Supplementary Information for

Investigating the role of typhoon-induced gravity waves and stratospheric hydration in the formation of tropopause cirrus clouds observed during the 2017 Asian monsoon

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Balloon trajectory and meteorological parameters

An onboard iMet radiosonde measured and transmitted the atmospheric conditions experienced by the balloon payload along with its location at every second to the ground station. Initially, the balloon moved southward for the first three kilometres and then it turned towards the west due to gradually increasing easterly winds with speed reaching to about 30 m/s near 15 km altitude. The balloon moved upwards with a gradually increasing ascent rate between 5-6 m/s until 15 km altitude. After 51 minutes of the launch, the balloon payload reached the CPT altitude (~17.9 km) having a minimum temperature of about -86.4 °C.

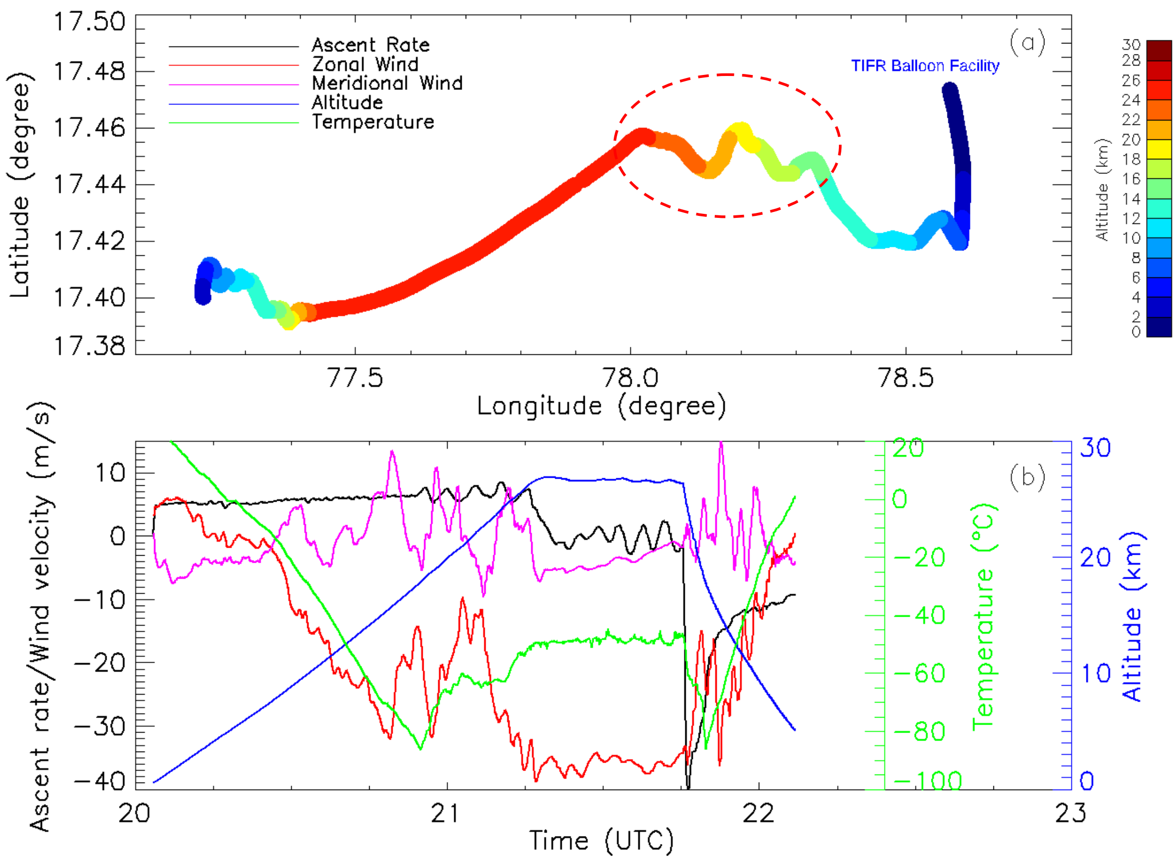

Figure S1: (a) Trajectory of the balloon flight launched on 23 August 2017 from TIFR Balloon Facility in Hyderabad, India with colours showing the altitude of the balloon payload. The region encircled by a red dashed ellipse represents the influence of gravity waves. (b) Temporal variation of the altitude (blue line), temperature (green line), ascent rate (black), zonal wind speed (red) and meridional wind speed (magenta). The Y-axis is the same for zonal, meridional wind and ascent rate. Legend is shown in (a).

The CPT temperature (altitude) measured from the daily 00 UTC (05:30 IST) radiosonde launch at Hyderabad airport on 23 August 2017 was -77.2 °C (17.2 km) which is warmer (lower) compared to that measured by our radiosonde on the same night at 20:55 UTC. Both the zonal and meridional wind speeds show large fluctuations in the UTLS region, especially near the CPT. The fluctuations in the meridional wind speed are also associated with change in its direction. The balloon experienced a rough ascent as revealed from the ascent rates exhibiting large wave-like fluctuations between 17 km and the balloon ceiling altitude (~27.2 km). It is interesting to note that each of these wave peaks is associated with a change in the direction of meridional wind. After floating and oscillating for about half an hour near the ceiling altitude, the payload was detached from the balloon at about 21:45 UTC using the telecommand and pyro-cutter system. Within half an hour, the payload descended to the ground with a parachute and then recovered by the recovery team from a location nearly 140 km to the west of the launch site.

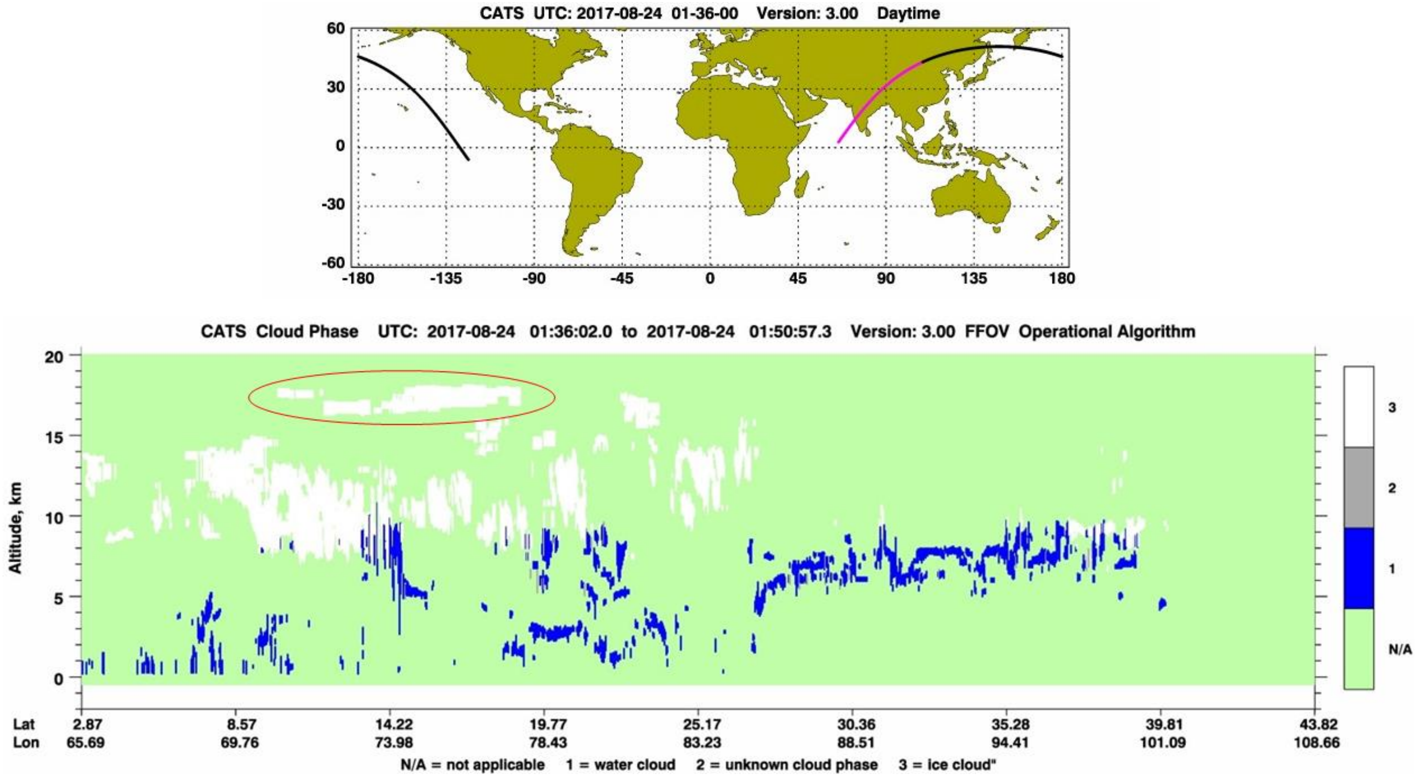

Figure S2: (Top) CATS orbit track on 24th August 2017 between 01:36 and 01:50 UTC. (Bottom) CATS cloud phase along its orbit track with red ellipse showing the large horizontal extent of the tropopause cirrus. (Source: https://cats.gsfc.nasa.gov/media/granules/20170824/external/CATS-ISS_L1B_M7.2_V3.00_2017-08-24_01-36-00_Fore_1_12.jpg).

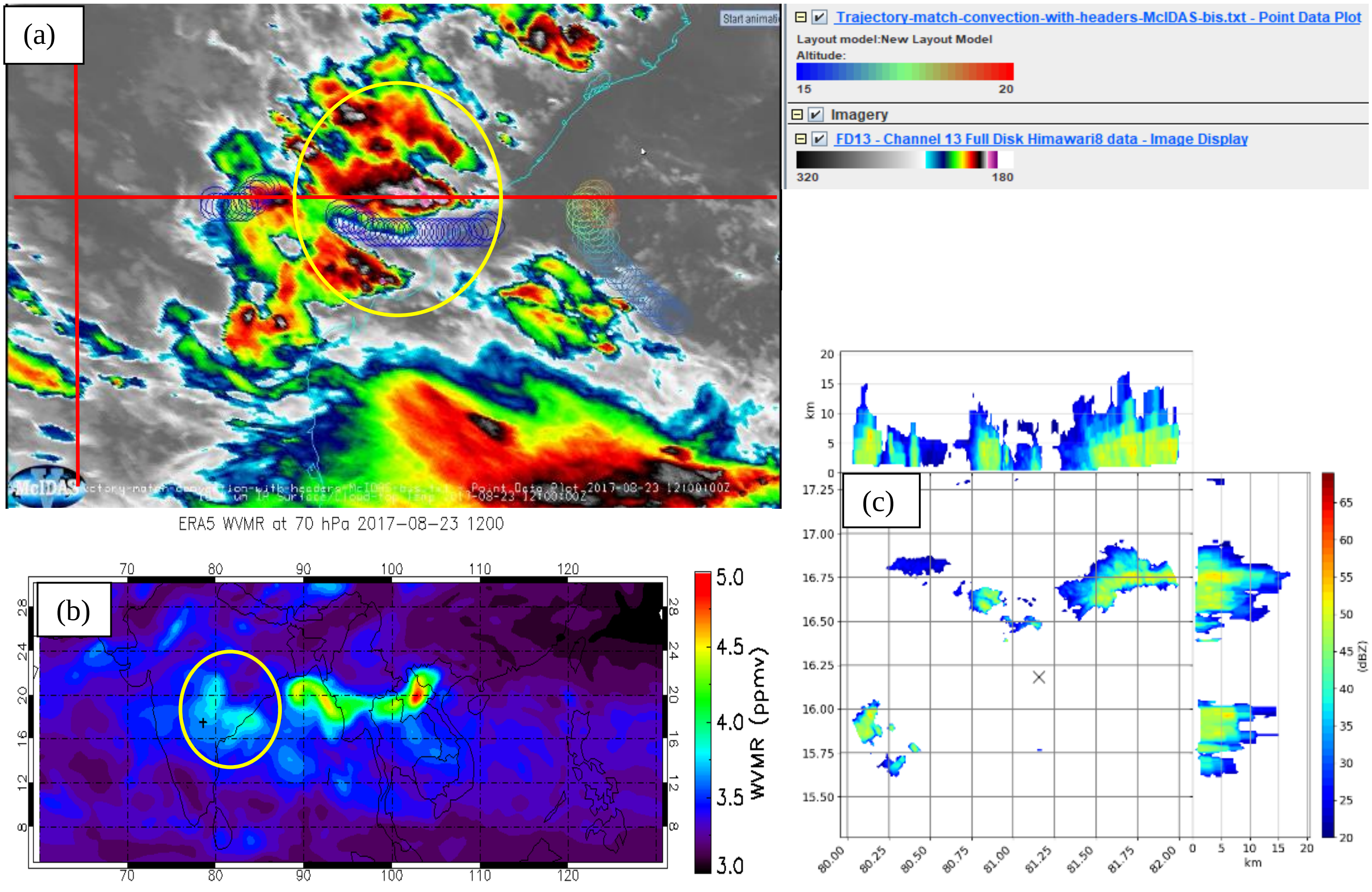

Figure S3: (a) 10.4 µm infrared cloud-top temperature from Himawari-8 on 23 August 2017 at 12:00 UTC showing the presence of deep convective clouds along the East coast of India with the location of the air-parcels represented by coloured circles initialized from the balloon measurement site at that time. The location of TIFR-BF is represented by the intersection of red horizontal and vertical lines. (b) Map of ERA5 water vapour mixing ratio at 70 hPa on 23 August 2017 at 12:00 UTC showing the enhanced water vapour over the East coast and over the Bay of Bengal. (c) Coincident maximum radar reflectivity from the IMD Machilipatnam Doppler Weather Radar station showing the location of deep convective clouds along the Indian East coast.

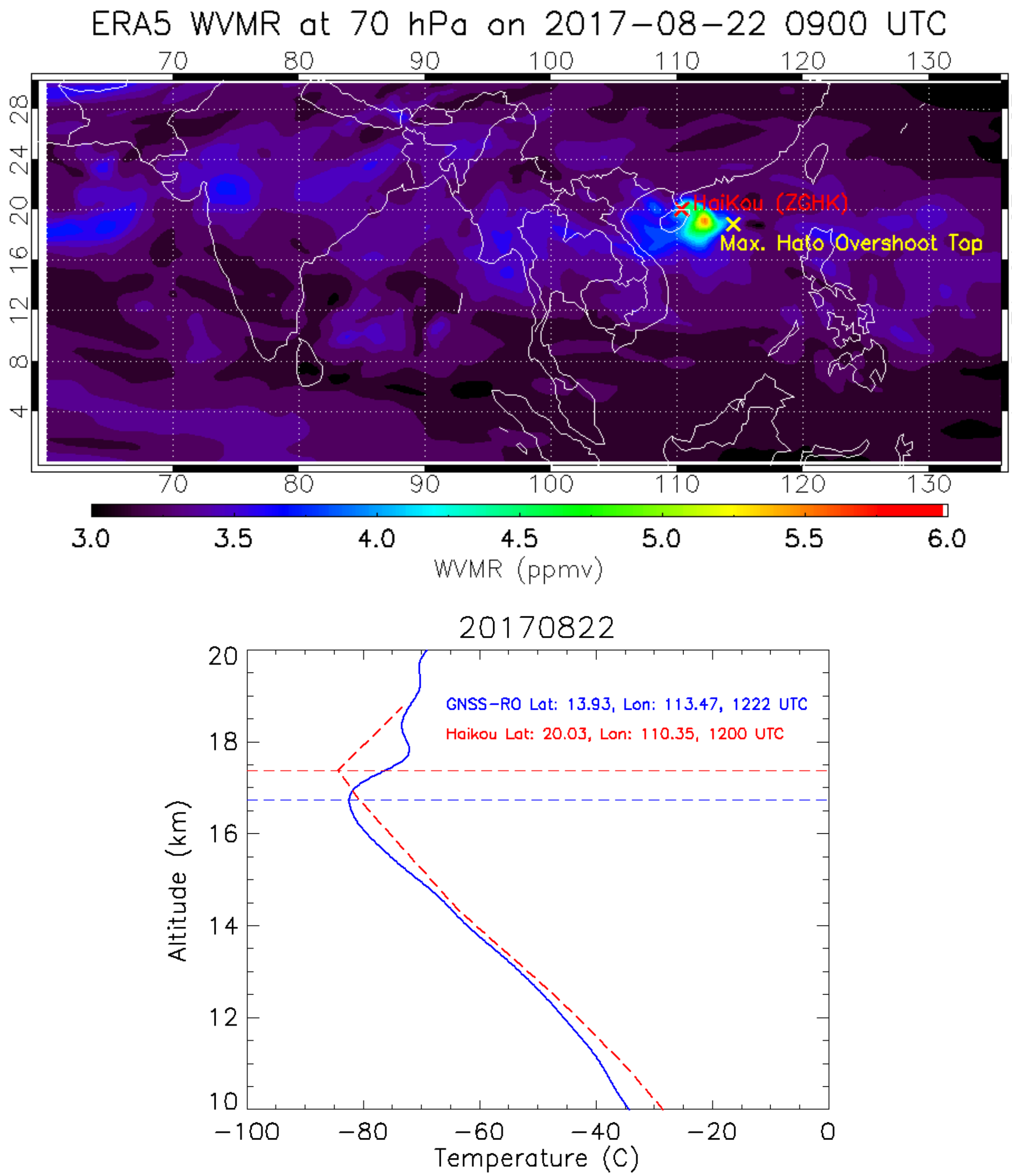

Figure S4: (Top) ERA5 water vapour mixing ratio at 70 hPa on 22 August 2017 at 09:00 UTC with the locations of the maximum typhoon Hato overshoot top altitude (yellow cross) and Haikou radio sounding station (red cross). (Bottom) Profile of temperature from radiosonde launched from Haikou station on 22 August 2017 at 12:00 UTC shown by red dashed line and GNSS-RO temperature profile at 12:22 UTC shown by solid blue line.

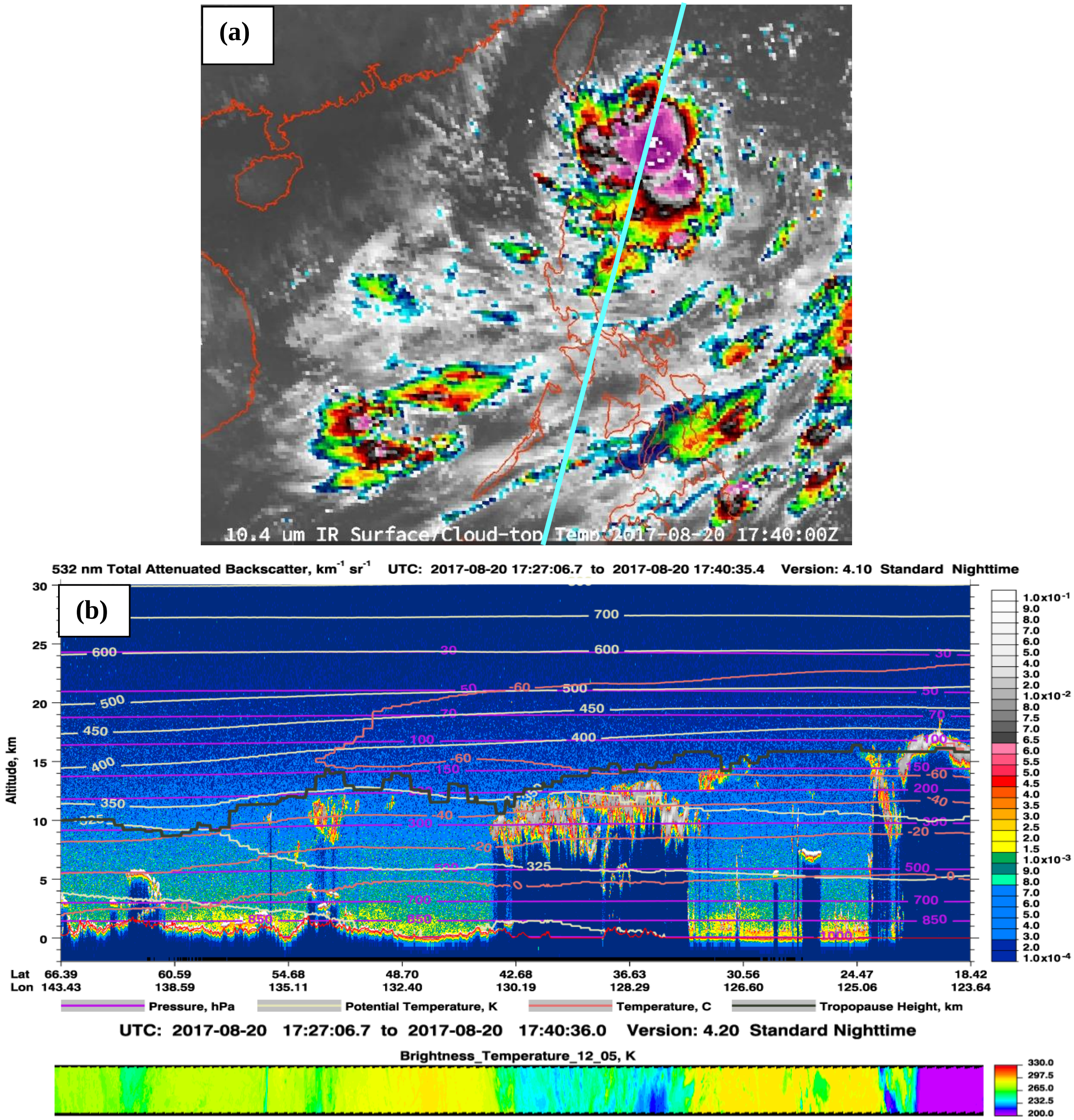

Figure S5: (a) 10.4 µm infrared cloud-top temperature from Himawari-8 at 17:40 UTC on 20 August 2017 showing the overshoots during the development phase of typhoon *Hato*. Cyan line represents the CALIPSO orbit track that observed the overshoot on 20 August 2017 between 17:27 and 17:40 UTC. (b) CALIOP total attenuated backscatter coefficient at 532 nm browse image showing the location of the overshooting cloud over a region near 19.9° N and 124° E with its top reaching ~18.6 km altitude (Source: CALIPSO/NASA). Complete attenuation of backscatter signal below 14 km altitude followed by low value of brightness temperature at 12.05 µm from Imaging Infrared Radiometer (IIR) instrument onboard CALIPSO indicate the presence of deep convective clouds.

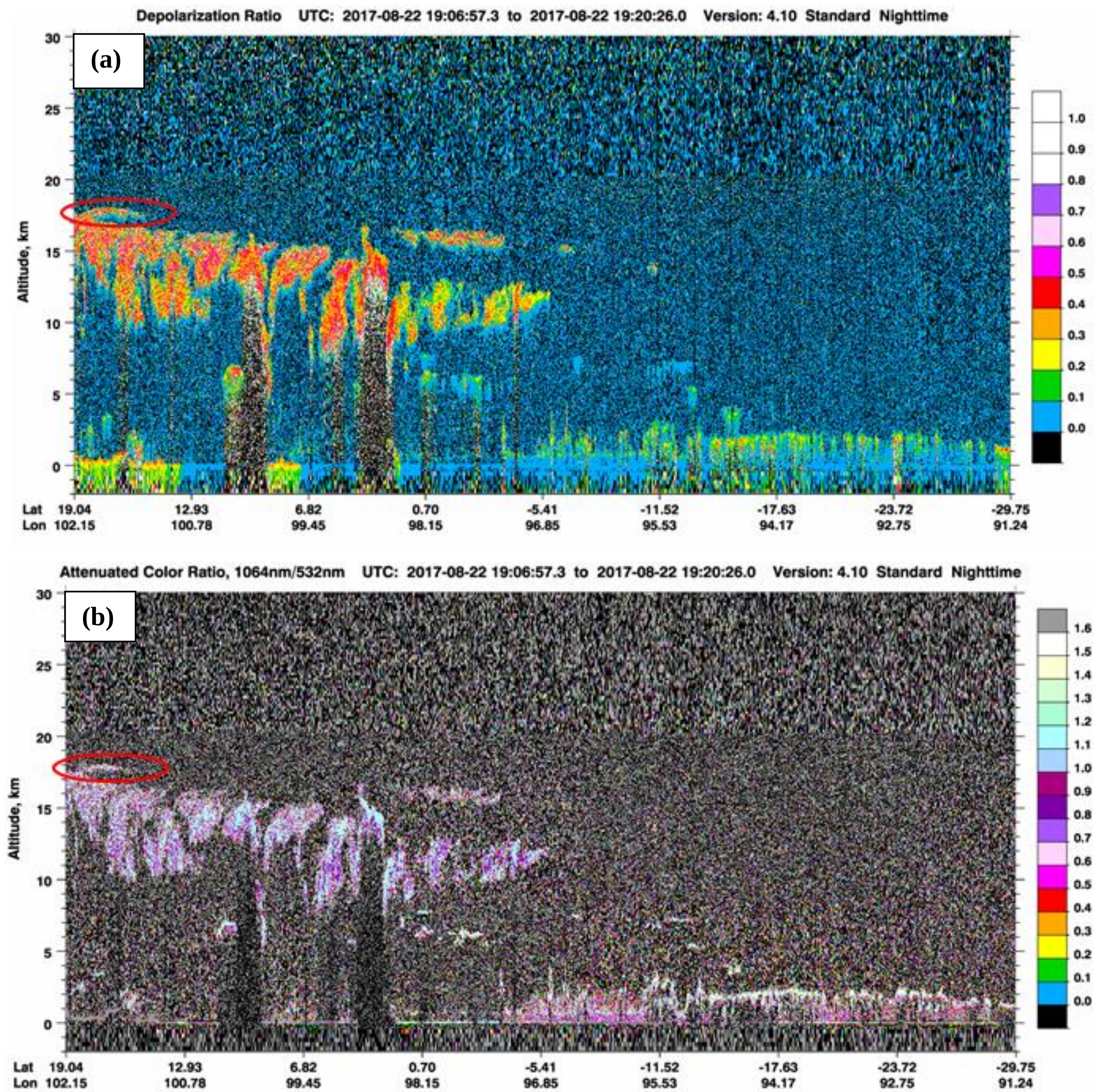

Figure S6: (a) CALIOP depolarization ratio and (b) attenuated colour ratio along its orbit track on 22 August 2017 between 19:06 and 19:20 UTC (Source: CALIPSO/NASA).

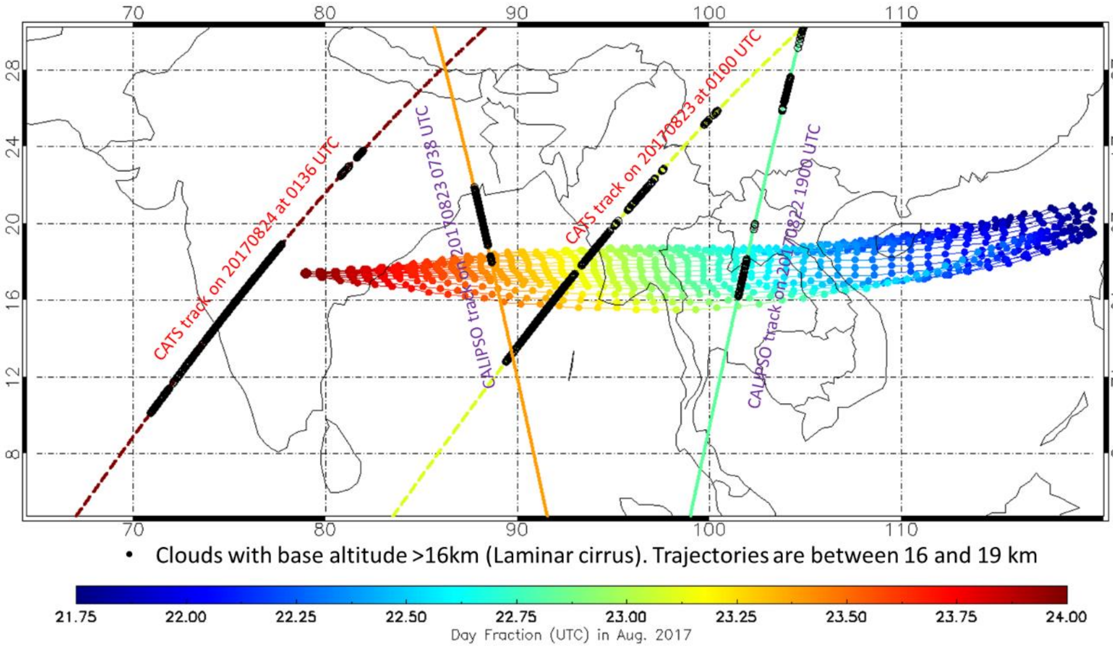

Figure S7: Time evolution of back-trajectories with orbit tracks of CALIOP and CATS color coded with respect to their overpass time. Black dots along the orbit tracks represent the locations of cirrus clouds with their base altitude above 16 km.

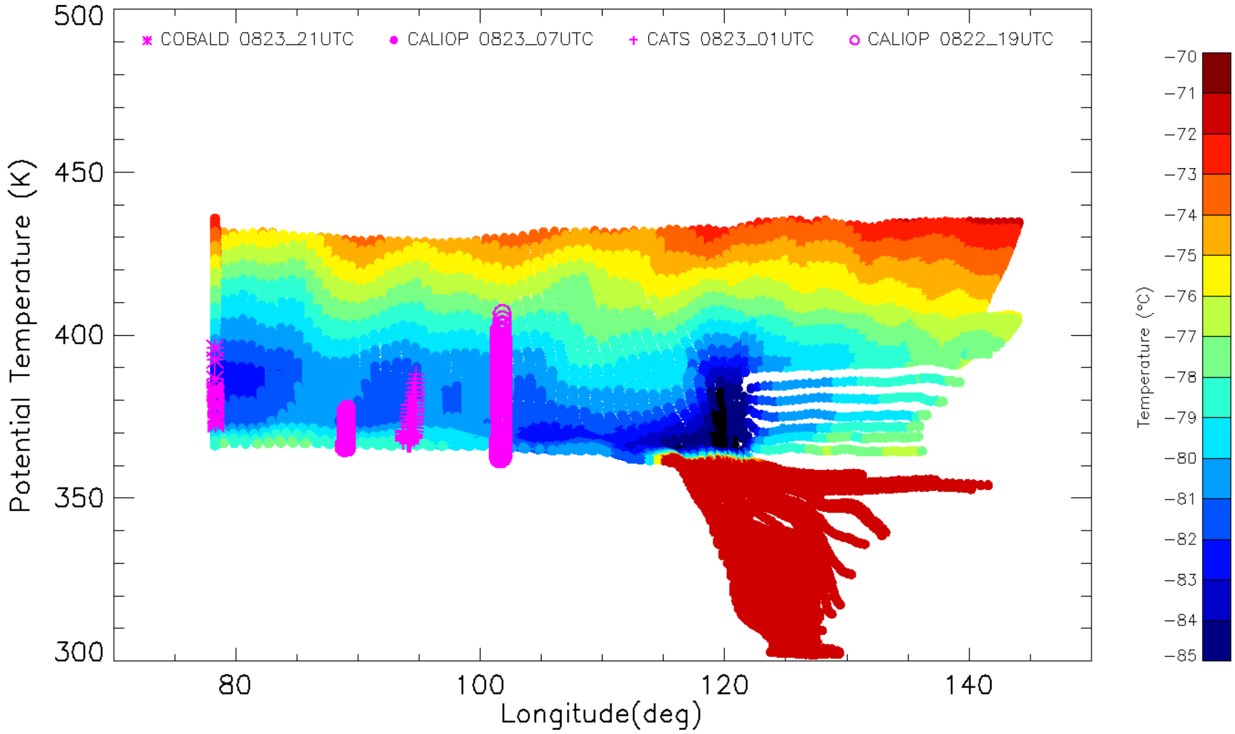

Figure S8: Temperature history of the air-parcels along the back-trajectories run from the balloon measurement sites between 16 and 19 km on 23 August 2017 as a function of longitude and potential temperature. Each filled coloured circle represents temperature value at every 100 m vertical resolution at each hour. Different magenta symbols represent the location of cirrus clouds near the tropopause obtained from CATS on 23 August 2017 at 01:00 UTC (plus), CALIOP on 22 August 2017 at 19:00 UTC (open circle) and on 23 August 2017 at 07:00 UTC (filled circle) and COBALD on 23 August 2017 at 21:00 UTC (asterisk).

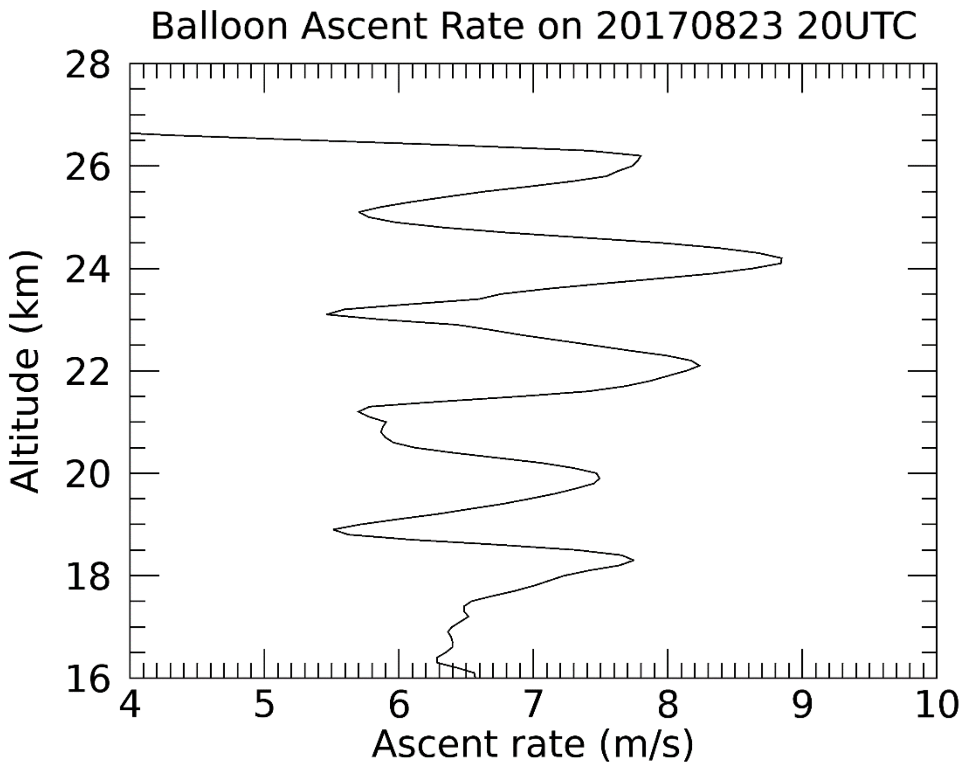

Figure S9: Vertical profile of GPS ascent speed (black line) of the balloon obtained from the radiosonde on 23 August 2017.

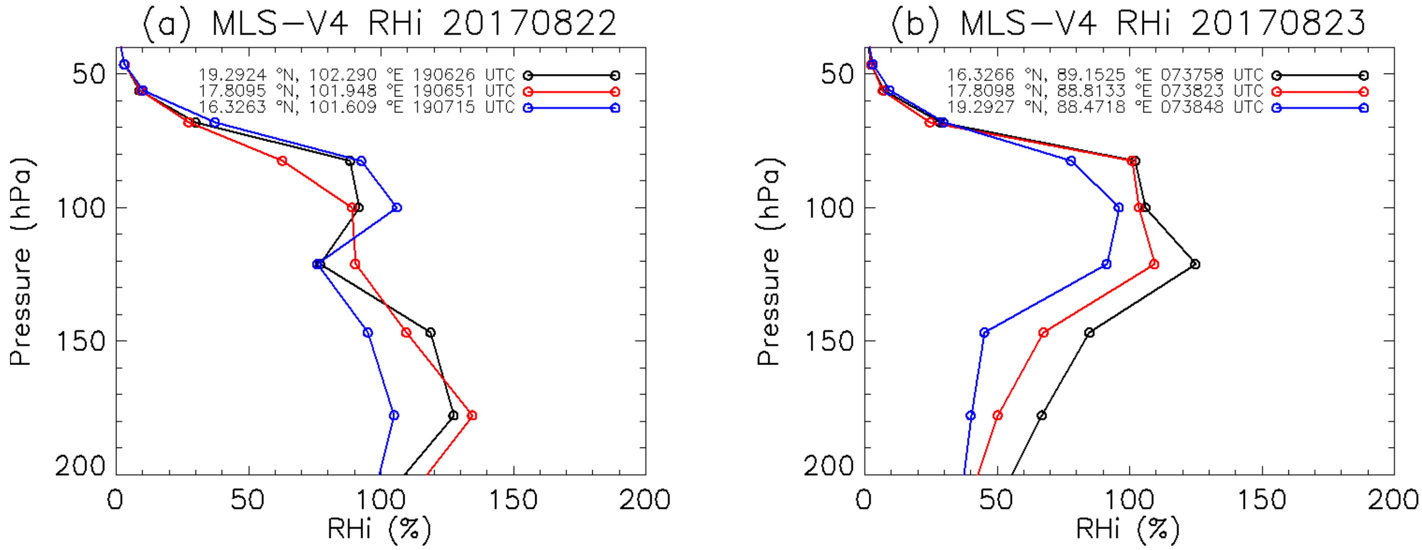

Figure S10: Profiles of relative humidity with respect to ice (RHi) from Aura-MLS instrument along the orbits that intersected the back-trajectories between 16°-19° N on (a) 22nd August 2017 and on (b) 23rd August 2017.