Dispersion of the Nabro volcanic plume and its relation to the Asian summer monsoon

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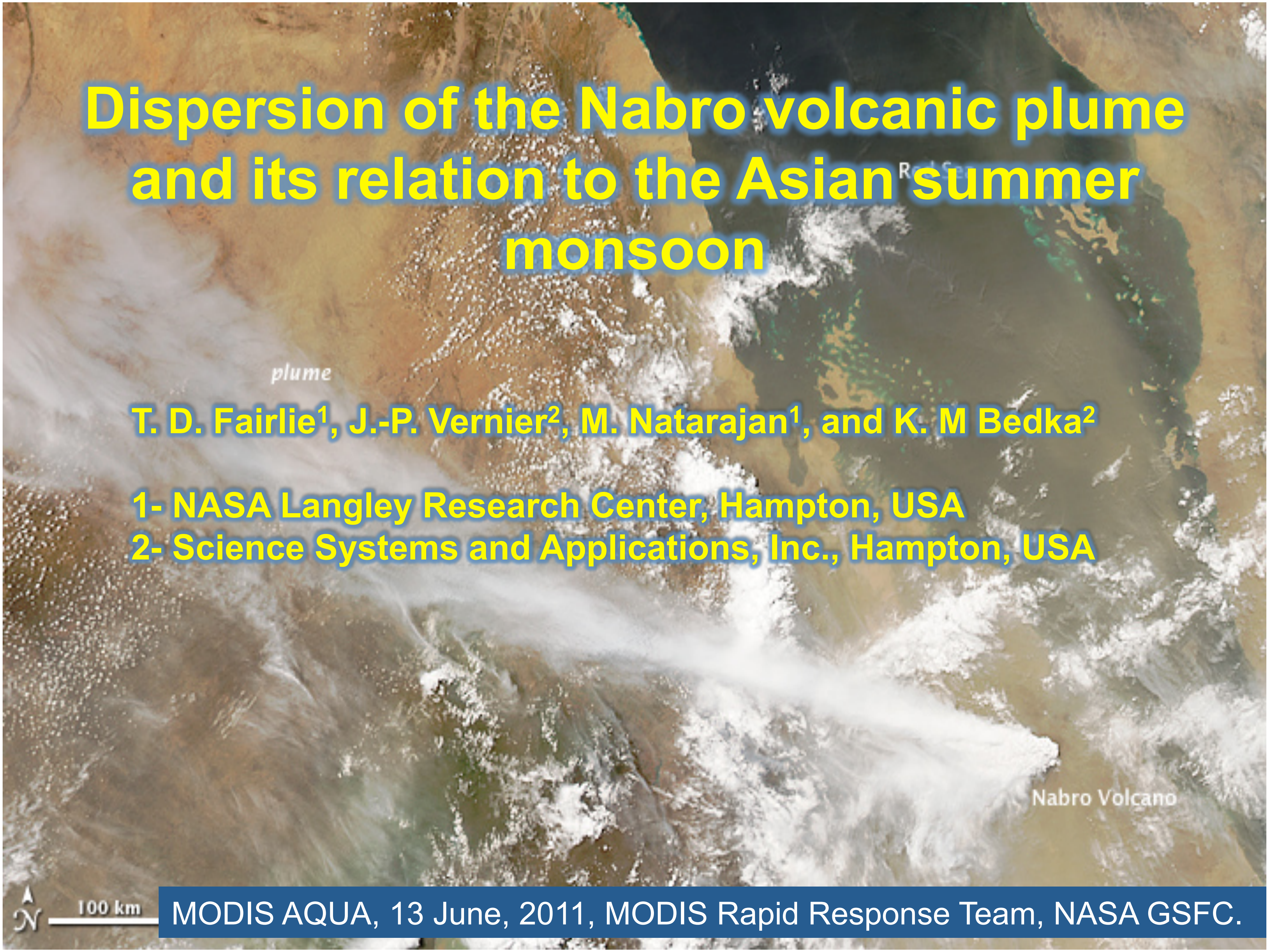


MODIS AQUA, 13 June, 2011, MODIS Rapid Response Team, NASA GSFC.

Background:

Mt. Nabro eruption of 12-13 June, 2011 considered the largest single injection of SO_2 (1.3 – 2.0 Tg) into the UTLS since Mt. Pinatubo in 1991 (20 Tg).

Volcanic plume was entrained into the Asian anticyclone (AA) which prevails in the UTLS in summer (Krotkov et al., 2011; Clarisse et al., 2011; Bourassa et al., 2012). Stratospheric layers were observed in the weeks following.

Bourassa et al., (2012, 2013) claimed the eruption was confined to the troposphere and *"only attained stratospheric altitudes through subsequent transport processes associated with deep convection"* in the SE Asian monsoon.

Implication: Volcanic eruptions need not inject SO_2 directly into the stratosphere to affect climate.

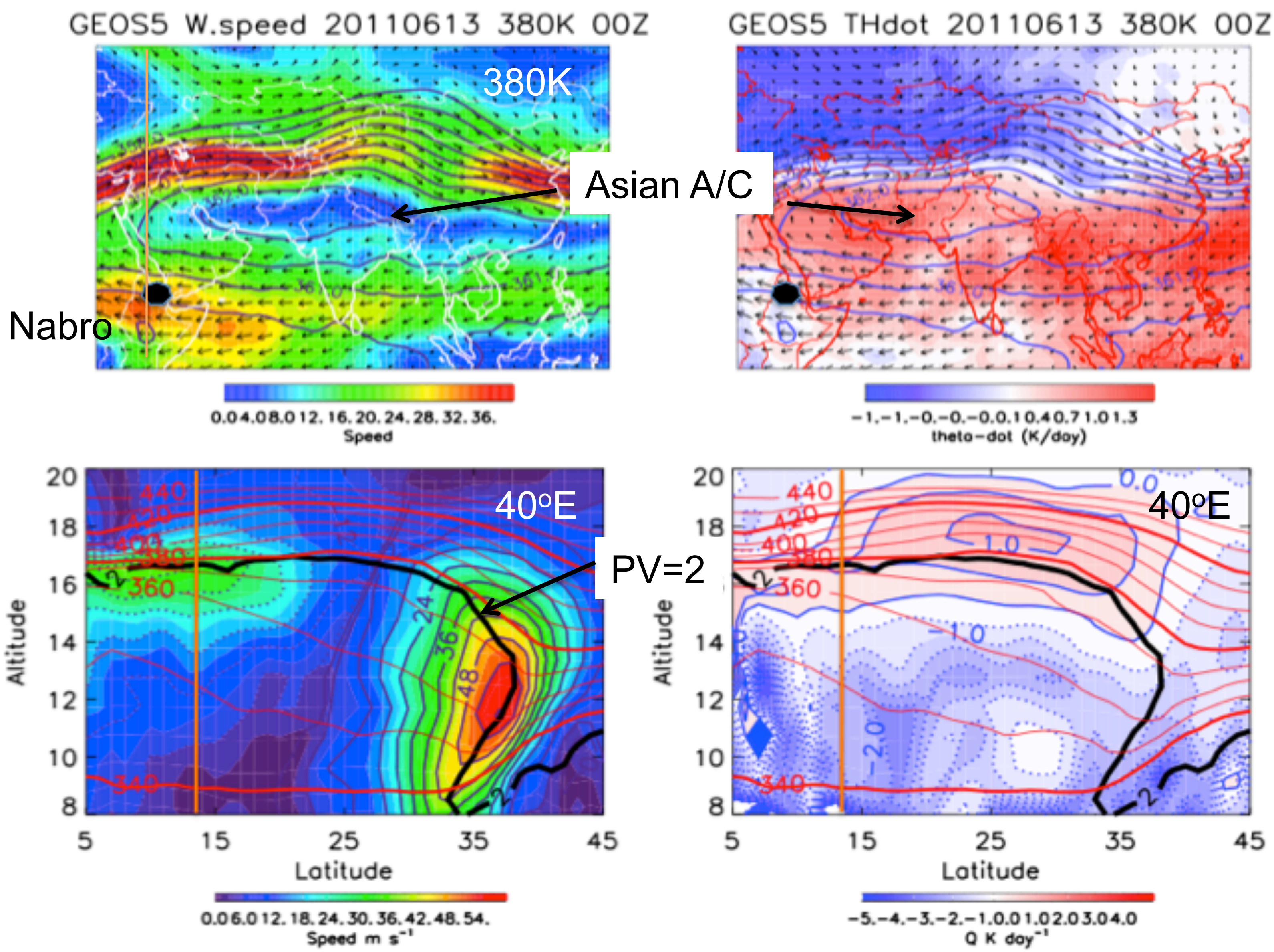
But, Vernier et al. (2013) and Fromm et al. (2013) showed that the eruption penetrated the stratosphere directly. CALIPSO observed stratospheric aerosol layers from June 15^{th} (no earlier data) well before the plume may have encountered convection.

This presentation

Here use trajectory cluster calculations to show that much of stratospheric aerosol layering observed by CALIPSO in the AA is explained by direct injection of the Nabro eruption to the LS, followed by differential advection in vertically sheared flow.

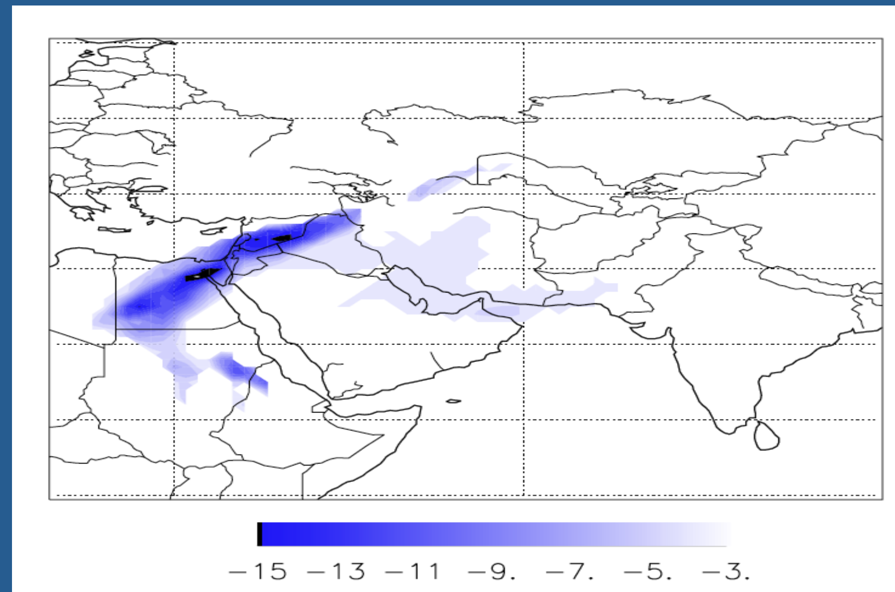
We also use CALIPSO obs. of the Nabro plume to infer diabatic ascent rates over Asia in subsequent months, and to provide TOA radiative forcing estimates for the Nabro case.

Meteorological Context for Nabro eruption



Entrainment of Nabro plume in the Asian anticyclone shown in AIRS SO_2 index for 14 June, and in corresponding air parcel trajectory maps

AIRS SO_2 index on 14 June, 2011

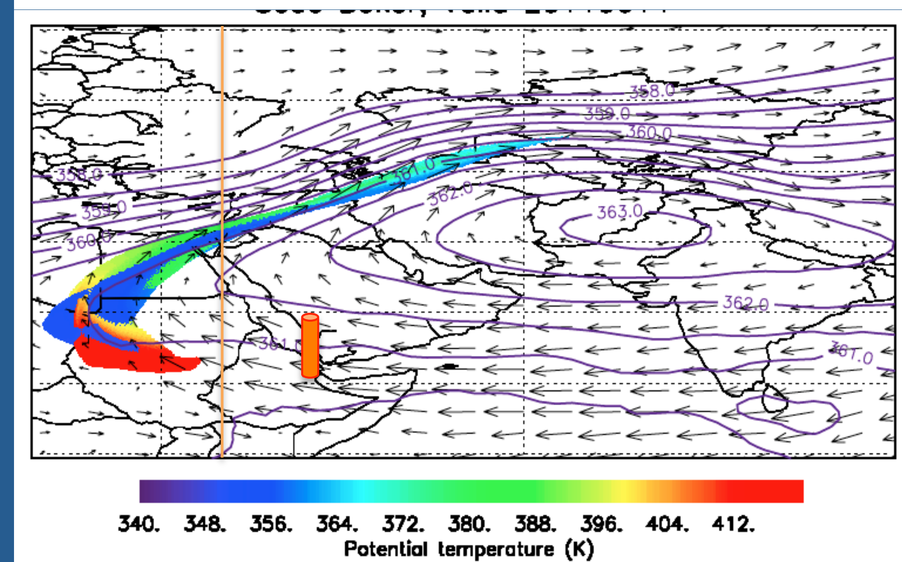


Air parcel trajectories initialized in 2 concentric cylinders, radius 10 and 20 km from Nabro (13.37°N, 41.7°E), between 12 -19 km altitude, 50 m apart in the vertical every 15 mins. for 4 h. (18 - 22Z, June 12th). (total of 38,352 air parcels released.)

3-D kinematic trajectories computed using NASA LaRC TM (Fairlie et al., 2009)

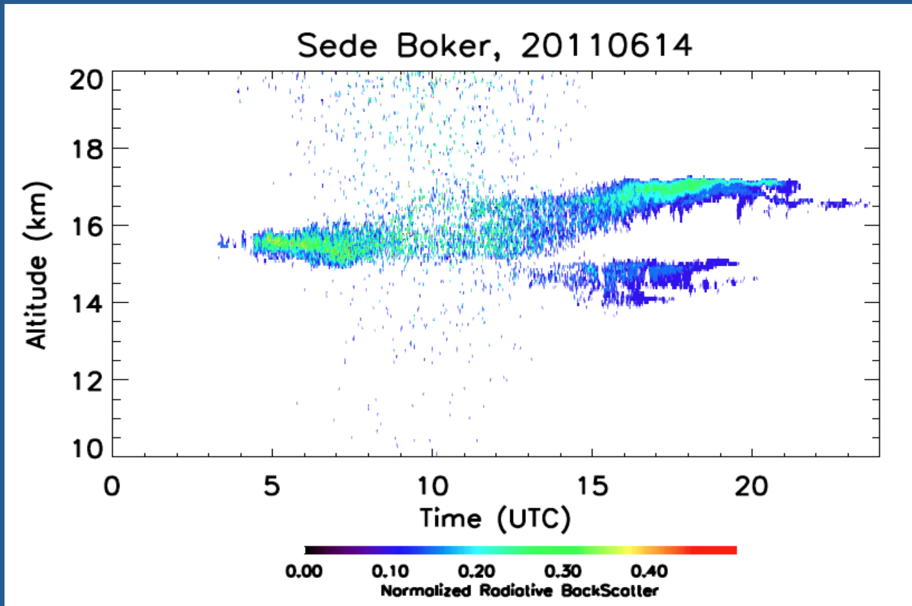
4th-order Runge- Kutta time-step of 15 minutes
NASA GMAO GEOS-5.2 6-h time-average winds (Rienecker et al., 2008), resolved to 1.25° x 1° in the horizontal, 72 levels in the vertical.

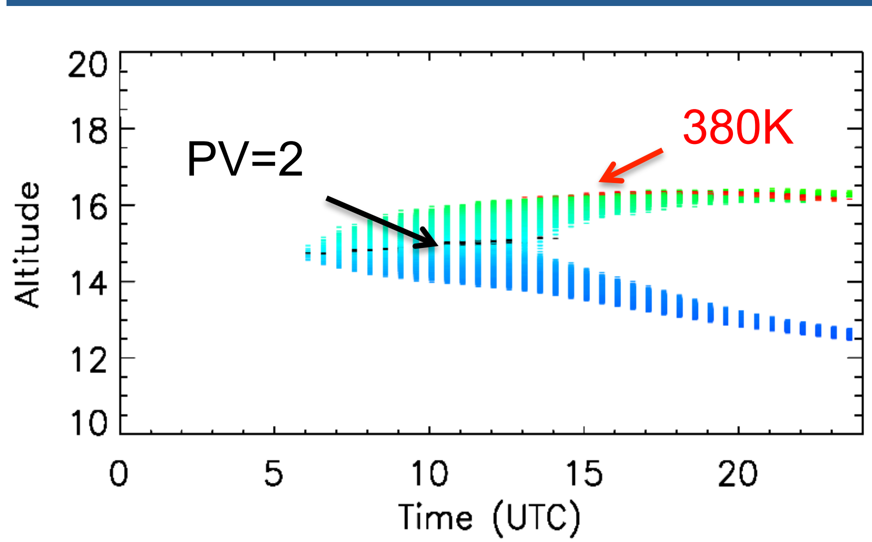
Trajectory map, with MSF and wind vectors at 380K. Air parcels initialized up to 420K shown



Trajectories colored by initial θ

MPLNET Lidar at Sede Boker (Israel) on 6/14 shows plume 14-17 km, subject to vertical wind shear; air parcel trajectory distribution found ~500 – 800m lower in altitude, but with similar structure

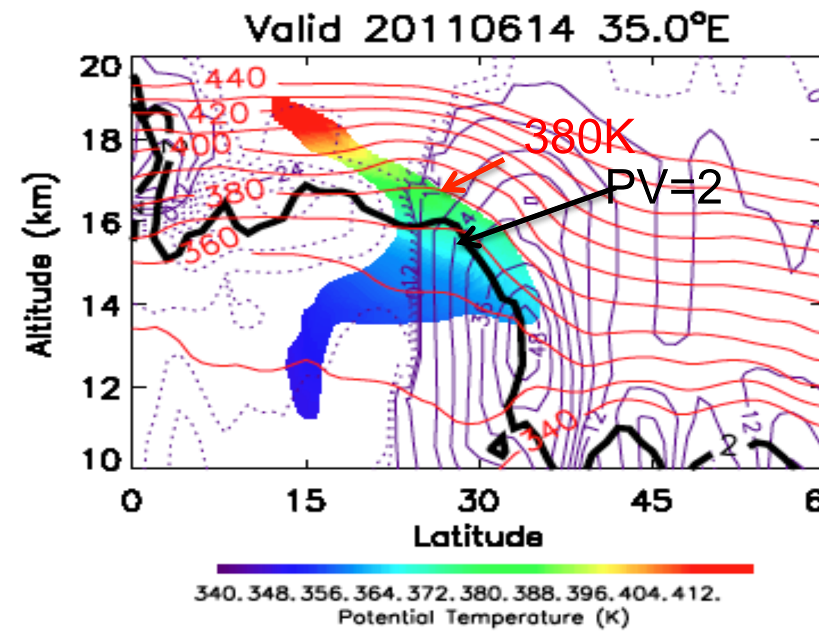




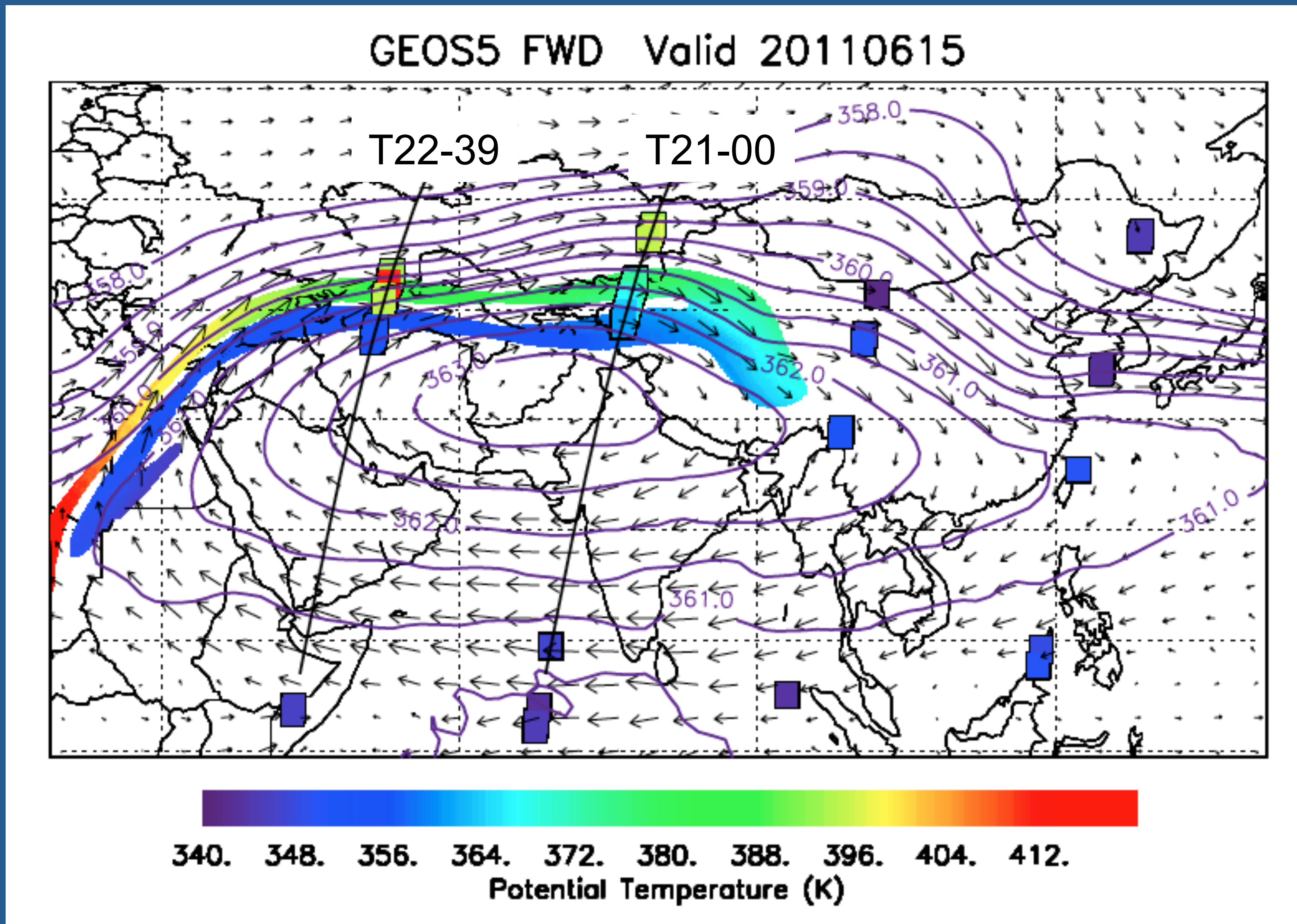
(Lidar data courtesy A. Karnieli, BGU, Israel, Judd Welton, NASA GSFC)

Differential advection of plume in vertically sheared flow.

Air parcel cross-section at 35^{o}E shows plume spanning the tropopause; fastest moving parcels close to the jet core.



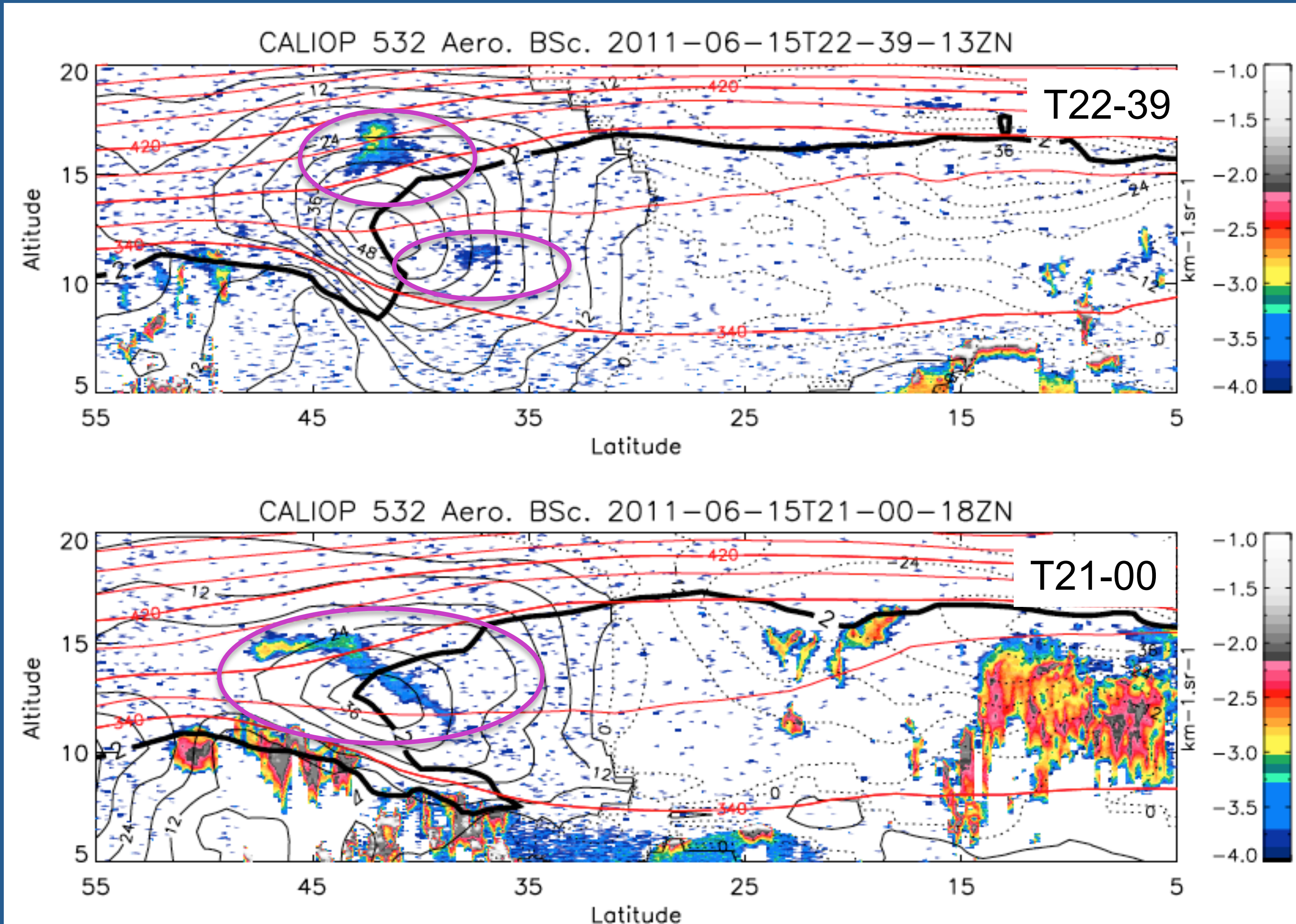
Trajectory map for June 15th (18-24Z)



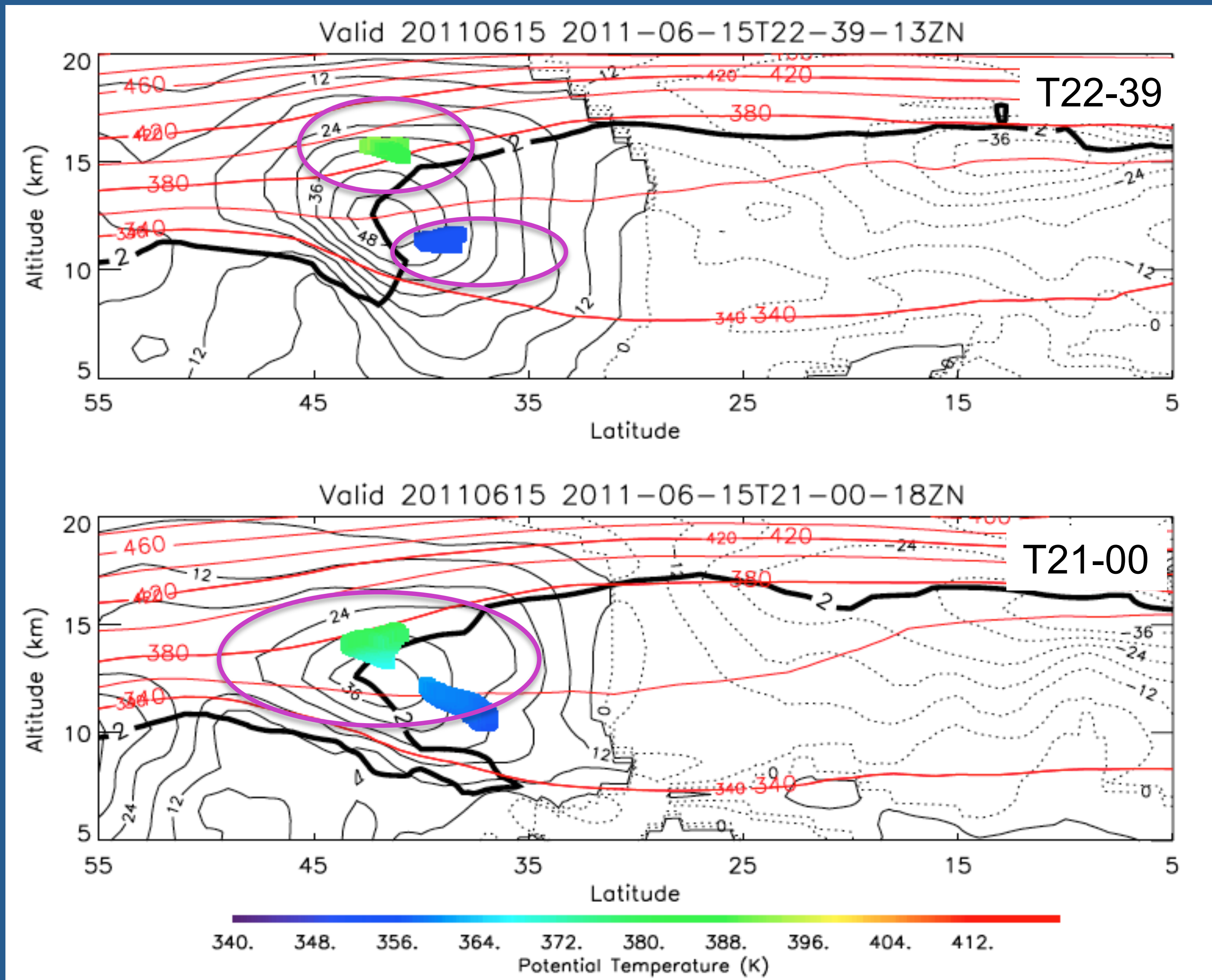
Head of plume over W. China 370-390K, trailing plumes in low strat. and upper trop.
θ of CALIOP aerosol tops shown along intersecting orbits.

Trajectories colored by initial θ

Aerosol backscatter on marked orbits, 15 June, 2011

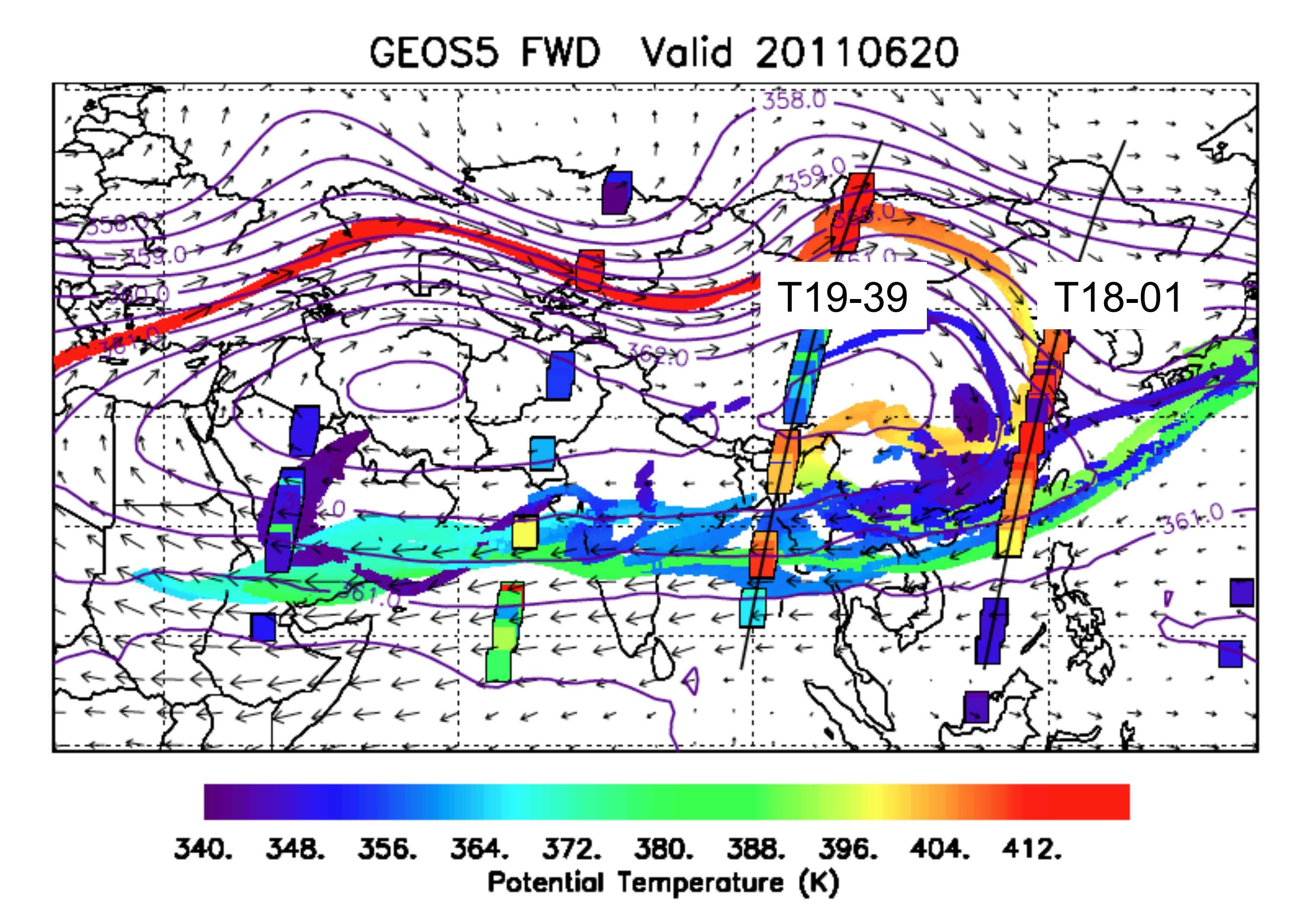


Corresponding trajectories, 15 June, 2011



Trajectories colored by initial θ

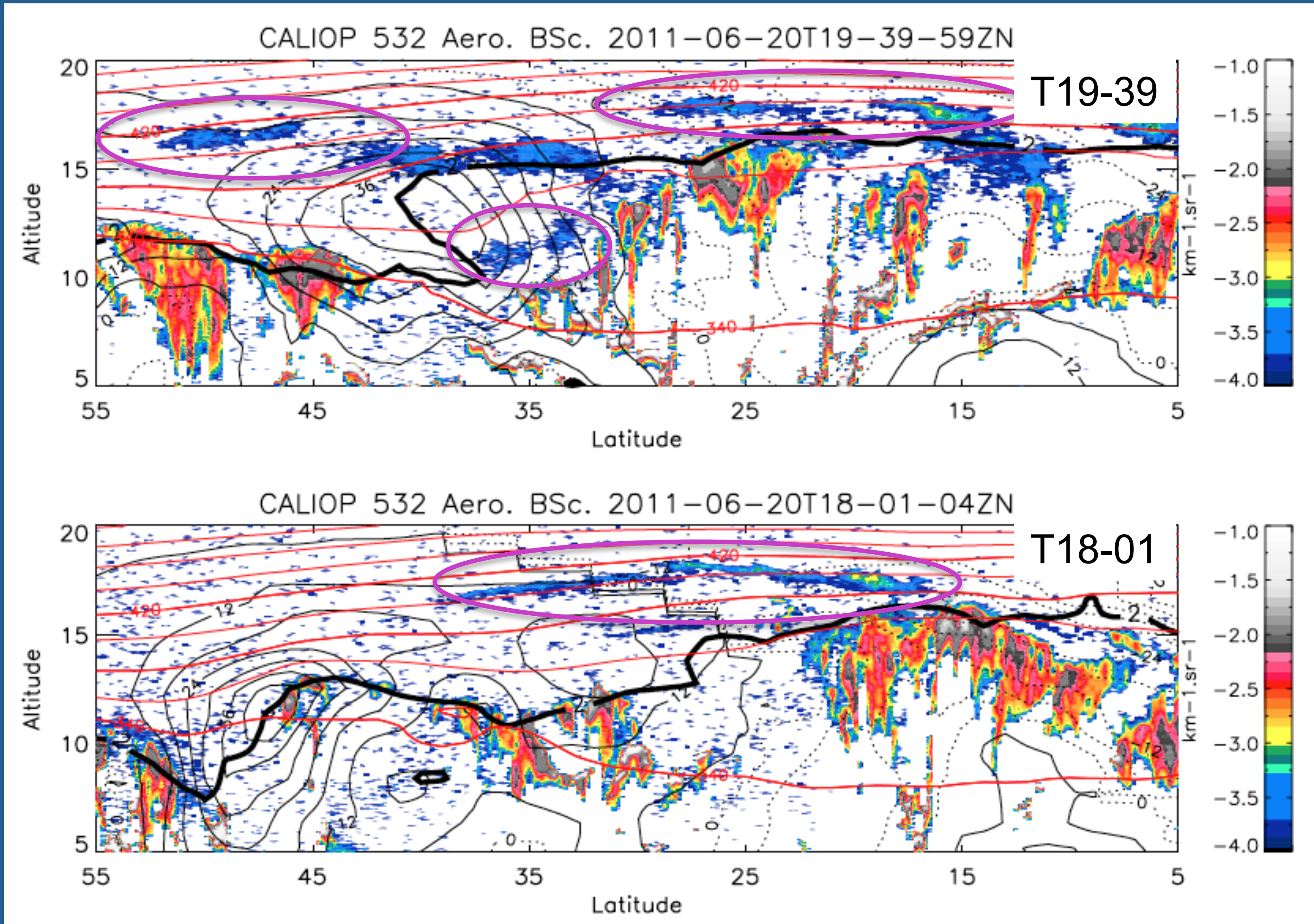
Trajectory map for June 20th (18-24Z)



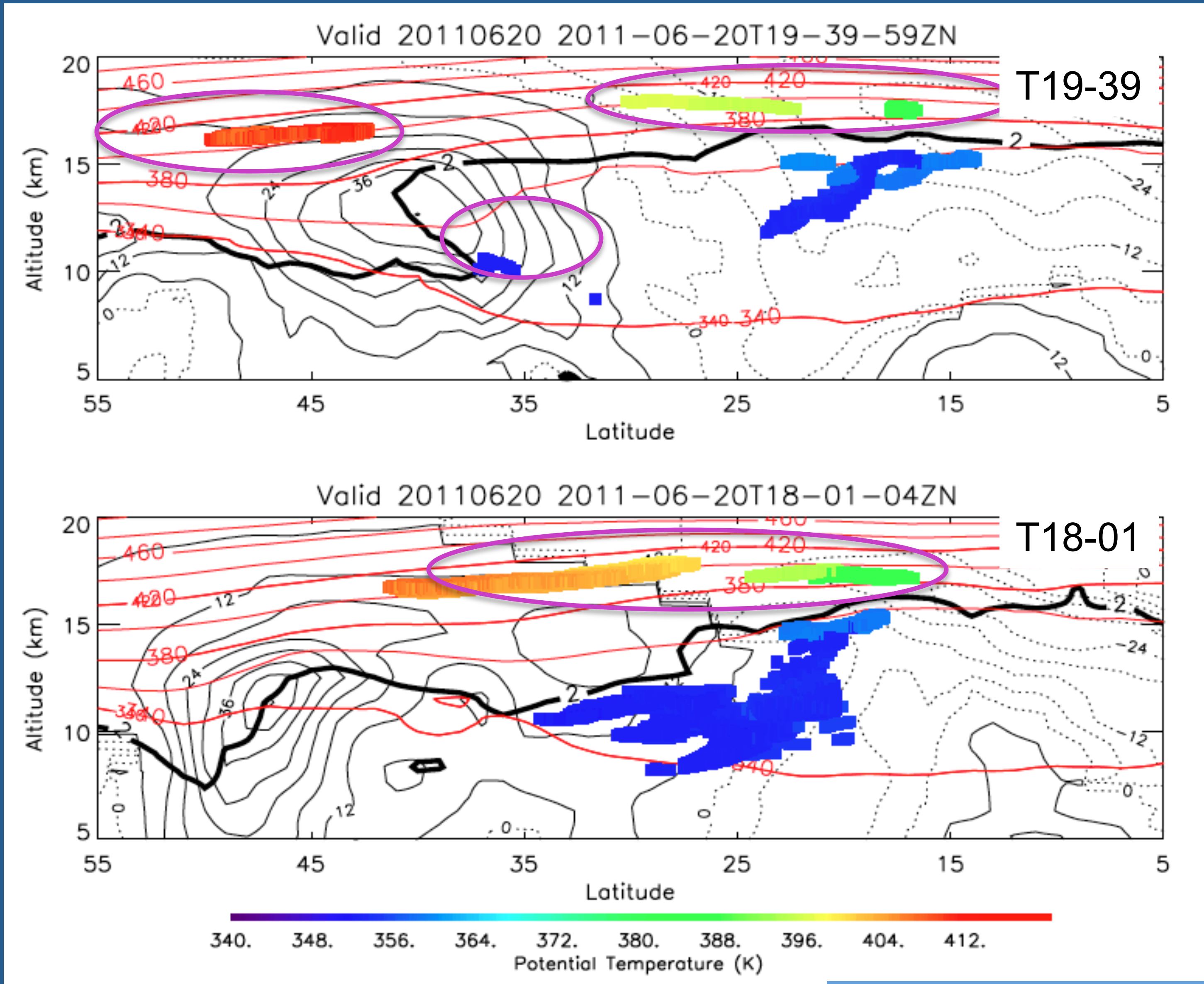
Head of the plume completing circuit of A/C. CALIOP shows aerosol tops ~400-410K over SE Asia.

Trajectories colored by initial θ

Aerosol backscatter on marked orbits, June 20th 2011

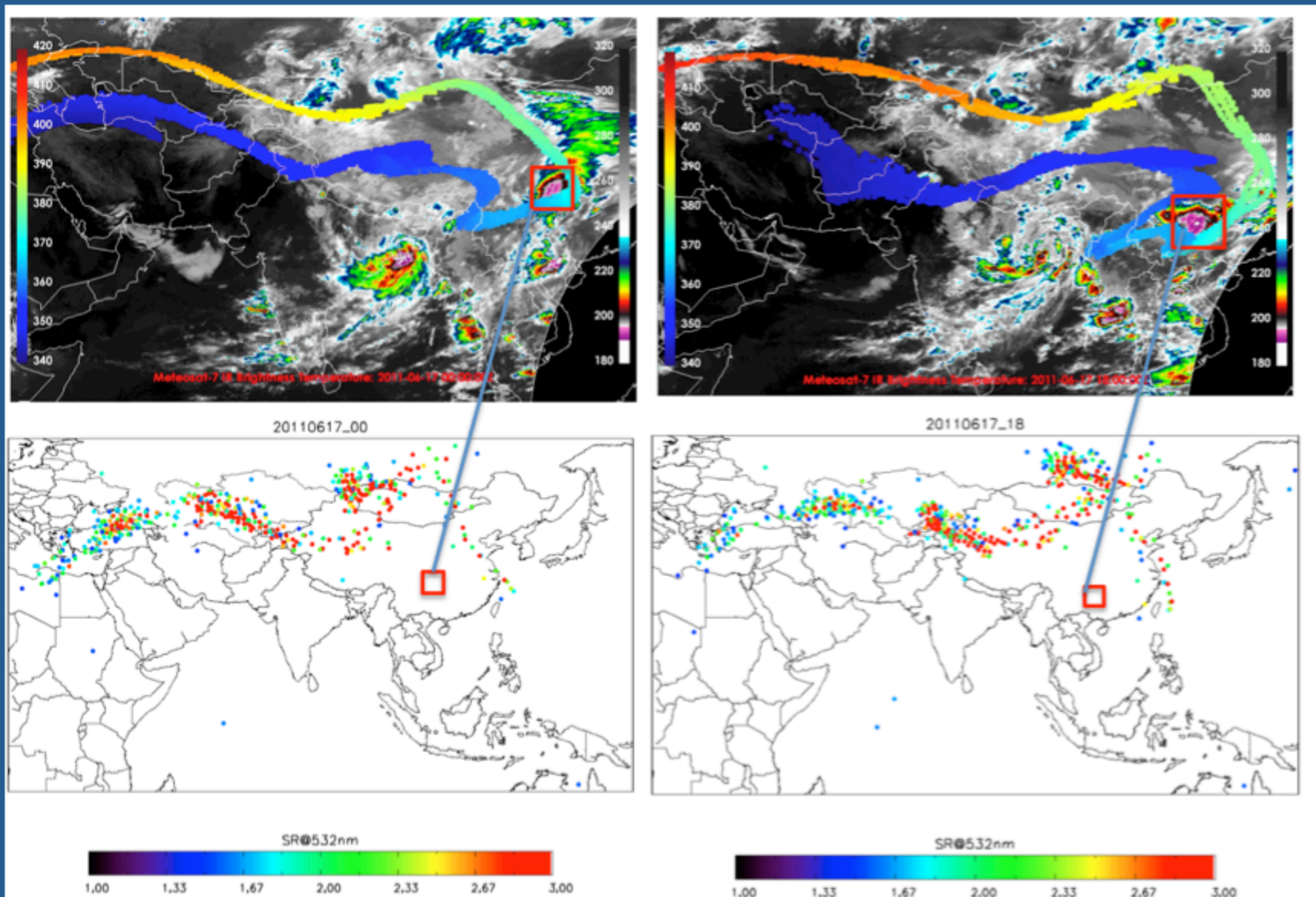


Corresponding trajectories, June 20th, 2011



Trajectories colored by initial θ

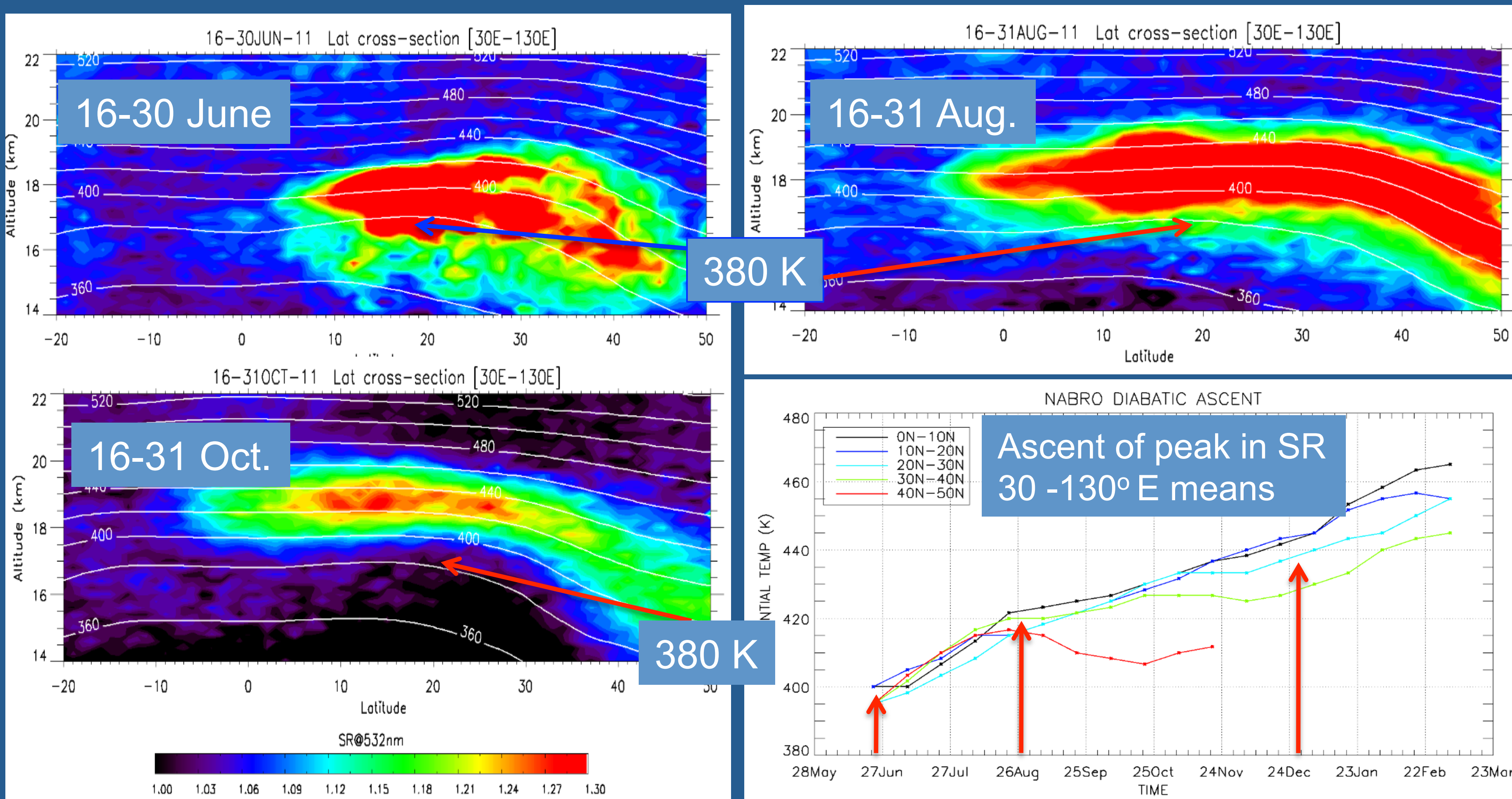
Coincidence of forward trajectories in the UT with Meso-scale Convective Systems, 17 June, 2011



Back trajectories computed from elevated CALIPSO SR observed 17-22 June originate well upstream of MCSs

Diabatic ascent rates inferred from CALIPSO Scattering Ratio

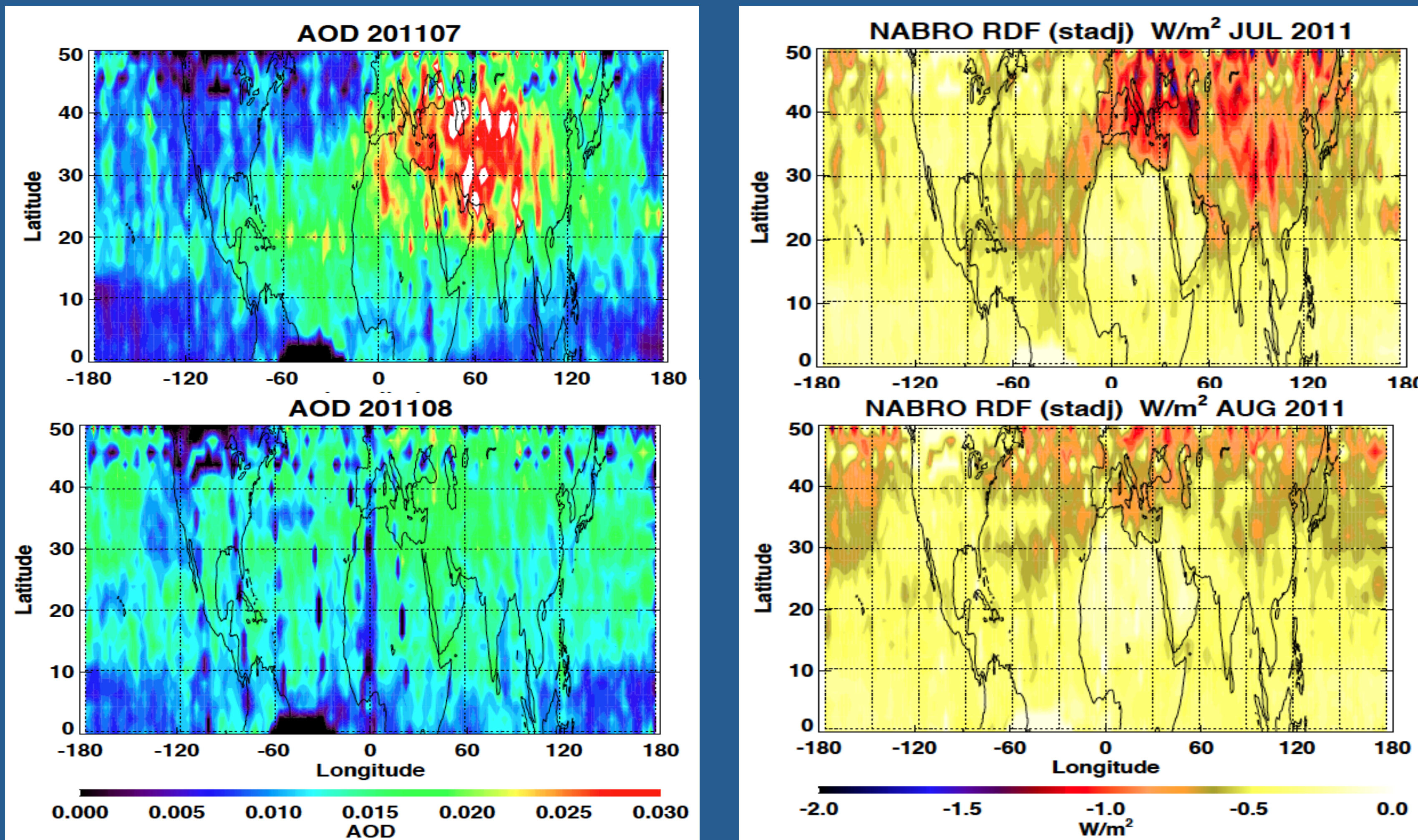
CALIPSO SR. 30 - 130°E means



CALIPSO obs. indicate diabatic heating rates of 10 K mth^{-1} (0.3 K day^{-1}) during monsoon; 3-5 K mth^{-1} (0.1-0.2 K day^{-1}) thereafter (likely 10-30% low – sedimentation neglected)

CALIPSO 532 nm AOD (above 14 km) and TOA aerosol radiative forcing*, July-Aug., 2011:

Local peaks in AOD and radiative forcing in July, with values ~ 0.04, and -1.6 Wm^{-2} locally, over Europe/Asia. [cf: Pinatubo: -15 Wm^{-2} locally; -4.5 Wm^{-2} (40^oS-40^oN mean (Minnis et al., 1993.) cf.: CERES SD de-seasonalized net mean flux for region ~ 1.5 Wm^{-2}]



*NASA LaRC Fu-Liou code, CALIOP aerosol (14-40 km), with strat. T adjustment

Conclusions

- Forward trajectory clusters indicate that stratospheric volcanic layers observed by CALIPSO in the AA following the Nabro eruption are explained by direct injection to the low stratosphere followed by quasi-isentropic advection in vertically-sheared flow.

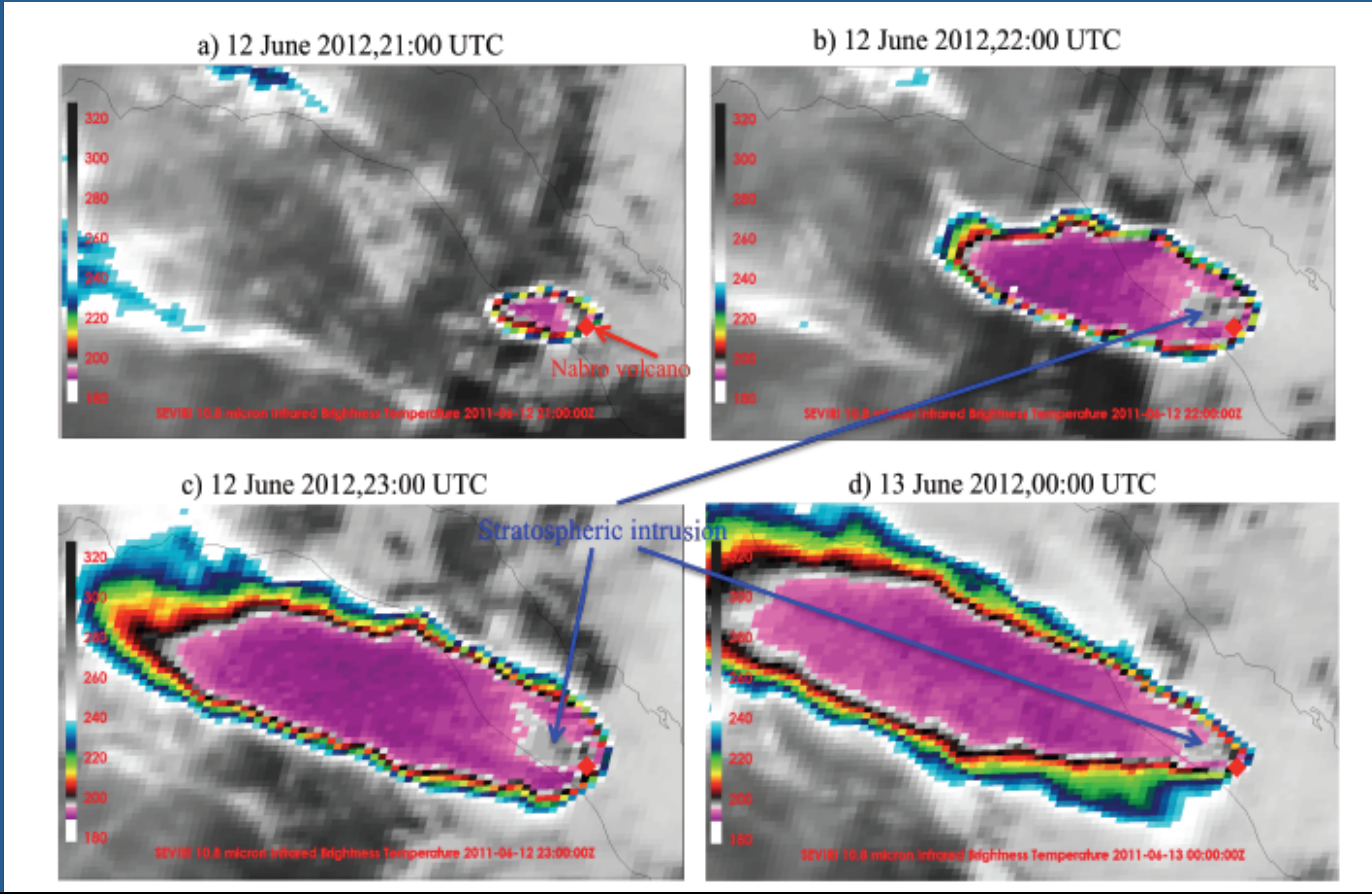
- Prominent meso-scale convective systems (MCS) observed in S.E. Asia (17 June) do not appear to be significant sources of stratospheric aerosol layers observed by CALIPSO in June.

- Estimated TOA radiative forcing is small (local peaks of ~-1.6 Wm^{-2} in July) within year-year variability (CERES).

- CALIPSO obs. indicate ~10 K mth^{-1} diabatic ascent rates in the low stratosphere Asian anticyclone from June – August, with reduced rates over Asia 3 – 5 K mth^{-1} thereafter.

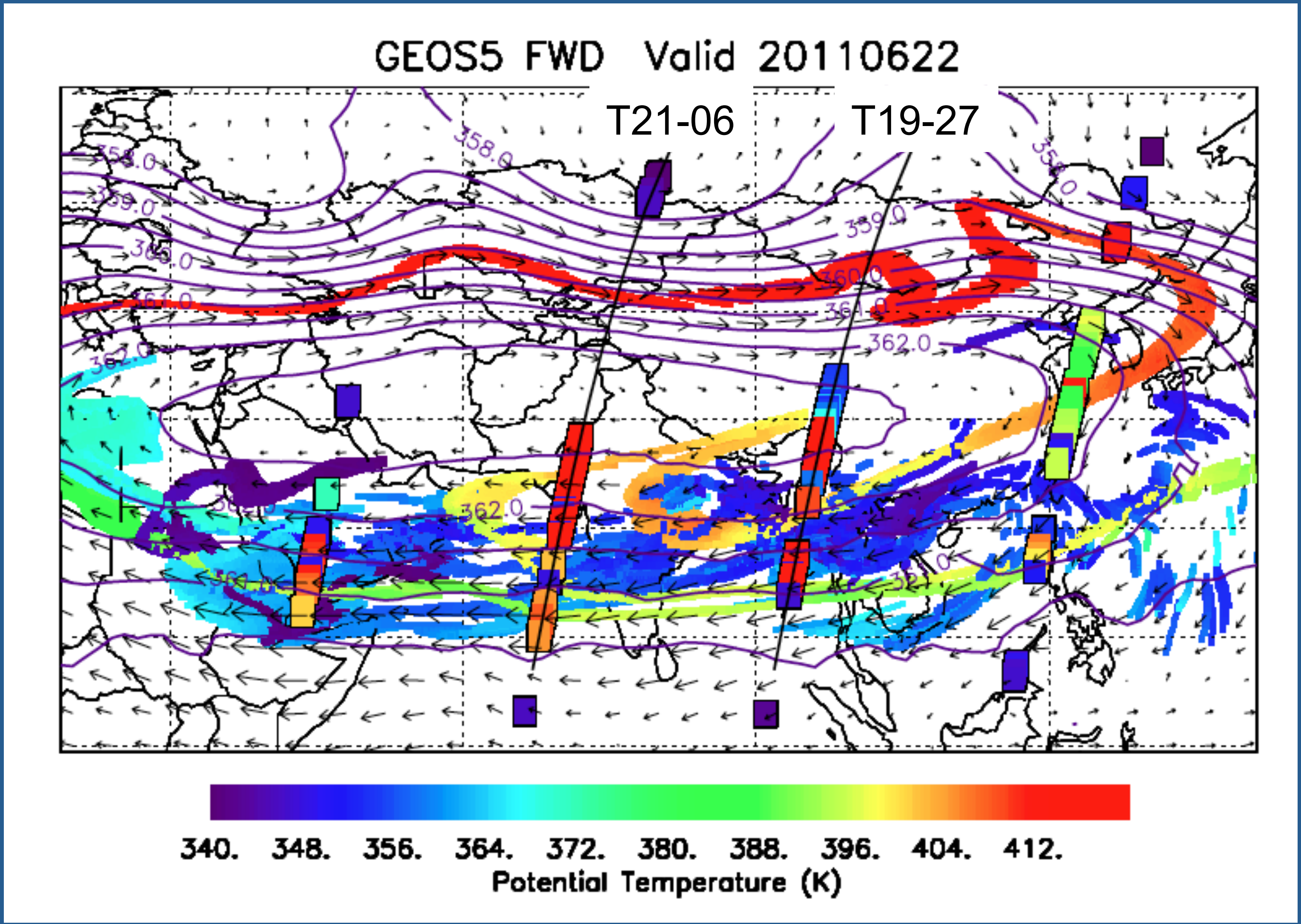
Thank you!

Cloud top BT from SEVIRI on Meteosat-9 immediately after the Nabro eruption shows direct stratospheric injection



- Cloud anvil of very low BT (~192K) spreading northwest, with enhanced BT (~203K) above the volcano is a signature of **stratospheric penetration.**
- Nearest radiosonde indicates 203K at ~19 km in the low stratosphere.

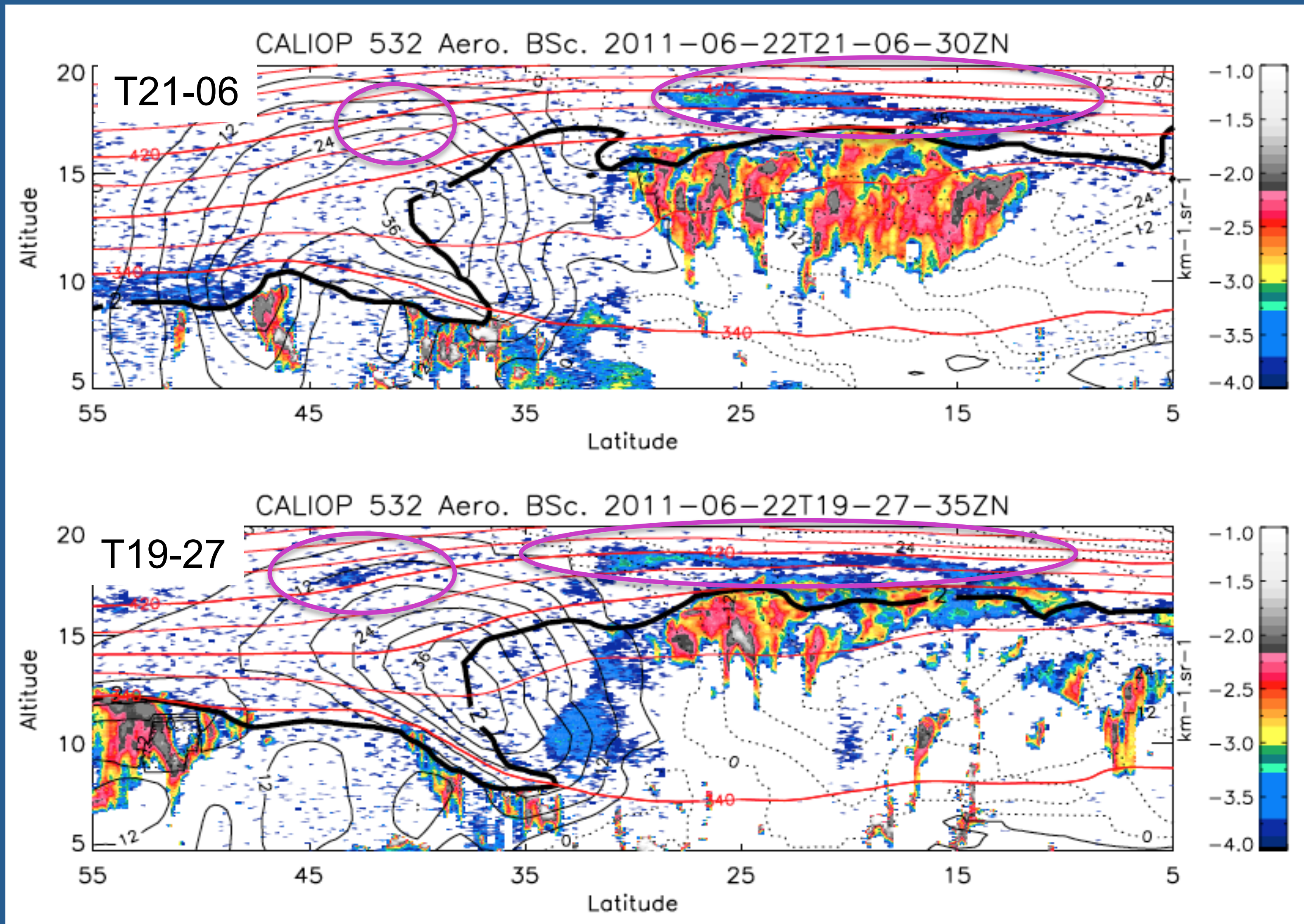
Trajectory map for June 22nd (18-24Z)



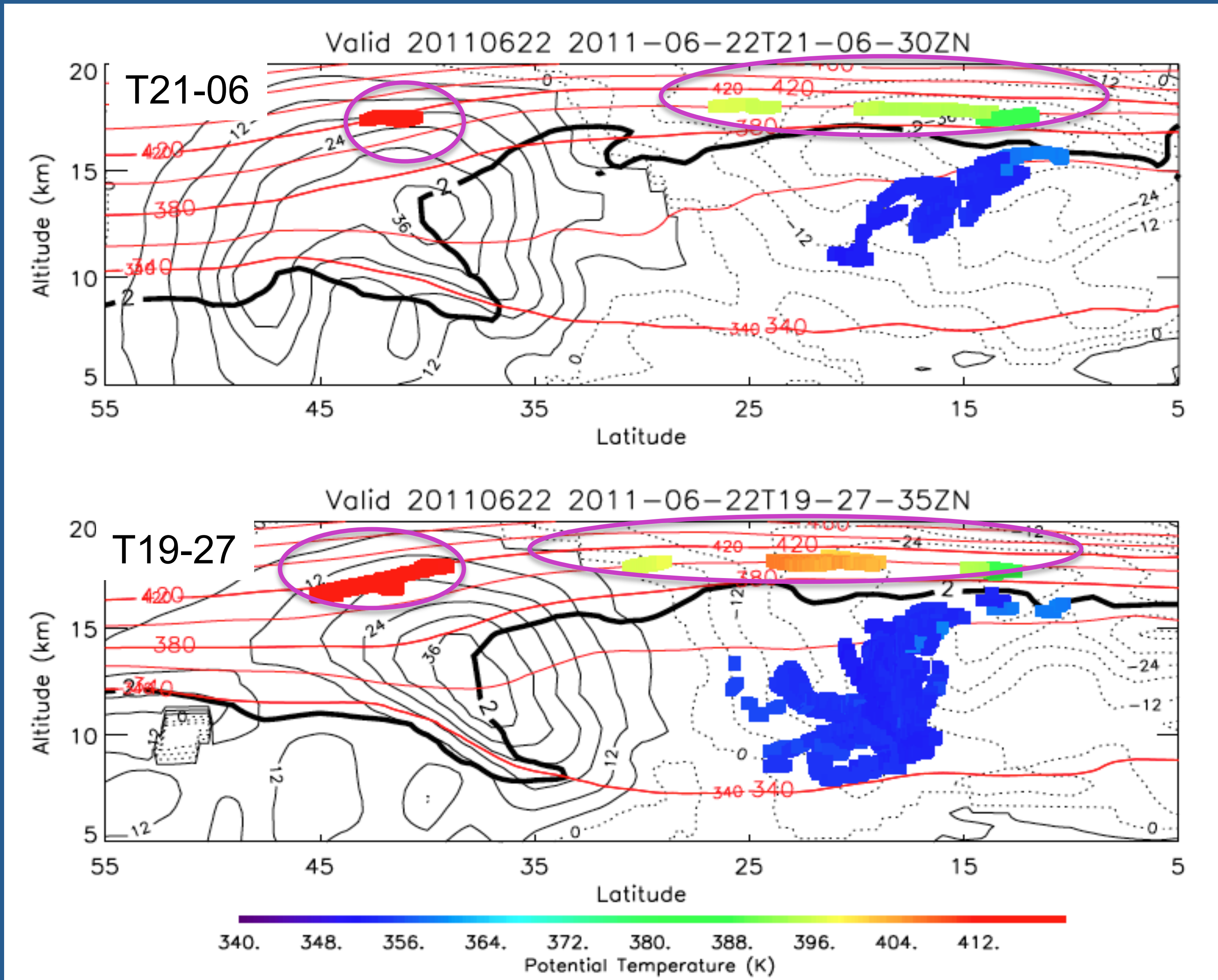
CALIOP shows aerosol tops up to 420K in SE Asia and Indian ocean.
Trajectory layers are found somewhat lower ~400K, but show similar structure.

Trajectories colored by initial θ

Aerosol backscatter on marked orbits, 22 June, 2011



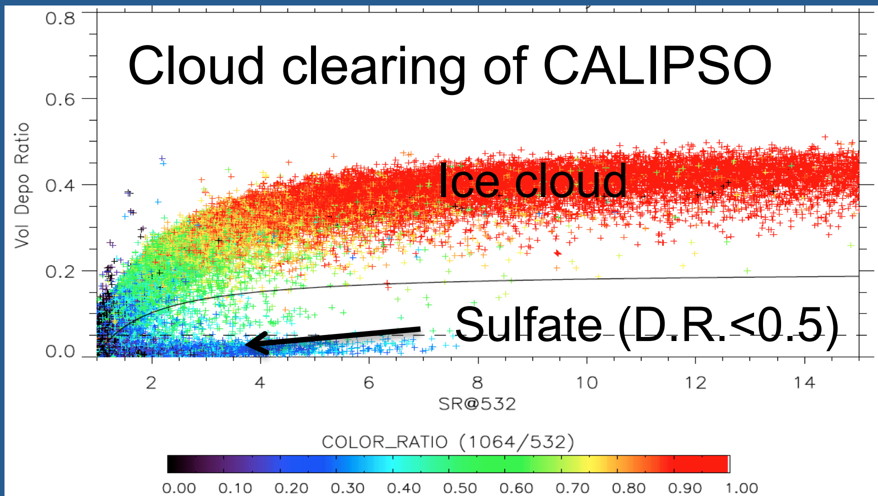
Corresponding trajectories, 22 June, 2011

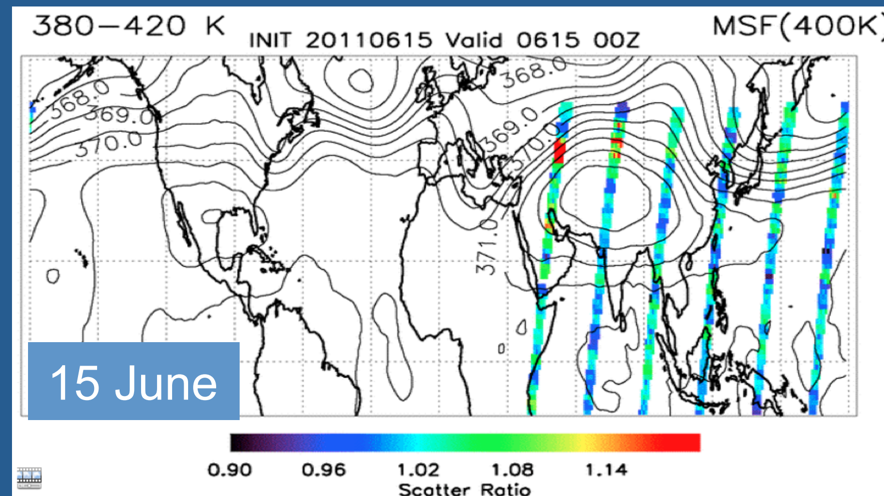


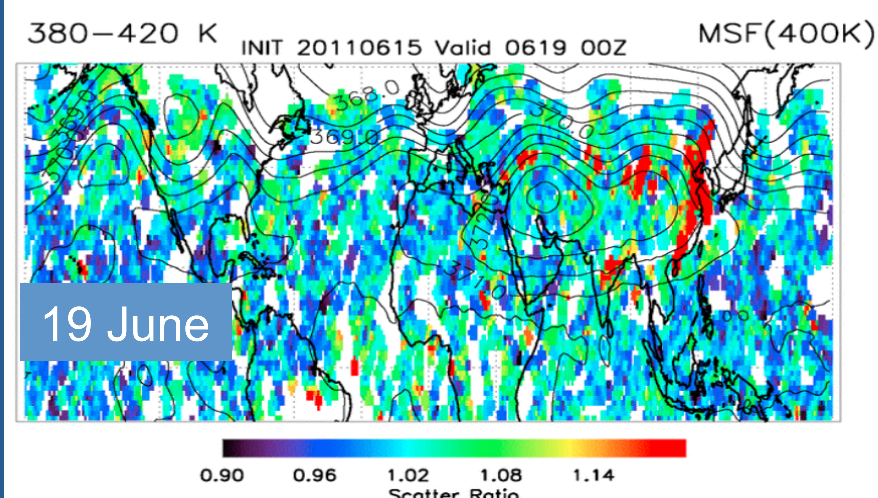
Trajectories colored by initial θ

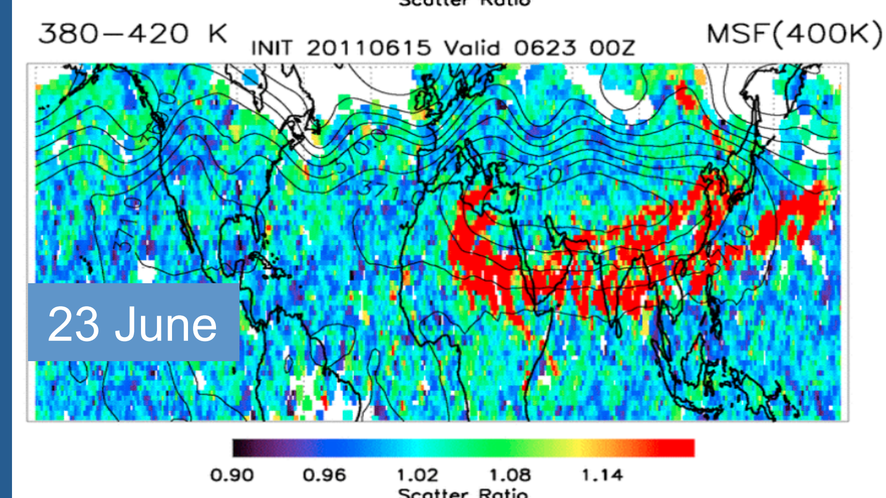
Trajectory mapping of Nabro plume in the low stratosphere

Air parcels initialized along CALIPSO orbital tracks between 14-20 km. 3D trajectories computed using GEOS-5 winds. Trajectory-mapped cloud-cleared, nighttime scattering ratio (SR) bridges gaps between obs., providing temporal continuity.
Analyses of SR below (380-420K) include parcels up to 10 days old.



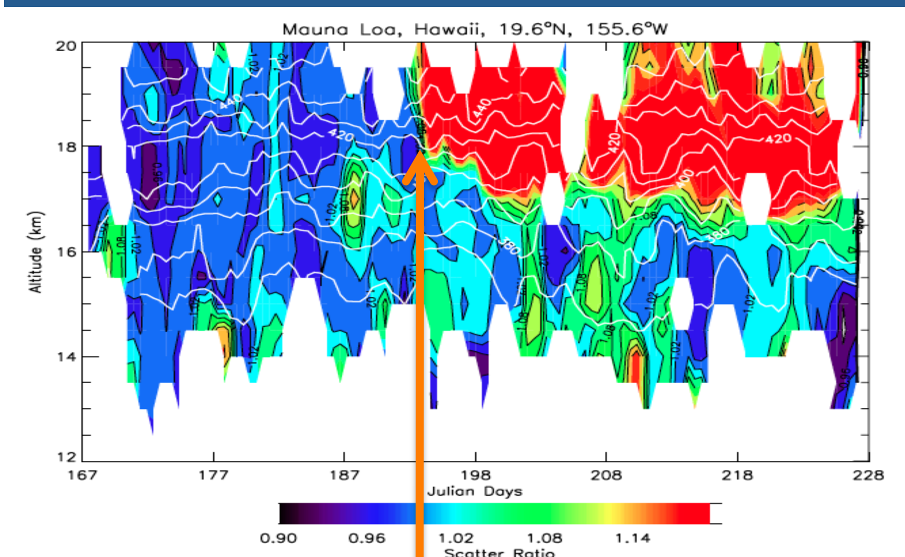




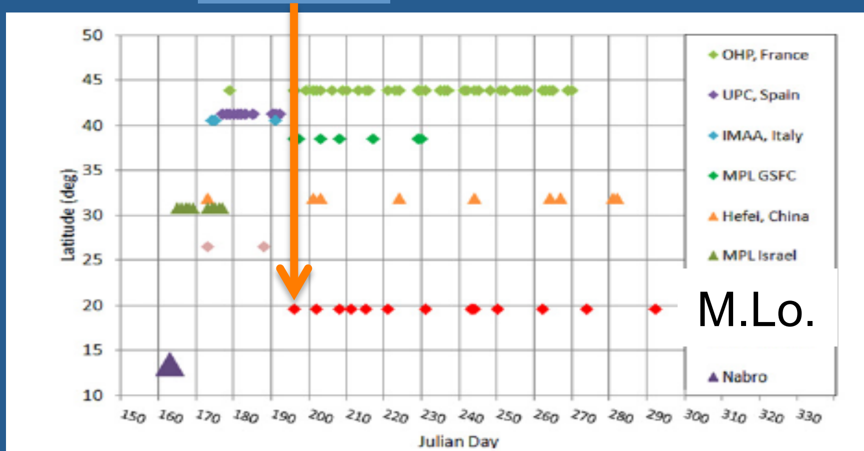


Time curtains of trajectory-mapped CALIPSO SR

Mauna Loa, HI



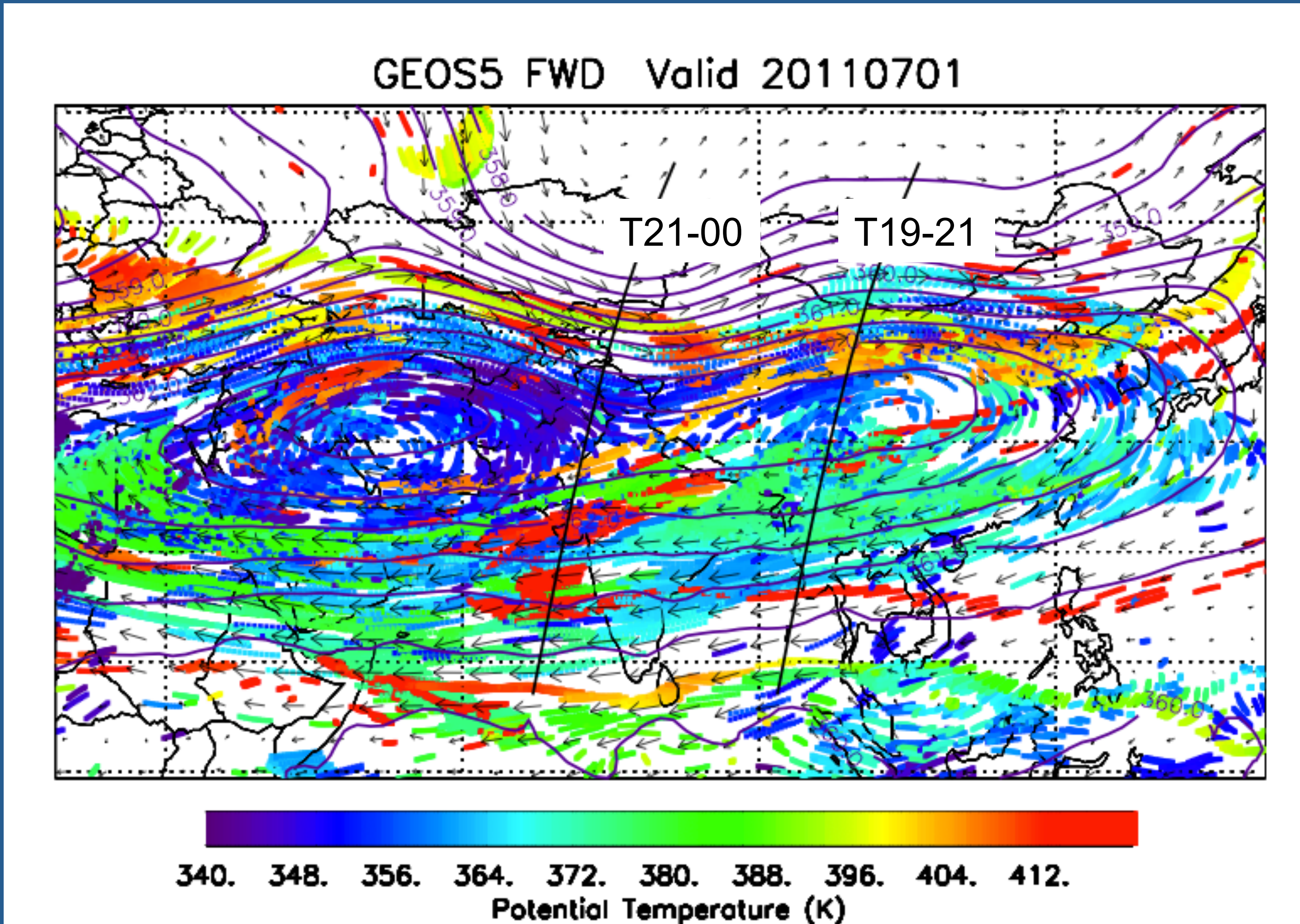
15 July



Trajectory-mapped products validated with ground-based lidar obs., and may be used to provide estimates of stratospheric AOD component for ground-based sensors.

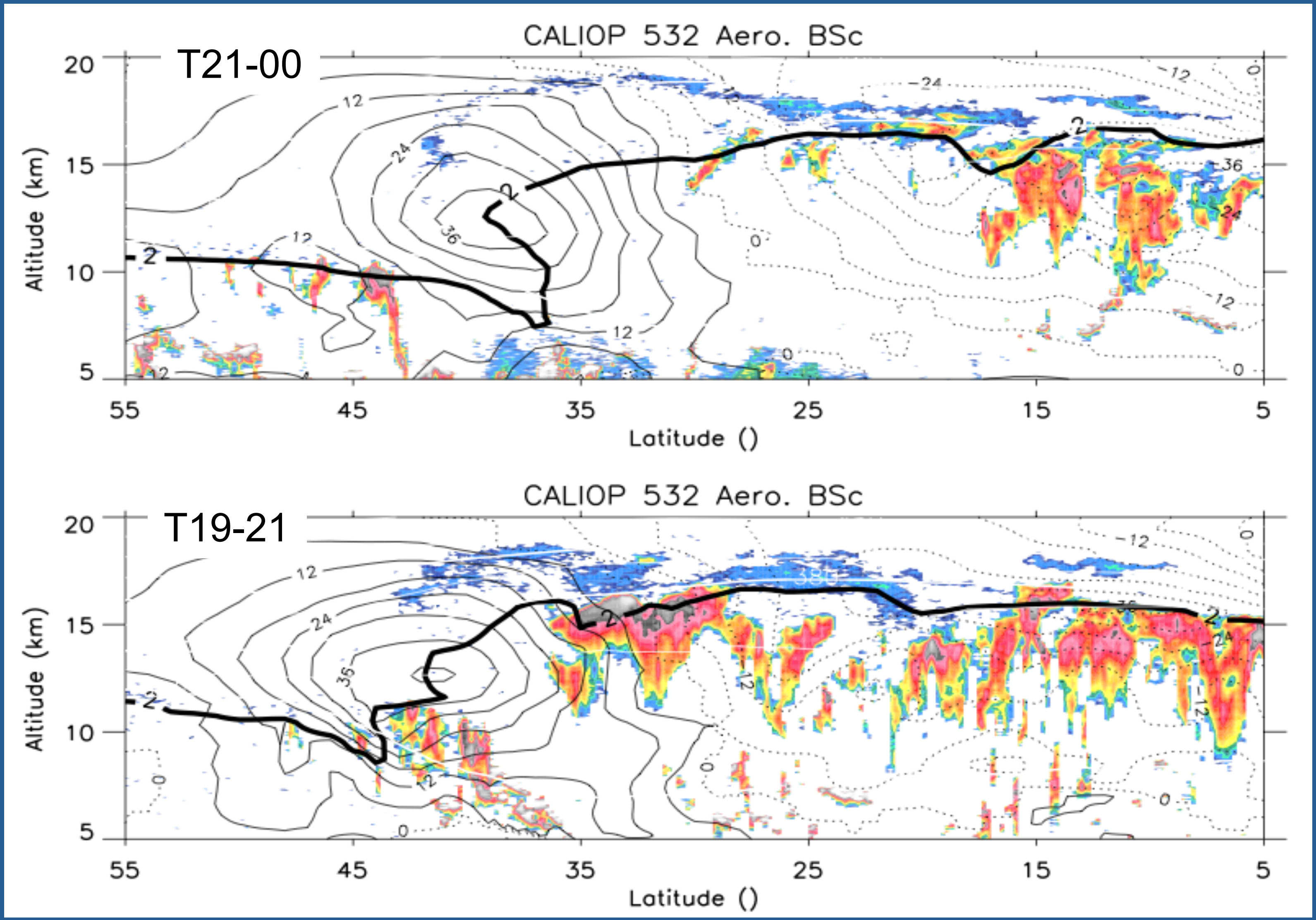
Lidar detections of Nabro plume (from Sawamura et al., 2012)

By 1 July (18-24Z)

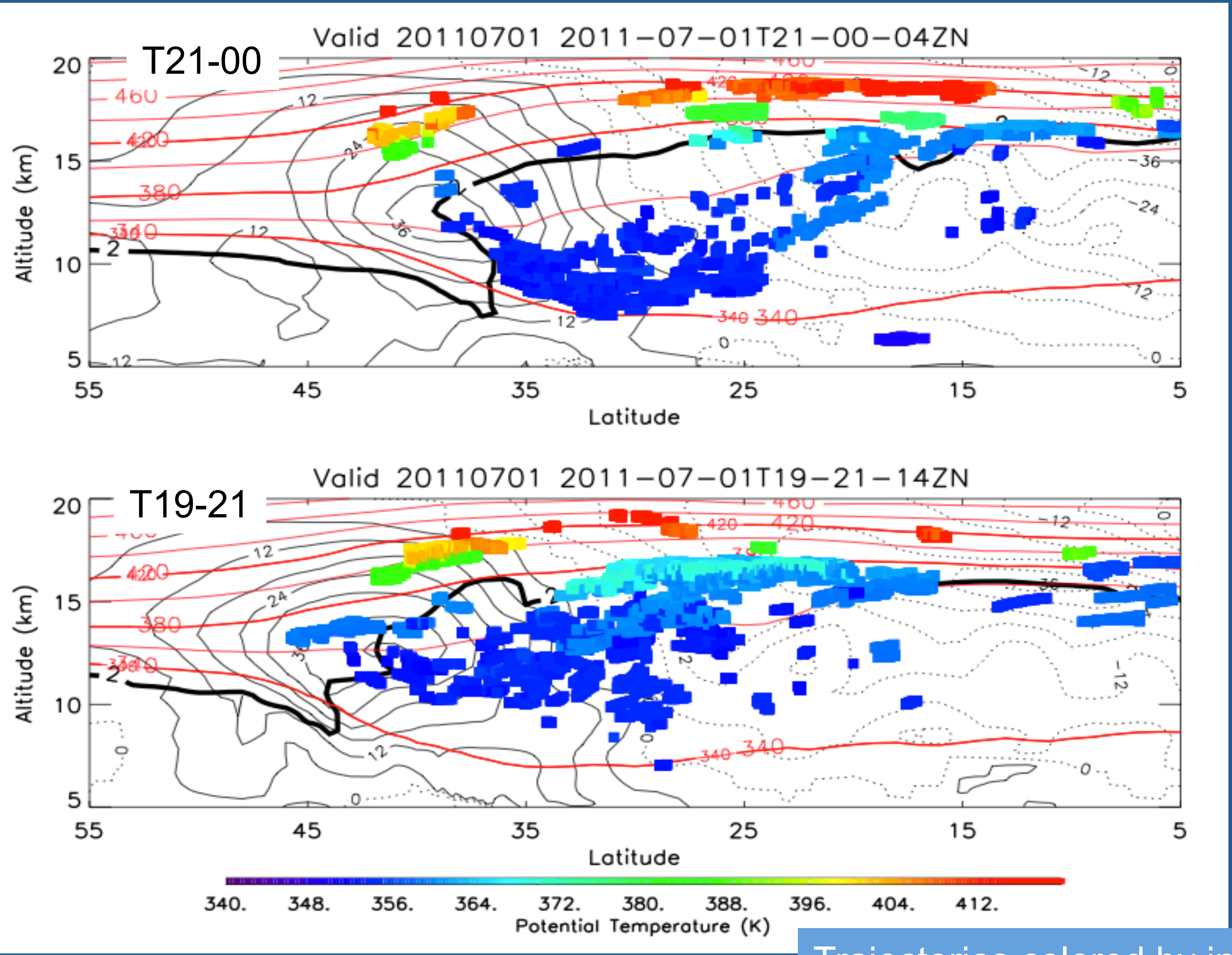


Trajectories colored by initial θ

Aerosol backscatter on marked orbits, 01 July, 2011



Corresponding trajectories, 01 July, 2011



Trajectories colored by initial θ

Cloud clearing of CALIPSO observations for Nabro case