# Formation of Tropopause Cirrus clouds by Typhoon-induced gravity waves during the Asian Summer Monsoon: A Case Study from the BATAL 2017 Campaign


**Amit Kumar Pandit**[1], Jean-Paul Vernier[1], T. Duncan Fairlie[2†], Kristopher M. Bedka[2], Melody A. Avery[2], Harish Gadhavi[3], M. Venkat Ratnam[4], Sanjeev Dwivedi[5], K. Amar Jyothi[6], Frank G. Wienhold[7], Holger Vömel[8], Hongyu Liu[1], Bo Zhang[1], B. Suneel Kumar[9], Tra Dinh[10], and A. Jayaraman[11]

[1]National Institute of Aerospace, Hampton, USA
[2]NASA Langley Research Center, Hampton, USA.
[3]Physical Research Laboratory, Ahmedabad, India.
[4]National Atmospheric Research Laboratory, Gadanki, India.
[5]Meteorological Centre, India Meteorological Department, Bhubaneswar, India.
[6]National Centre for Medium Range Weather Forecasting, Noida, India.
[7]ETH Zurich, Zurich, Switzerland.
[8] National Centre for Atmospheric Research, Boulder, USA.
[9]Tata Institute of Fundamental Research Balloon Facility, Hyderabad, India.
[10]Department of Physics, University of Auckland, New Zealand and
[11]Bangalore University, Bangalore, India.

*†Deceased on 27th April 2022*

*Contact:* amit.pandit@nianet.org

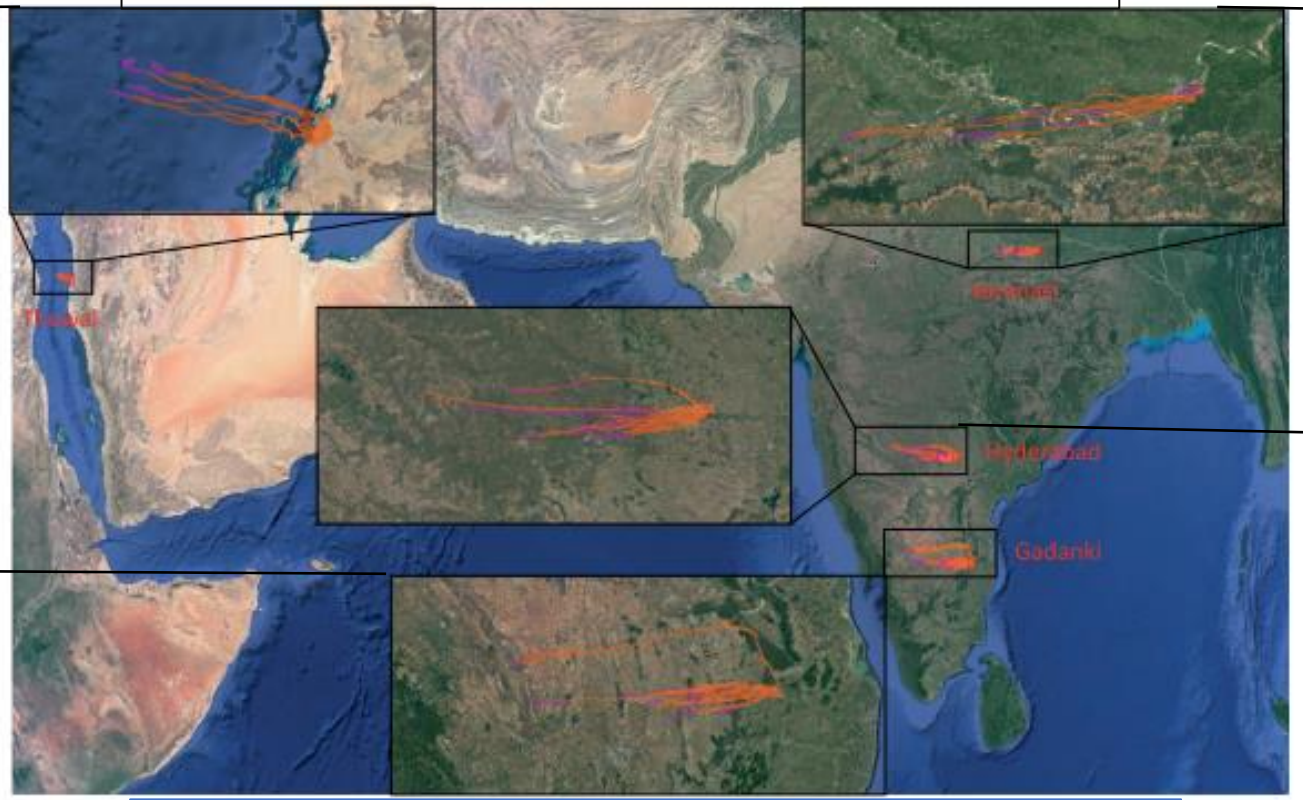

*Strateole-2 Workshop on Tropical UTLS Processes*
*8-9 June 2023, LASP, University of Colorado, Boulder, USA.*

# BATAL is built on International Partnerships

# BATAL campaigns 2014-2019

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

Balloon Trajectories: Ascent/Descent (2015)



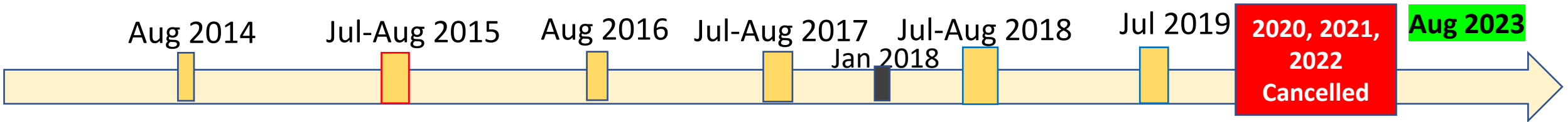

Banaras Hindu University (BHU), Varanasi, India

National Atmospheric Research Laboratory (NARL), Gadanki, India

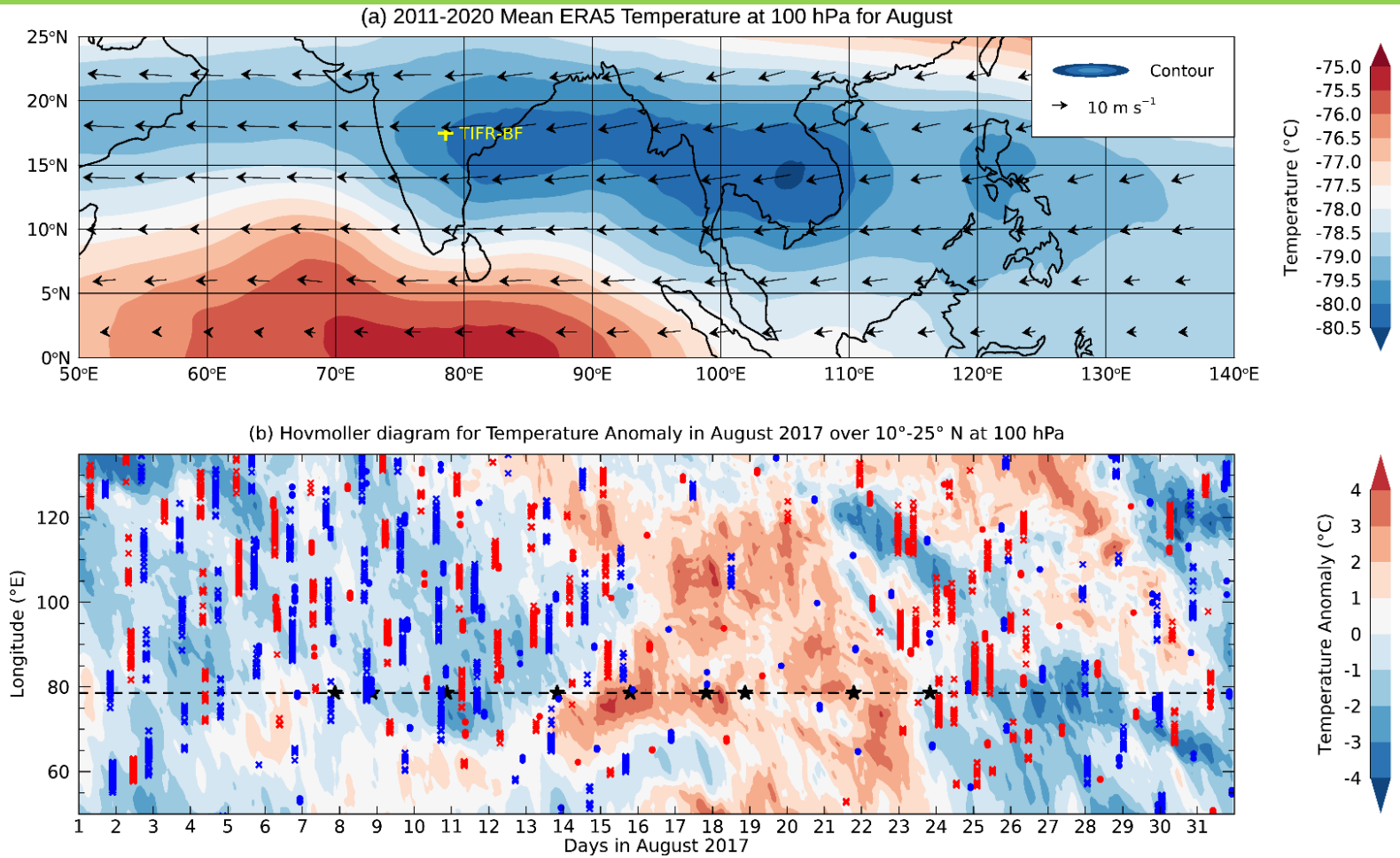
Tata Institute for Fundamental Research (TIFR) Balloon facility

- **5**-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**



# Motivation and Objectives

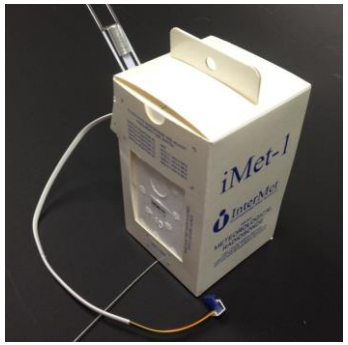



- Number concentrations and shapes of ice-crystals smaller than 100 microns are uncertain (Heymsfield et al., 2017).
- Past aircraft measurement results were influenced by shattering effects of ice-crystals.
- Satellite derived (DARDAR) number concentrations are overestimated, and they do not represent 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**

# Balloon-borne Instruments for Measuring Ice Crystals in Cirrus Clouds

## iMet Radiosonde + COBALD (A Backscattersonde)



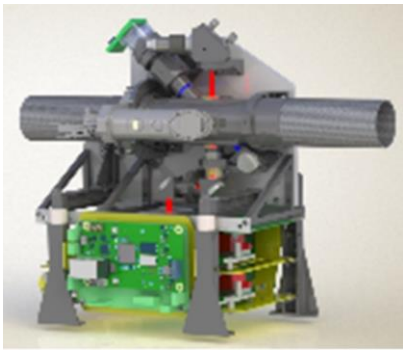

+

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

**Micro-COPP**

**FSSP**

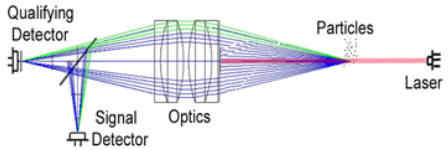
- Forward Scattering Spectrometer Probe
- Size distribution and concentration of cloud particles
- 1 to 50 µm over 20 bins

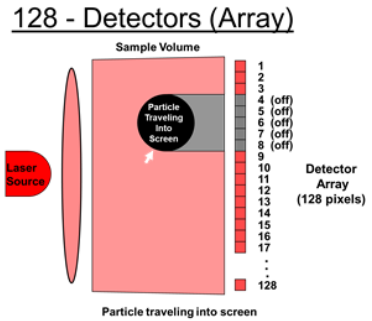
**2D-S**

- 2-Dimensional Optical Array Probe
- size distribution, concentration, and area/extinction of cloud droplets, precipitation and ice crystals
- Size range: 5µm-1mm
- 10 to 25 µm pixel resolution

**CPI**

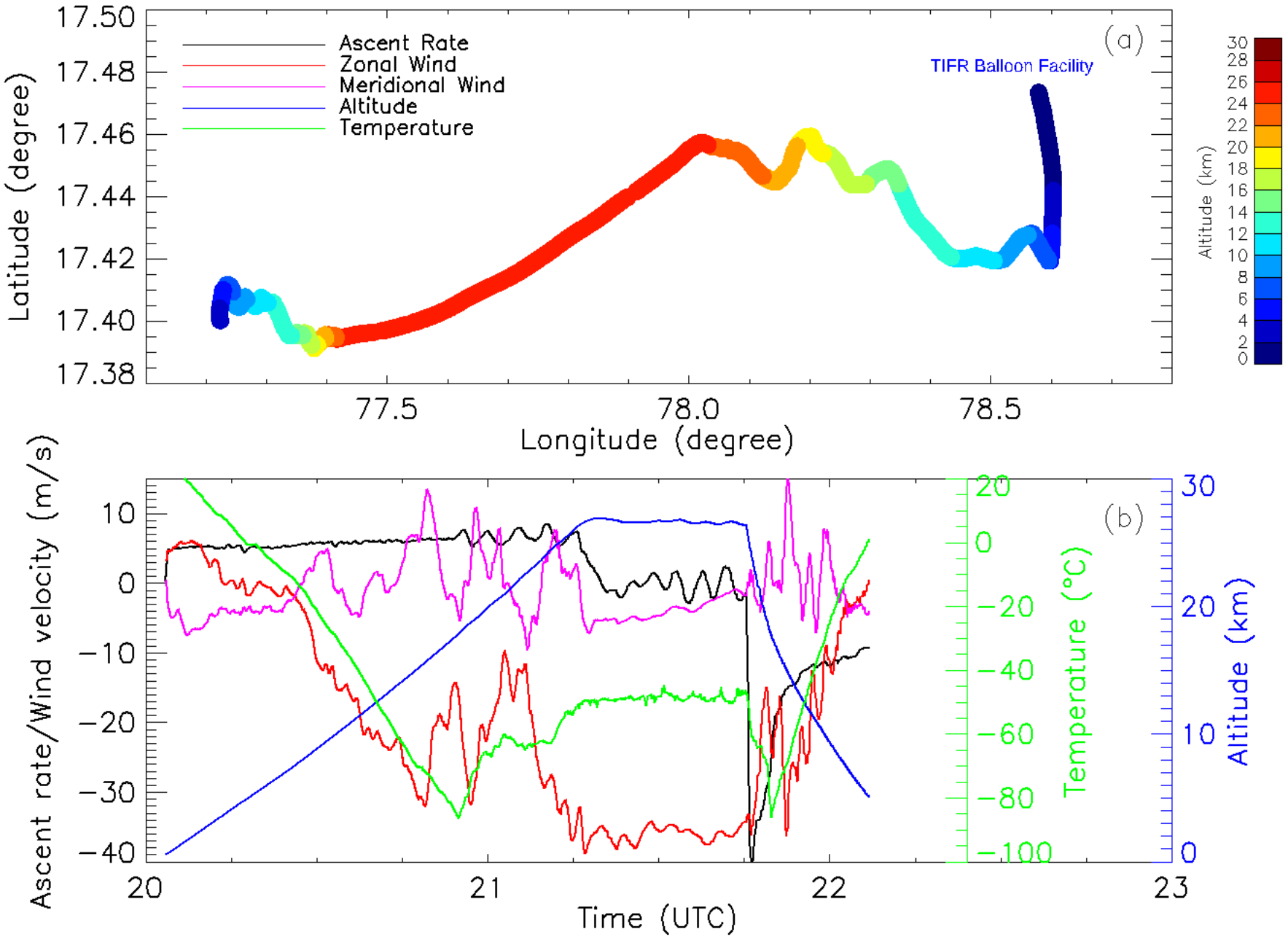
- Cloud Particle Imager
- Digital camera
- Up to 400 frames per second
- Size range: 5µm-1mm
- Resolution 1 µm



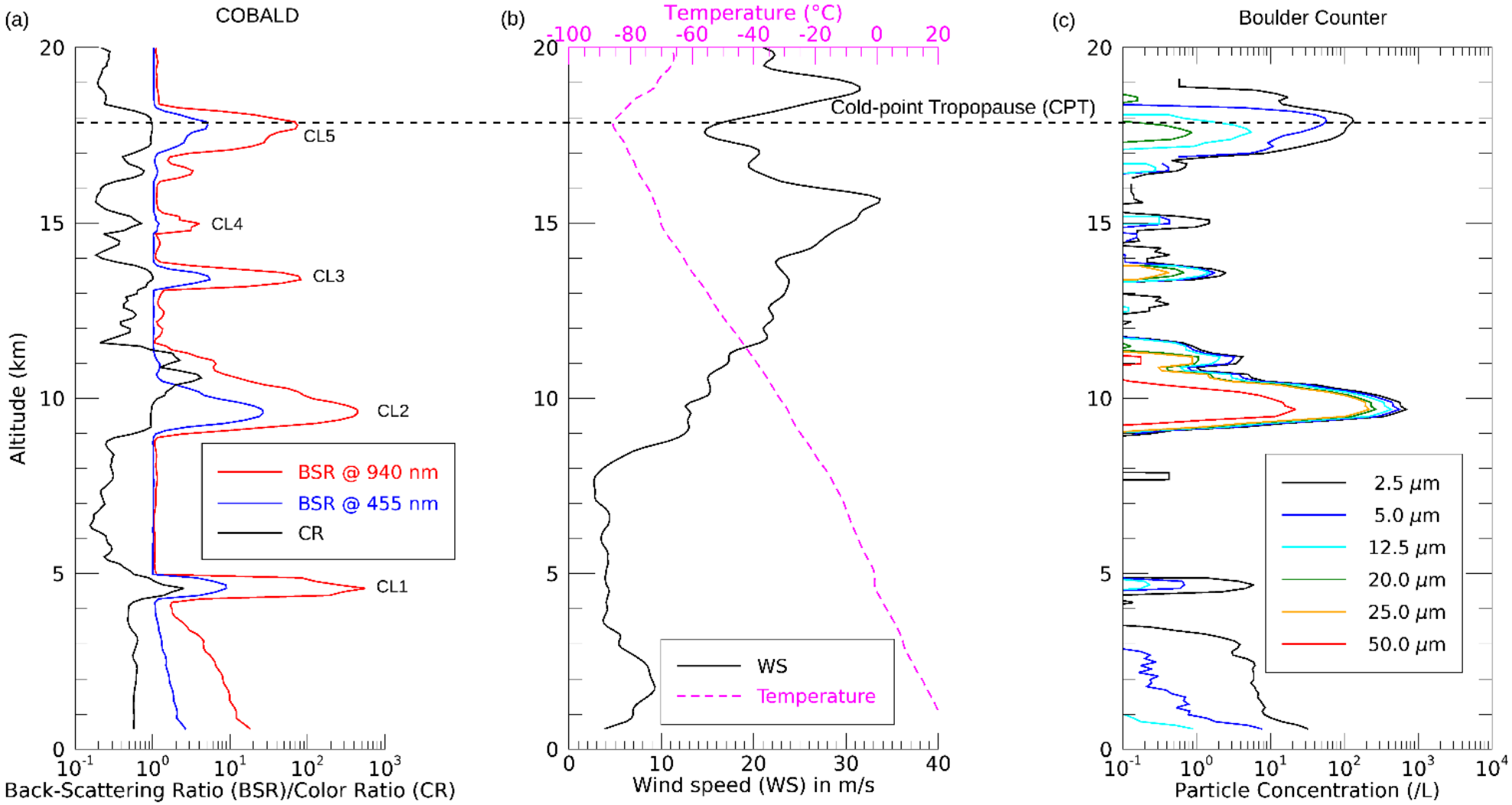




SPECinc
Cloud Physics and Instrumentation

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



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



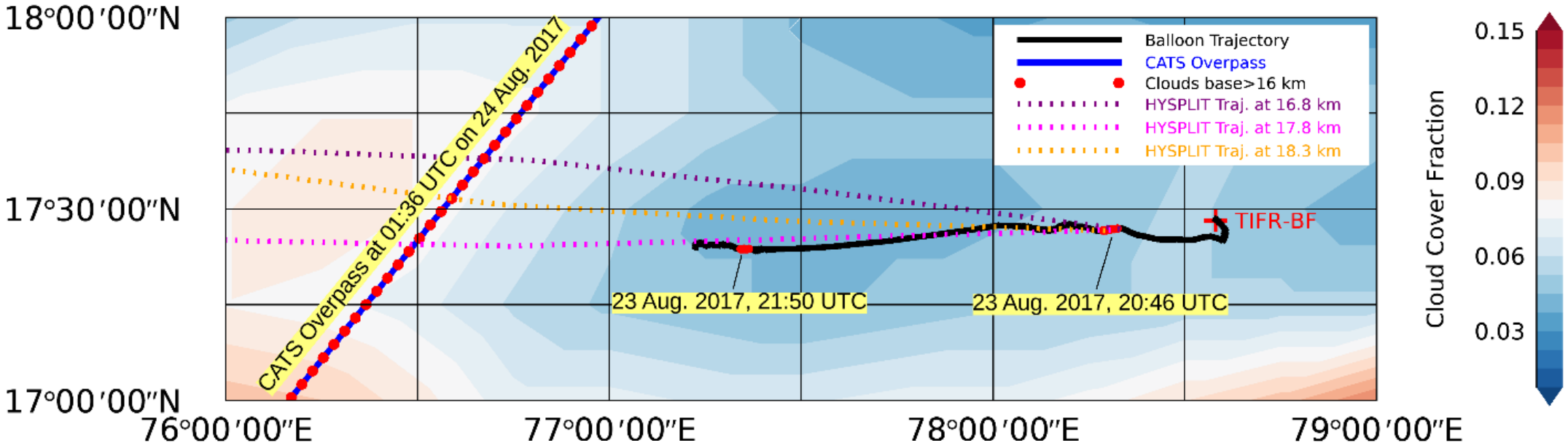

- Backscatter Ratio (BSR): Ratio of total backscattering coefficient ($\beta = \beta_{p} + \beta_{m}$) to the molecular backscattering coefficient ($\beta_m$)
- Color Index (CI) and Particulate Color Ratio (CR): $CI = (\mathrm{BSR}_{940}-1)/(\mathrm{BSR}_{455}-1) = 18.\left(\frac{\beta_{p940}}{\beta_{p455}}\right) = 18.CR$

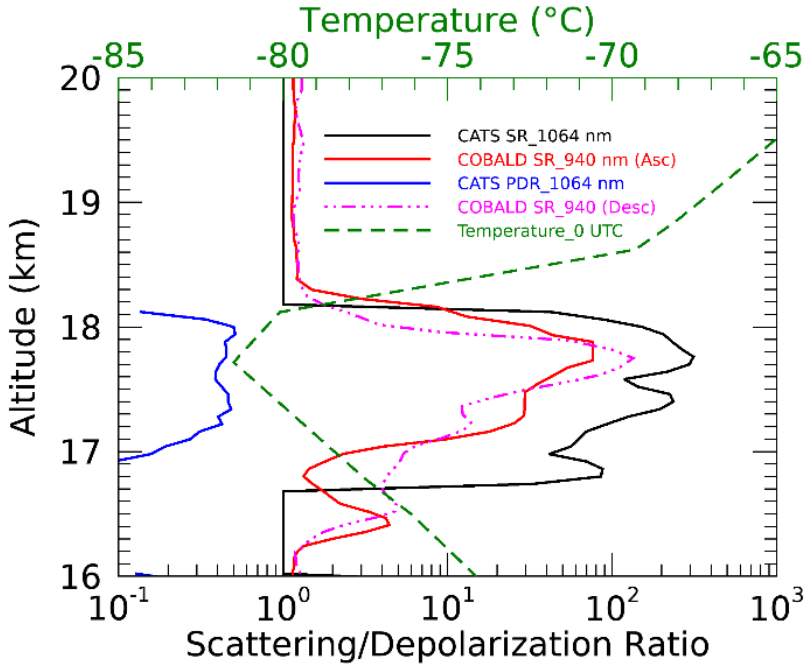
CR<0.7 – Aerosol

CR>0.7 - Cloud

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

# Validation of Balloon Measurements using CATS Lidar observations onboard ISS

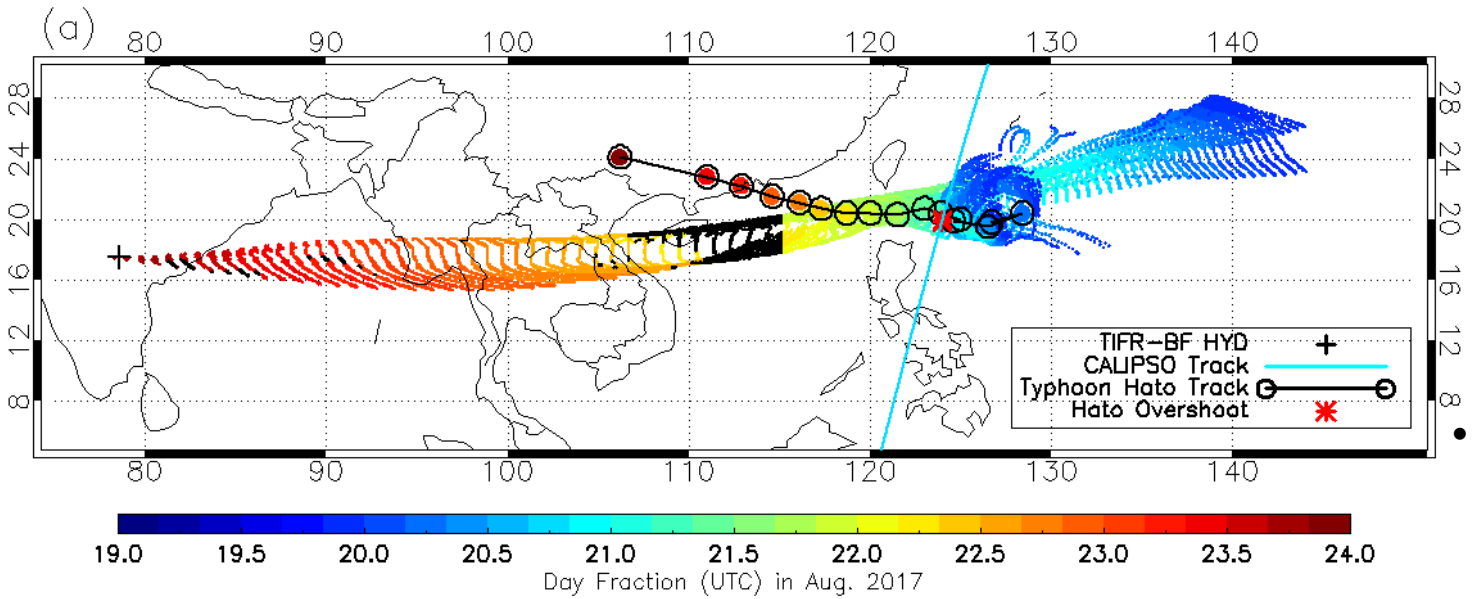


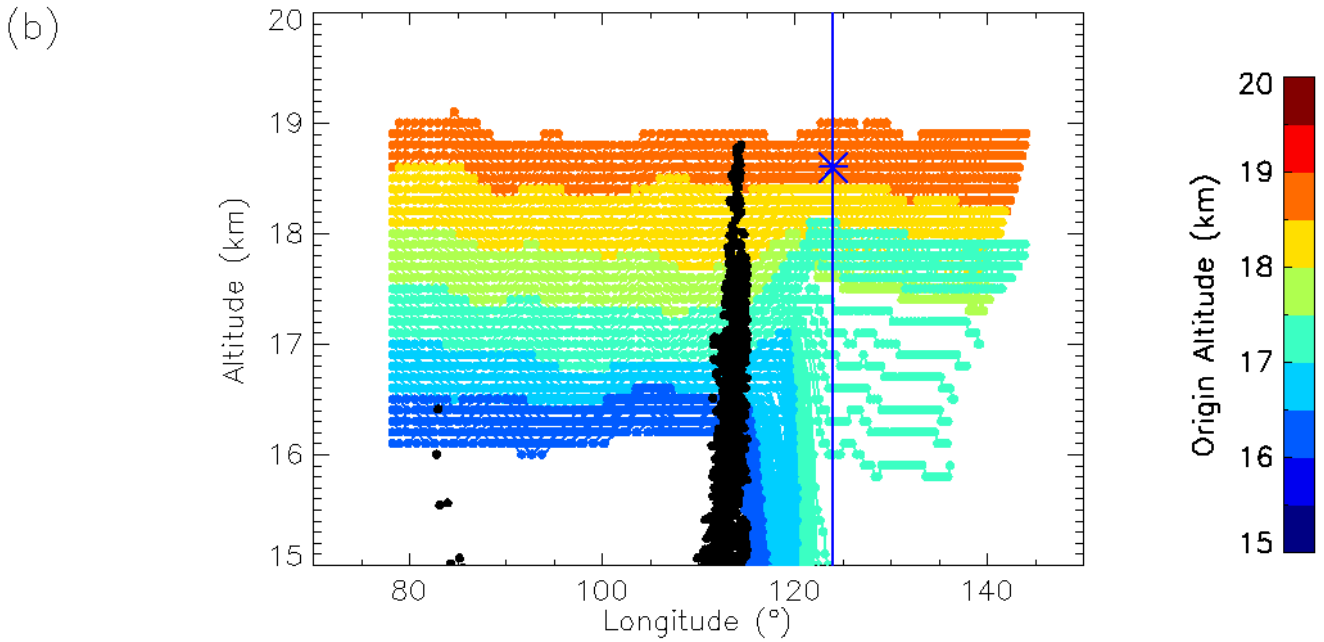



# Satellite Observations, Lagrangian Back-trajectories and Reanalysis

| Satellite/Model | Resolution | Output Parameters |
|---|---|---|
| **CALIOP/CALIPSO** (L2 5km V4.2 Clay & Cpro products) | Vertical:60 m,<br>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,<br>Horizontal: 5km along the orbit track | 1064 backscatter ratio, cloud base and top heights |
| **Himawari-8** | Horizontal: ~2 km for IR bands,<br>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**<br>(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

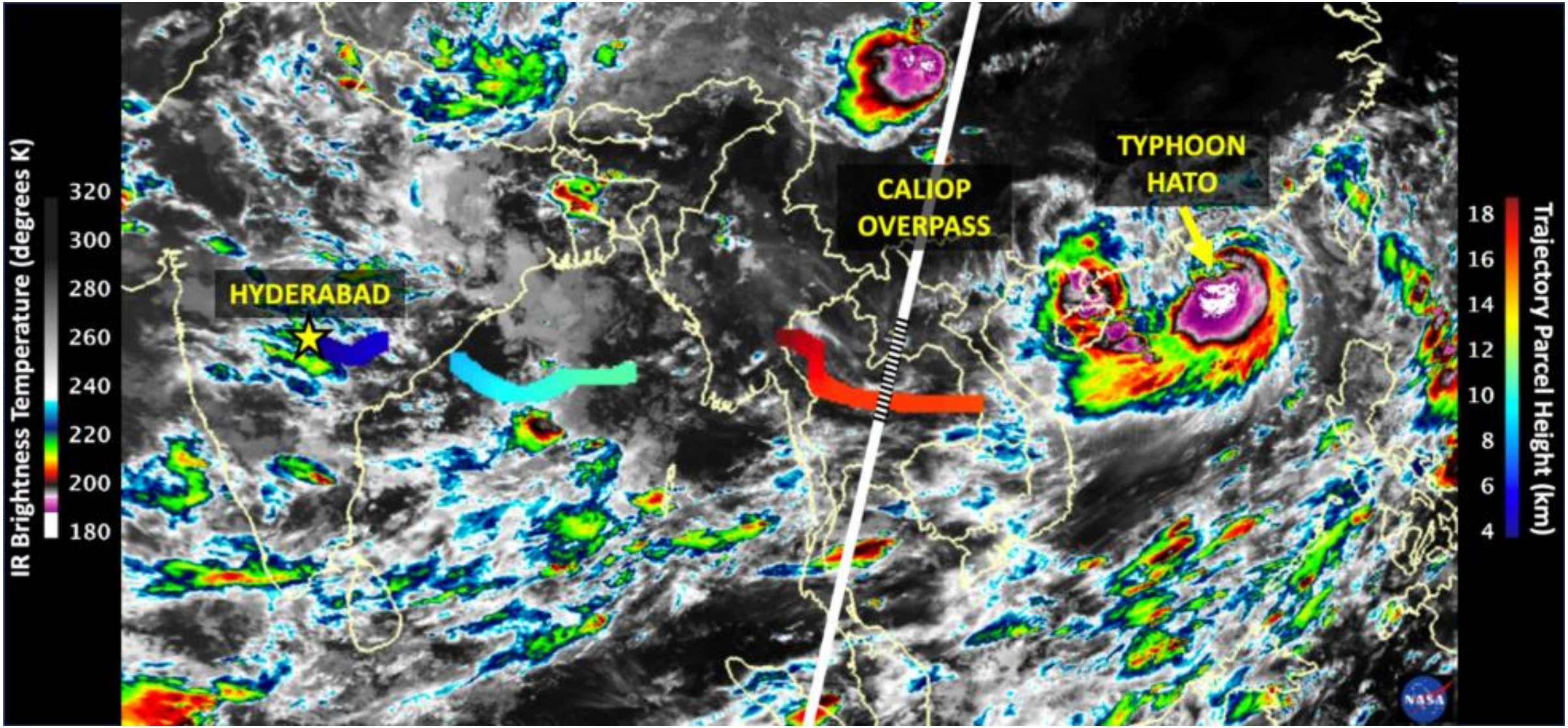


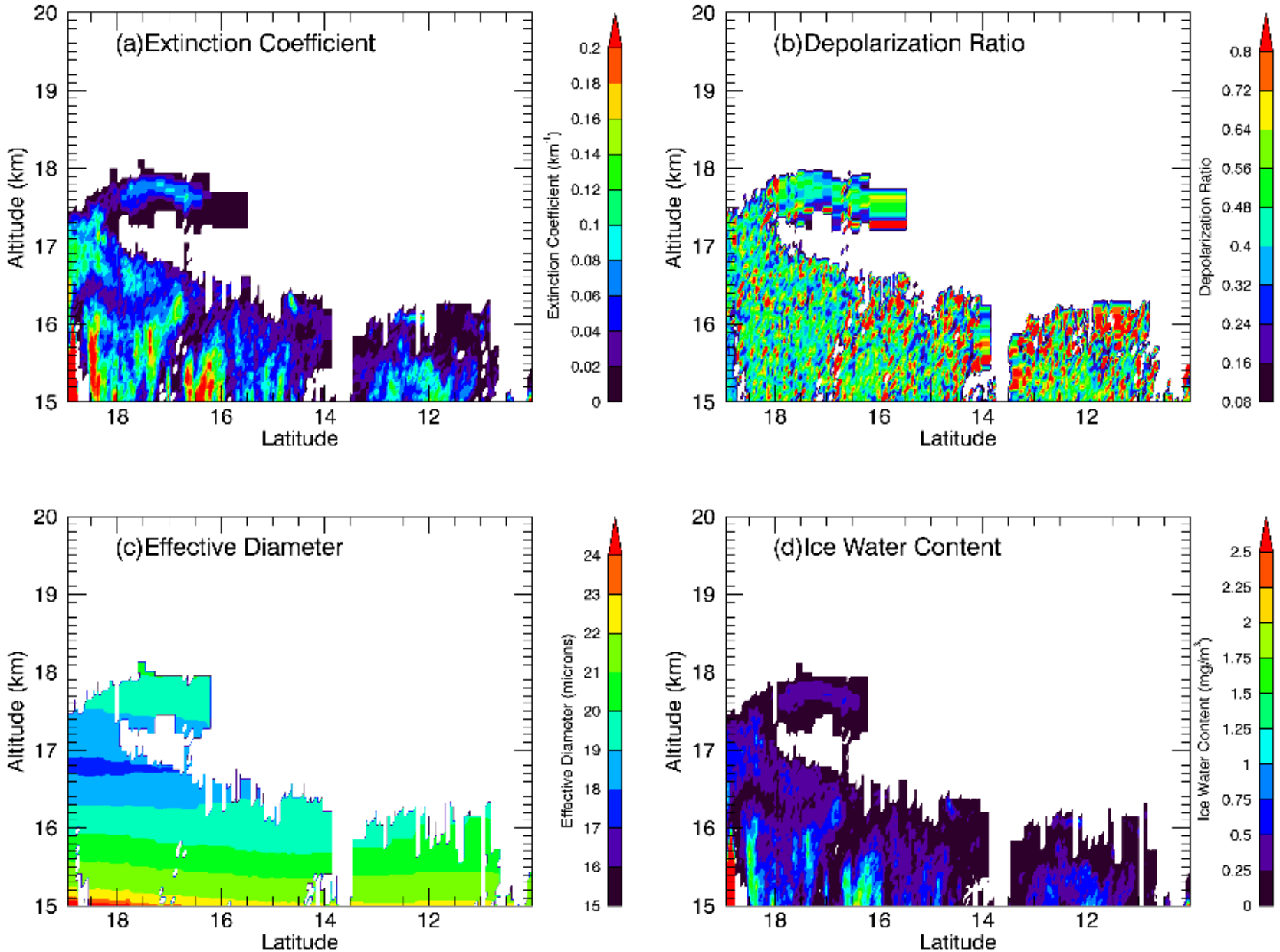

- Back-trajectories initialized from the tropopause cirrus site between 16-18 km are influenced by local and distant convection.
- Local convection: Late afternoon convection near the East coast India.
- Distant Convection: Typhoon Hato – a category-3 tropical cyclone.

Bedka and Khlopenkov (2016)

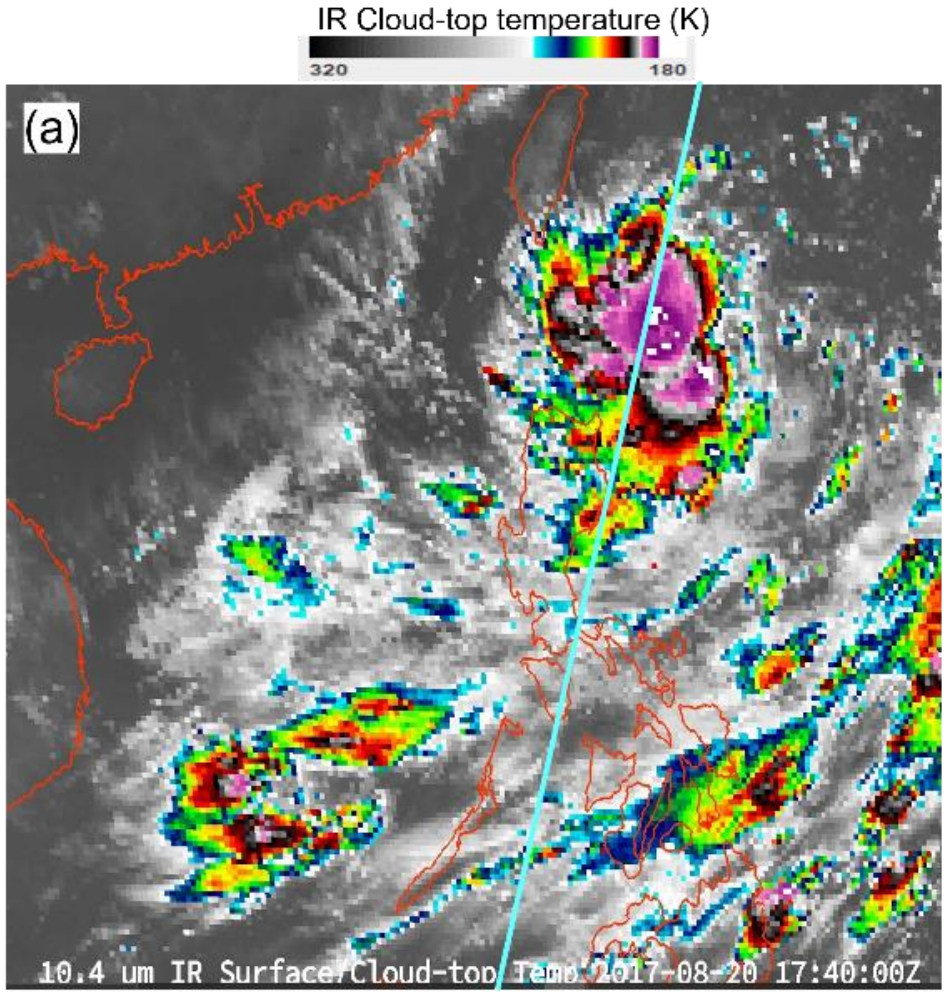
# Formation Mechanism: Typhoon *Hato*

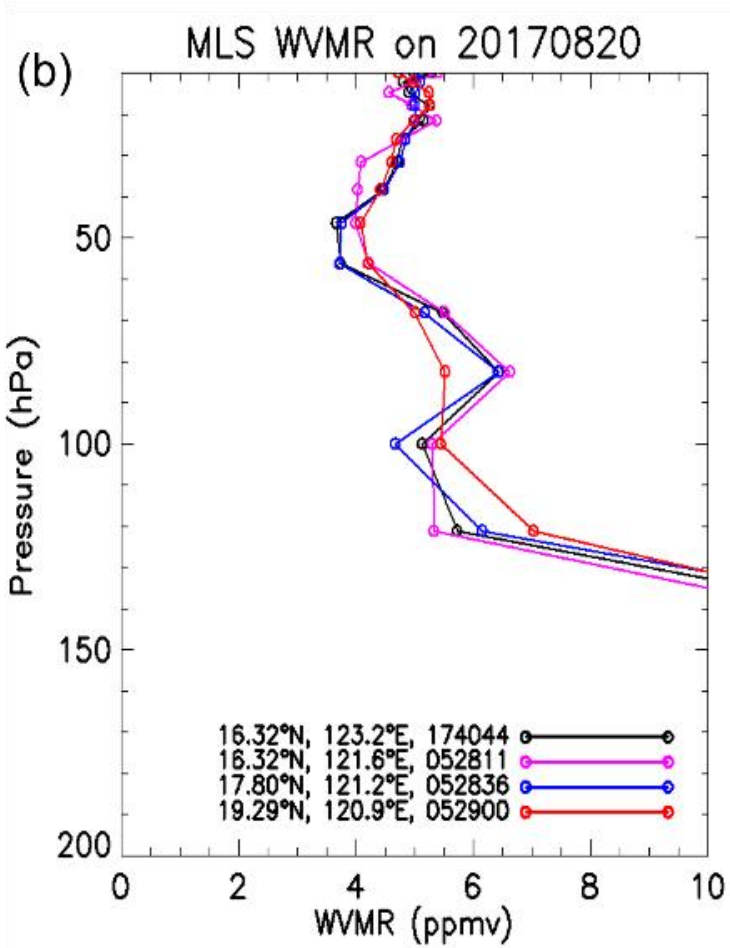


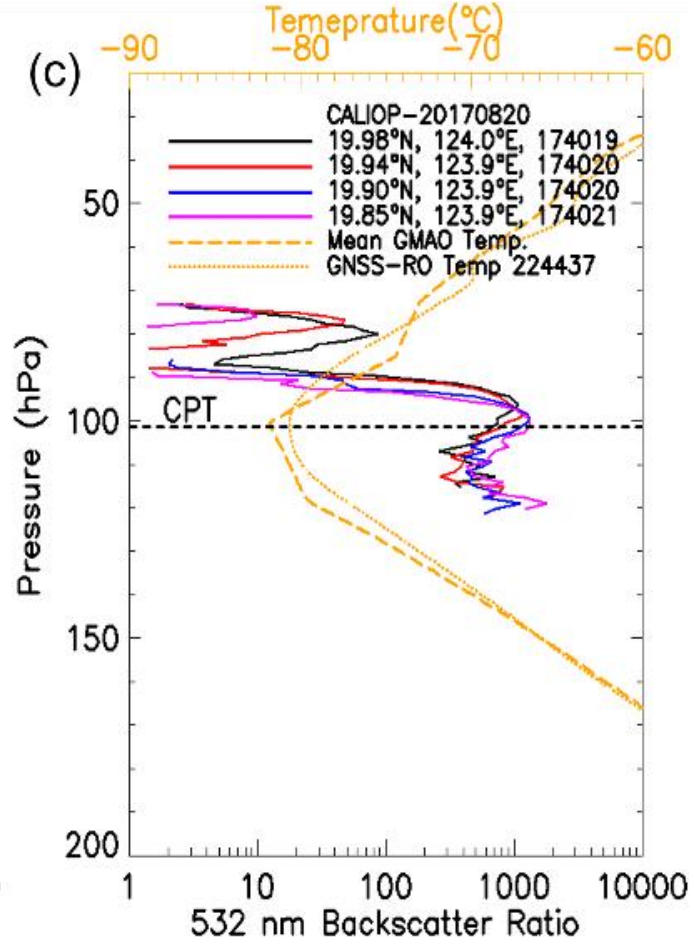
# Tropopause Cirrus from the Outflow of Typhoon *Hato*



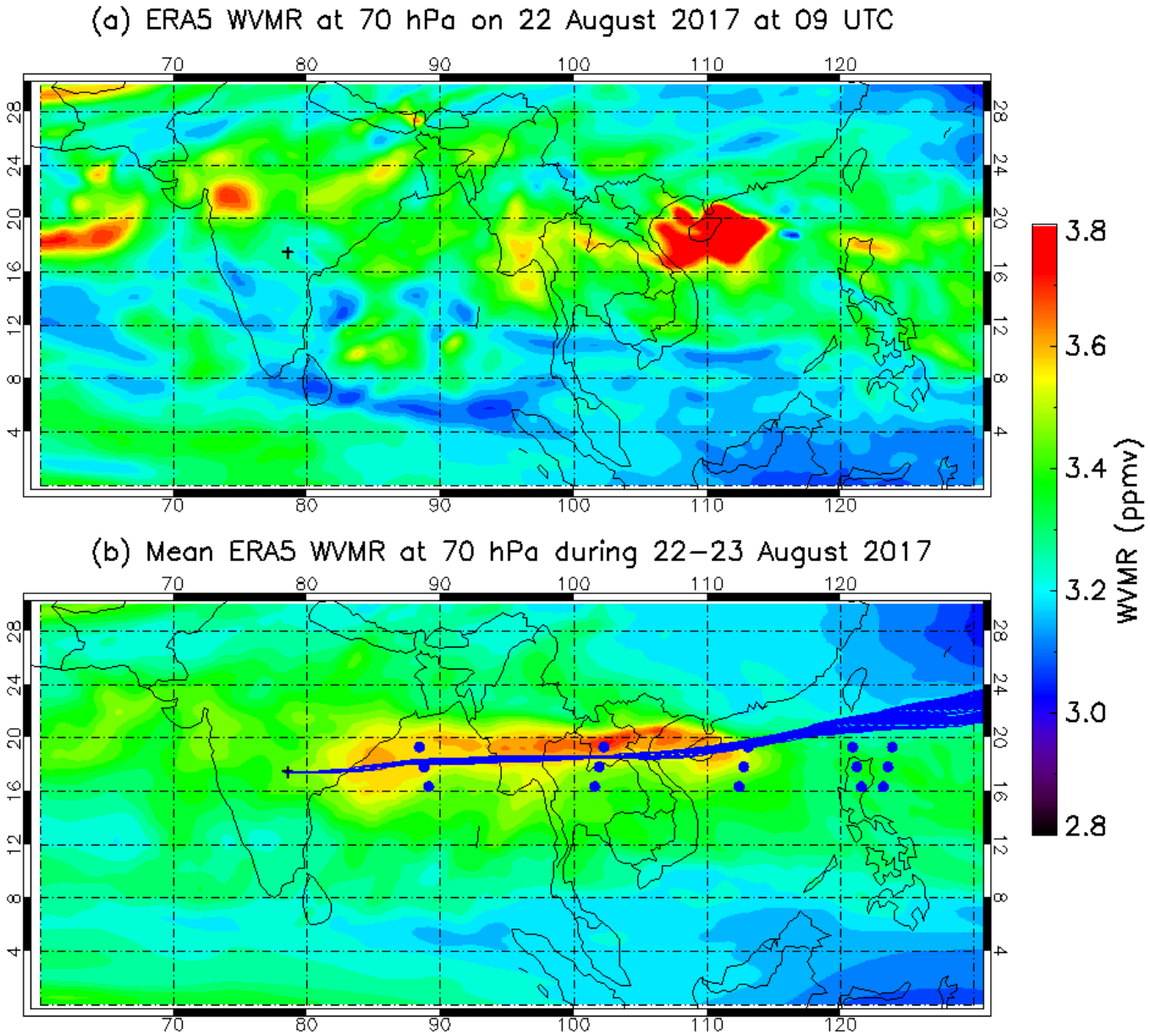
# Lower Stratospheric Hydration due to Overshooting Convection on 20 Aug 2017



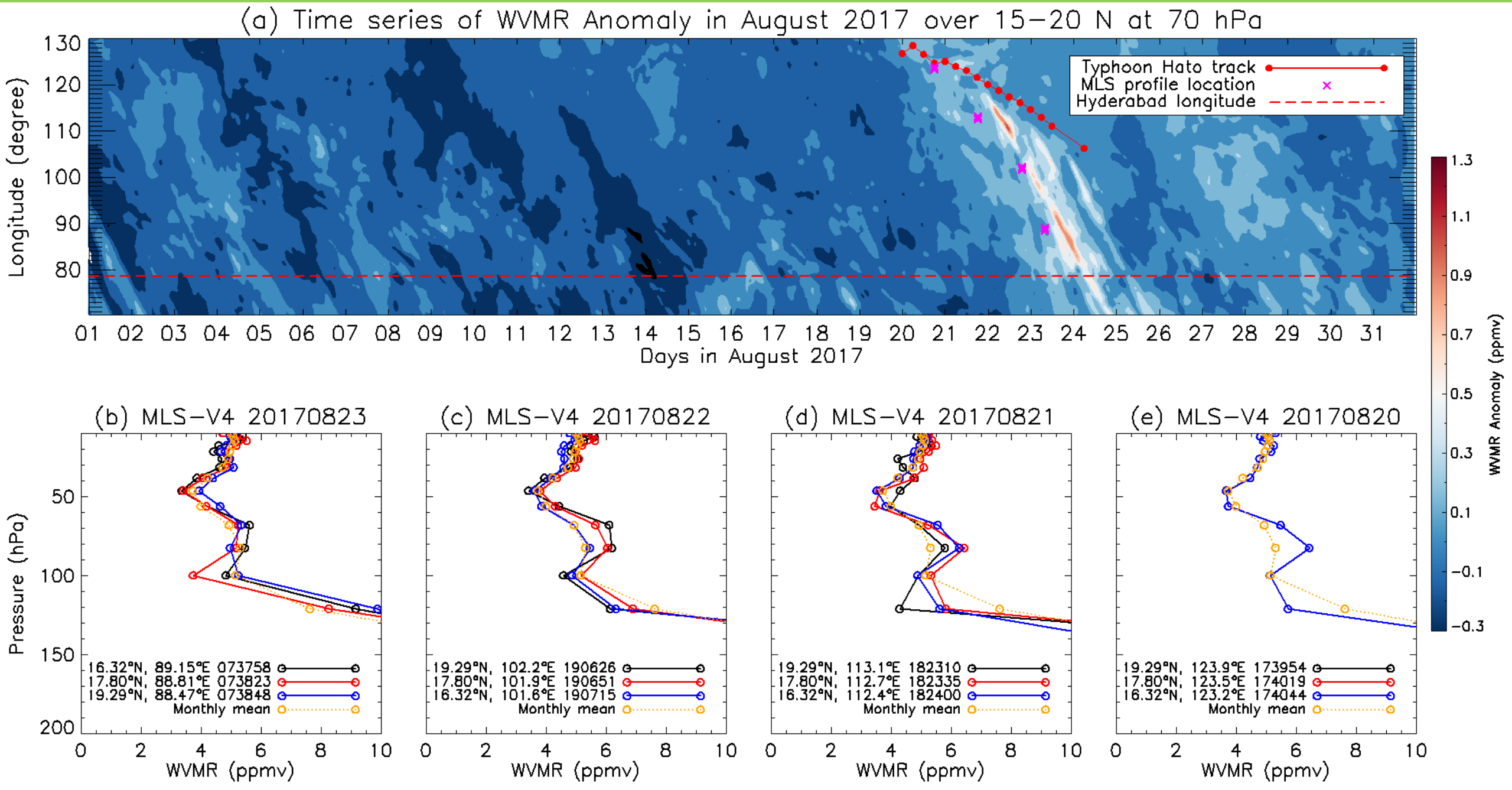



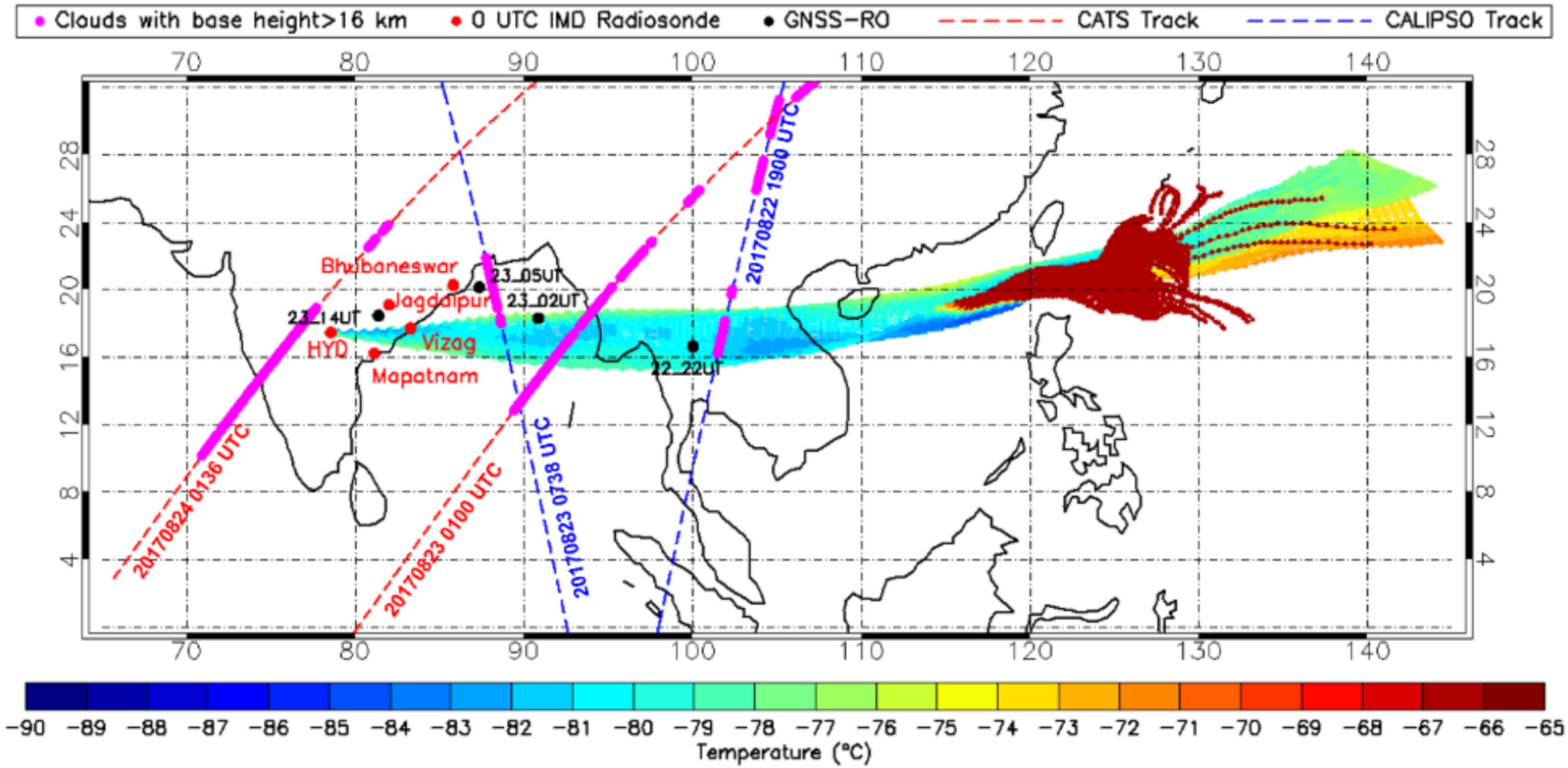
# Advection of Hydration Patch by the ASM Anticyclone towards Hyderabad



# Advection of Hydration Patch by the ASM Anticyclone towards Hyderabad

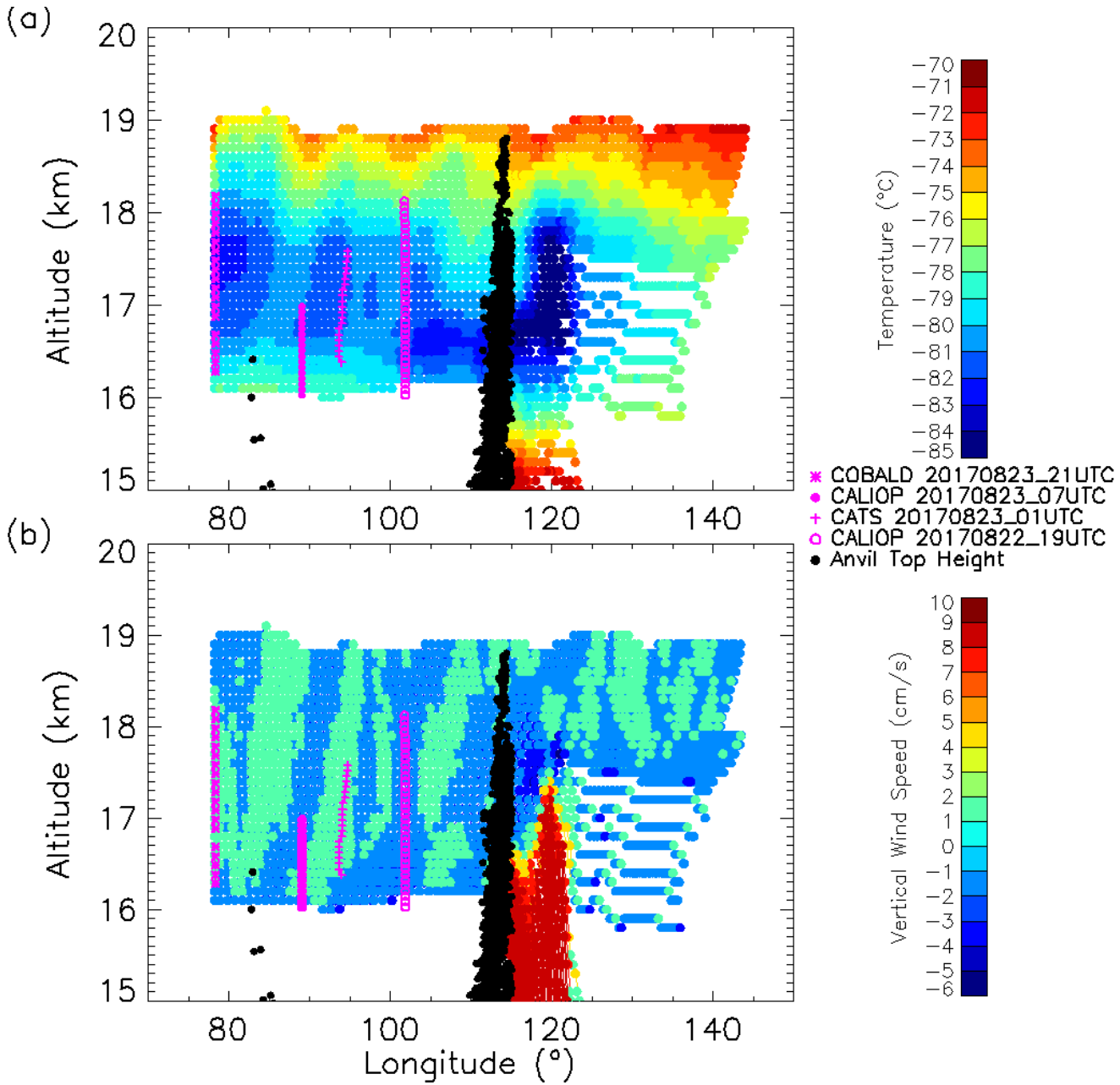


# Temperature history of Air Parcels & CALIOP/CATS clouds

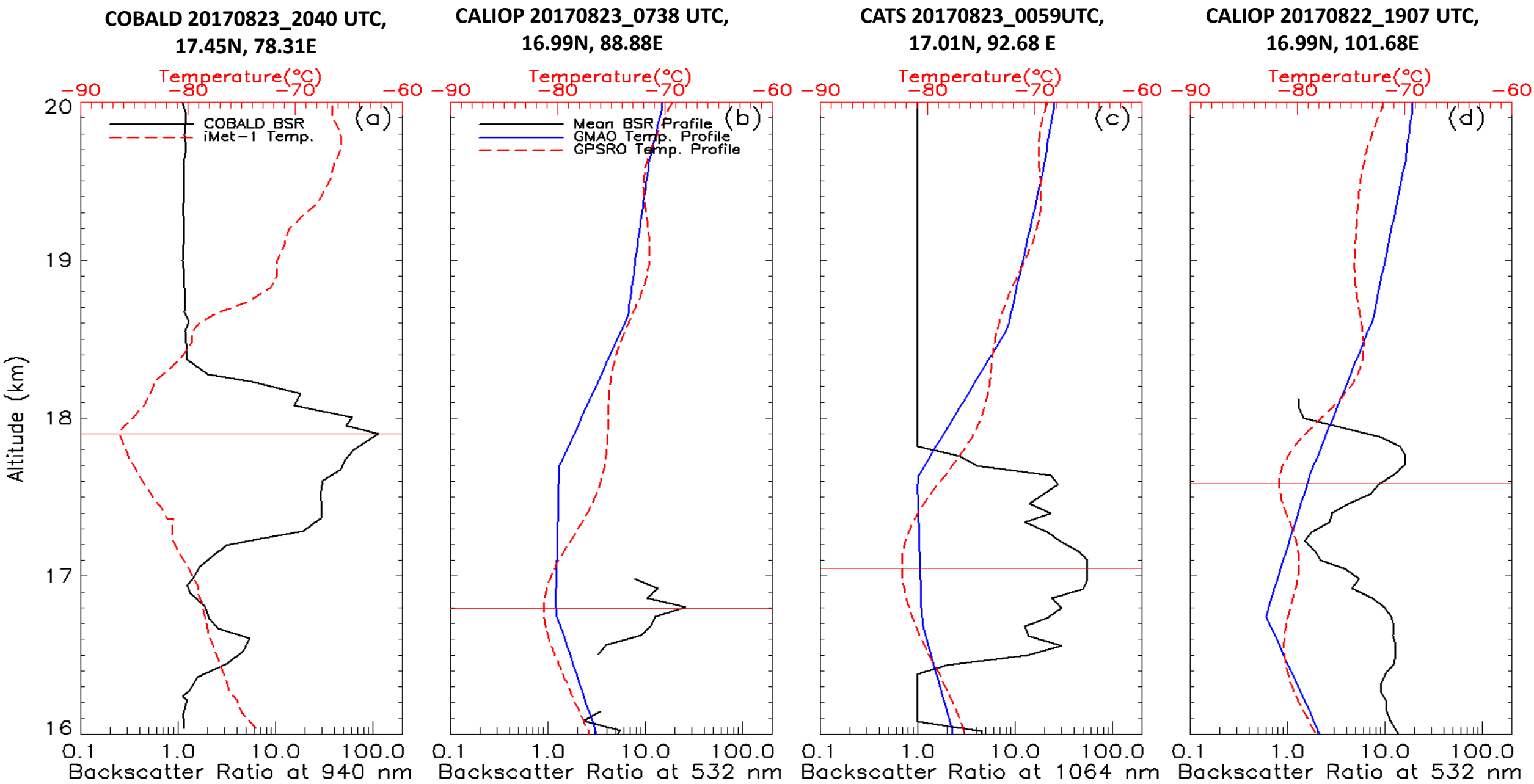



Tropopause cirrus clouds are found in the colder regions along the back-trajectories

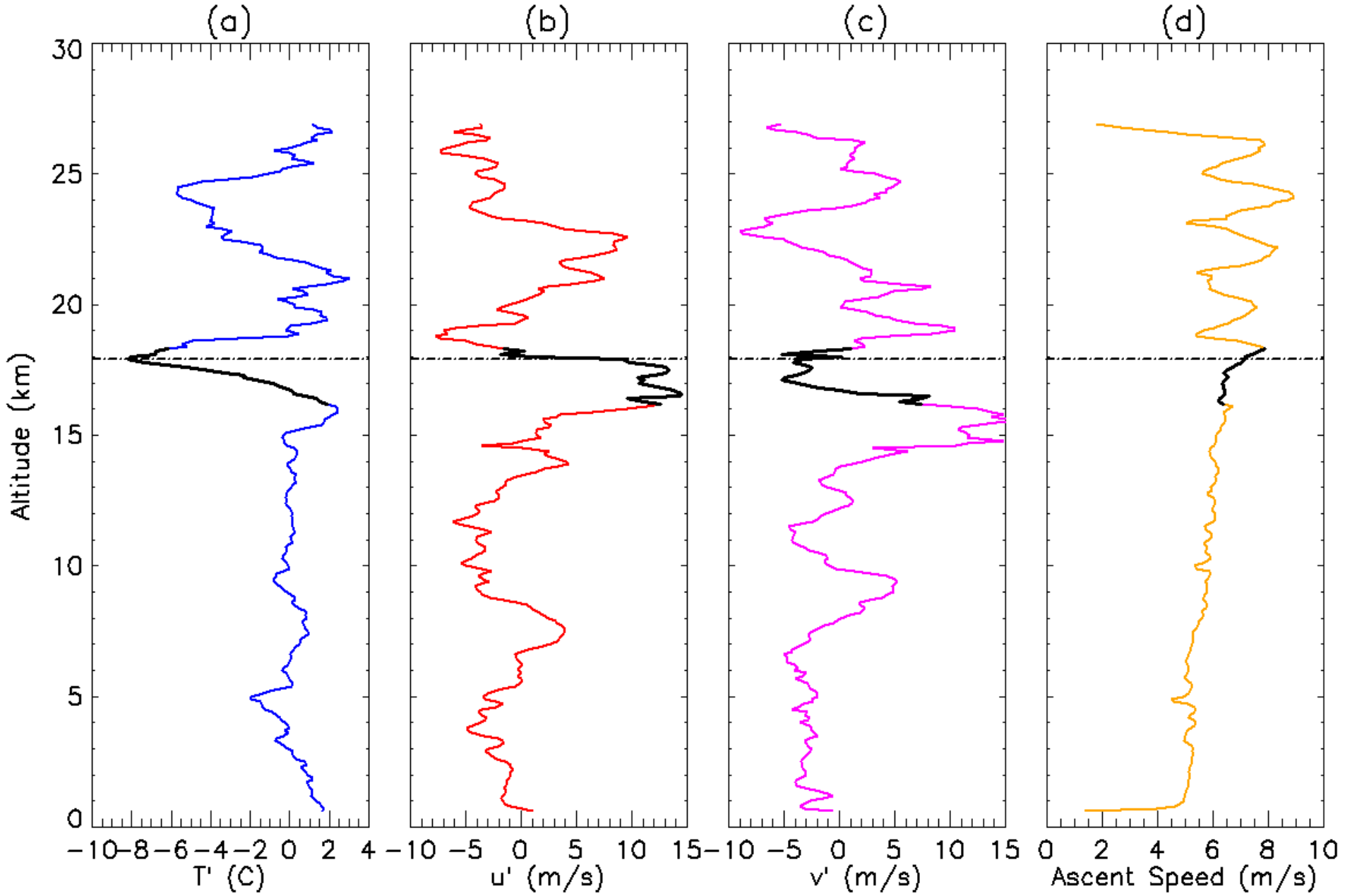
# Temperature, Vertical Velocity of Air Parcels, & CALIOP/CATS Clouds Vs Altitude



# GPSRO Temperature Profiles & CALIOP/CATS Scattering Ratio



# Anomalies in Temperature (T'), Zonal (u') and Meridional Wind Speed (v')



# 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 (16-18 km) during the Asian Summer Monsoon.
- Ice-crystals in tropopause cirrus cloud layer observed on 23$^{rd}$ August 2017 are smaller than 50 μm.
- 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 influenced by a Category-3 Typhoon, *Hato* which hit Macau and Hong Kong on 23 August 2017. The presence of tropopause cirrus cloud layers in the cold temperature anomalies and updrafts along the back-trajectories indicated towards the role of typhoon-induced gravity waves in their formation.


**Acknowledgements**

- **NASA UARP/ACMAP, ISRO, NPP, and NIA for the funding support.**
- **Technical and logistical support from NASA LaRC, NIA, USRA, TIFR-BF, NARL and PRL.**


**Thank you!**

# Back-up Slides

# Formation of Tropopause Cirrus clouds by Typhoon-induced gravity waves during the Asian Summer Monsoon: A Case Study from the BATAL 2017 Campaign

**BATAL: Balloon measurement campaigns of the Asian Tropopause Aerosol Layer**

(July-August 2014-2019)

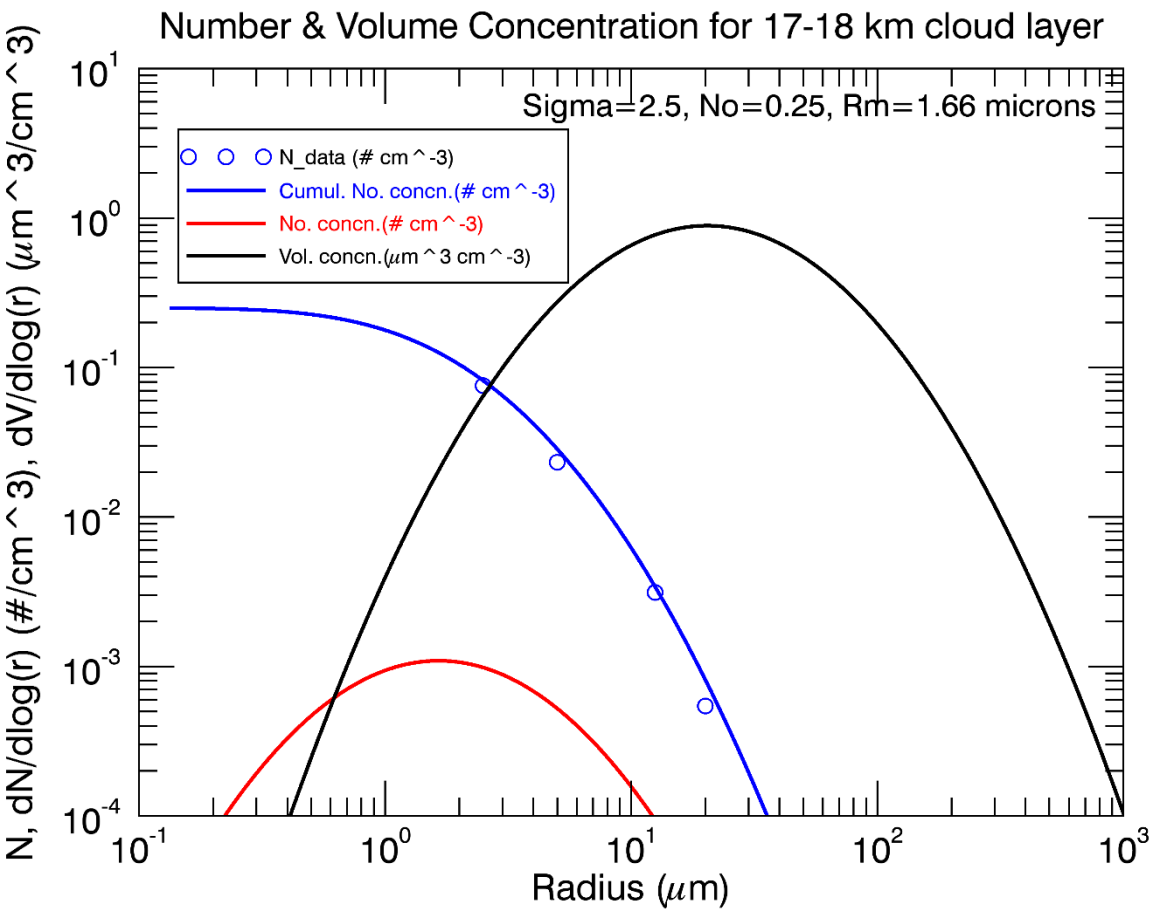
Gadanki, India
**Hyderabad, India**
Varanasi, India
Thuwal, Saudi Arabia

NATIONAL INSTITUTE OF AEROSPACE


## Acknowledgements

- NASA UARP/ACMAP, ISRO, NPP, and NIA for the funding support.
- Technical and logistical support from NASA LaRC, NIA, USRA, TIFR-BF, NARL and PRL.

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



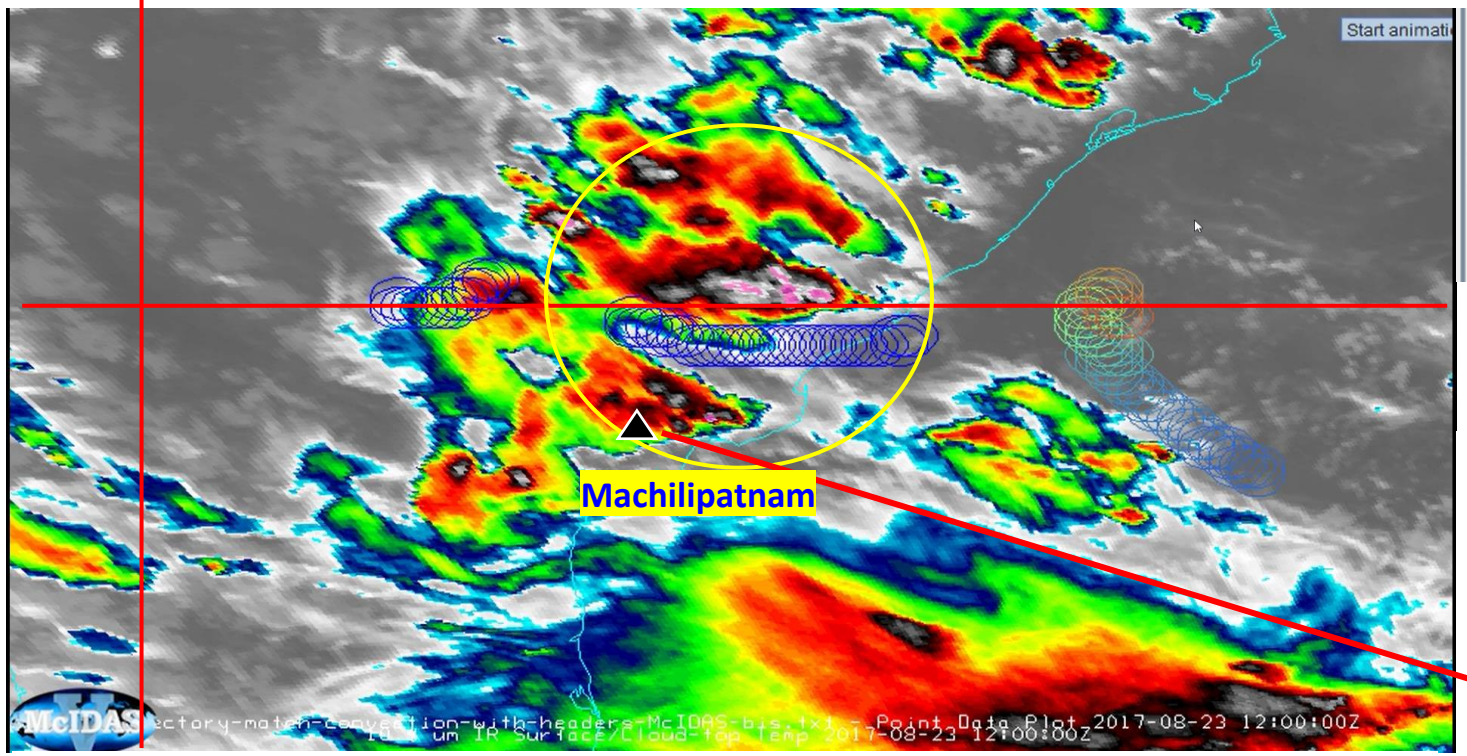

Using the log-normal size distribution,

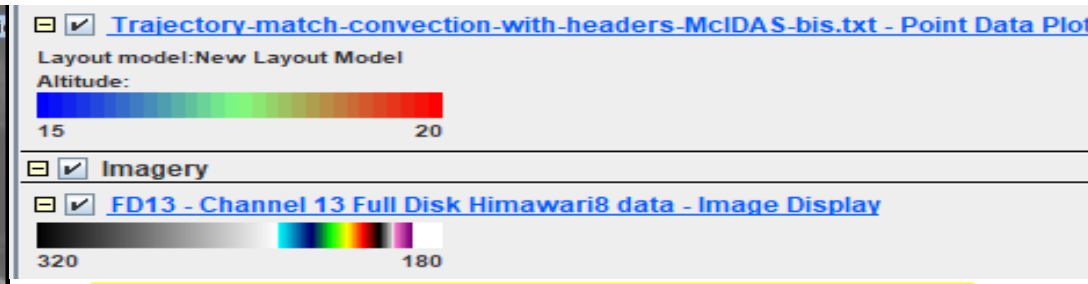
$$\frac{dN(r)}{d(r)} = N_0 \frac{\exp[-\frac{1}{2}\left\{\frac{ln^2\left(\frac{r}{r_m}\right)}{ln^2\sigma}\right\}]}{rln\sigma\sqrt{2\pi}}$$

we can derive:

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

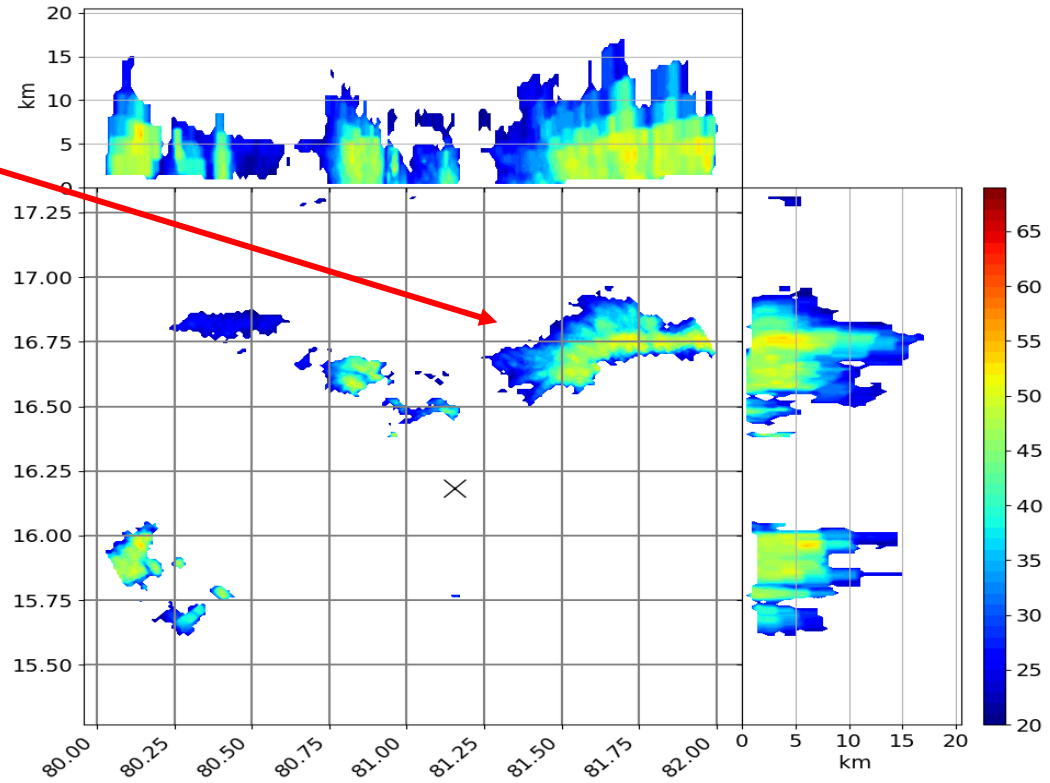
# Formation Mechanism: Local Convection



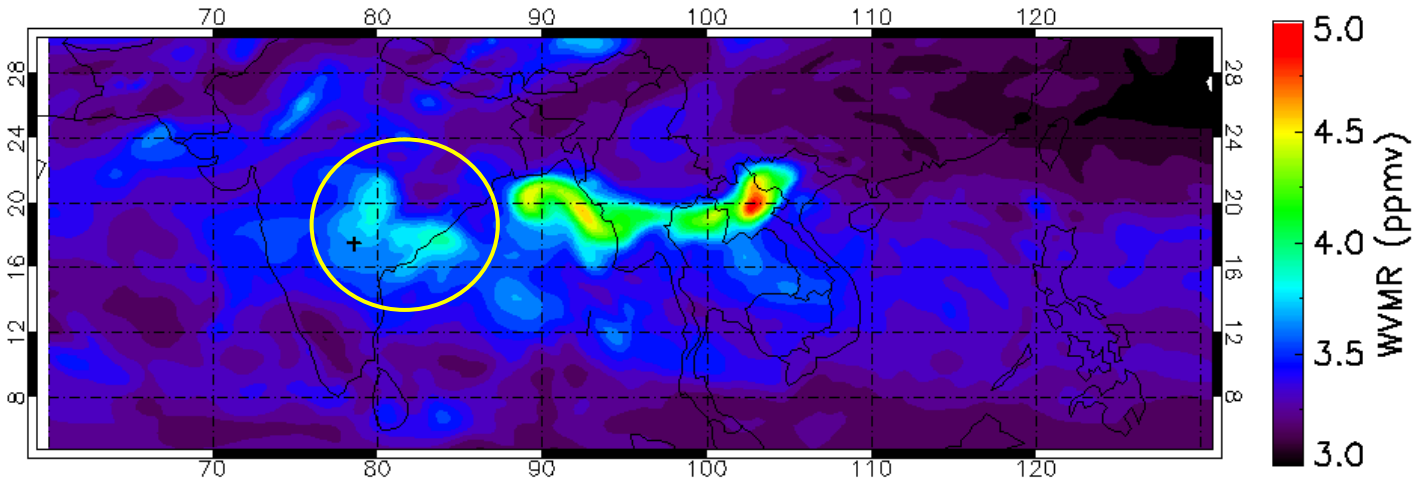




- No nearby CATS and CALIOP overpasses
- No MLS WVMR profiles

Machilipatnam Doppler Radar, 20170823, 1201 UTC



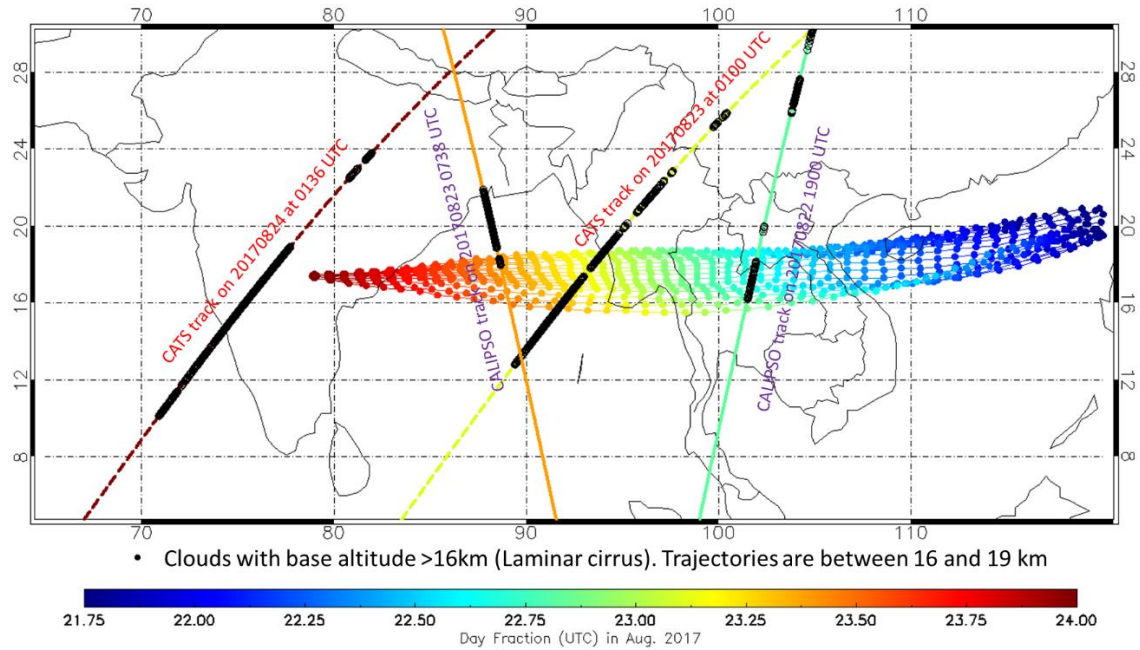

ERA5 WVMR at 70 hPa 2017-08-23 1200



# Tropopause Temperature Variations on 23 August 2017 in and around Hyderabad

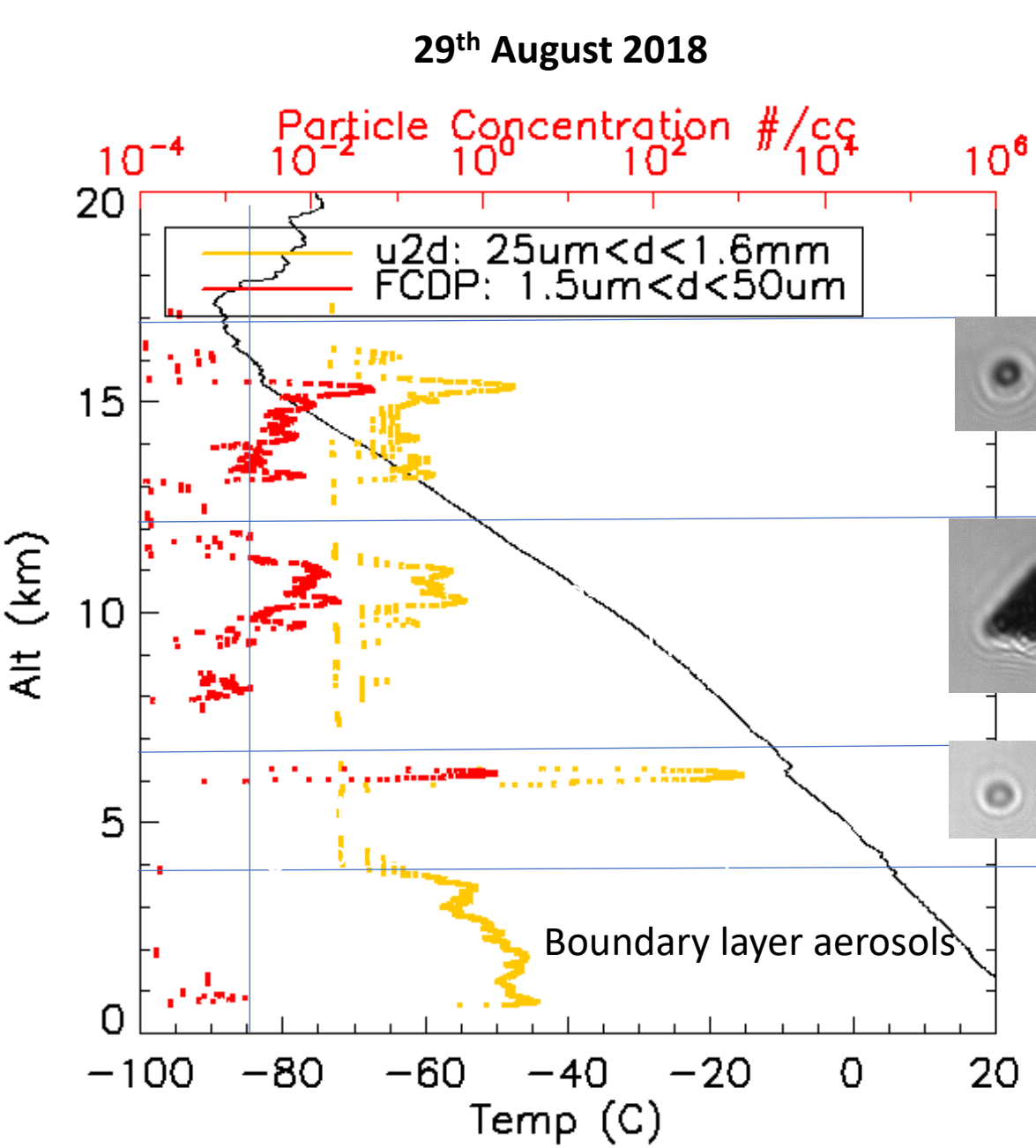
| Date/Time | 23 Aug 2017, 0UTC | 23 Aug 2017, 14 UTC | 23 Aug 2017, 2046 UTC | 23 Aug 2017, 2150 UTC | 24 Aug 2017, 0 UTC |
|---|---|---|---|---|---|
| Lat/Lon | ~ 17.40, 78.46, 0UTC | 18.449, 81.40, 14UTC | 17.445N, 78.297, 20:54:59 UTC | 17.396, 77.359, 21:49:46 UTC | ~ 17.40, 78.46, 0UTC |
| Displacement 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

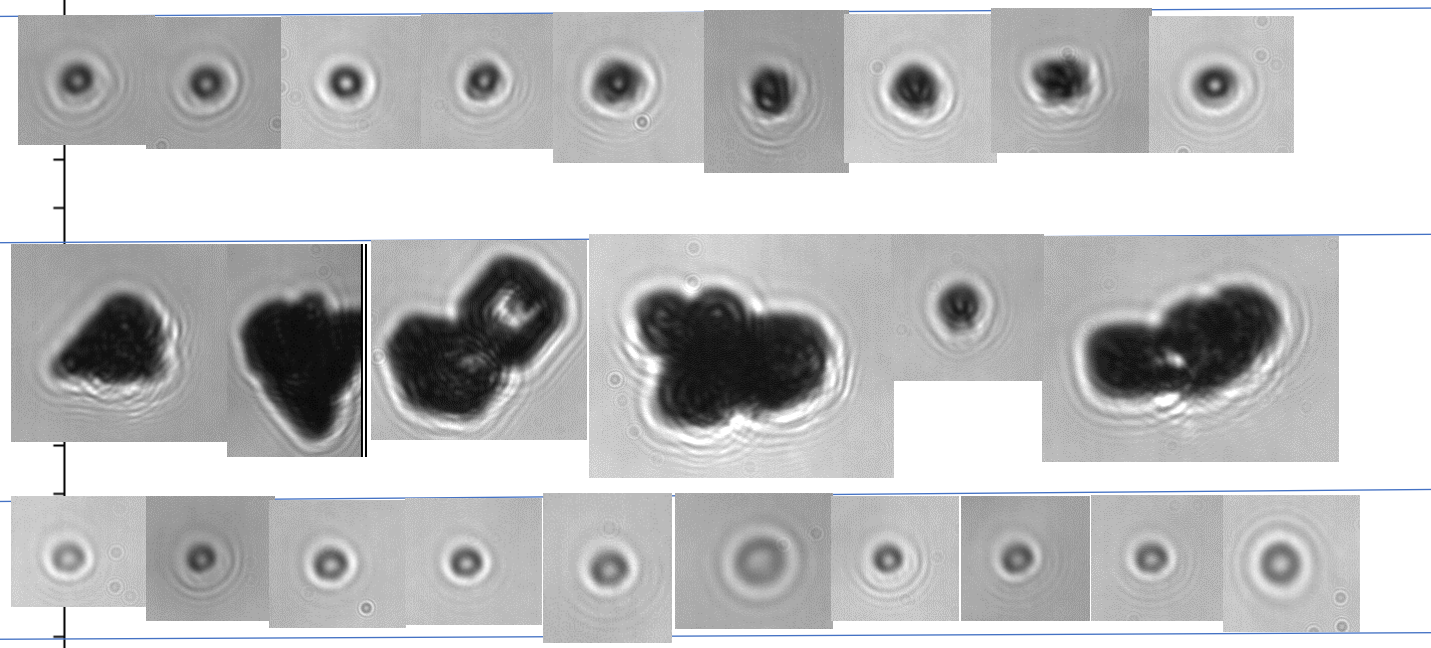



- Clouds with base altitude >16km (Laminar cirrus). Trajectories are between 16 and 19 km

# Micro-COPP Measurements on 29th August 2018




Cloud Particle Imager (CPI)




- Balloon measurements unaffected by shattering