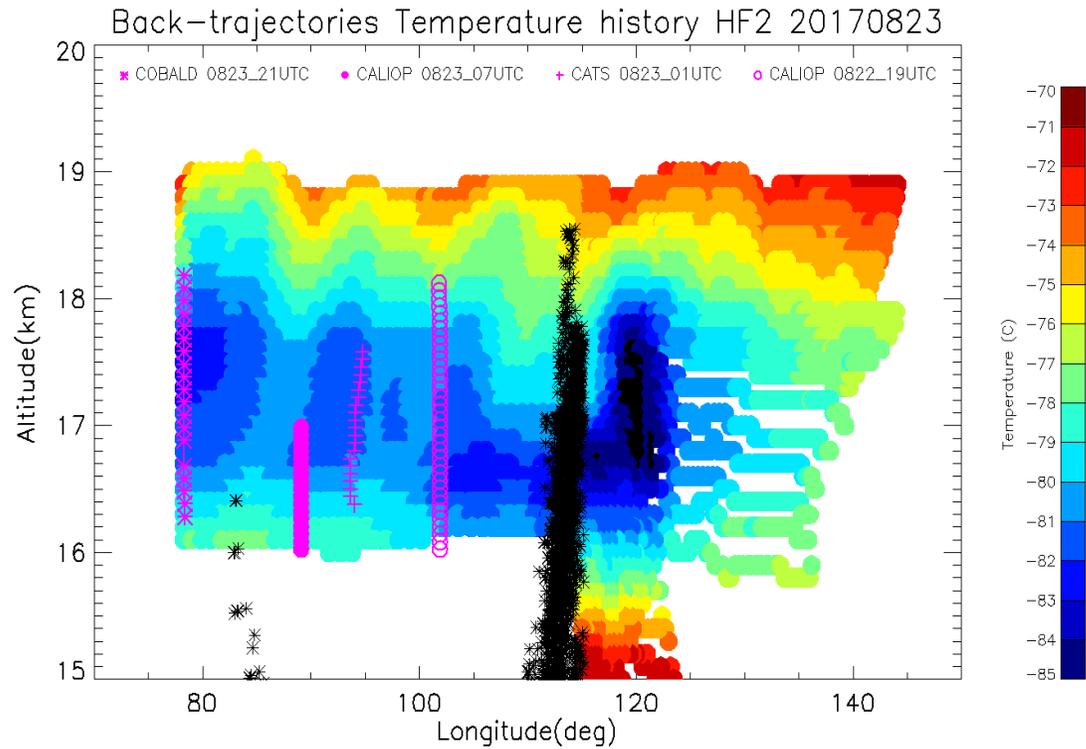
• 0 UTC IMD Radiosonde

• GPSRO Temperature profile



Tropopause cirrus clouds are found in the colder regions along the back-trajectories

Temperature, Vertical Velocity of Air Parcels, & CALIOP/CATS Clouds Vs Altitude



Locations of cirrus clouds in colder regions are shown in Magenta colored symbols

Presence of cirrus clouds in wave-like cold-temperature anomalies along the back-trajectories

Updraft shown by MERRA-2 vertical wind can cause cooling necessary for cirrus cloud formation

Questions

How realistic are these features in MERRA-2 temperature and vertical wind?

Do observations validate these features?

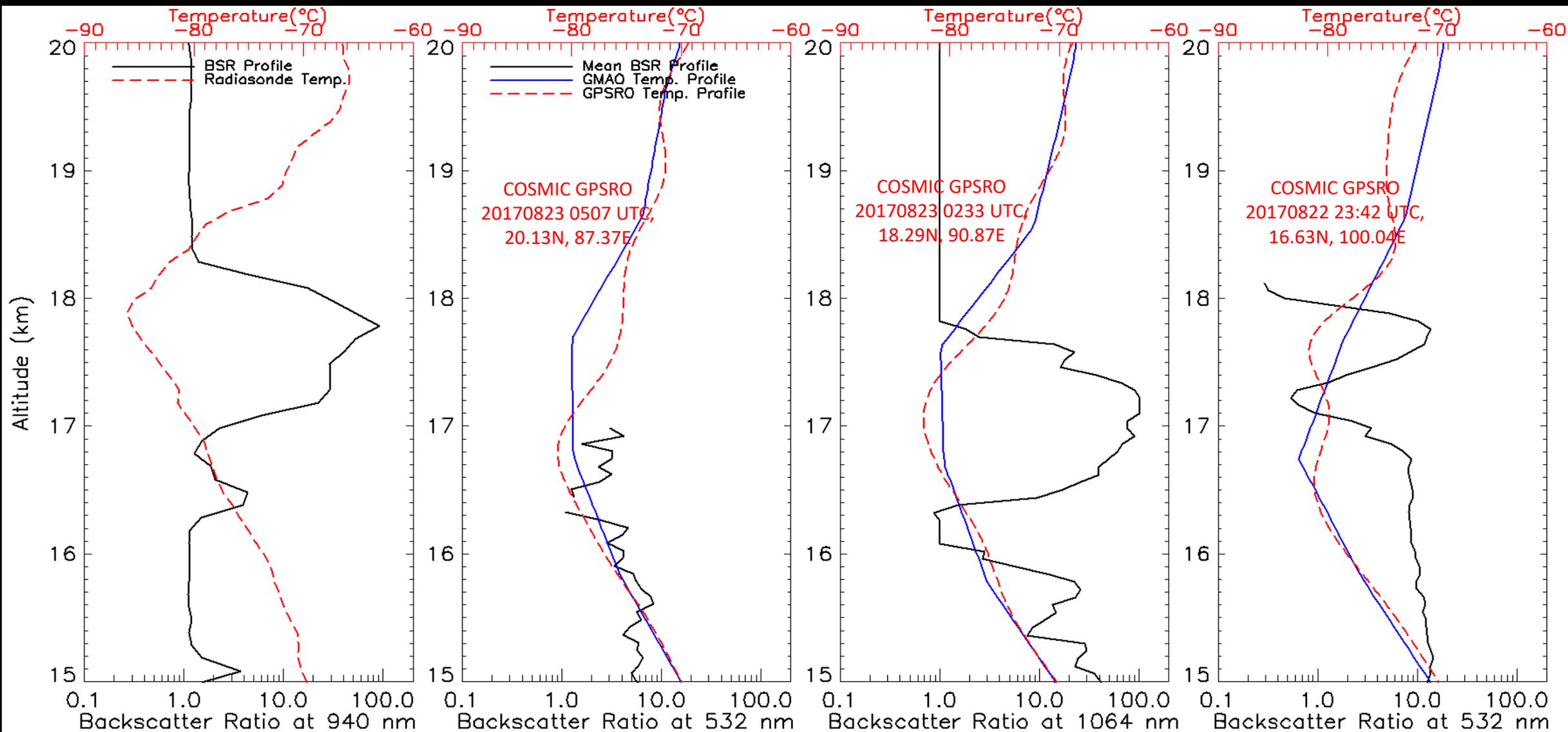
GPSRO Temperature Profiles & CALIOP/CATS Scattering Ratio

COBALD 20170823_2040 UTC,
17.45N, 78.31E

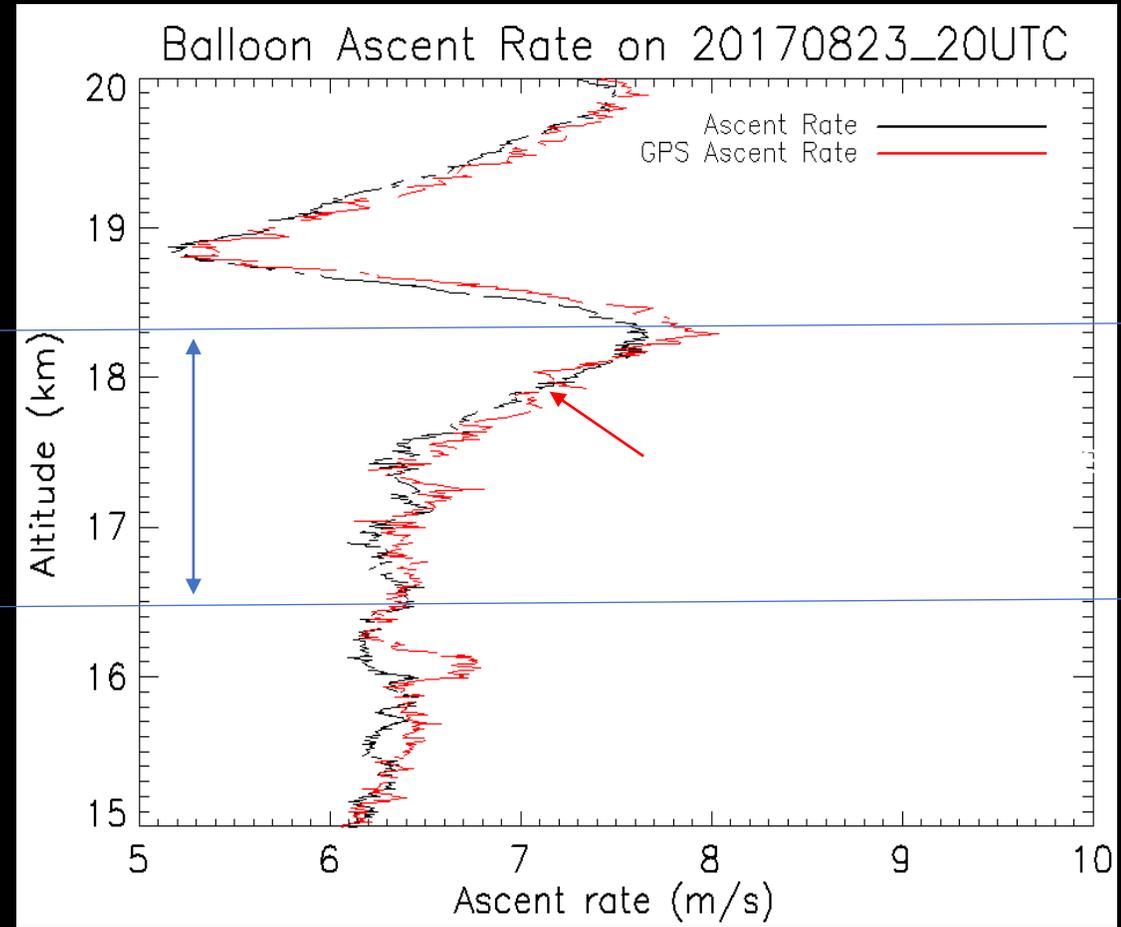
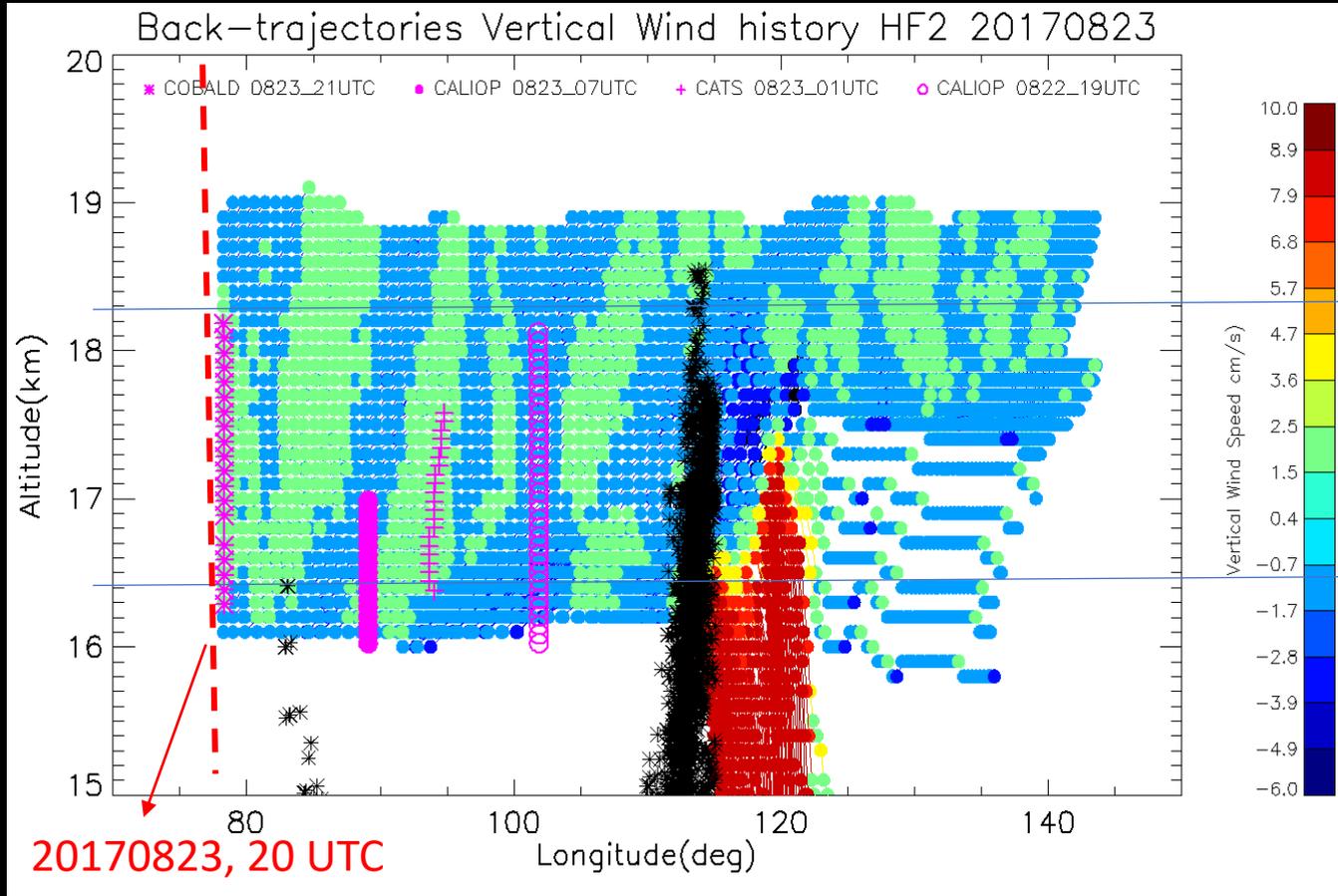
CALIOP 20170823_0738 UTC,
16.99N, 88.88E

CATS 20170823_0059UTC,
17.01N, 92.68 E

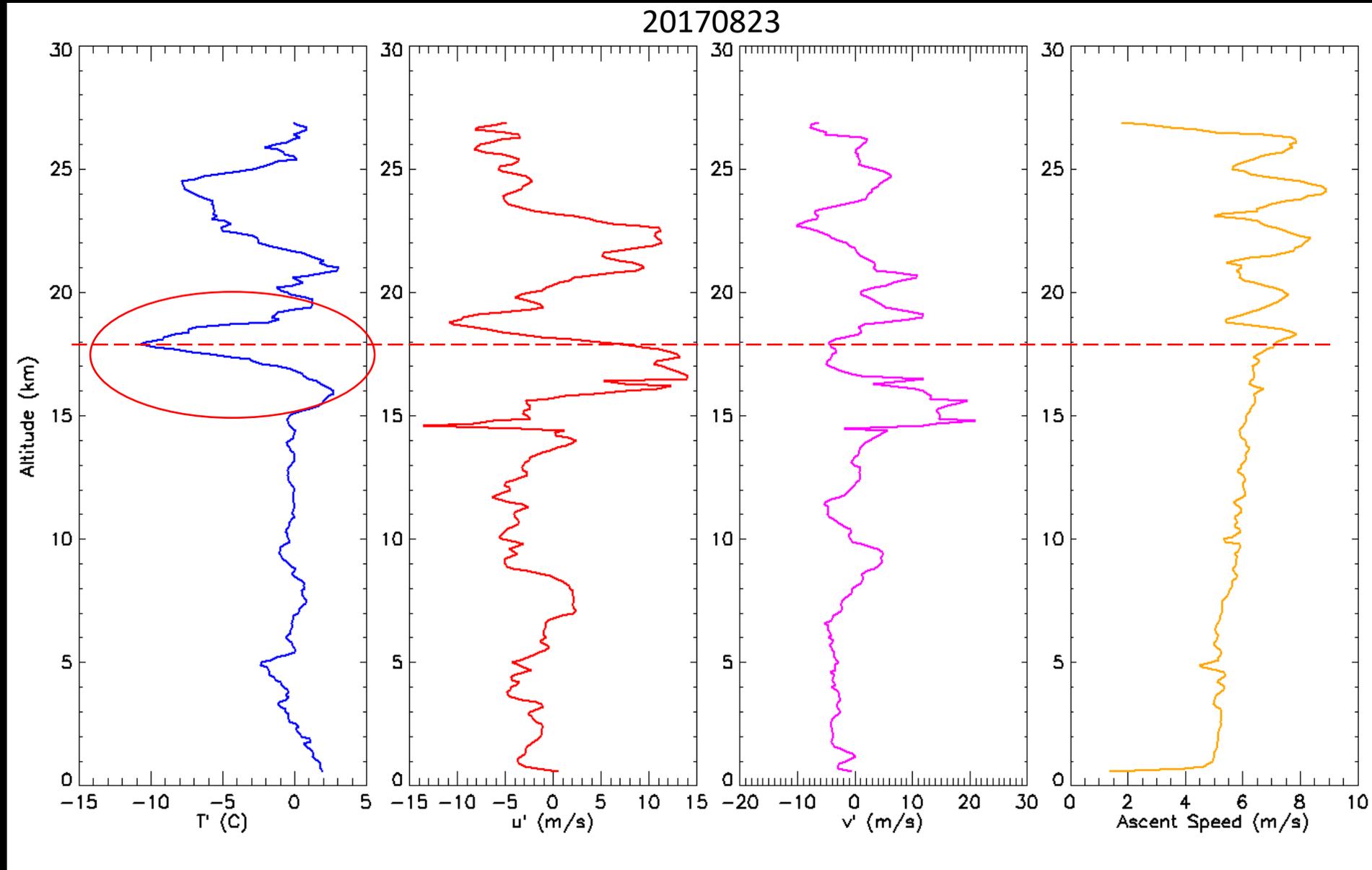
CALIOP 20170822_1907 UTC,
16.99N, 101.68E



Drastic Change in Balloon Ascent Speed near the Tropopause



Role of Typhoon Induced Gravity Waves: Anomalies in T, U & V wind velocity



Anomalies are calculated by subtracting the monthly mean 0 UTC temperature profile from the balloon profile over Hyderabad

Concluding Remarks

- First balloon-borne measurements of ice-crystal characteristics over the Asian Summer Monsoon region are conducted during the BATAL campaign in Hyderabad, India.
- Cirrus clouds form frequently in the cold-temperature anomalies near the cold-point tropopause during Asian Summer Monsoon.
- Boulder Counter & COBALD measurements were used to derive optical and microphysical properties of a tropopause cirrus.
- Ice-crystals in tropopause cirrus cloud layer are smaller than $50 \mu\text{m}$ with a mean concentration of about 47.5 L^{-1} .
- The ice-water content for this layer estimated from our measurements is 0.17 mg/m^3 .
- Layer mean lidar ratio (30.9 sr) is also estimated using independent measurements of backscatter and extinction coefficients from COBALD and Boulder Counter measurements, respectively.
- The formation mechanism responsible for this tropopause cirrus is investigated using three-dimensional back trajectories, observations from space-borne lidars (CALIOP/CALIPSO and CATS/ISS) along with cloud-top brightness temperature images from Himawari-8 satellite and temperature from GPS radio occultation temperature measurements.
- These combined data suggest that the formation of the tropopause cirrus is likely influenced by a Category-3 Typhoon, *Hato* which hit Macau and Hong Kong on 23 August 2017.

Significance of this Study

- Demonstrates that how microphysical properties and optical properties of a tropopause cirrus cloud layer can be obtained using a COBALD & a Boulder Counter.
- This study demonstrates how stratospheric hydration due to overshooting convection in a typhoon during the ASM can influence the formation of tropopause cirrus clouds under gravity wave induced temperature fluctuations.
- The occurrence frequency of tropopause overshooting deep convective clouds (Aumann et al., 2018) and the intensity of tropical cyclones are expected to increase in a warmer climate (Emanuel, 2005; Stocker et al., 2013), which in turn are likely to increase the occurrence of ice-injections with consequences for the stratospheric composition, thin tropopause cirrus clouds and further feedbacks on global climate (Dessler et al., 2016; Solomon et al., 2010).

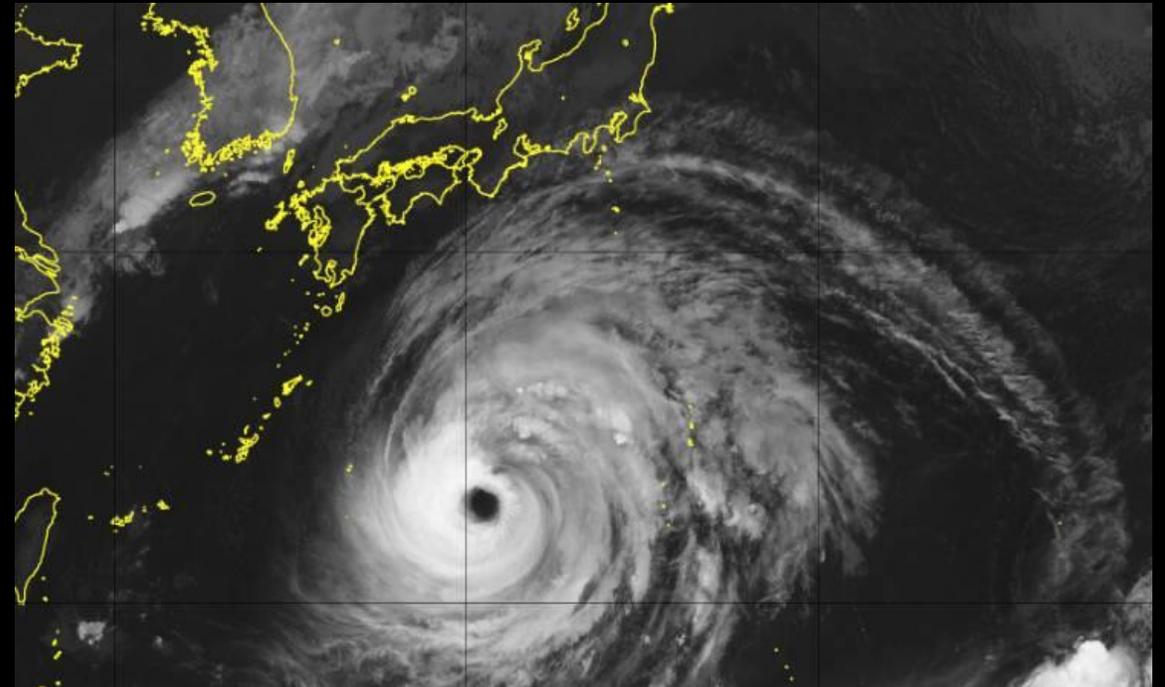
“If I had the funding, the big problem I would like to pursue is...”

- The intensity and frequency of extreme convective clouds and tropical cyclones are going to increase under global warming (Aumann et al., 2018; Emanuel, 2005).
- Relative roles of mesoscale deep convective clouds versus typhoons in stratospheric hydration and tropopause dehydration during the Asian Summer Monsoon?



Source: <https://alchetron.com/Cumulonimbus-cloud>

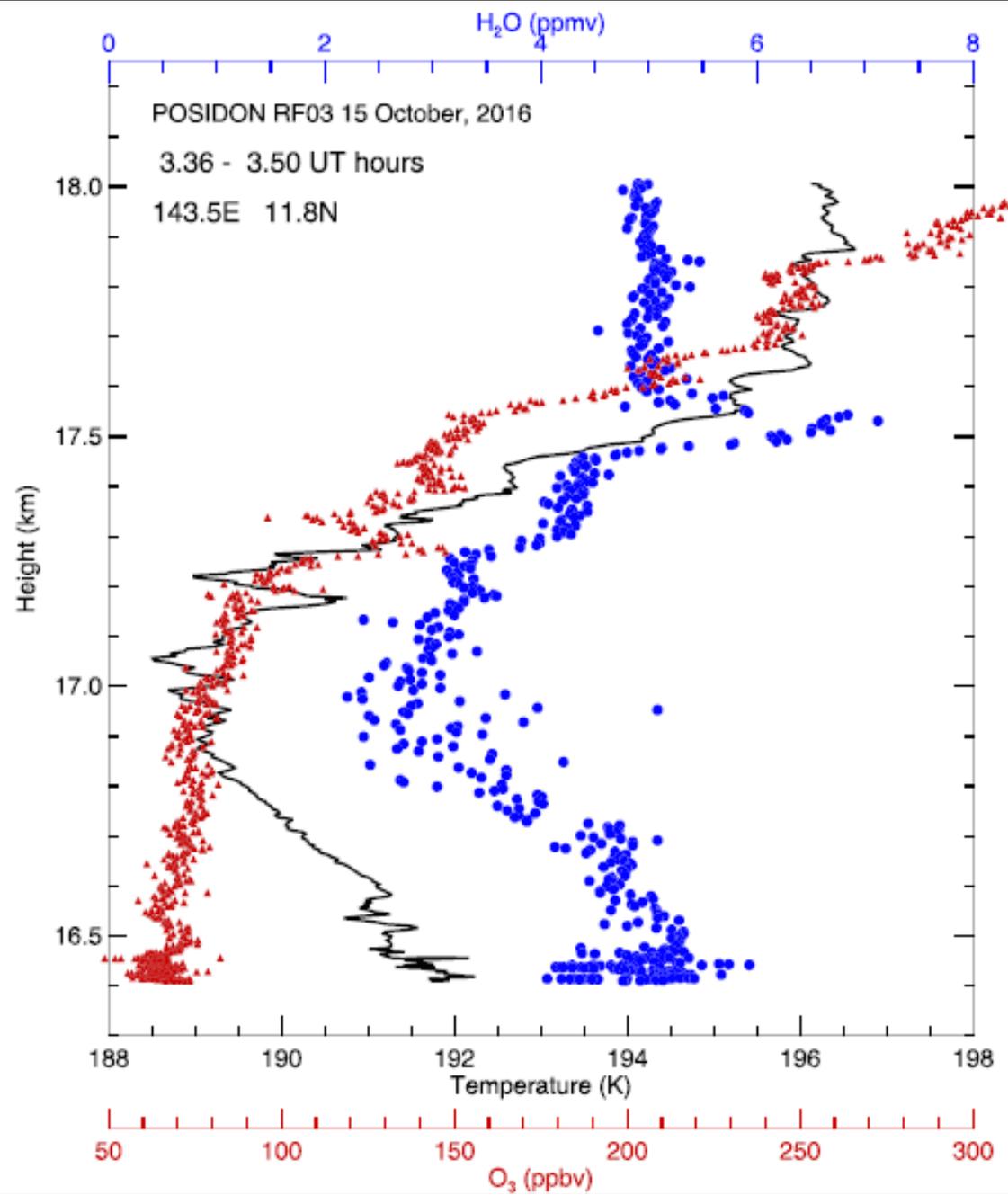
Vs



Source: <https://www.japantimes.co.jp/news/2021/09/30/national/heavy-rain-forecast-across-eastern-japan-friday-due-typhoon-mindulle/>

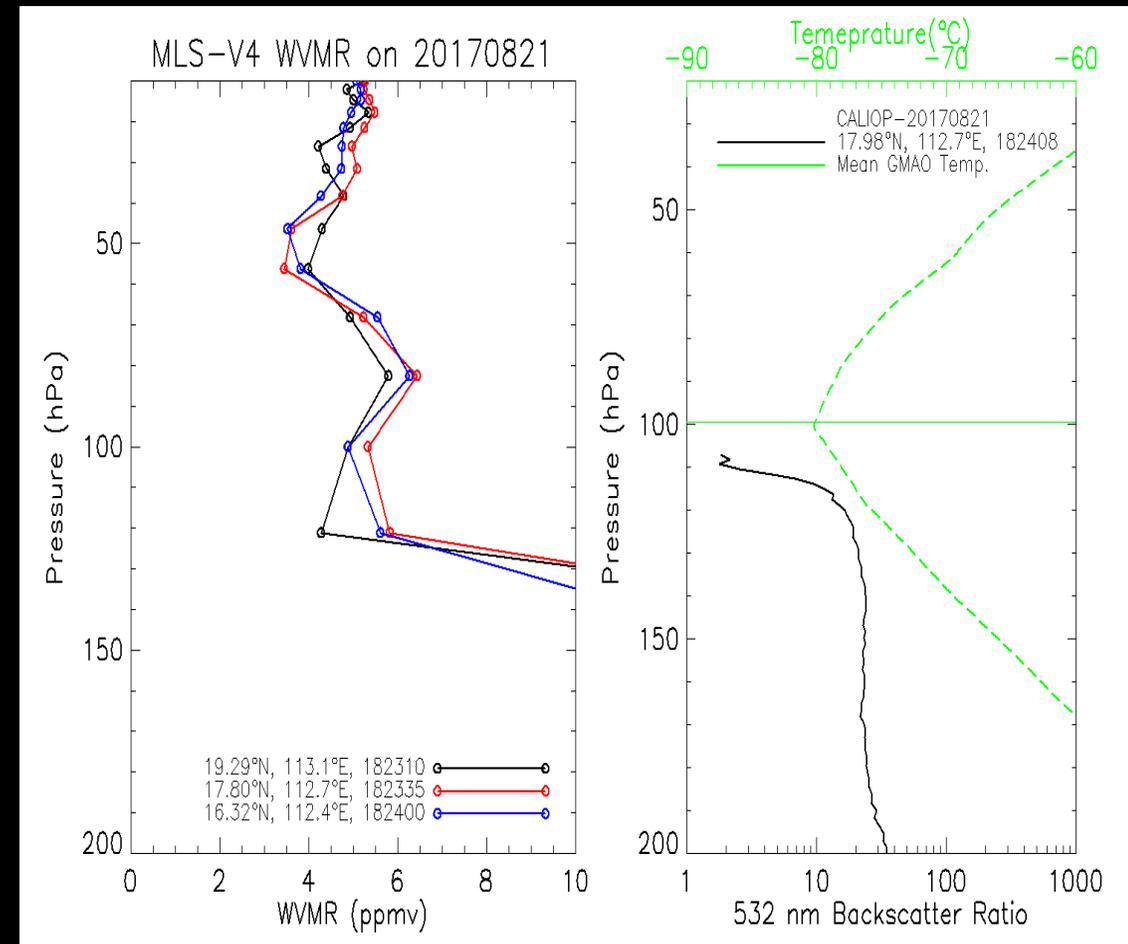
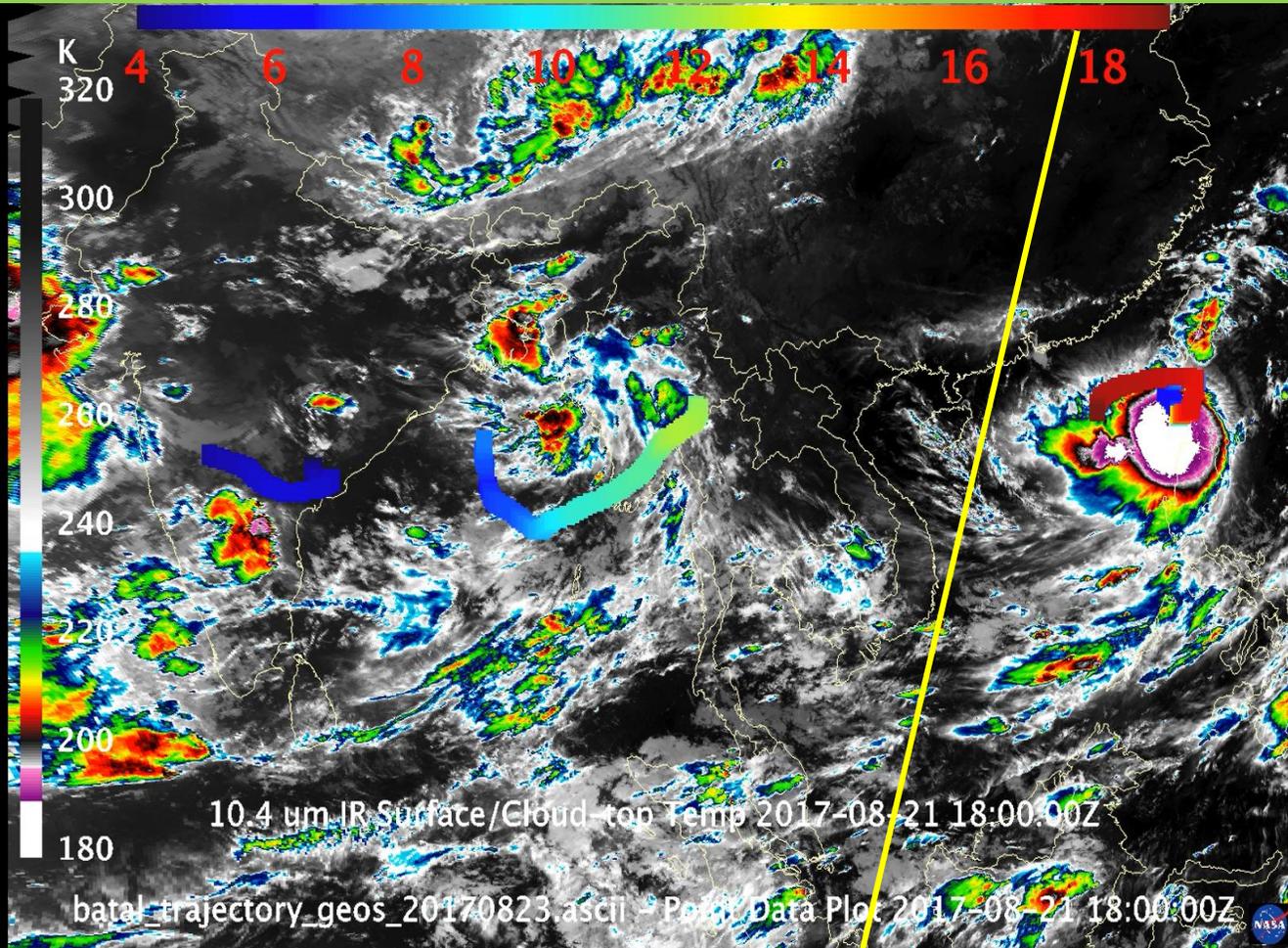


Thank You!



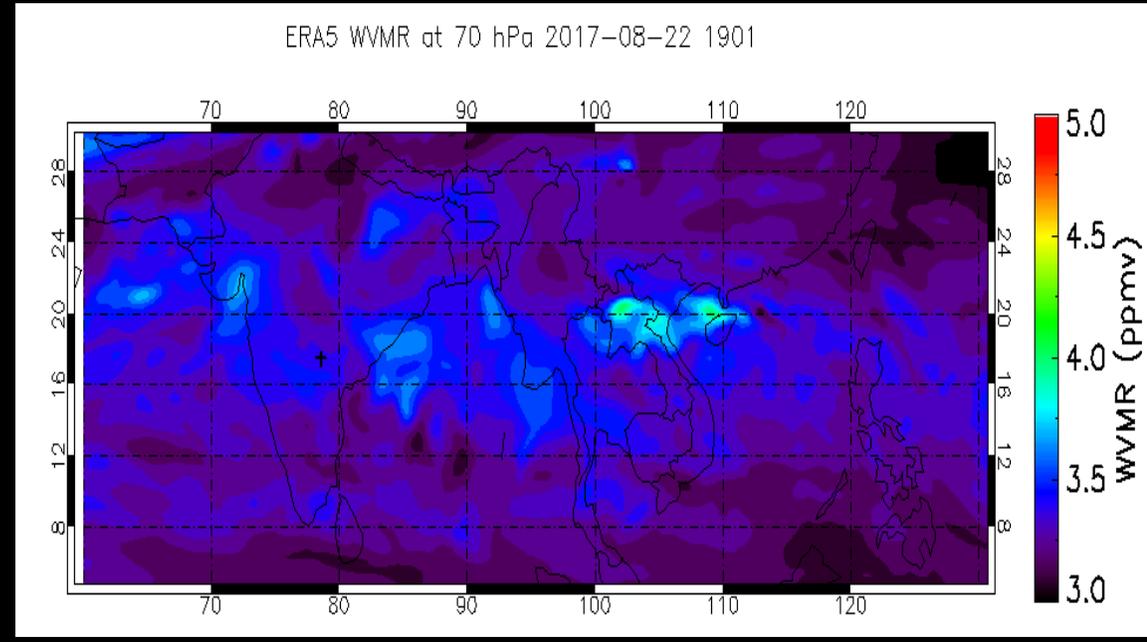
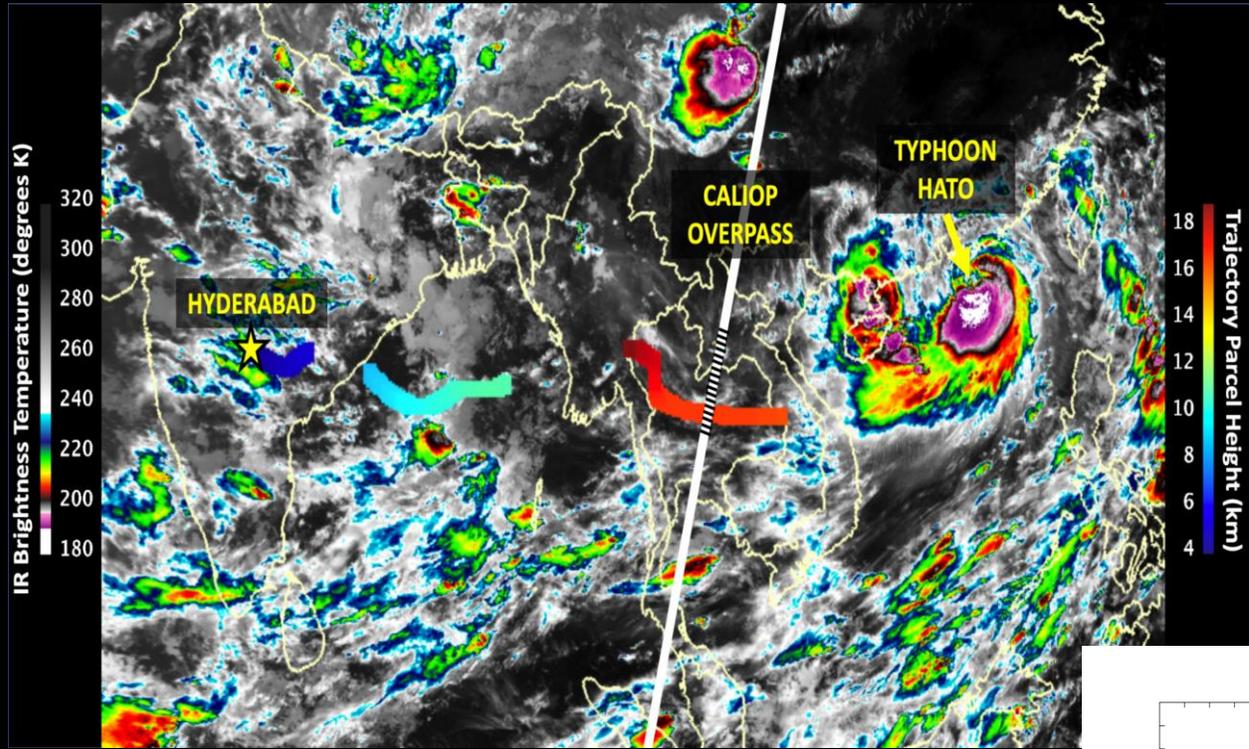
Typhoon Haima

Himawari-8, CALIOP and MLS Observations on 21st Aug. 2017 at 18 UTC

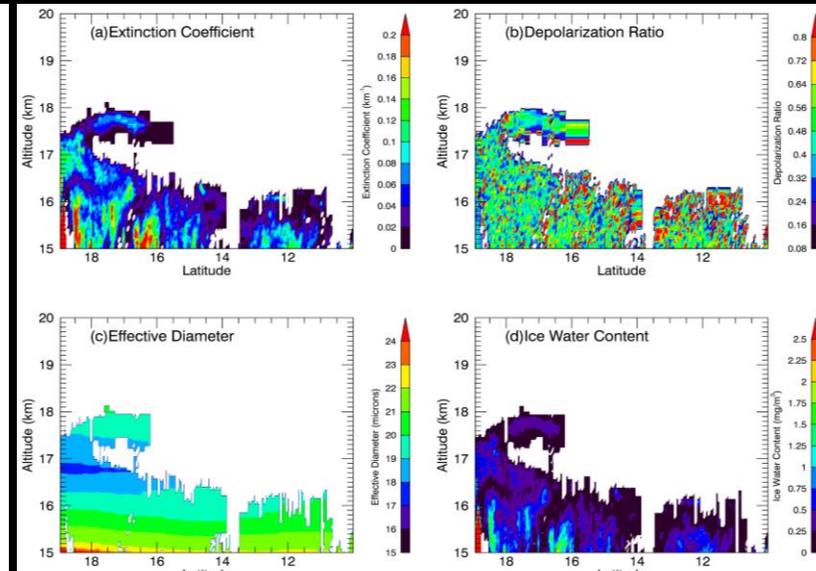
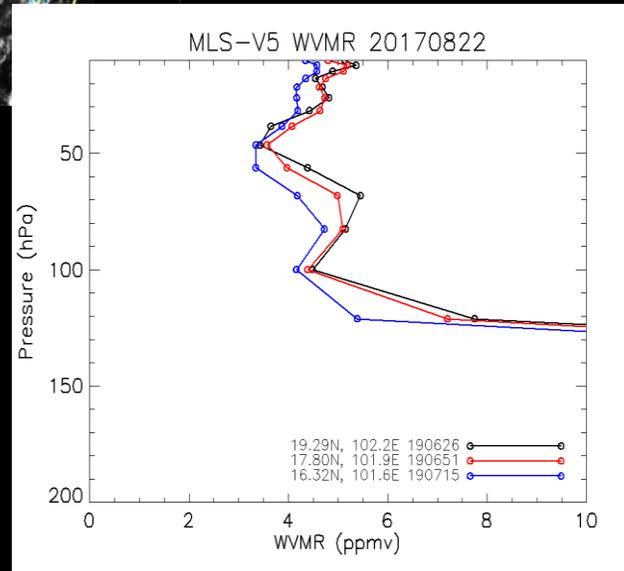


Before the passage of the air-parcels: CALIOP observations showed no layered clouds near the cold-point tropopause

Back-trajectories, Cloud-top Brightness Temperature from Himawari-8 and CALIOP cloud measurements

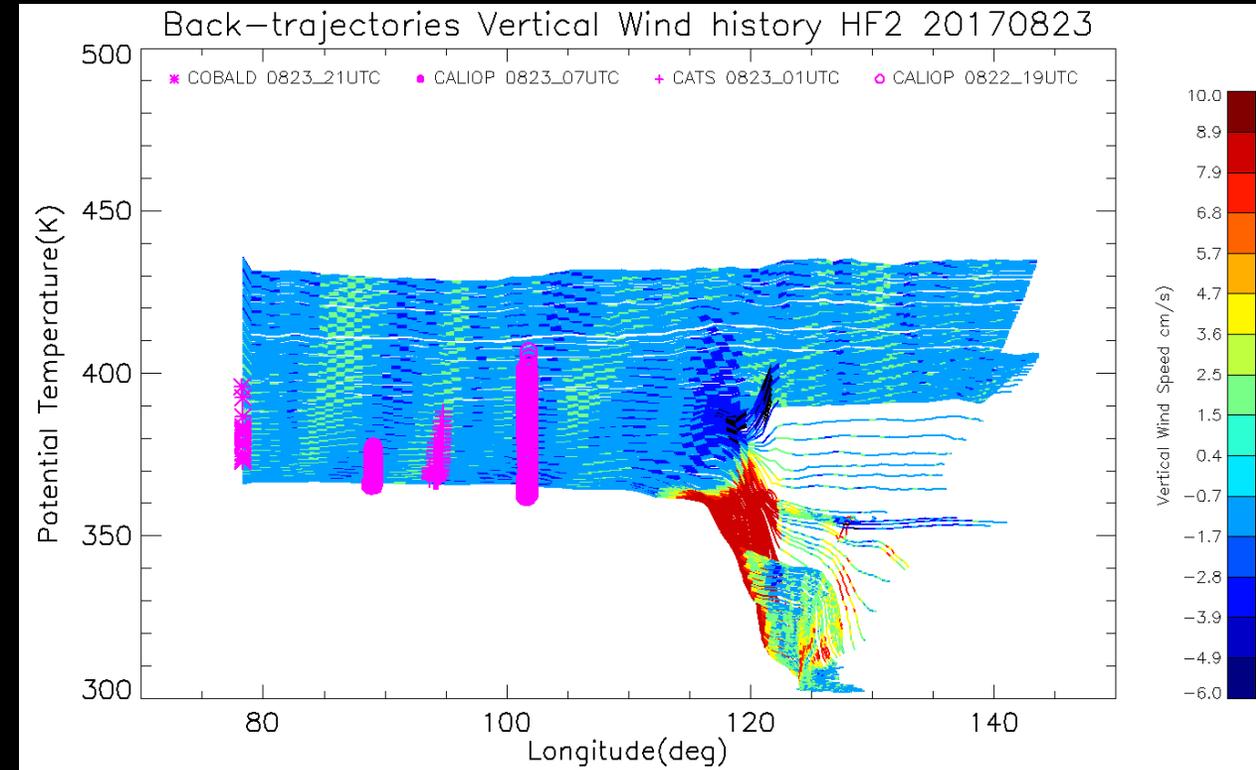
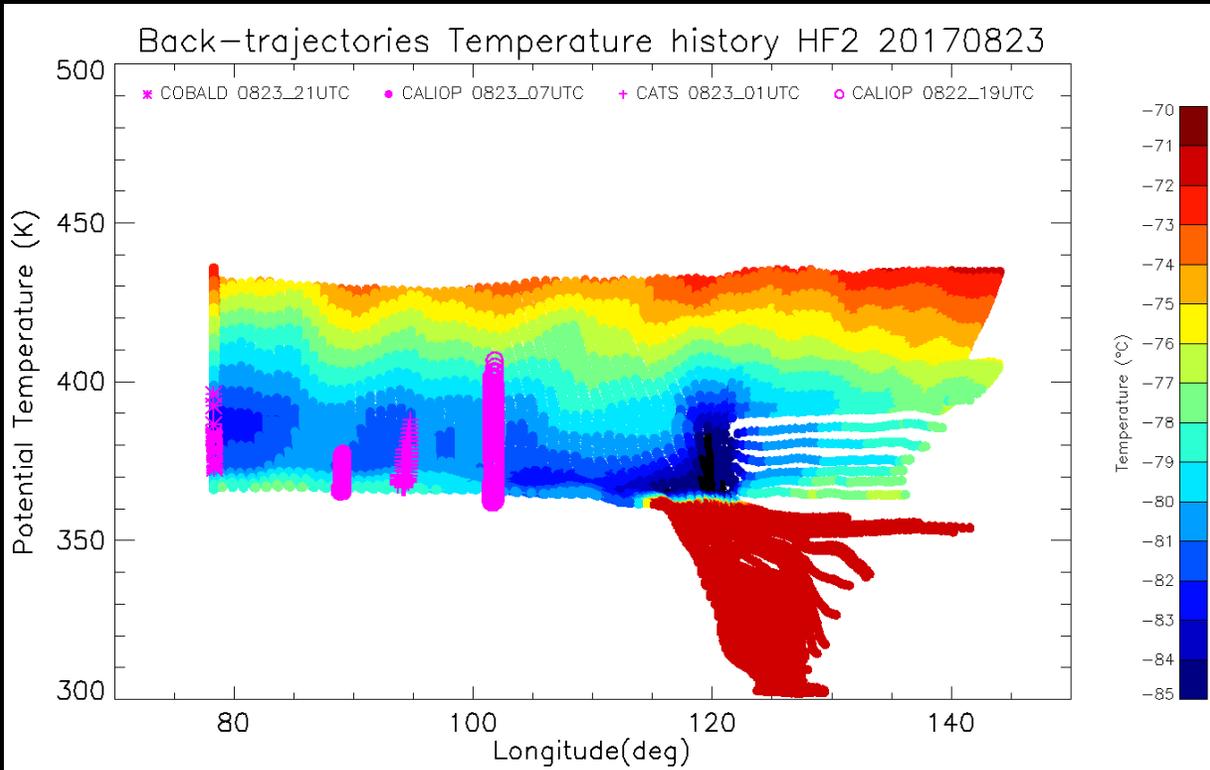


Himawari-8 10.4 μm Cloud Top Brightness Temperature on 22 Aug 2017 at 19 UTC



Temperature, Vertical Velocity of Air Parcels, & CALIOP/CATS Clouds Vs Theta

Locations of cirrus clouds in colder regions are shown in Magenta colored symbols



Questions

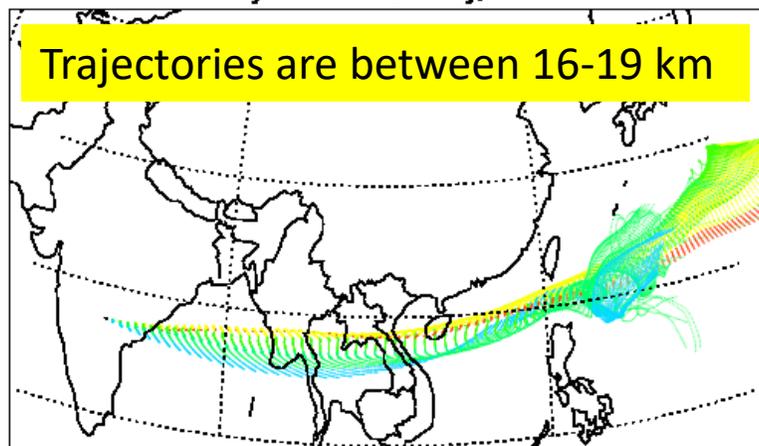
How realistic are these features in MERRA-2 temperature and vertical wind?

Do observations validate these features?

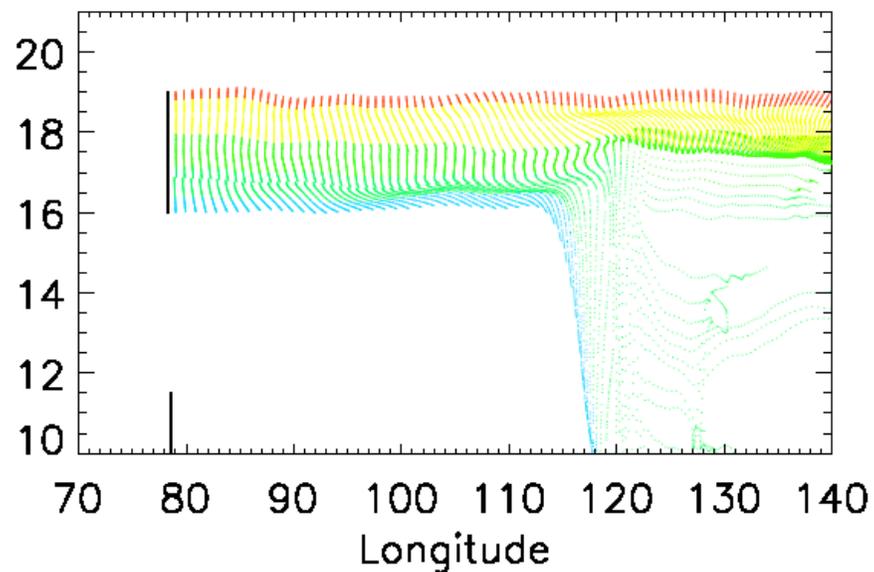
Formation Mechanism: Back-trajectories & Cloud tops from Himawari-8

GEOS5 BWD Traj @ ouds.N raj, 20170823 120hr

Trajectories are between 16-19 km

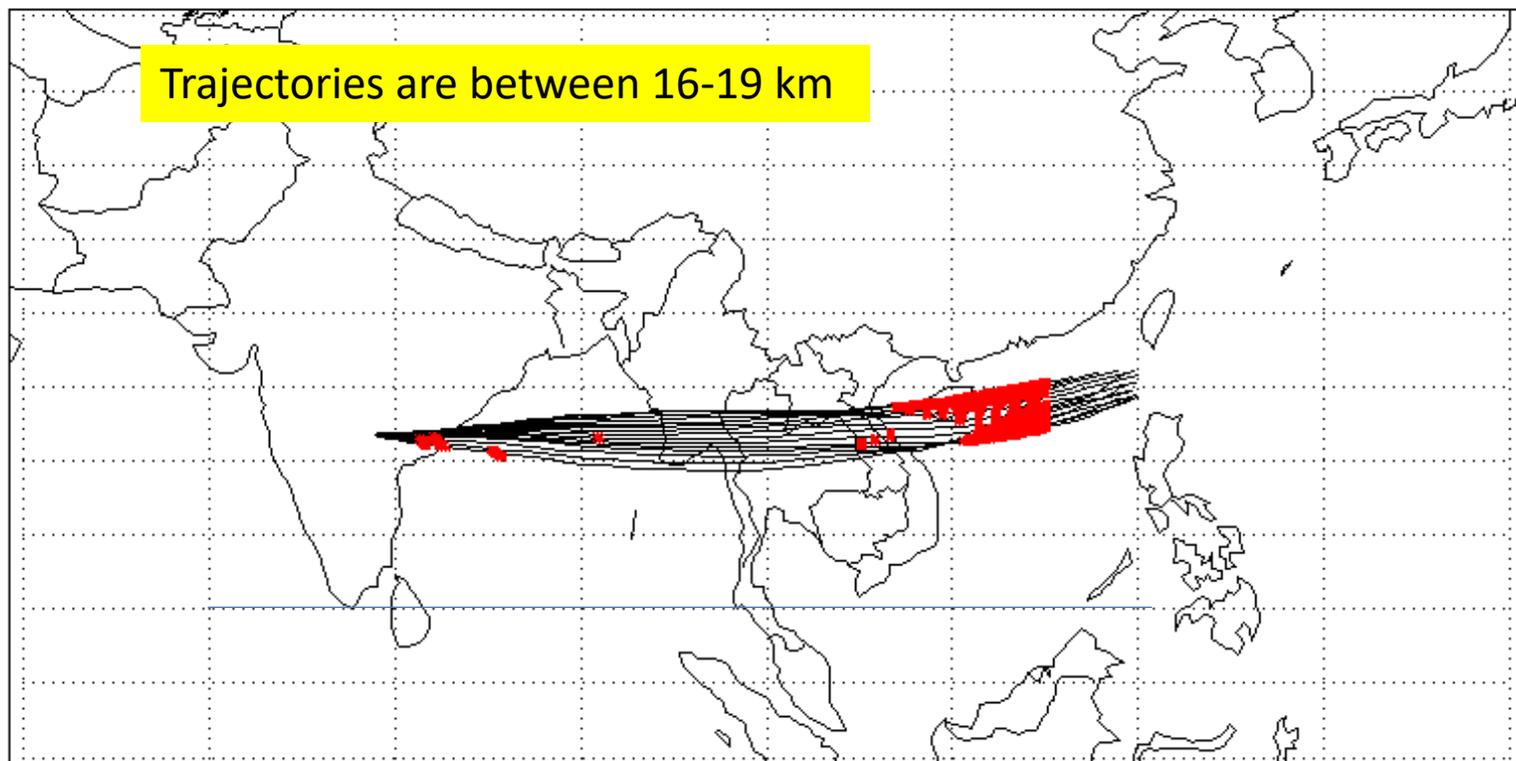


14000 15600 17200 18800
Alt_orig (m)



HF2 August 23rd 2017 Convective Influence

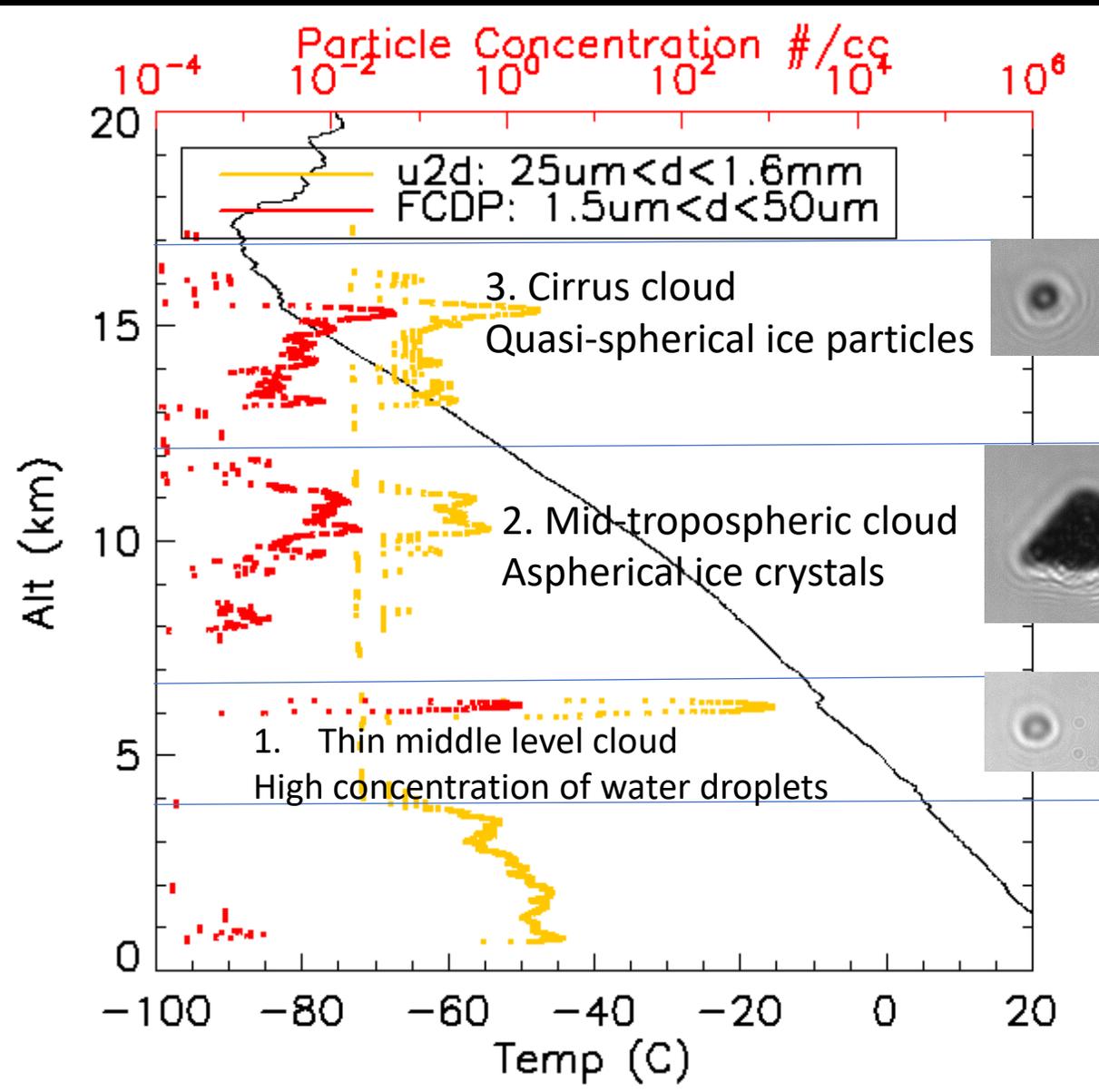
Trajectories are between 16-19 km



Back-trajectories initialized from the tropopause cirrus location using Langley Trajectory Model (LaTM) and Convective influence from Himawari-8 Cloud top BT images

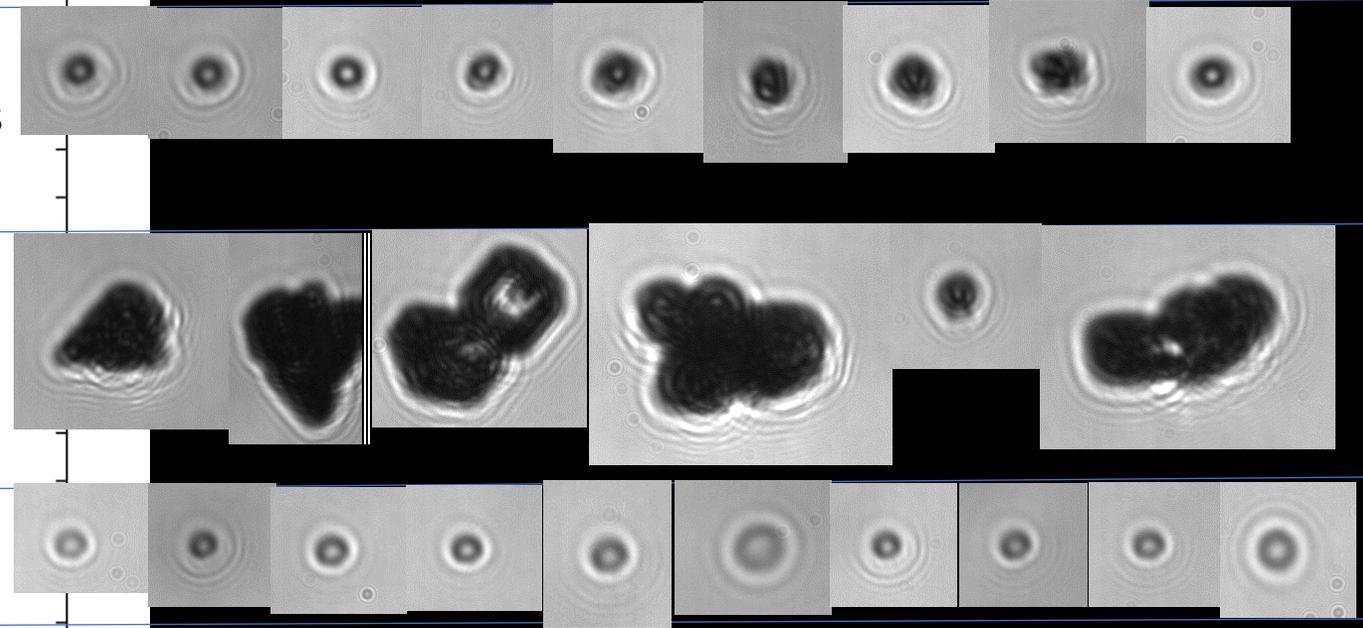
Micro-COPP Measurements on 29th August 2018

29th August 2018



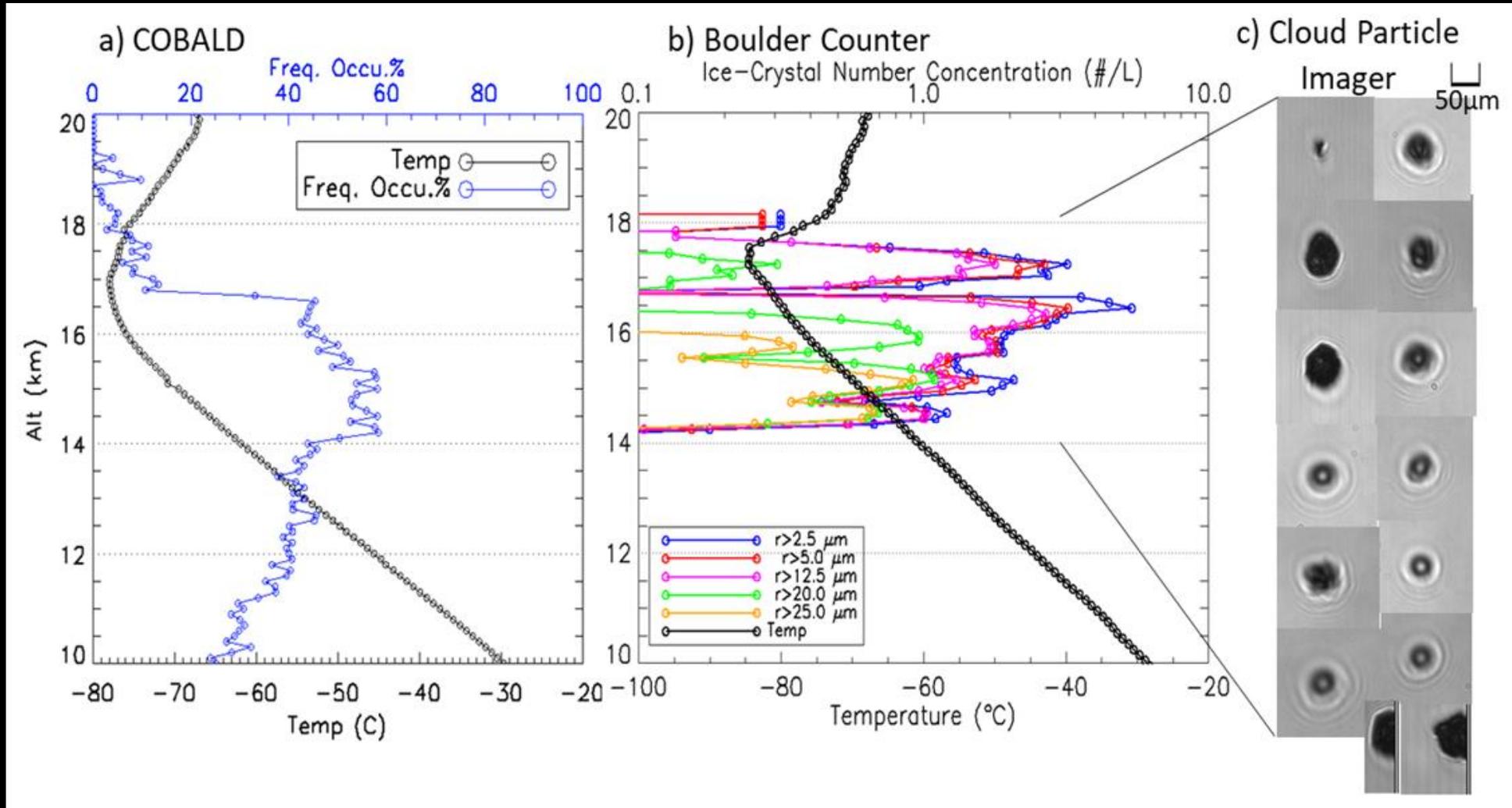
Cloud Particle Imager (CPI)

200 μm



Balloon measurements unaffected by shattering

Occurrence Frequency, Number Concentration & Shape of Ice crystals



Micro-COPP Vs COBALD

29 August 2018

29 August 2018

