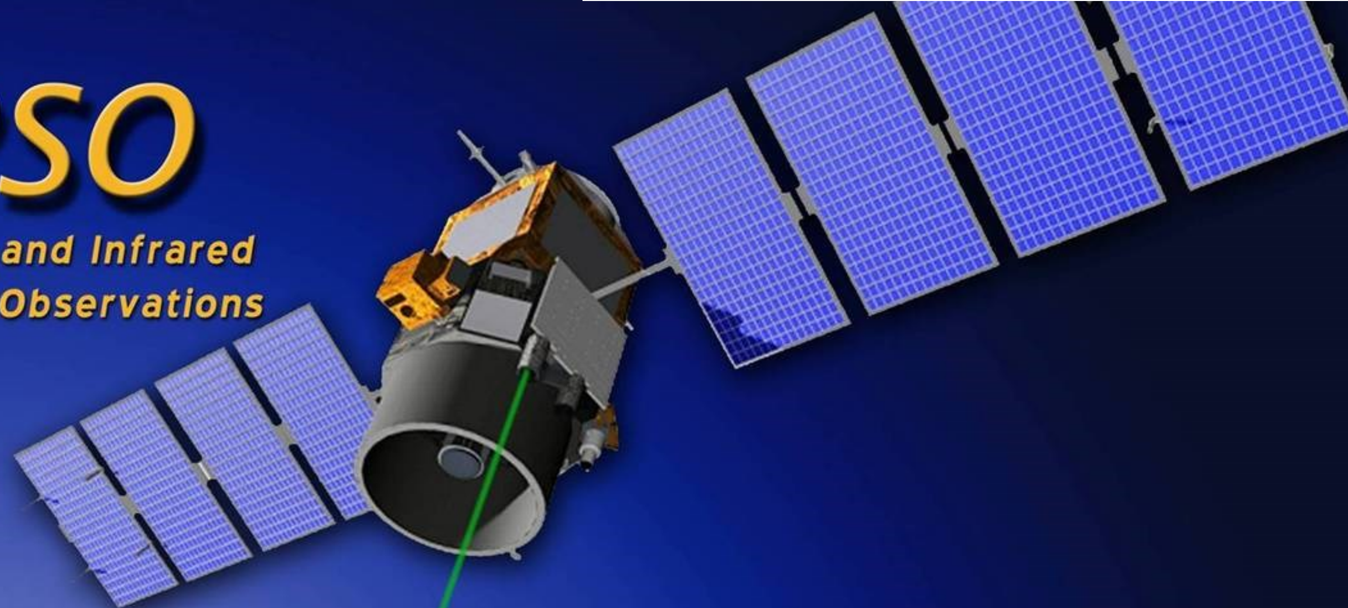
CALIPSO

Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations



9+ Years of CALIPSO PSC observations: An evolving climatology

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21 April 2015

OUTLINE

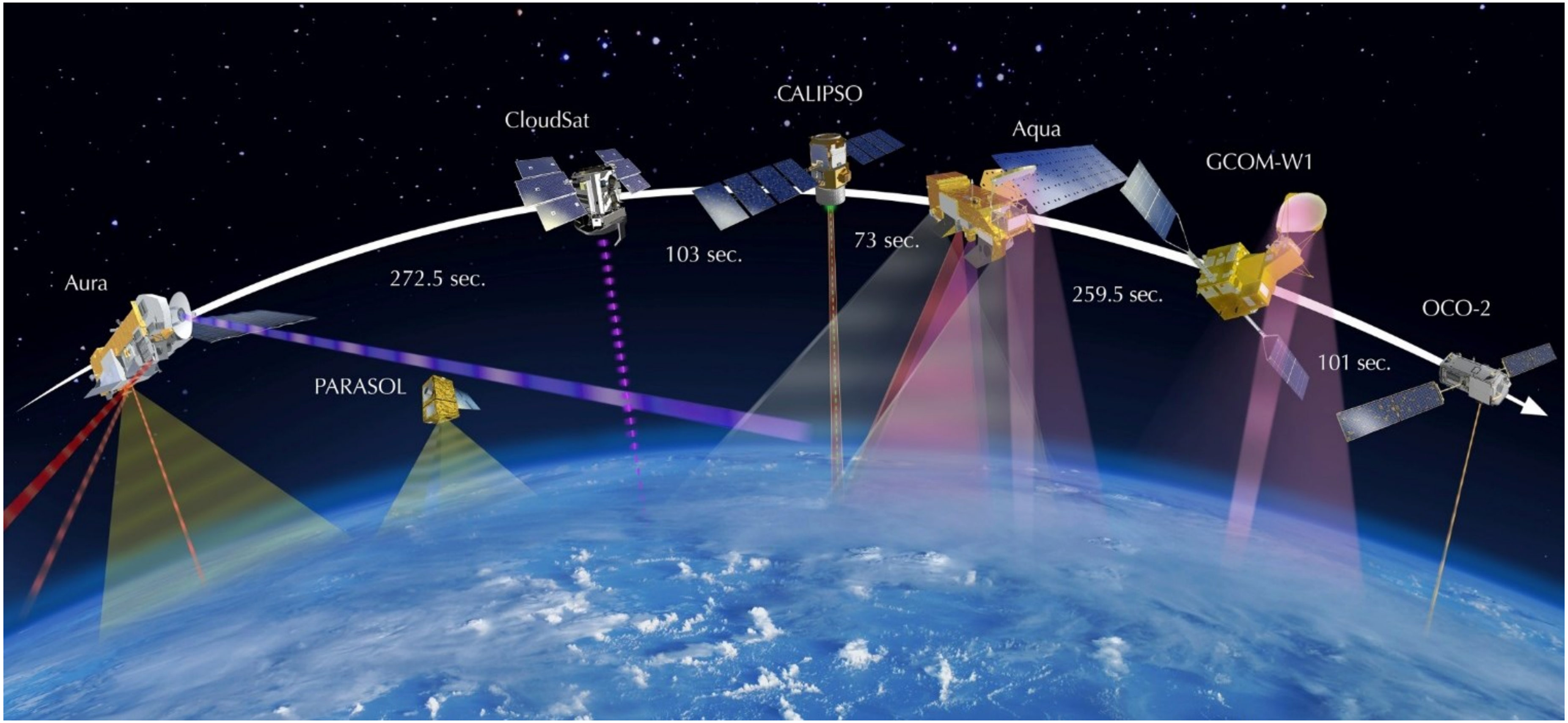
- CALIPSO mission overview and status
- CALIOP PSC detection and composition classification
- Seasonal distribution and variability of PSCs
  - ➢ Antarctic observations: 2006-2013
  - ➢ Arctic observations: 2006-2014
- Comparison with occultation and ground-based data records
- Radiative impacts of PSCs
- Summary and conclusions

CALIPSO Mission Overview

(Cloud-Aerosol Lidar and Infrared Pathfinder Spaceborne Observations)

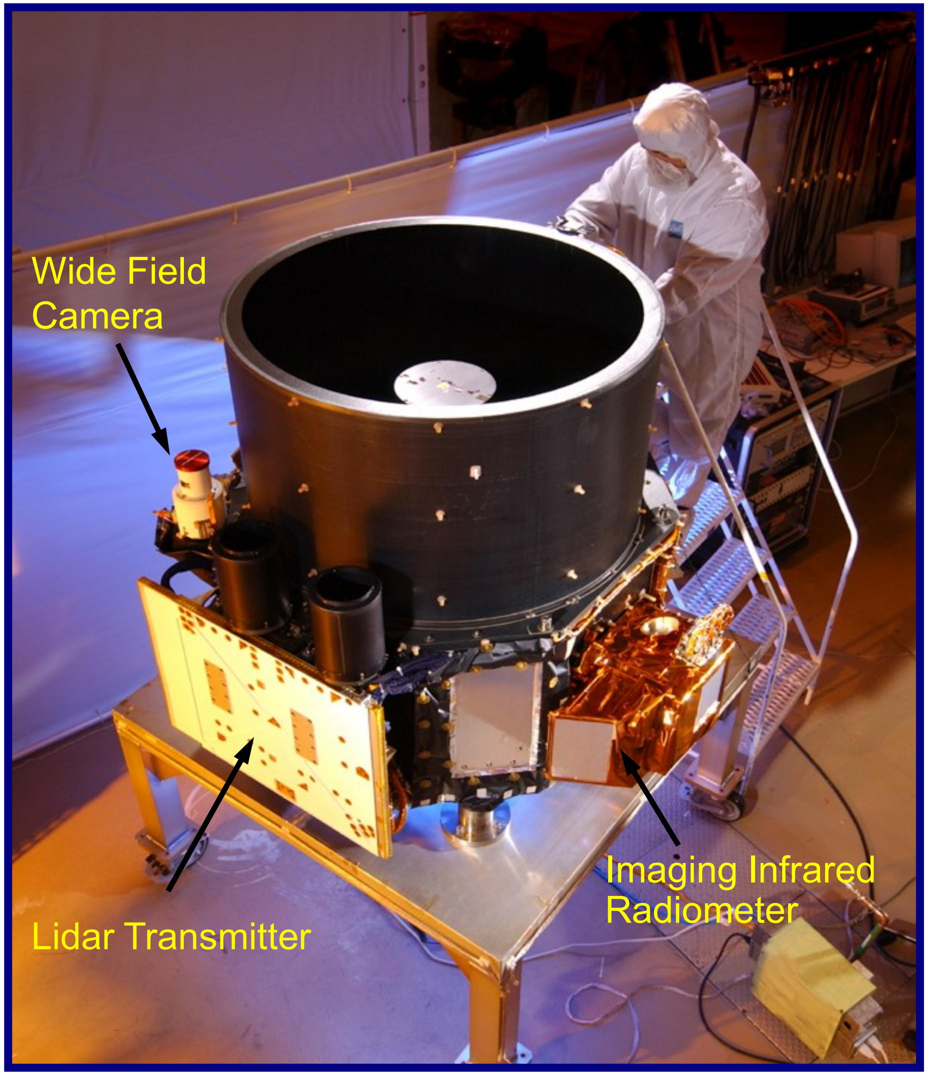
- **NASA-CNES collaboration, launched 28 April 2006 with nominal 3-year mission**
- **705-km, Sun-synch (98° inclination) orbit in A-Train satellite constellation**
- **Designed to probe the vertical structure and properties of aerosols and clouds**
- **Currently operating in Extended Mission Phase (bi-annual review)**
- **Platform and payload operating as expected or better**

A-Train Satellite Constellation



- 705-km, Sun-synchronous (98° inclination) orbit
- Formation flying enables measurement overlap of active and passive instrument techniques – *a New Era for space-based remote sensing science*

Instrument Payload



CALIOP

Laser	Nd: YAG, 2x110 mJ
Wavelength	532 nm, 1064 nm
Repetition rate	20.16 Hz
Receiver telescope	1.0 m diameter
Polarization	532 $\|\|$ and $\perp$
Footprint/FOV	100 m / 130 μrad
Vertical resolution	30 - 60 m
Horizontal resolution	333 m
Lin. dynamic range	22 bits

Imaging Infrared Radiometer (IIR)

Wavelength	8.65, 10.6,12.05 μm
Spectral resolution	0.6-1.0 μm
IFOV / Swath	1 km / 64 km
NETD @ 210K	0.3 K
Calibration	±1 K

Wide-Field Camera (WFC)

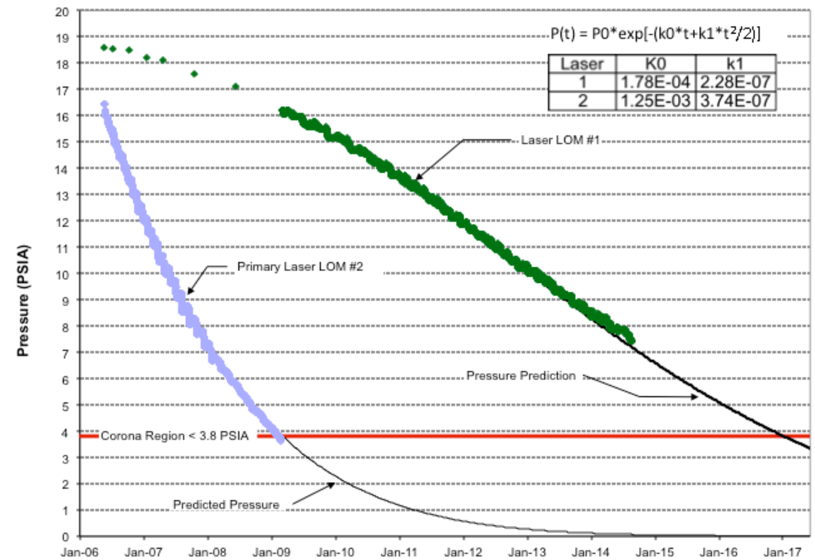
Wavelength	645 nm
Spectral bandwidth	50 nm
IFOV / Swath	125 m / 61 km

CALIOP Performance and Trends

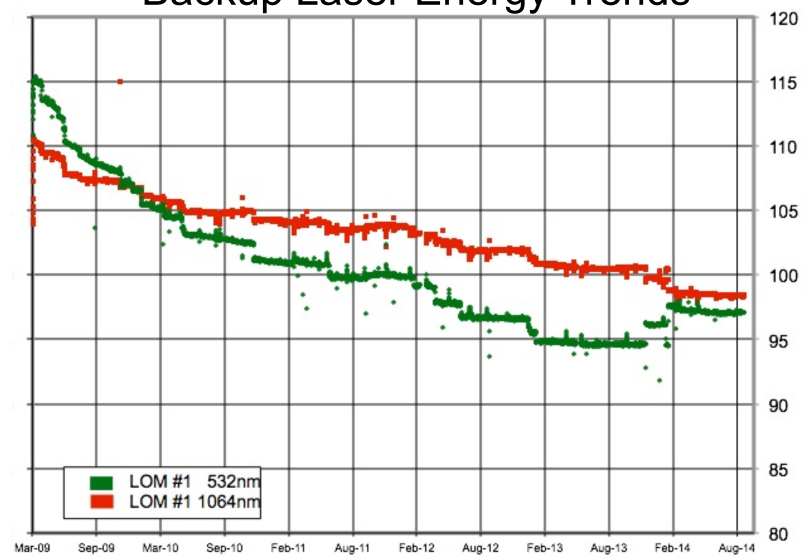
- CALIOP designed with primary laser transmitter and second, fully-redundant backup system
- Switched to backup laser in Feb 2009
- Over 1.6 billion shots for primary laser and > 3.3 billion shots for backup laser
- Corona region < 3.8 psi and likely cause primary laser became erratic in 2009
- Backup laser expected to reach corona region in 2017
- Backup laser energy levels stable with 532-nm night-time SNR currently ~90% of SNR at launch
- Study underway to evaluate feasibility of restarting primary laser in 2017

➢ **Performance has met or exceeded nearly all requirements and expected to remain stable for several more years**

Laser Canister Pressures

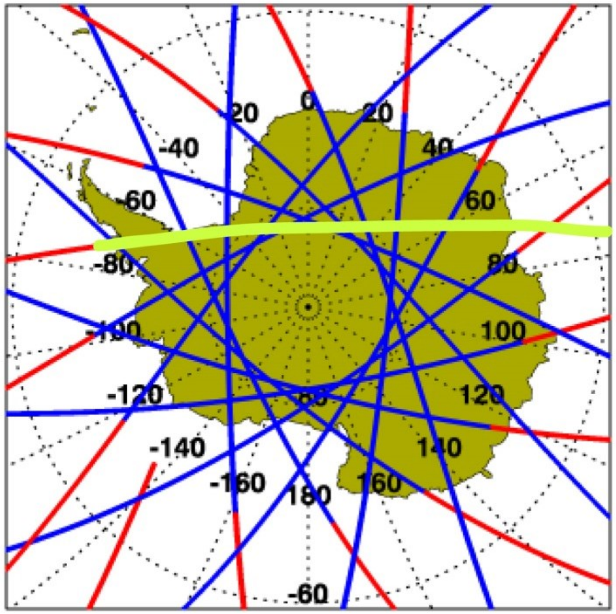


Backup Laser Energy Trends



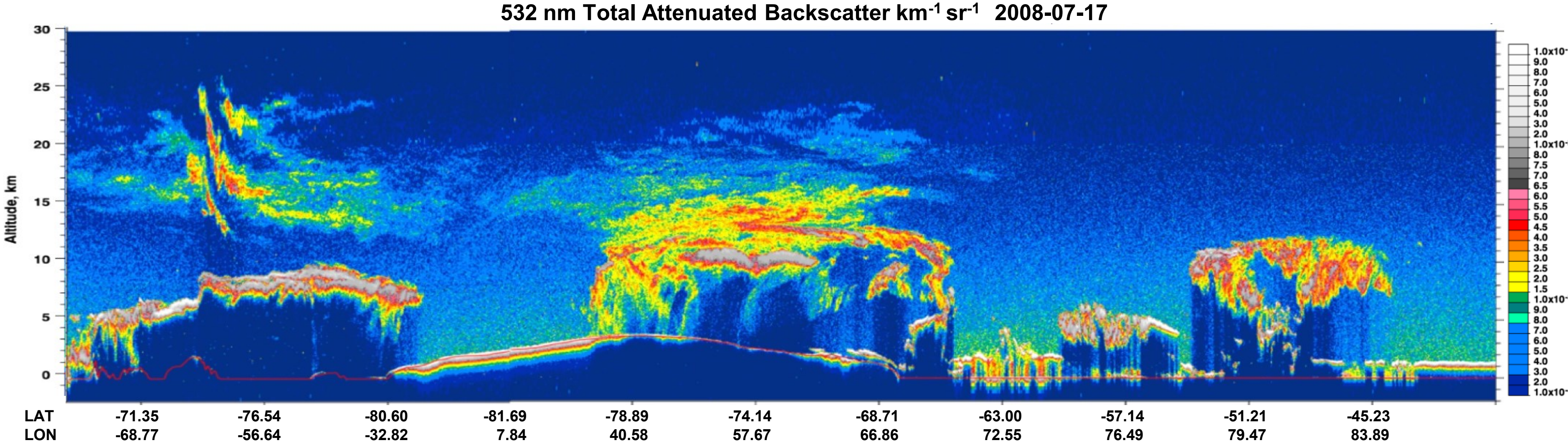
CALIOP Providing Unique (and unexpected) Dataset for PSC Studies

Typical Daily Antarctic Winter Coverage
2008/07/17 (blue=night, red=day)



- Extensive measurement coverage over polar regions into polar night
- High spatial resolution (5-km horizontal x 180-m vertical resolution PSC product)
- Combination of total backscatter and polarization sensitive measurements provide information on PSC composition

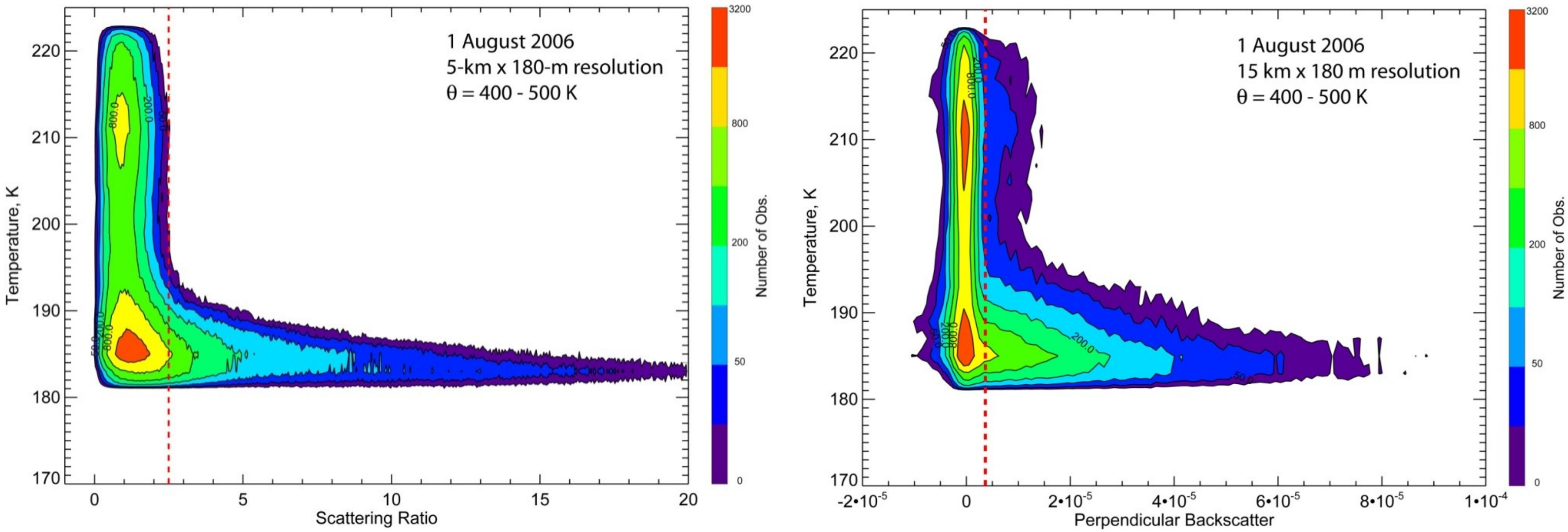
532 nm Total Attenuated Backscatter km^{-1} sr^{-1} 2008-07-17



Why are we interested in PSCs?

- PSCs form in the Antarctic and Arctic stratosphere (altitudes ~15-30 km) when temperatures fall below about 195 K (-78 C)
- At least 3 particle compositions exist: super-cooled ternary solution (STS) H_2SO_4-HNO_3-H_2O droplets, nitric acid trihydrate (NAT) crystals, H_2O ice
- PSCs play key role in springtime chemical depletion of ozone at high latitudes
  - PSC particles serve as catalytic sites for heterogeneous chemical reactions
  - If PSC particles grow large enough to sediment, they can irreversibly remove gaseous odd nitrogen (denitrification)
- Significant gaps in knowledge still exist
  - Large solid particle formation and their denitrification potential (NAT rocks)
  - Limit our ability to accurately represent PSCs in global models
  - Calls into question our prognostic capabilities concerning future ozone loss

CALIPSO PSC Detection Algorithm
(Second Generation)



- PSCs are detected as statistical outliers in 532 nm scattering ratio (total/molecular backscatter, R_{532}) or perpendicular backscatter, $\beta_{\perp}$
- Successive horizontal averaging (5, 15, 45, & 135 km)
- Spatial coherence test to minimize false positives

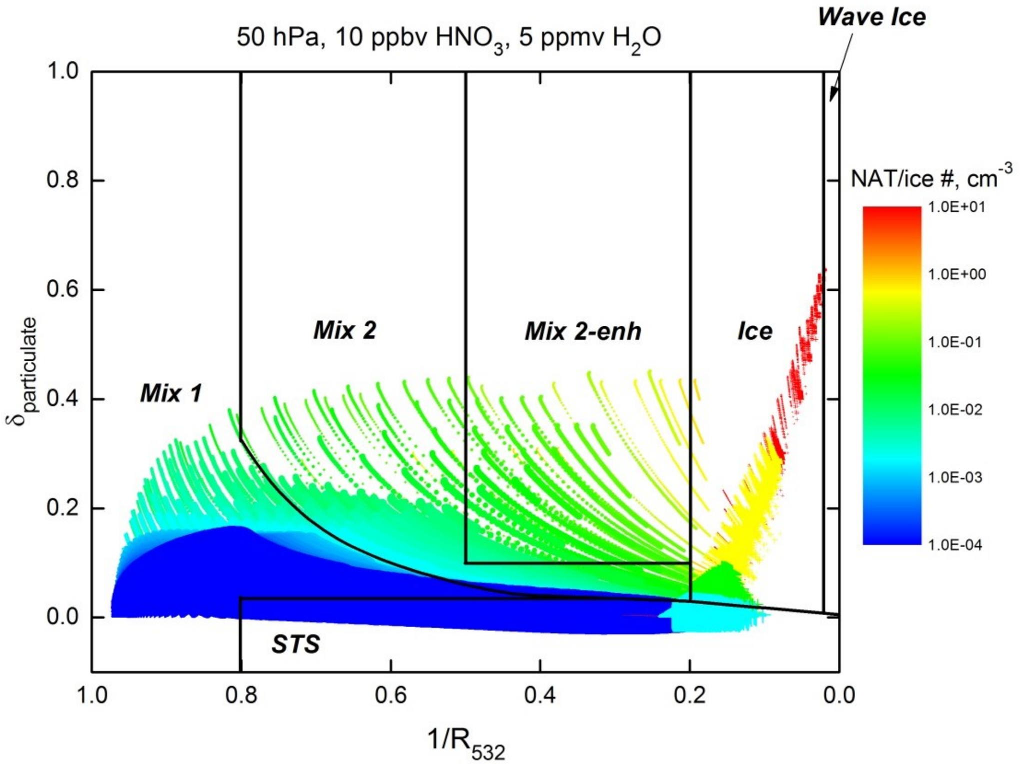
Pitts et al., CALIPSO Polar Stratospheric Cloud Observations: Second Generation Detection Algorithm and Composition Discrimination , *Atmos. Chem. Phys., 9,1-13, 2009*.

CALIOP PSC Composition Classification

- Based on comparison of CALIOP particle depolarization ratio δ_P and inverse scattering ratio $1/R_{532}$ observations with theoretical optical calculations (Pitts et al., 2007-2013)
  - ➢PSCs separated into six composition classes
  - ➢$\beta_\perp$ outliers: NAT mixtures/ice; R_{532} outliers: STS

- Standard CALIPSO Level 2 PSC data product available from Langley Atmospheric Sciences Data Center:

(https://eosweb.larc.nasa.gov/project/calipso/calipso_table)



❖**STS = supercooled ternary (H_2SO_4-H_2O-HNO_3) solution**

❖**Mix 1, Mix 2, Mix 2-enh(anced) = external mixtures of liquid (binary H_2SO_4 aerosol or STS) droplets and NAT particles (in increasing number density)**

❖**Ice, wave ice = H_2O ice (synoptic, mountain-wave-induced)**

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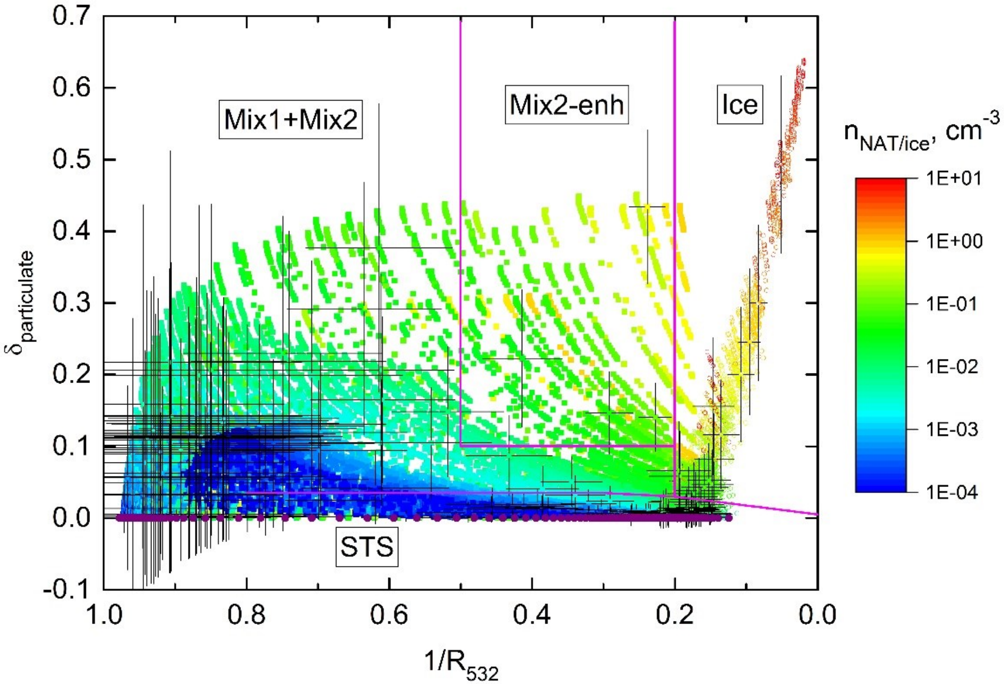

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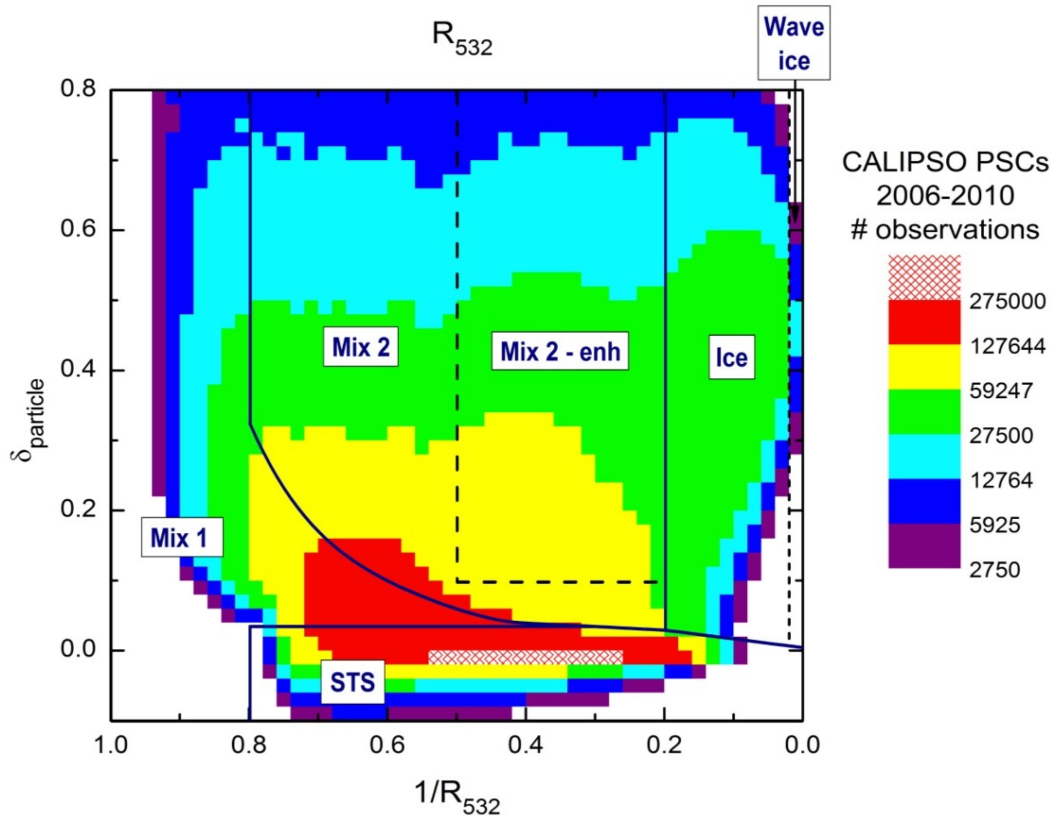

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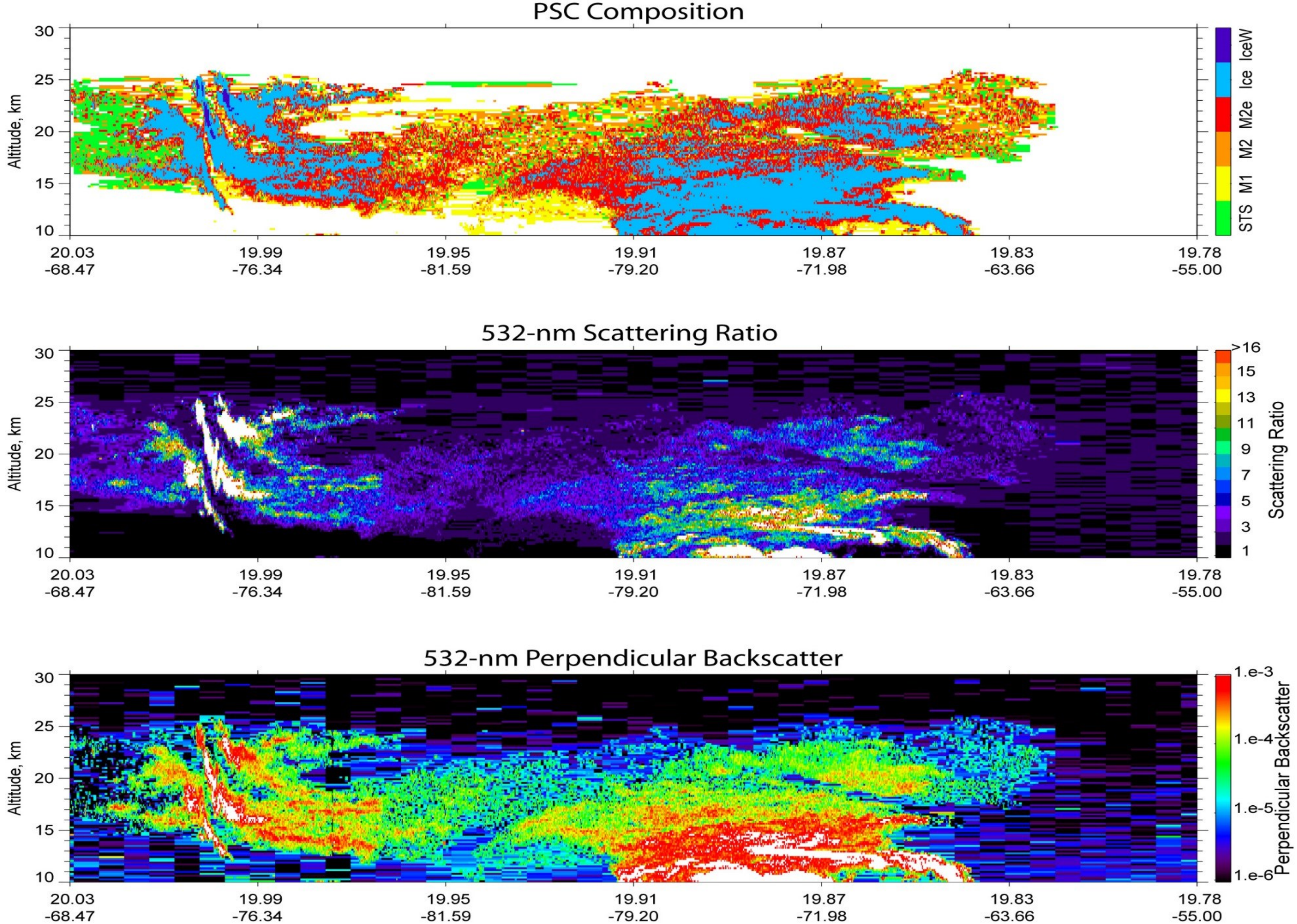
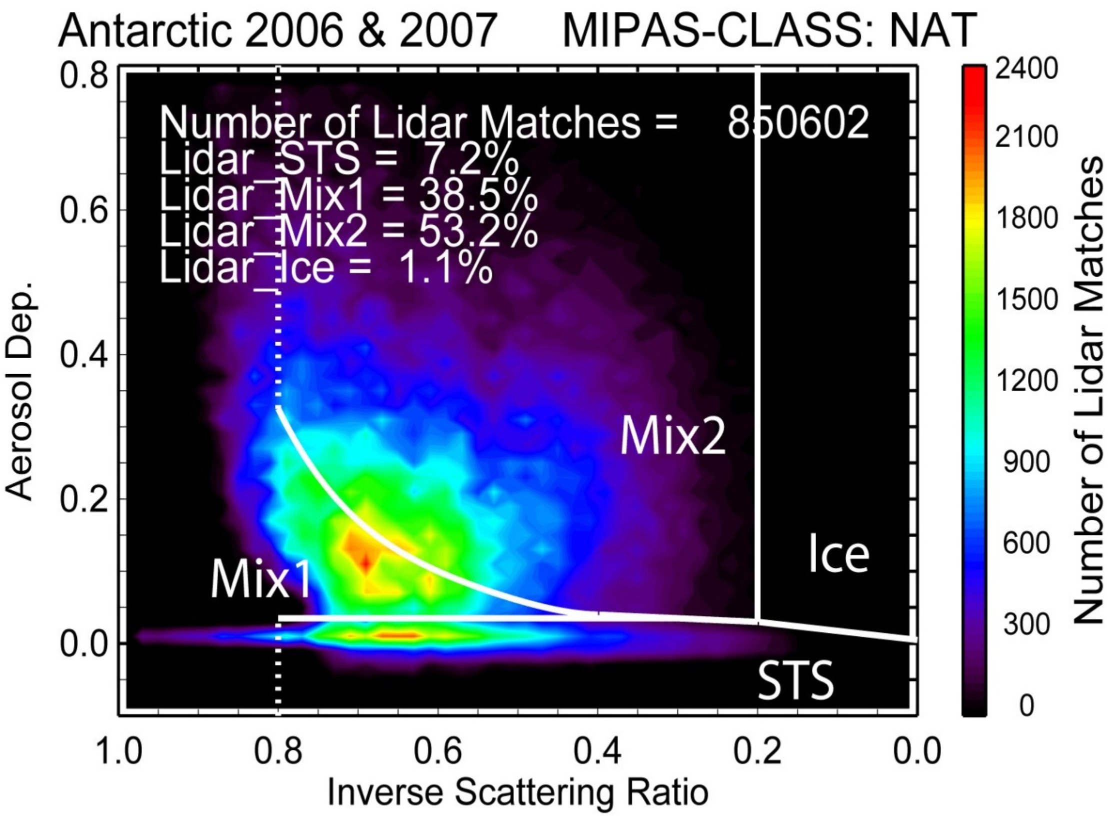
CALIOP PSC Composition Classification

17 July 2008



CALIPSO vs MIPAS PSC Composition

Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) on Envisat

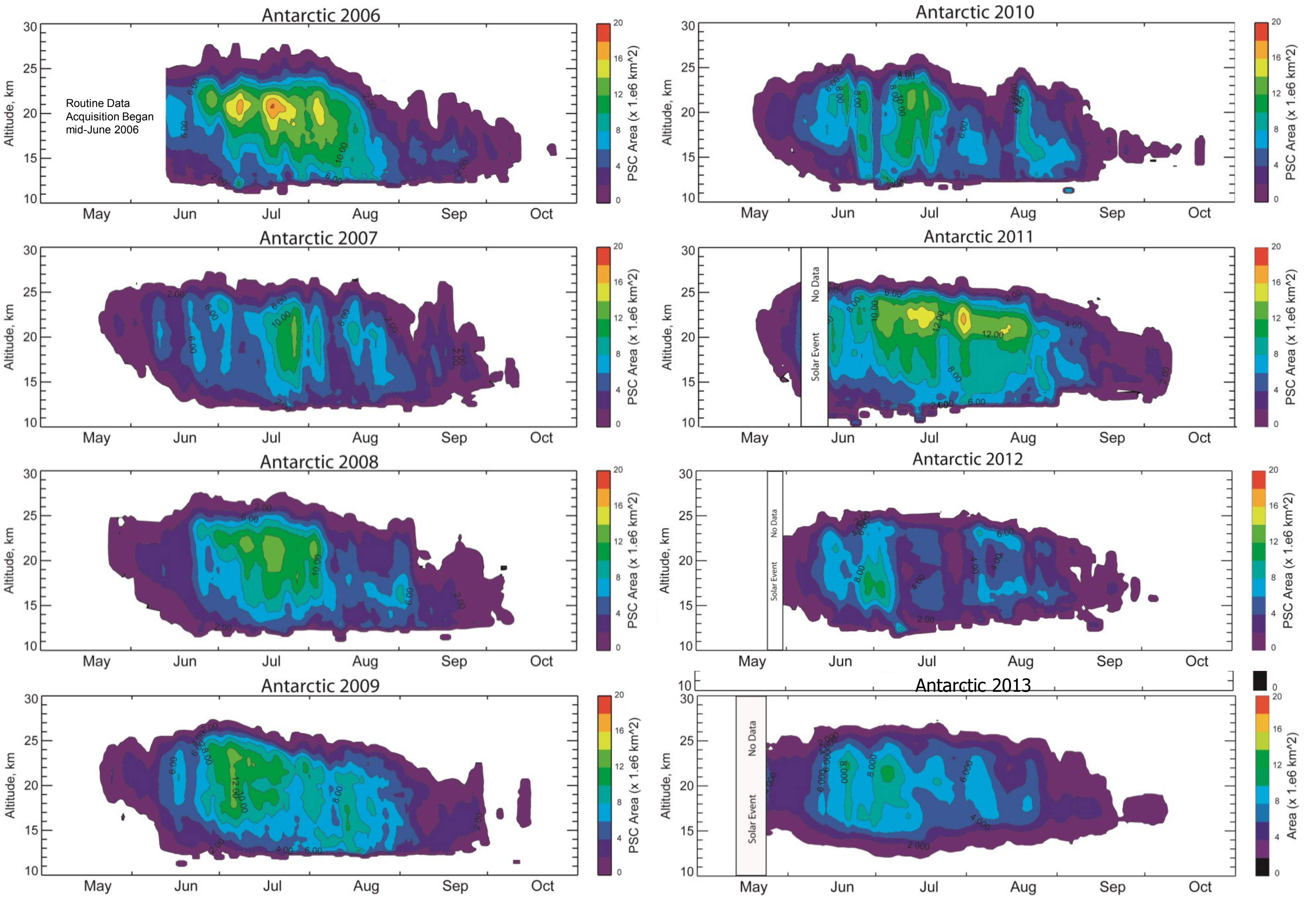


- **Different approaches: lidar vs. IR limb emission/scattering (12-13 μm)**
- **Approximately 3000 coincident (<6hr,<200km) PSC observations in Antarctic in 2006-2007**
- **>90% agreement between MIPAS NAT and CALIPSO NAT Mixtures**

Höpfner, M., M. C. Pitts, and L. R. Poole: Comparison between CALIPSO and MIPAS observations of polar stratospheric clouds, *J. Geophys. Res., 114*, 2009.

CALIOP Antarctic PSC Observations
2006-2013

Antarctic PSC Area: 2006-2013
(5-day smoothing)

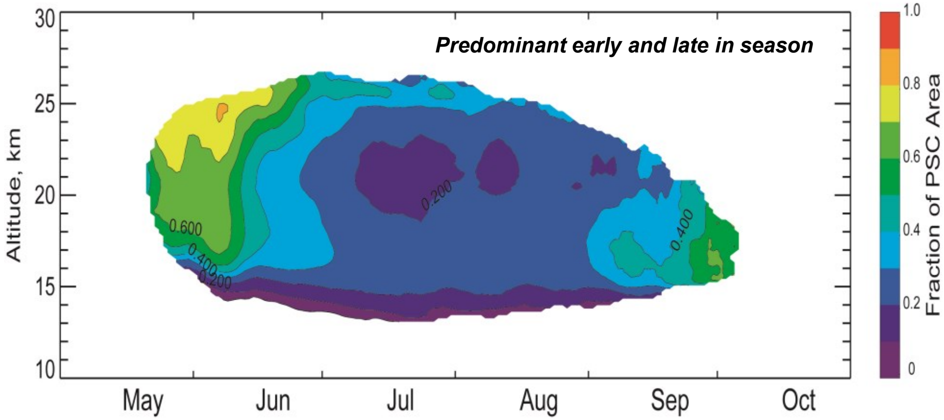


Antarctic PSC Area Fraction by Composition

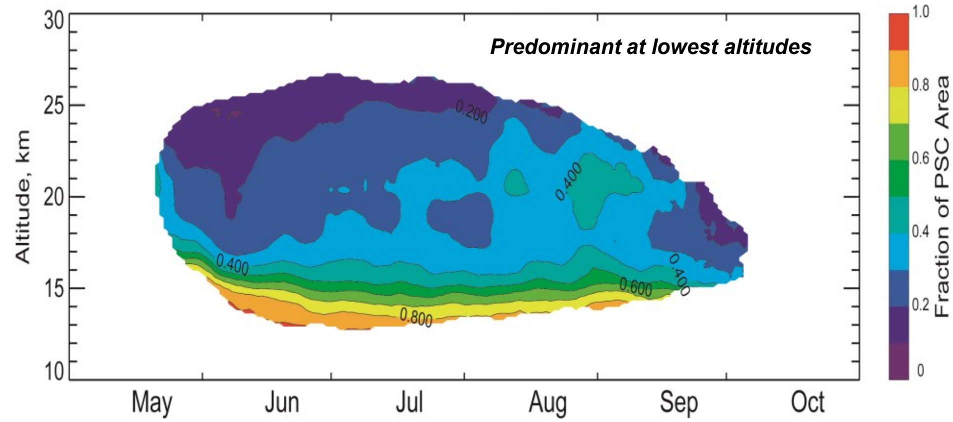
Vortex Average: 2006-2013

(5-day smoothing)

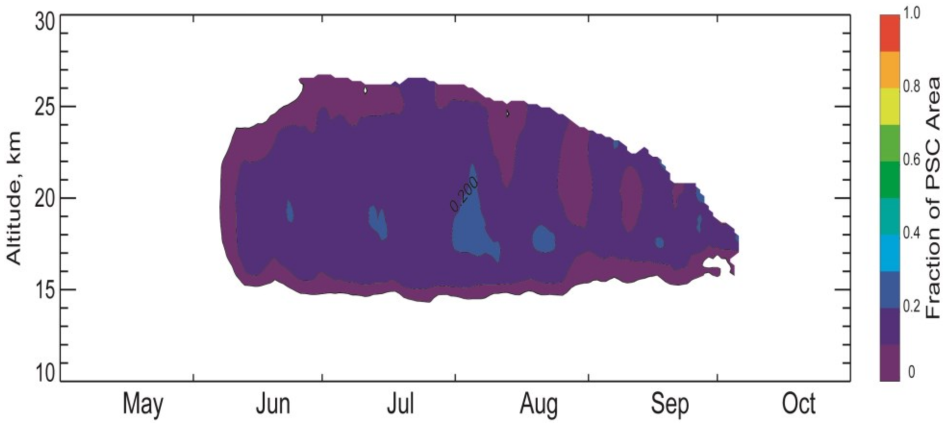
STS



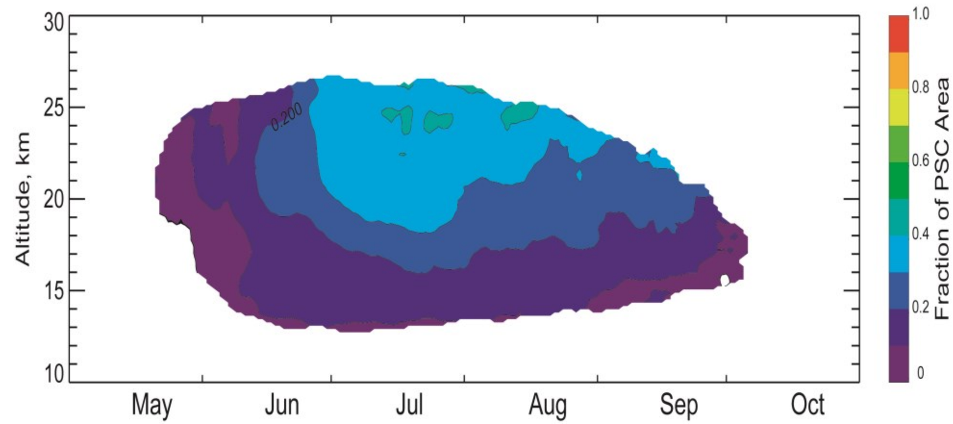
Mix1+Mix2



Ice



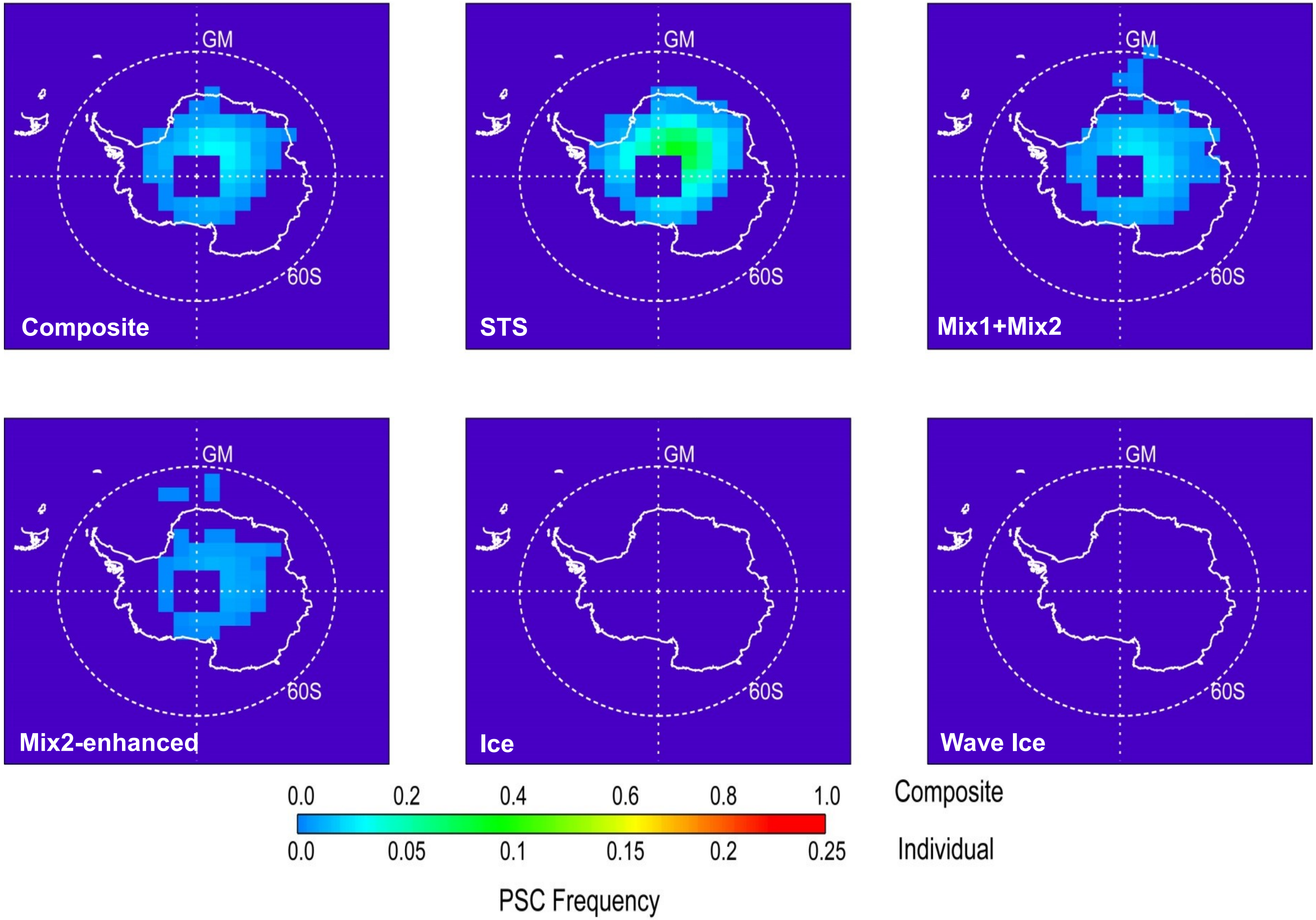
Mix2-enhanced



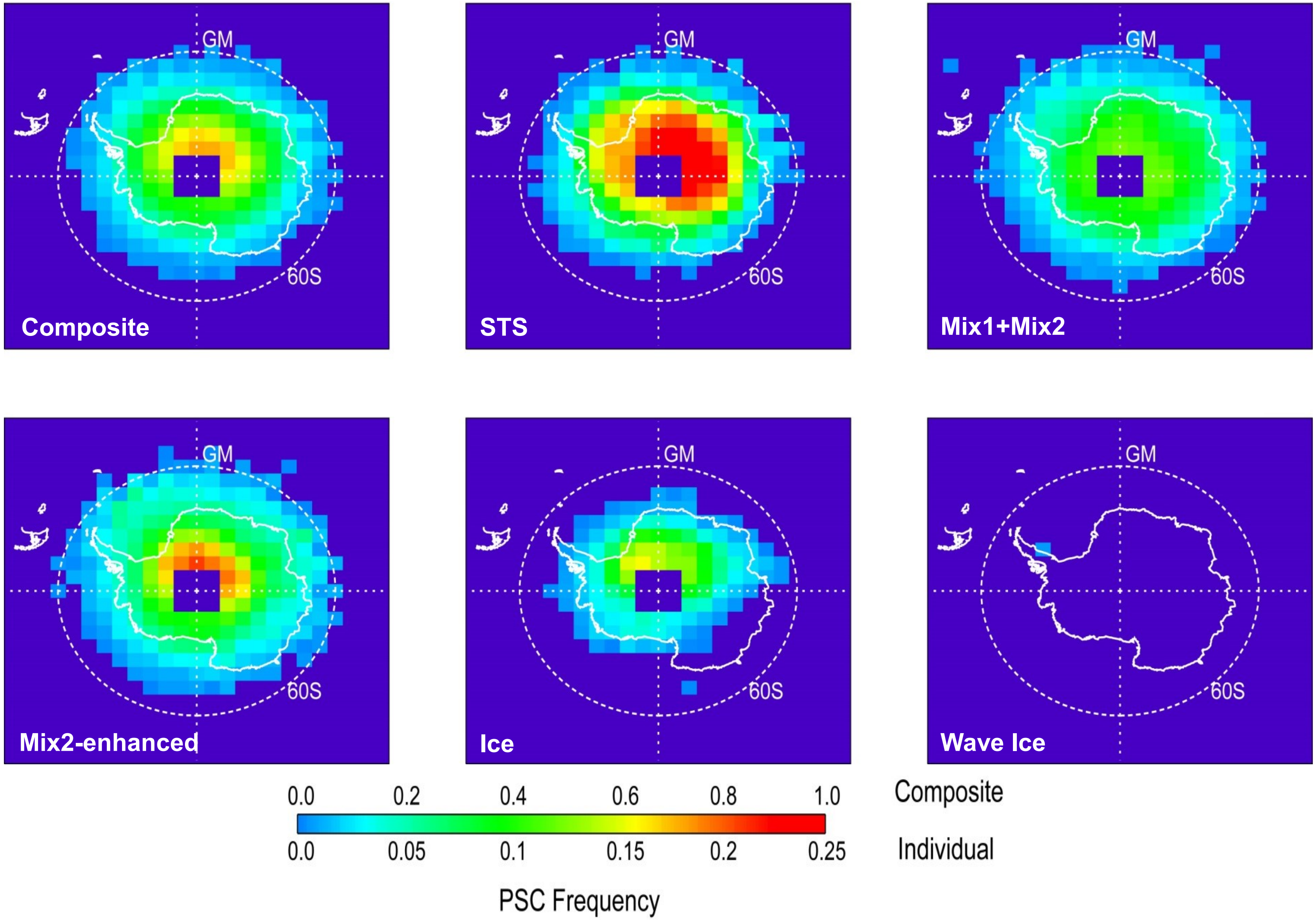
Monthly Average Spatial Distributions (2006-2013)

Antarctic PSCs at 20 km altitude

May



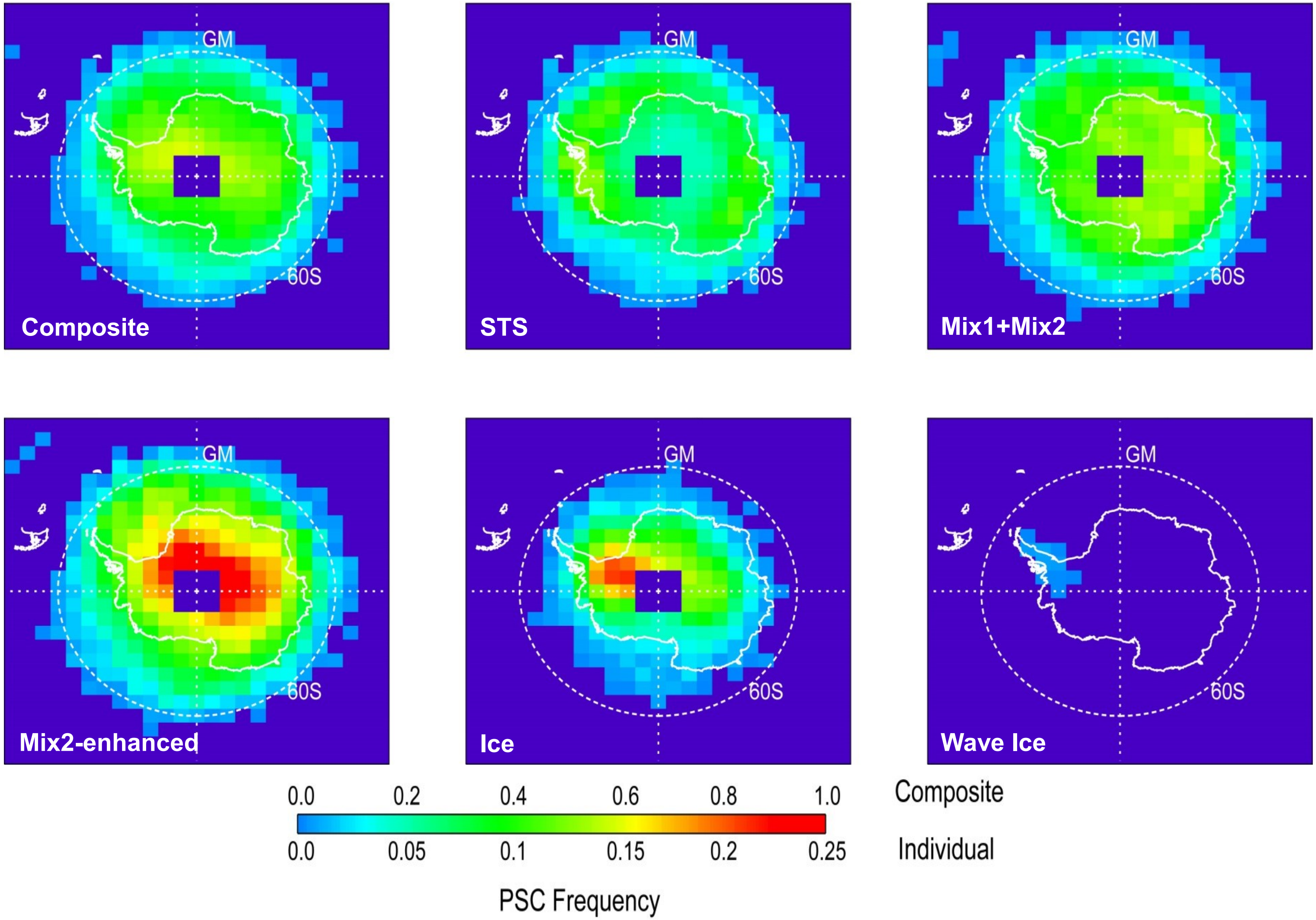
Monthly Average Spatial Distributions (2006-2013)
Antarctic PSCs at 20 km altitude
June



Monthly Average Spatial Distributions (2006-2013)

Antarctic PSCs at 20 km altitude

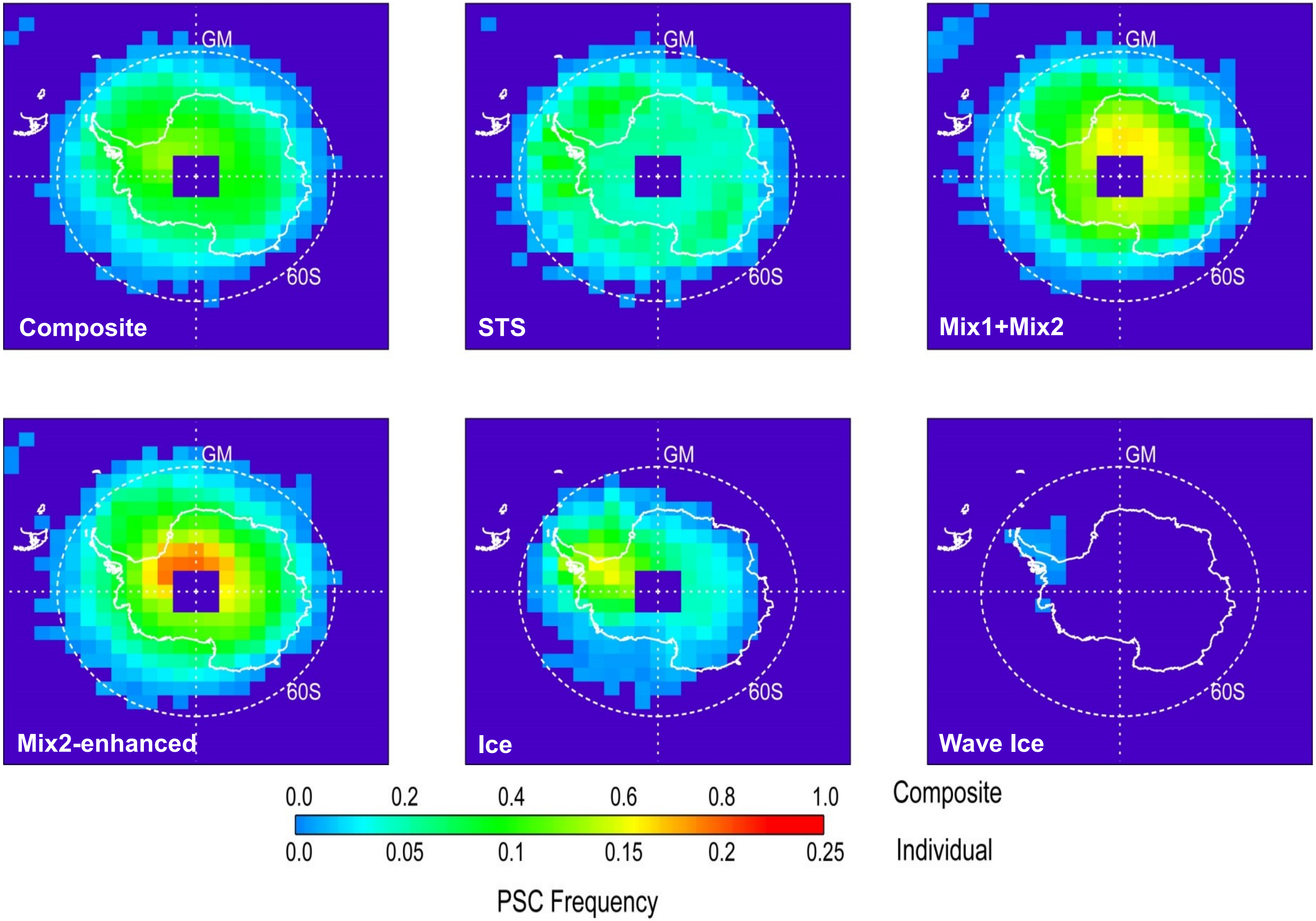
July



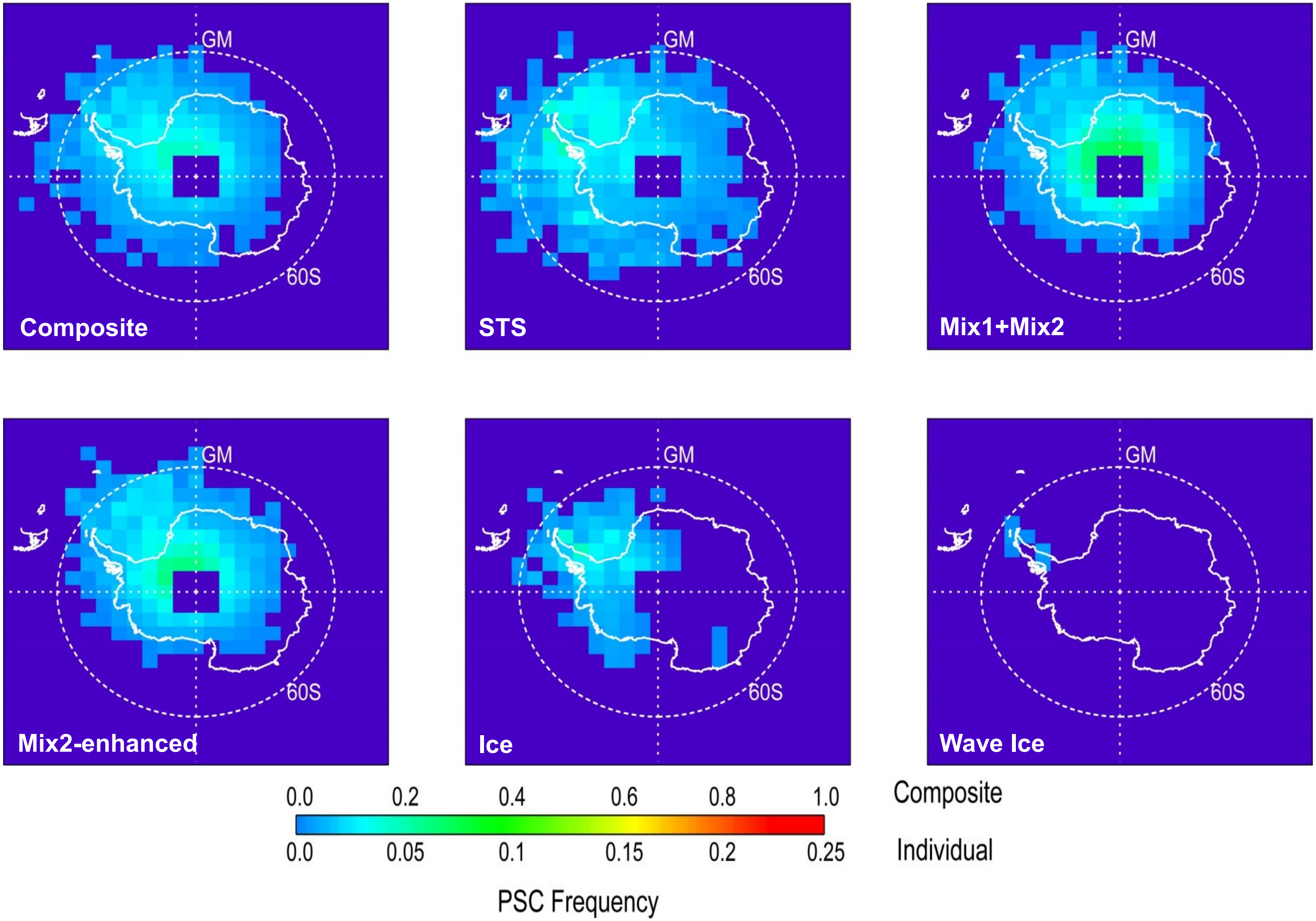
Monthly Average Spatial Distributions (2006-2013)

Antarctic PSCs at 20 km altitude

August



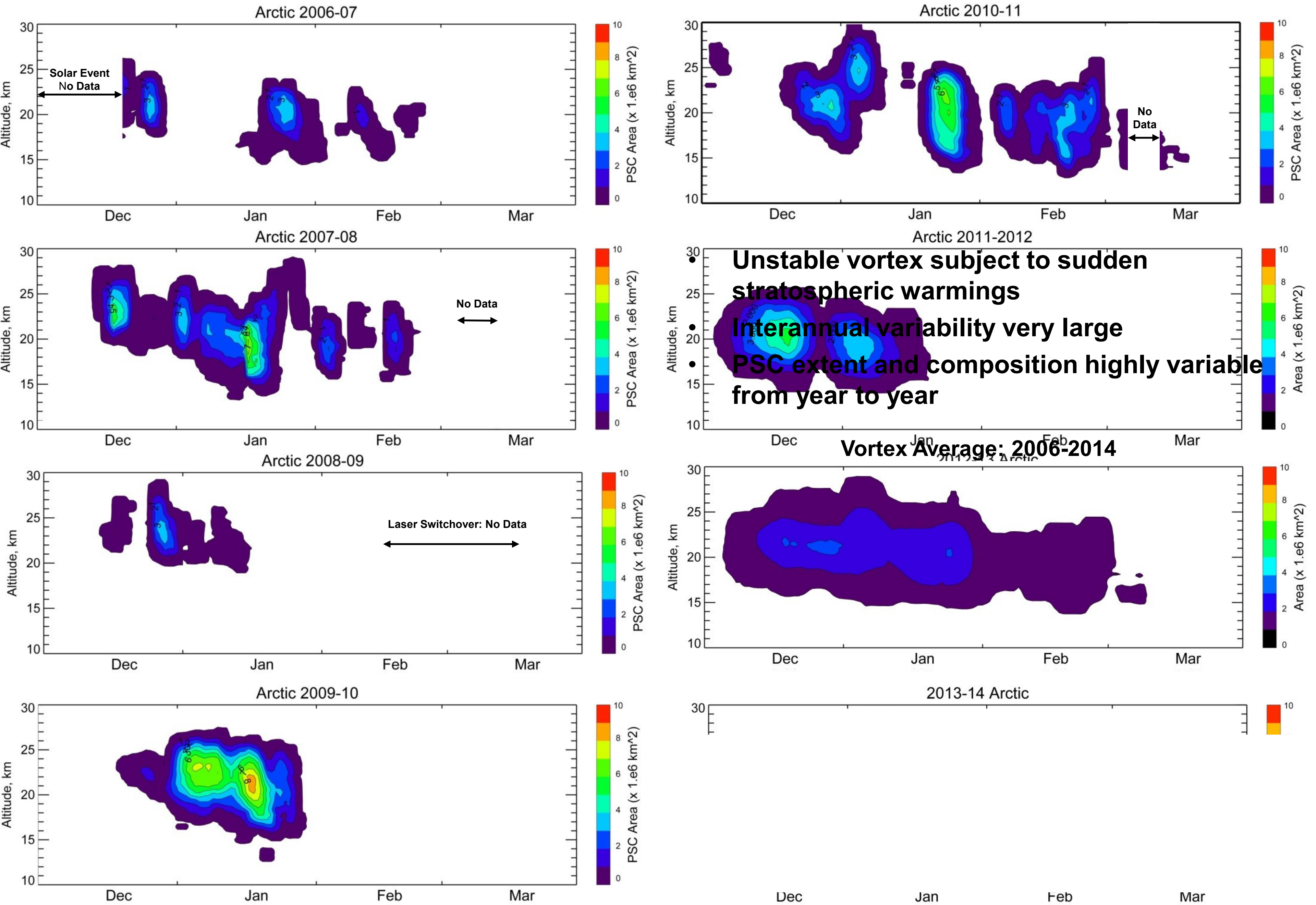
Monthly Average Spatial Distributions (2006-2013)
Antarctic PSCs at 20 km altitude
September



CALIOP Arctic PSC Observations
Dec.2006-Feb.2014

Arctic PSC Area: 2006-07 to 2013-14

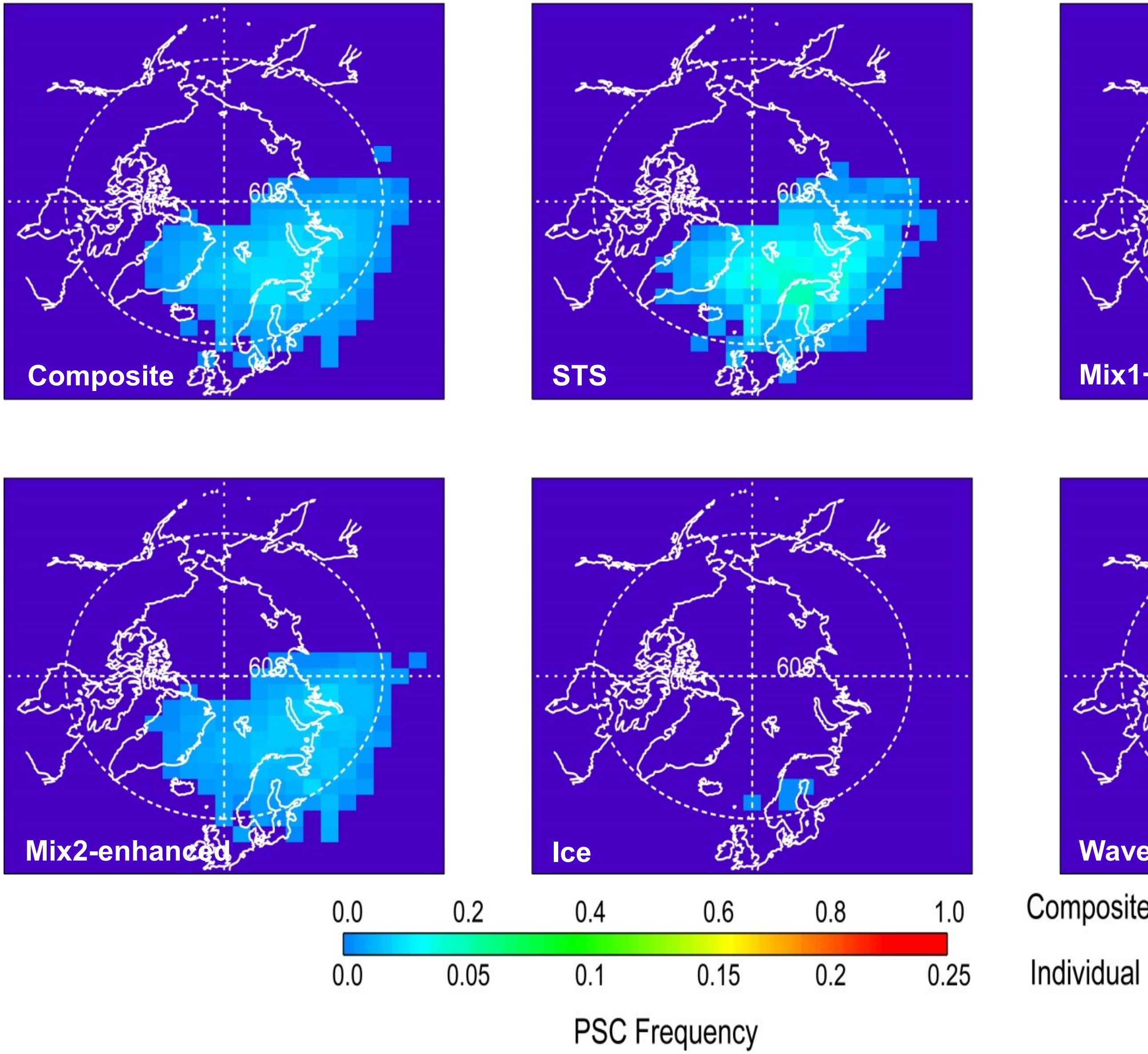
(5-day smoothing)



- Unstable vortex subject to sudden stratospheric warmings
- Interannual variability very large
- PSC extent and composition highly variable from year to year

Monthly Average Spatial Distributions (2006-2014)
Arctic PSCs at 20 km altitude

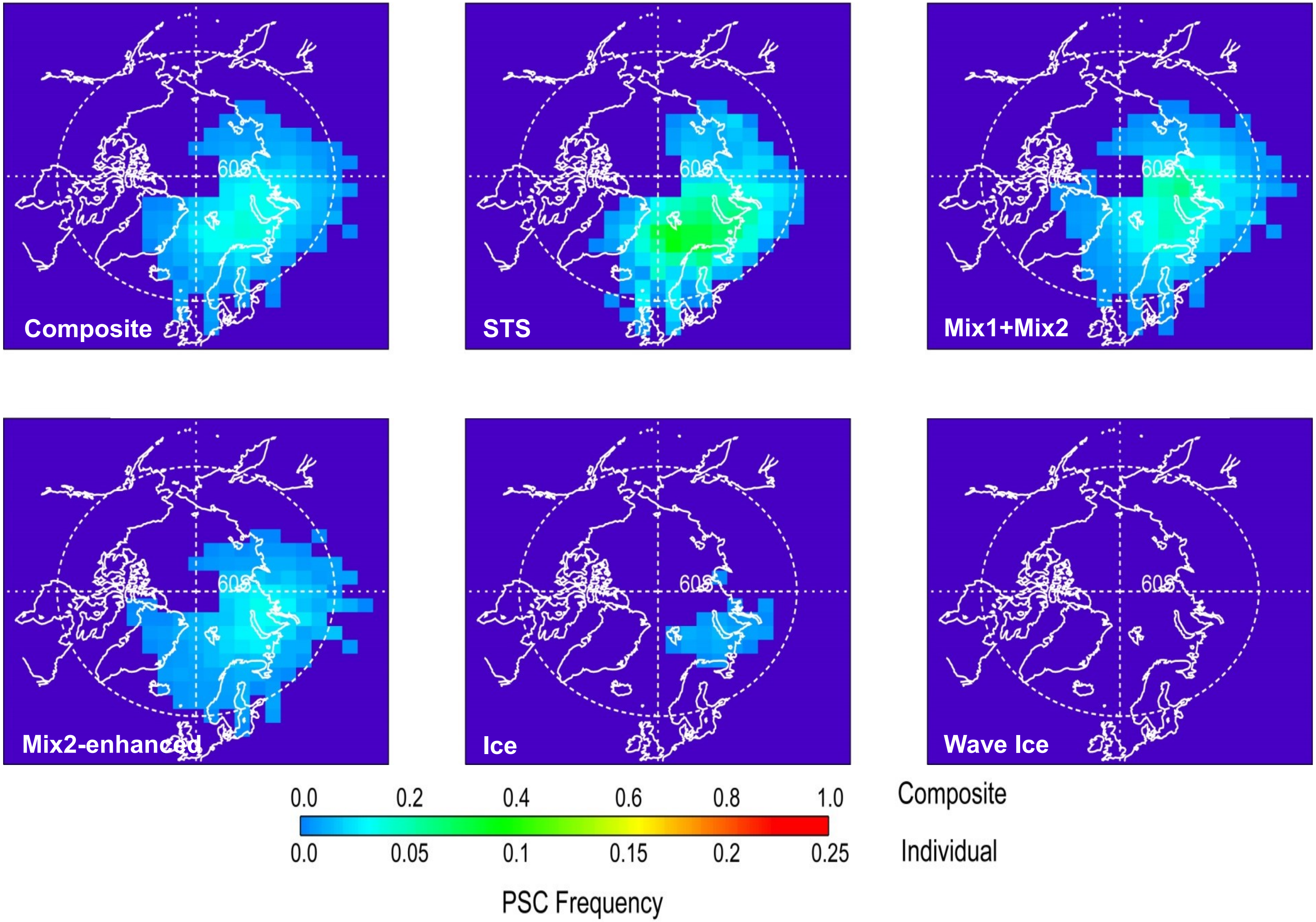
December



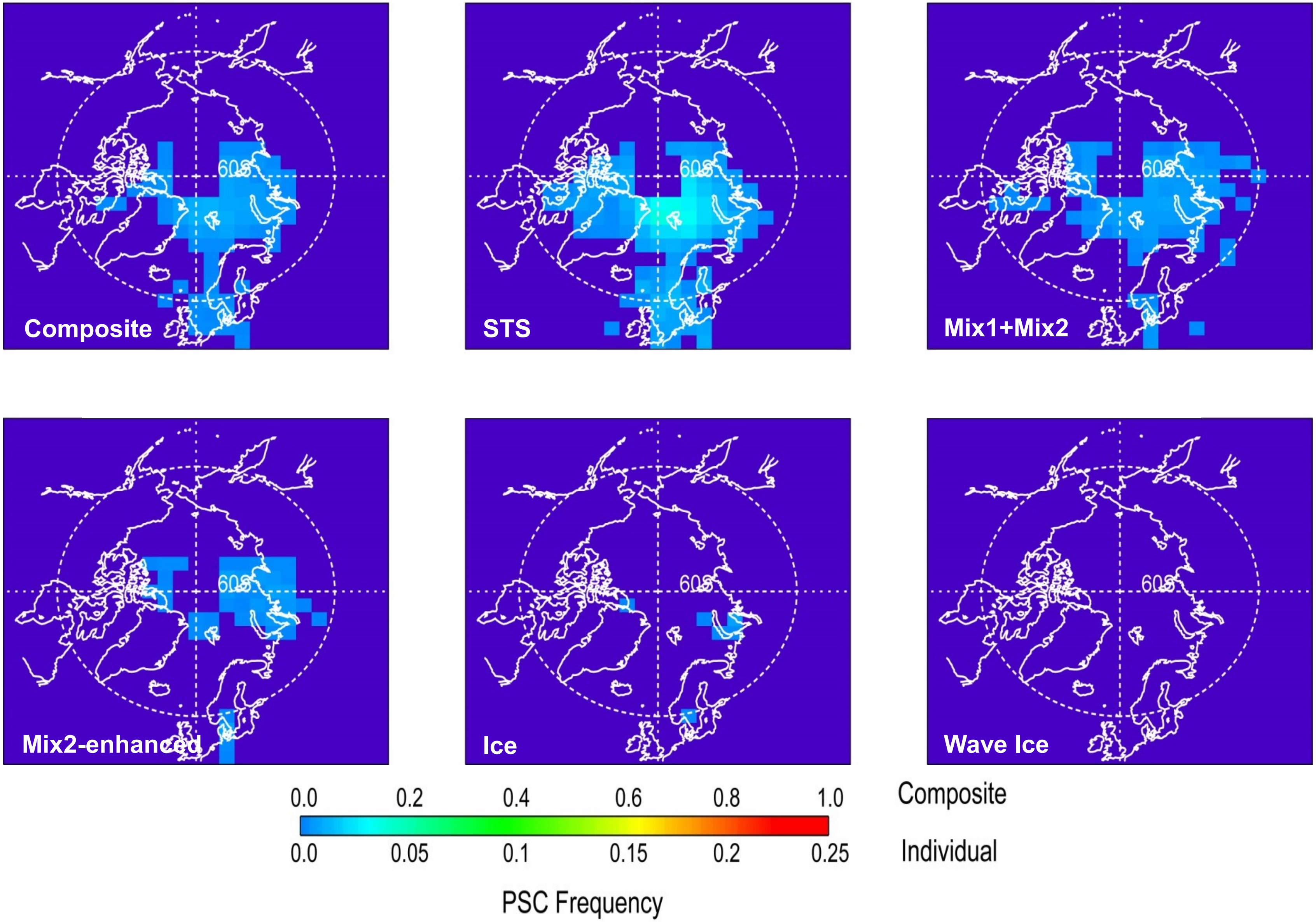
Monthly Average Spatial Distributions (2006-2014)

Arctic PSCs at 20 km altitude

January



Monthly Average Spatial Distributions (2006-2014)
Arctic PSCs at 20 km altitude
February



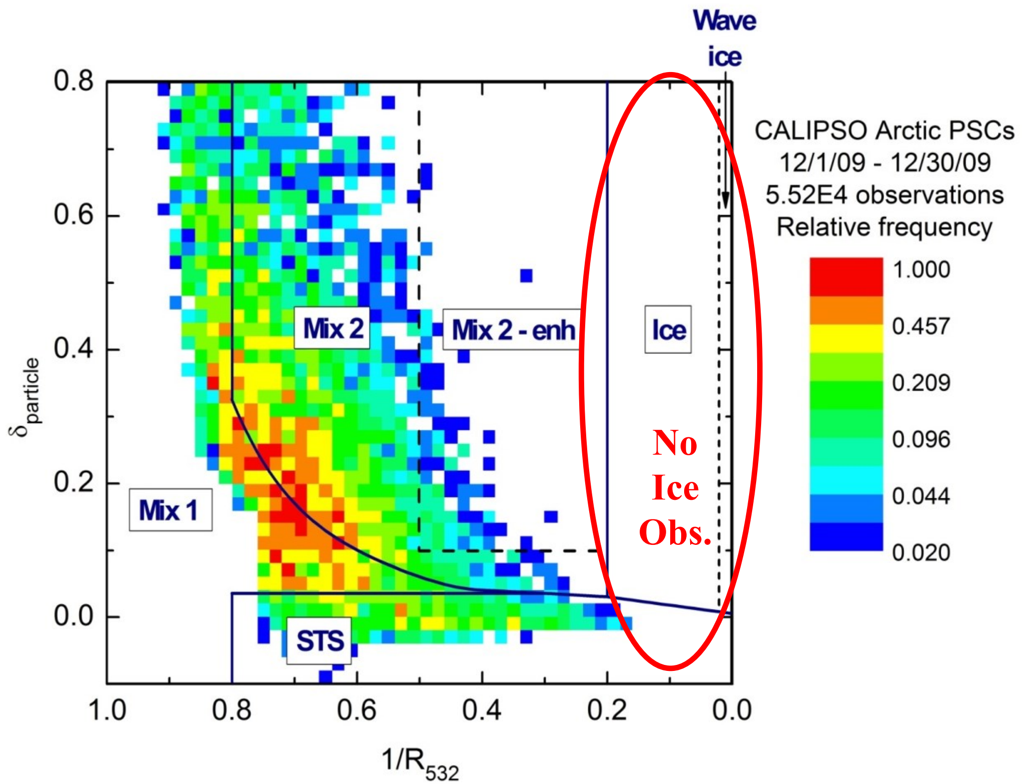
CALIPSO and RECONCILE

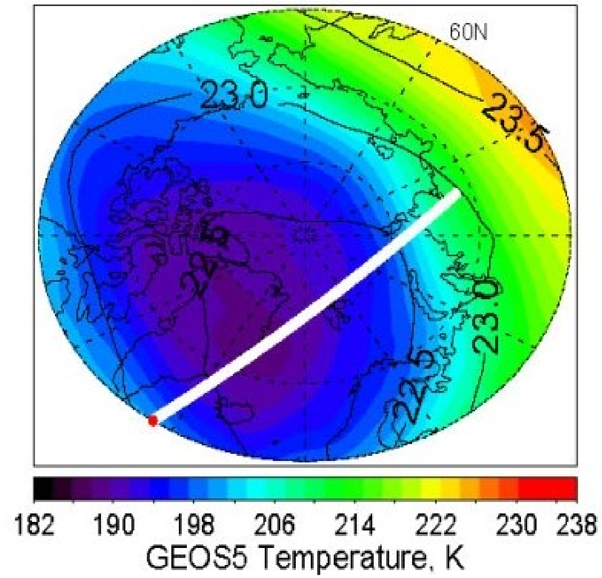
- ✓Invited to participate as Associated Partners in July 2009
- ✓CALIPSO quick-look images used to identify PSC regions for flight planning purposes
- ✓Provide overall context to PSC season (Arctic-wide view of PSCs)
- ✓Possible direct Geophysica underflights of CALIPSO, as well as coordination of COBALD balloon launches with CALIPSO overpasses
- ✓Quick-look comparison of CALIPSO PSC data products with aircraft and balloon-borne data during field mission
- ✓Comprehensive comparisons during extended post-campaign data analysis phase

CALIPSO Arctic PSC Observations

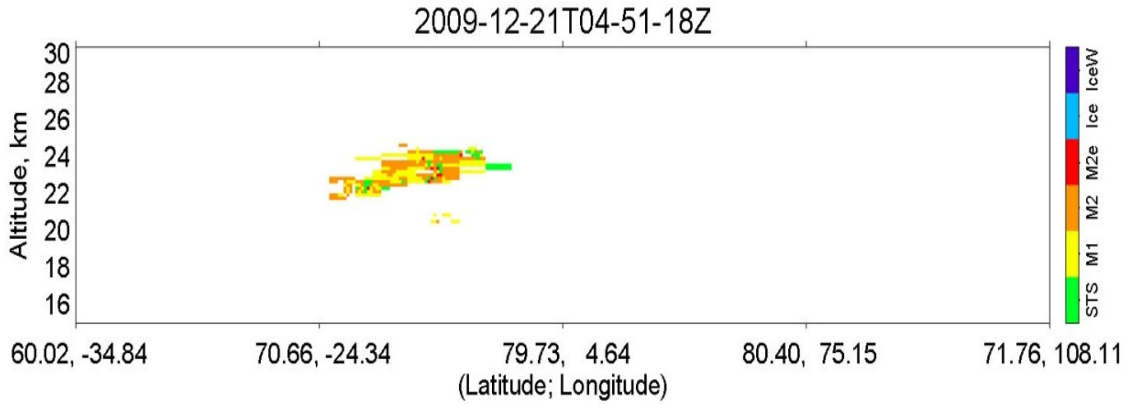
15-30 December 2009

→ NAT observed before ice was present

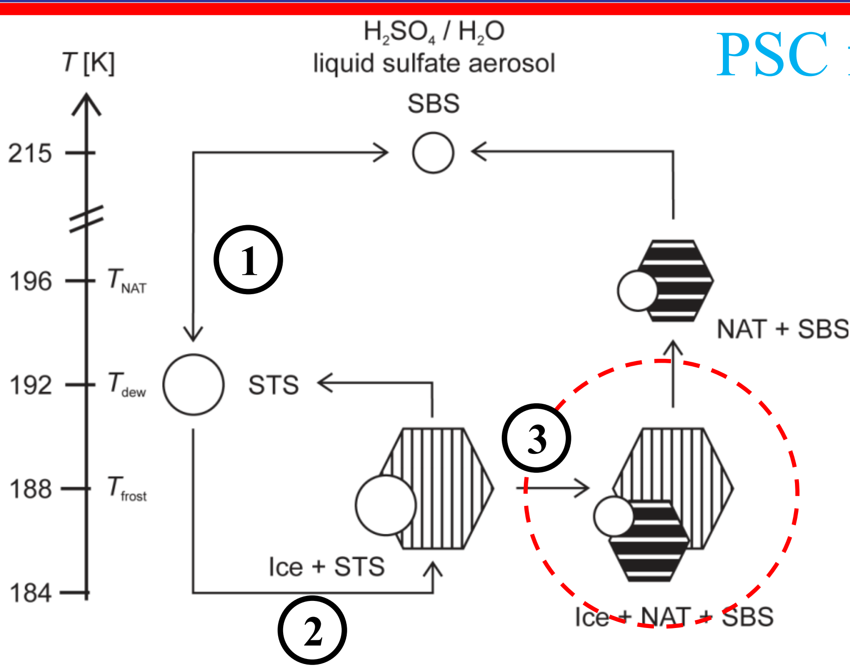


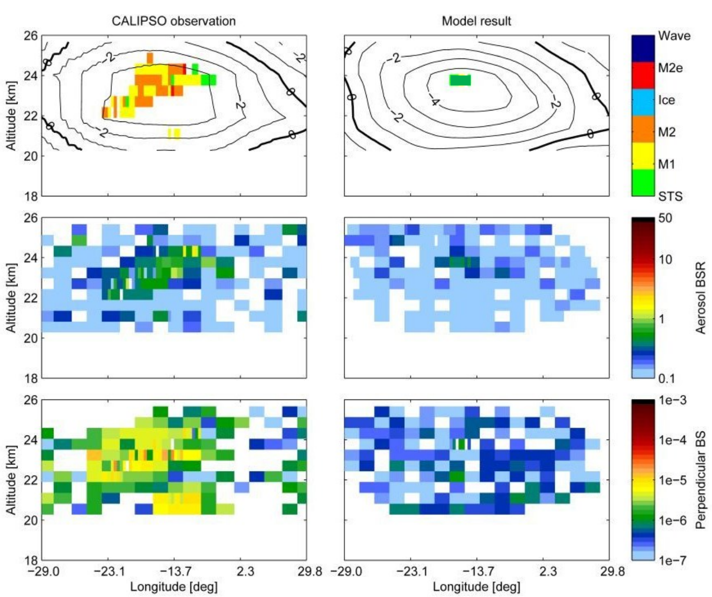


Sample Orbit →



Heterogeneous NAT Nucleation





PSC formation: conventional understanding

1) Growth of liquid particles due to uptake of HNO_3

   (Dye et al., 1992; Carslaw et al.,1994)

2) Homogeneous nucleation of ice particles

   (Koop et al., 2000)

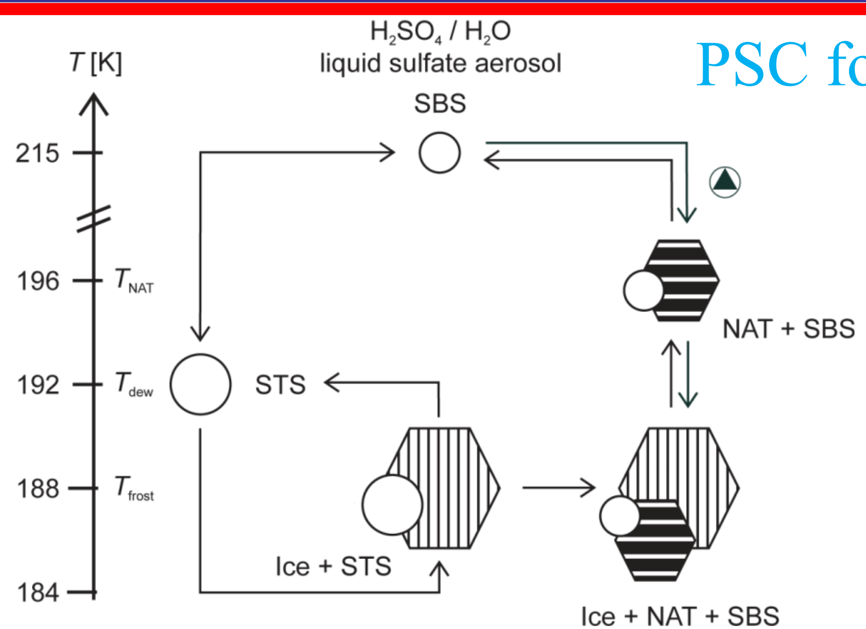
3) NAT nucleation on preexisting ice particles

   (Carslaw et al., 1998)

Conventional wisdom:
NAT can only form through nucleation on pre-existing ice particles

Heterogeneous NAT Nucleation

PSC formation: new heterogeneous pathway

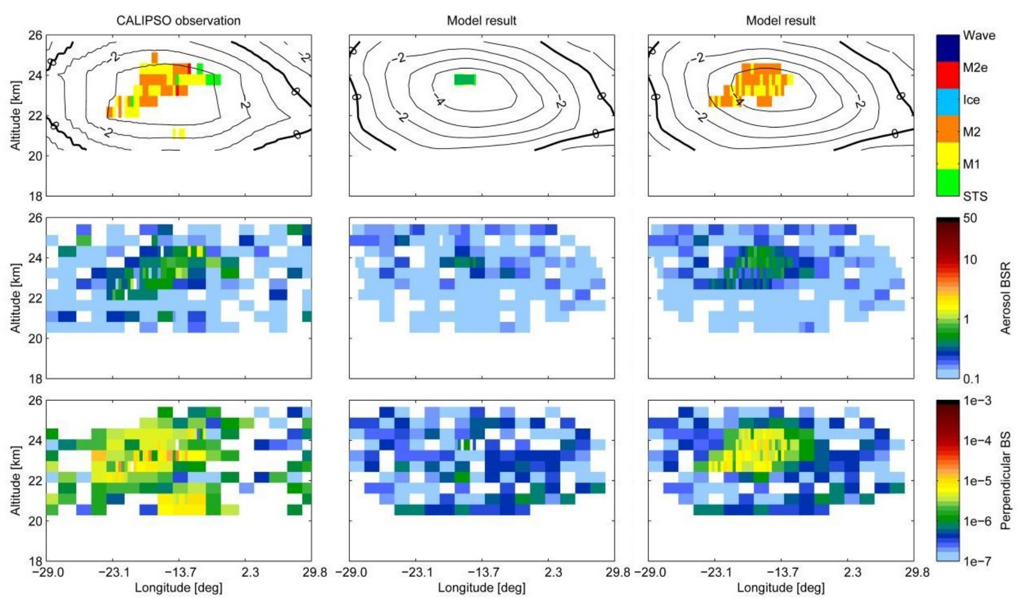


▲ Heterogeneous nucleation on foreign nuclei

(Evidence for the existence of foreign nuclei, e.g. Weigel et al., 2014)

Parameterization based on active site theory

(Marcolli et al., 2007)

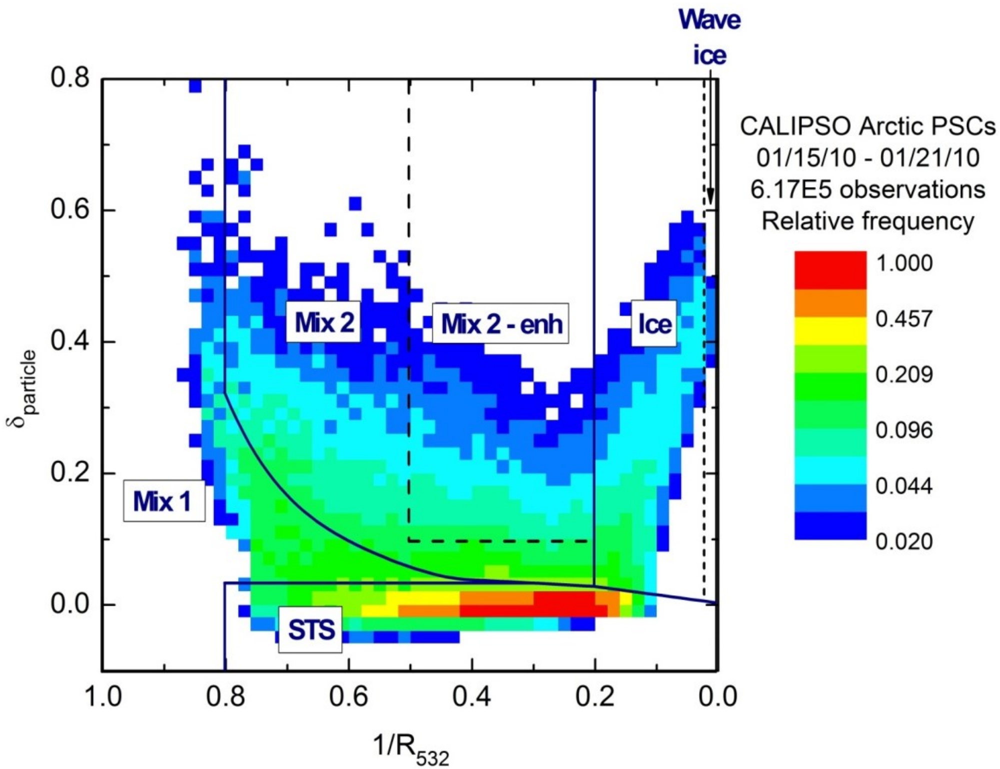


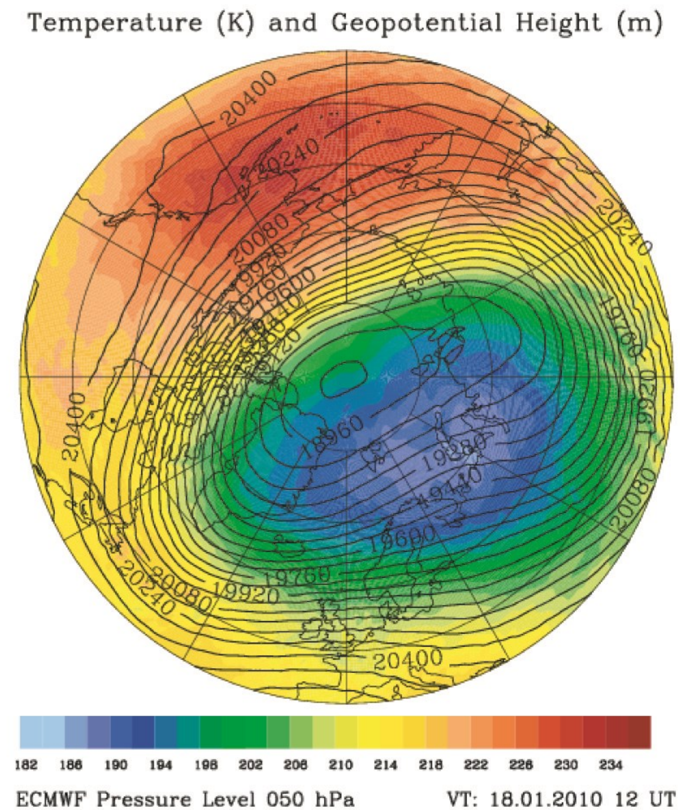
Heterogeneous nucleation on pre-existing solid particles (not ice) required to explain CALIOP NAT observations in December 2009

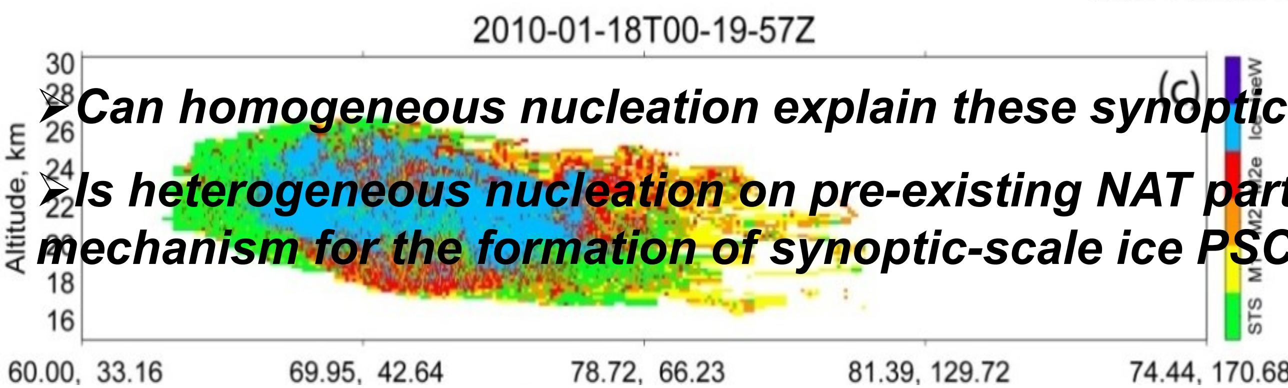
See Hoyle et al., *Atmos. Chem. Phys., 13*, 9577-9595, 2013.

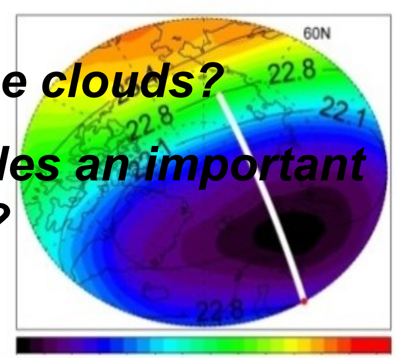
Another Surprise: Synoptic scale regions of ice

15-21 January 2010



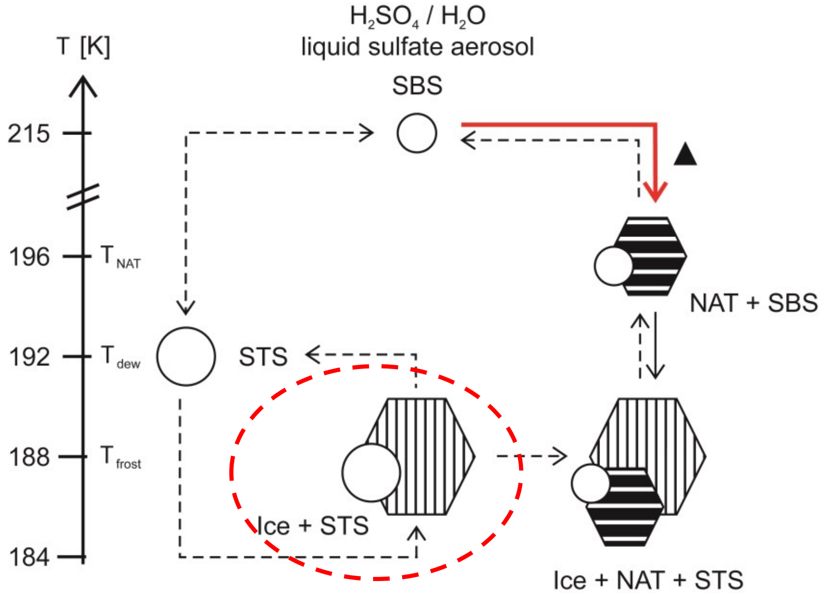






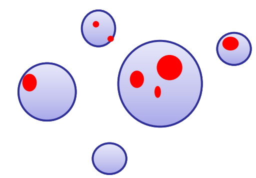
- *Can homogeneous nucleation explain these synoptic ice clouds?*
- *Is heterogeneous nucleation on pre-existing NAT particles an important mechanism for the formation of synoptic-scale ice PSCs?*

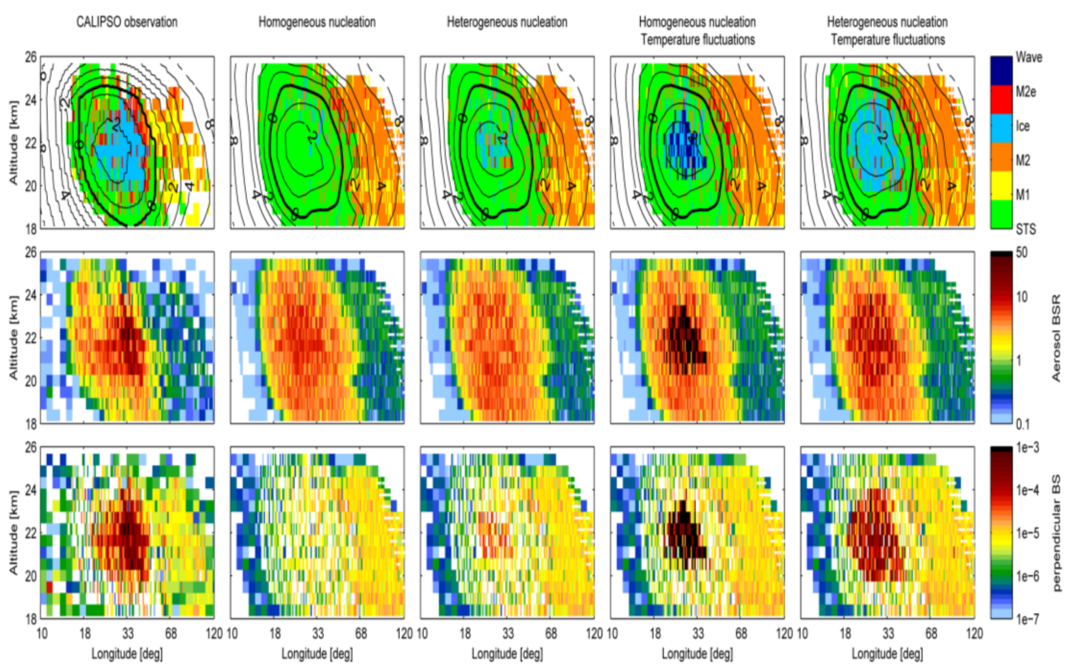
Heterogeneous Ice Nucleation



Heterogeneous ice and NAT formation on dust imbedded in LSA (immersion freezing)

Homogeneous nucleation cannot explain synoptic scale ice PSC observations

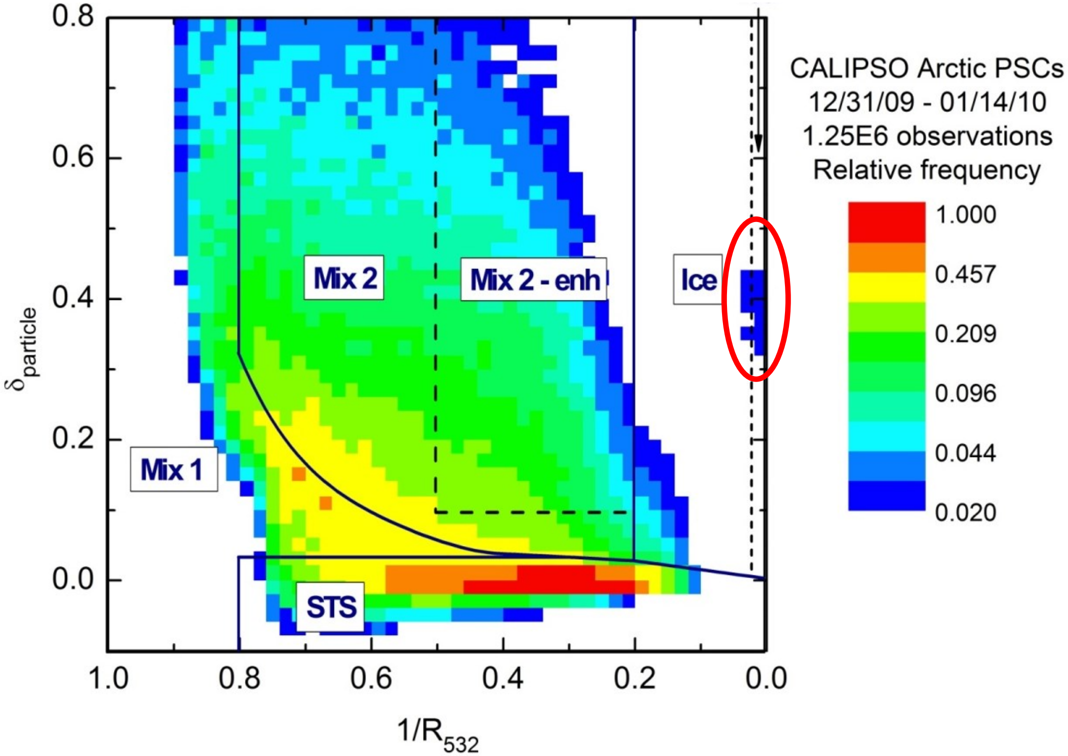


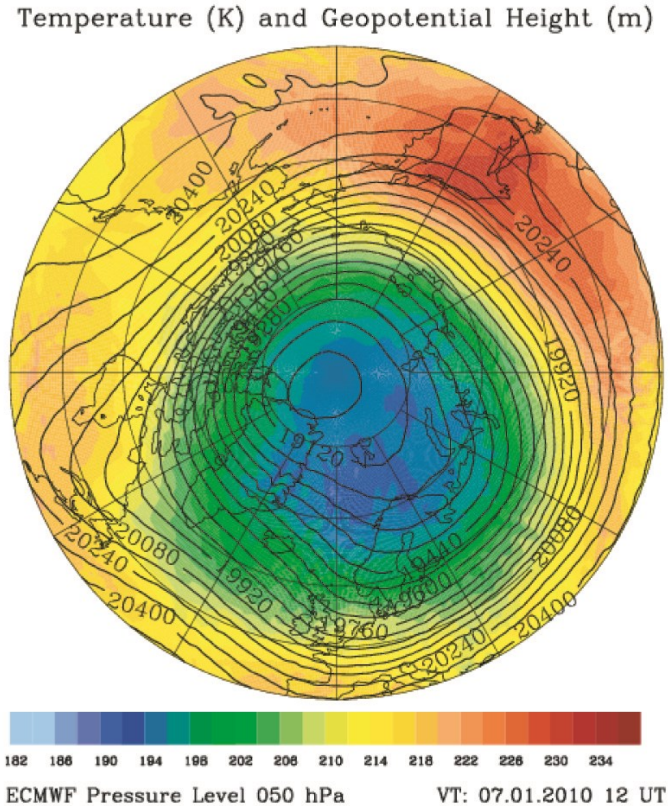


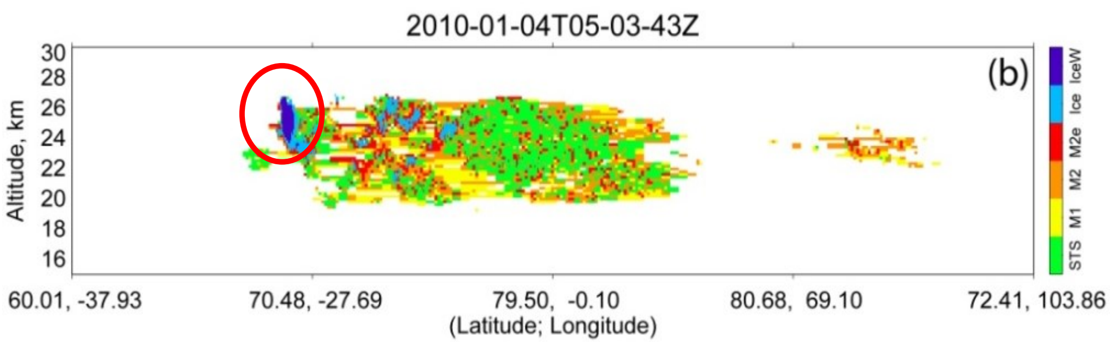
Heterogeneous nucleation on pre-existing solid particles <u>plus</u> small-scale temperature fluctuations required to explain CALIOP synoptic ice observations in January 2009

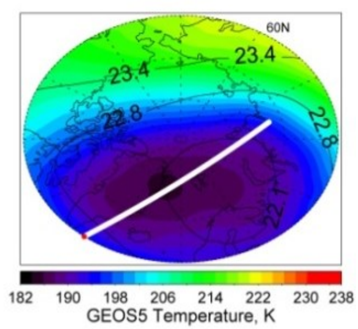
See Engel et al., *Atmos. Chem. Phys.*, *13*, 10769-10785, 2013.

Period 2: 31 December – 14 January

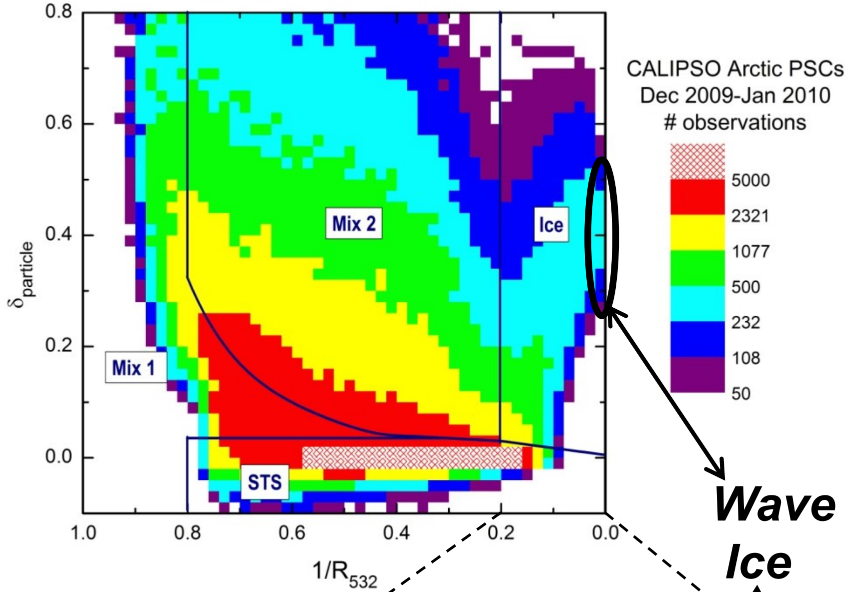


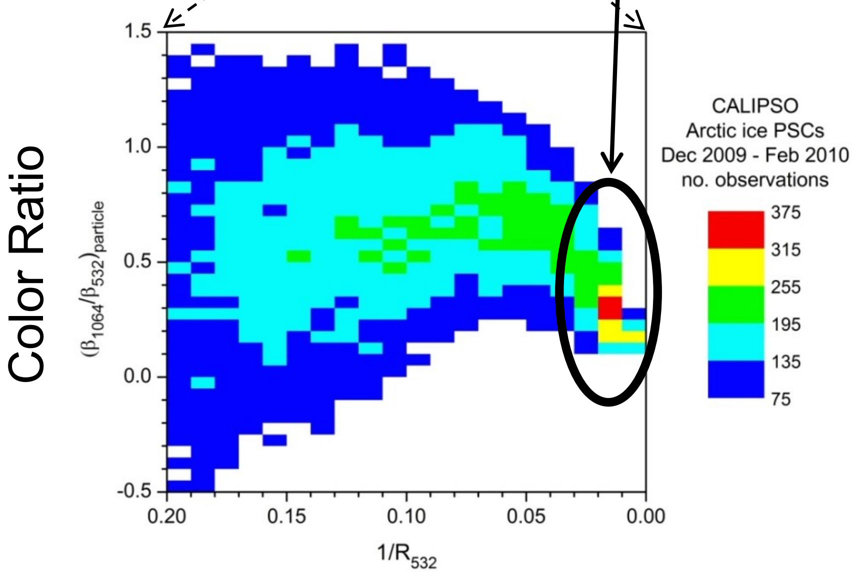




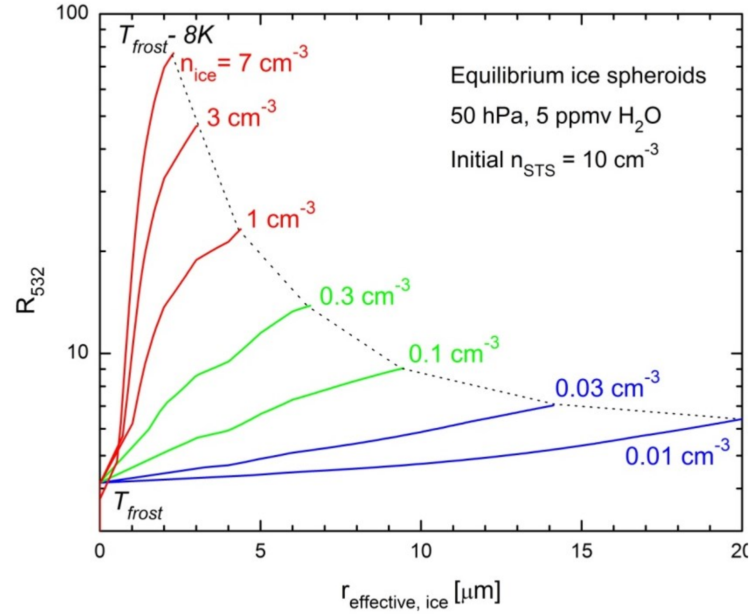


Synoptic Ice versus Wave Ice PSCs





Optical Model Calculations



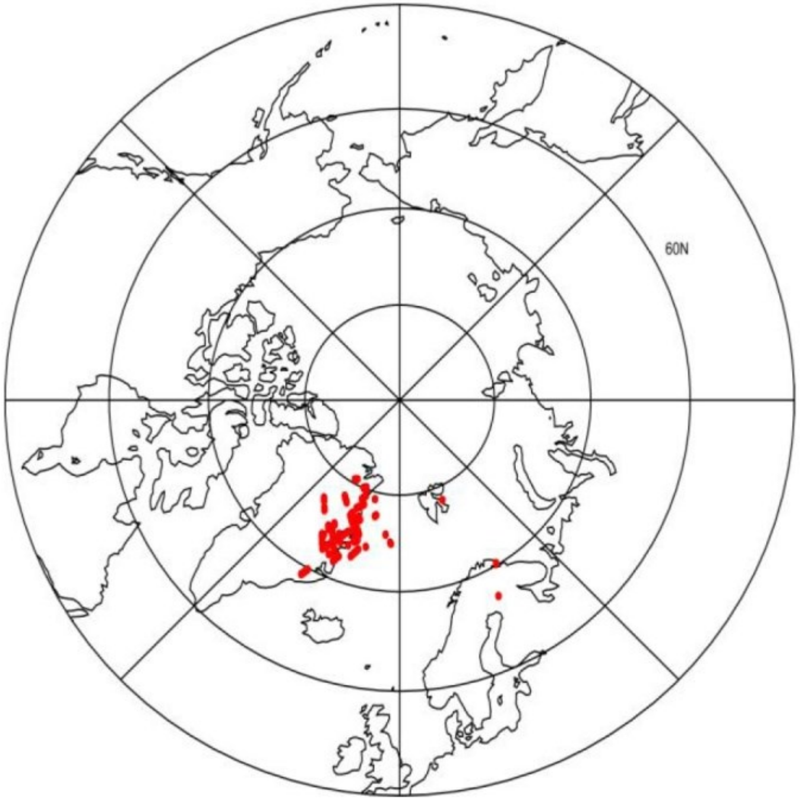
Characteristic Particle Number and Size Parameters

Wave Ice:	$n_{ice} > 5\ cm^{-3}$ $r_e < 2\text{-}3\ \mu m$
Synoptic Ice:	$n_{ice} < 1\ cm^{-3}$ $r_e > 5\ \mu m$

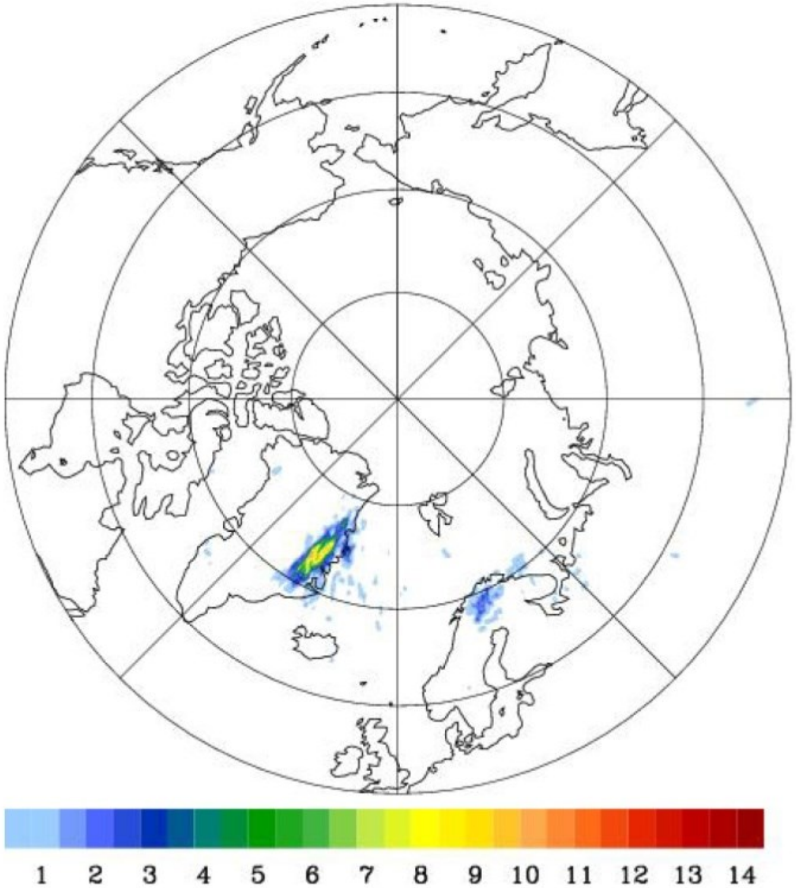
CALIPSO Wave Ice Discrimination

31 December – 14 January

CALIPSO Observed Wave Ice Clouds (R_{532} > 50)



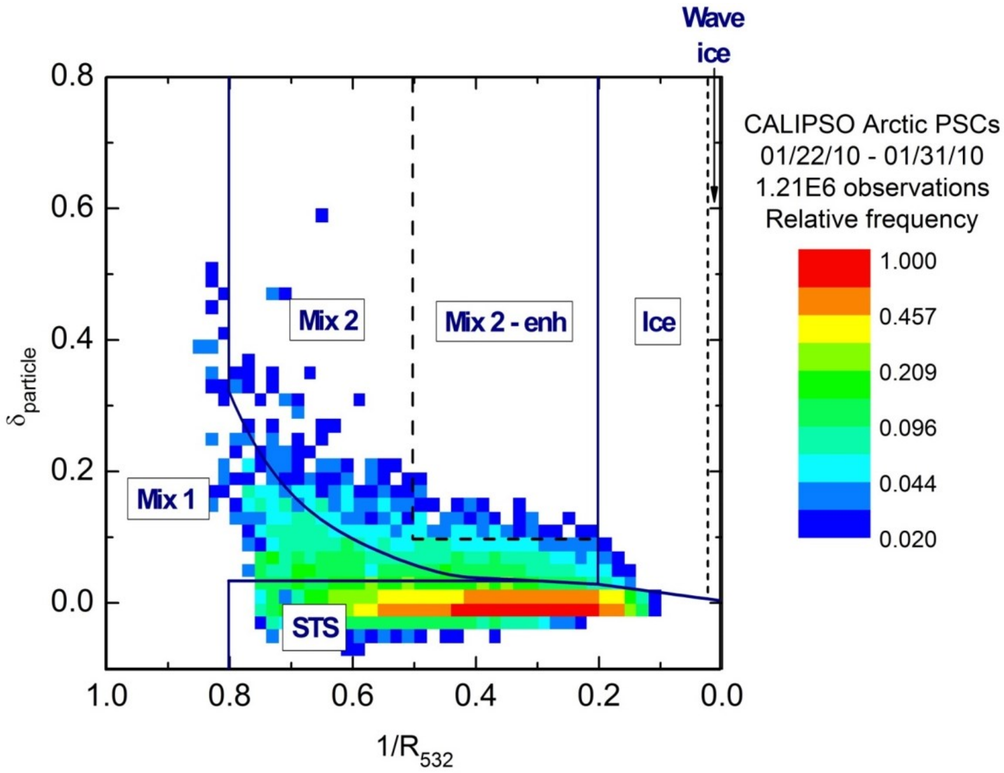
ECMWF Analyzed Mountain Wave Events

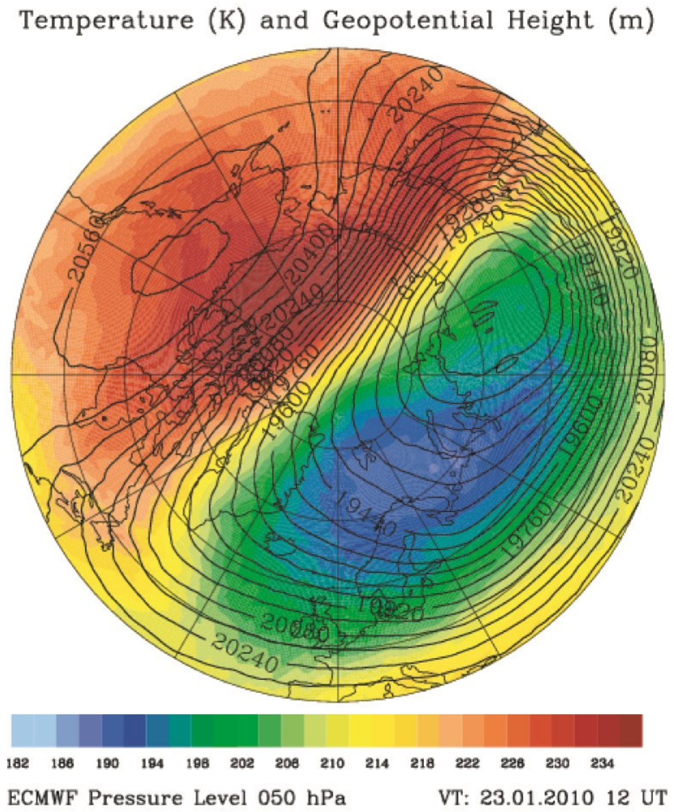


Dörnbrack et al., *Atmos. Chem. Phys.*, *12*, 3659-3675, 2012.

Pitts et al., *Atmos. Chem. Phys.*, *11*, 2161-2177, 2011.

Period 4: 22-28 January 2010

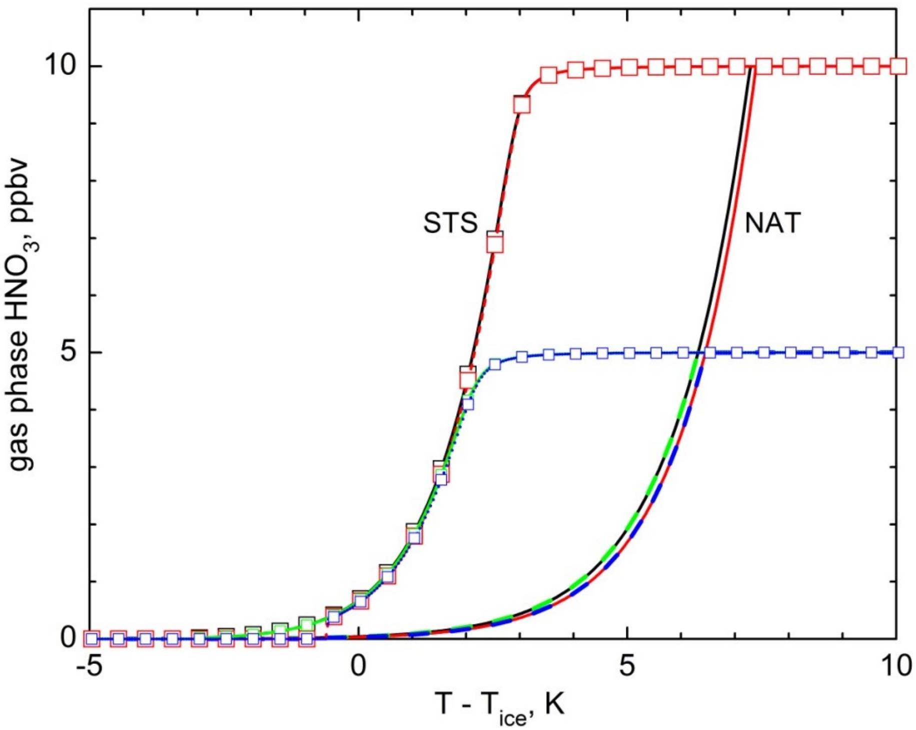




- *Abundant STS; essentially no ice*
- *Many fewer Mix 2 & Mix 2-enh*
  - *Displacement of cold pool from vortex center limits NAT particle growth*
  - *Mountain wave source of NAT nuclei turned off*

Assessment of CALIOP PSC Composition

(Pitts et al., ACPD, 12, 24643–24676, 2012)



NAT: Hansen and Mauersberger, 1988
STS: Carslaw et al., 1995

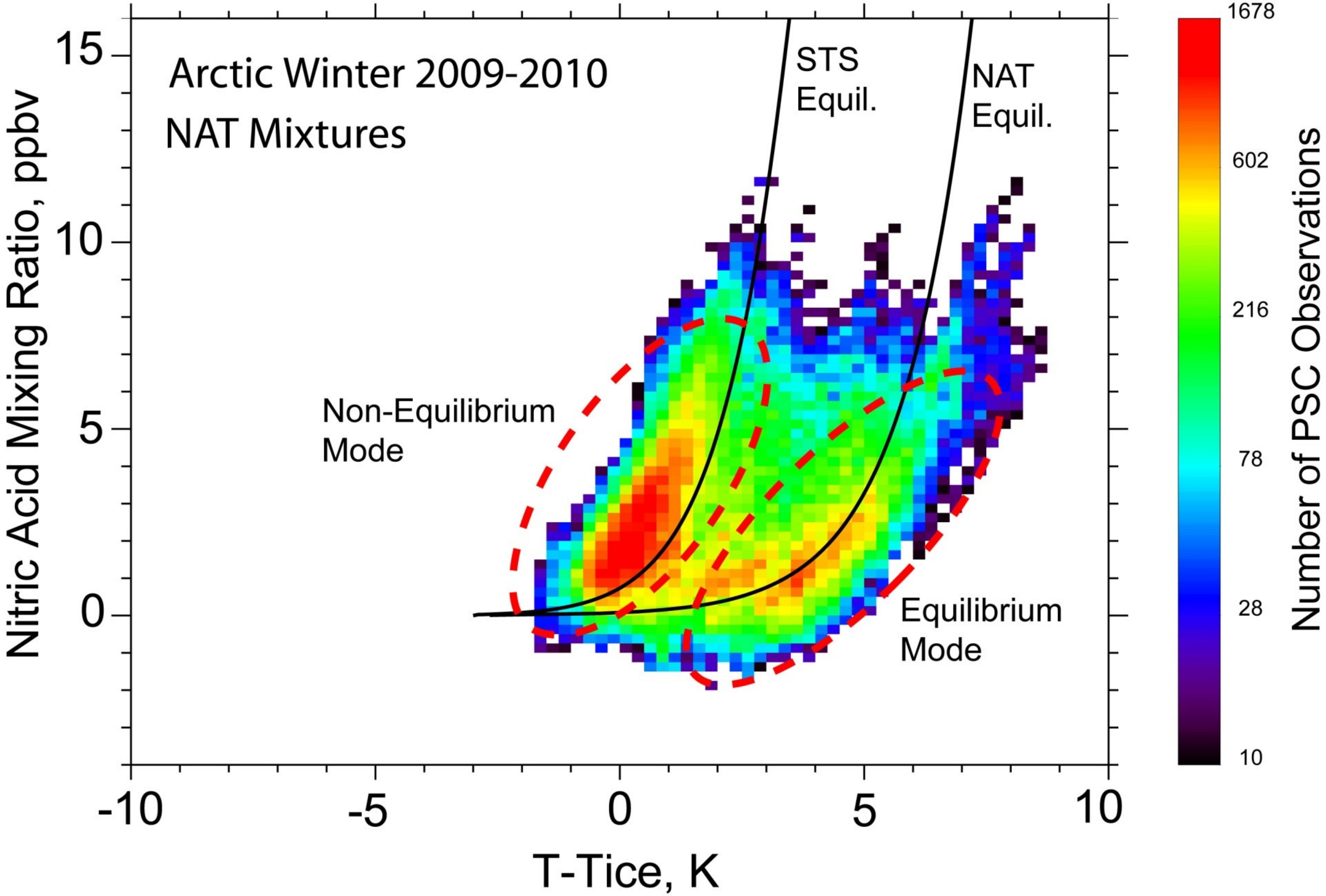
Approach

•Analyze CALIOP PSC observations in conjunction with the Aura MLS HNO_3 and H_2O data and GEOS-5 T analyses.

•Compare observed uptake with modeled uptake for equilibrium STS and NAT.

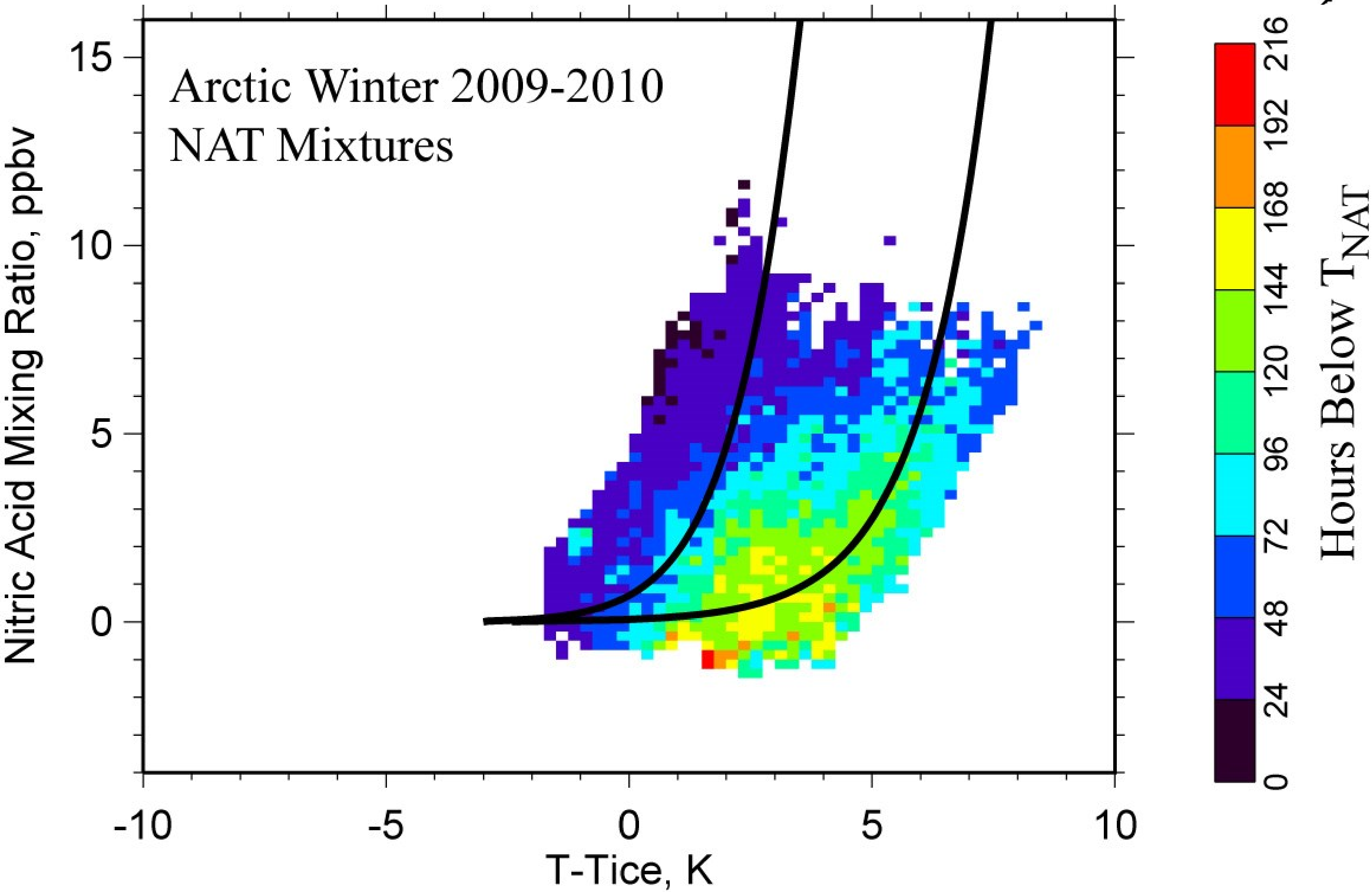
- ➢Indicates how well PSCs in the various composition classes conform to expected thermodynamic existence regimes.
- ➢offers some insight into the kinetics of PSC growth.

NAT Mixture Clouds Have Two Preferred Distinct Modes of HNO_3 Uptake

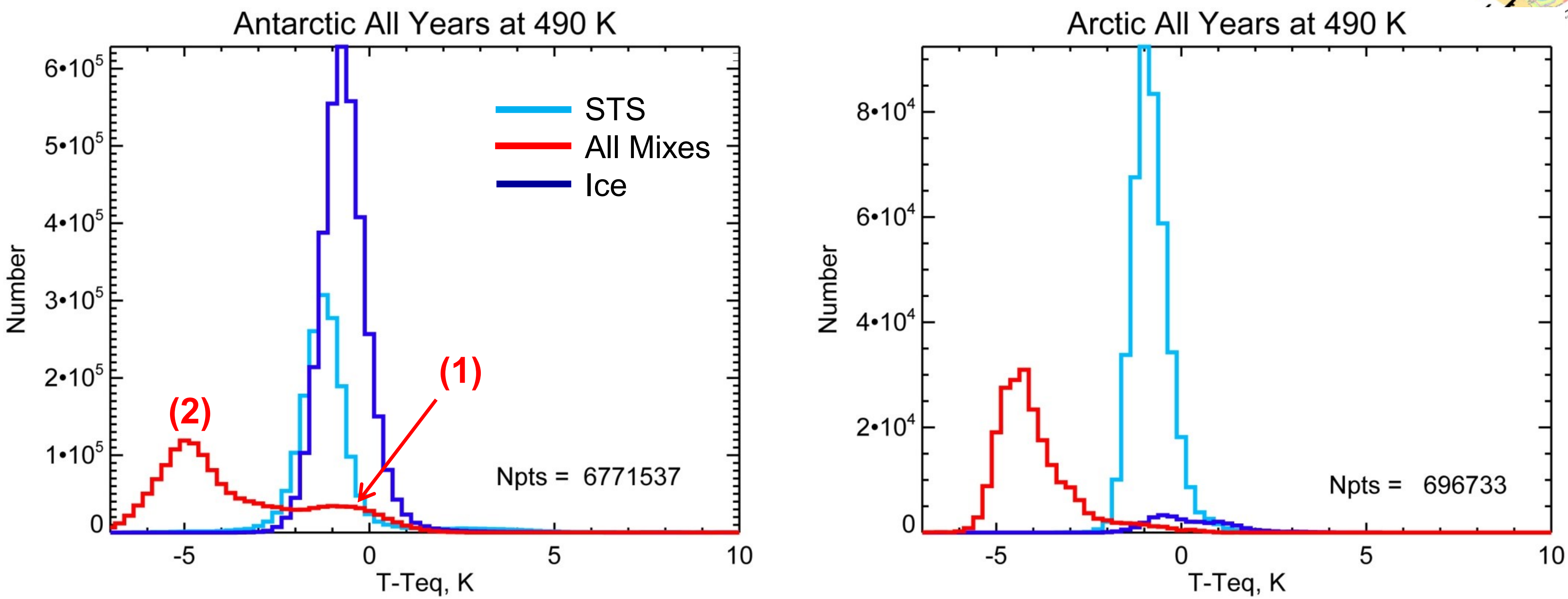


Pitts et al., ACPD, 12, 24643–24676, 2012.

Time Below T_{NAT}



PSC Temperature Existence Regimes



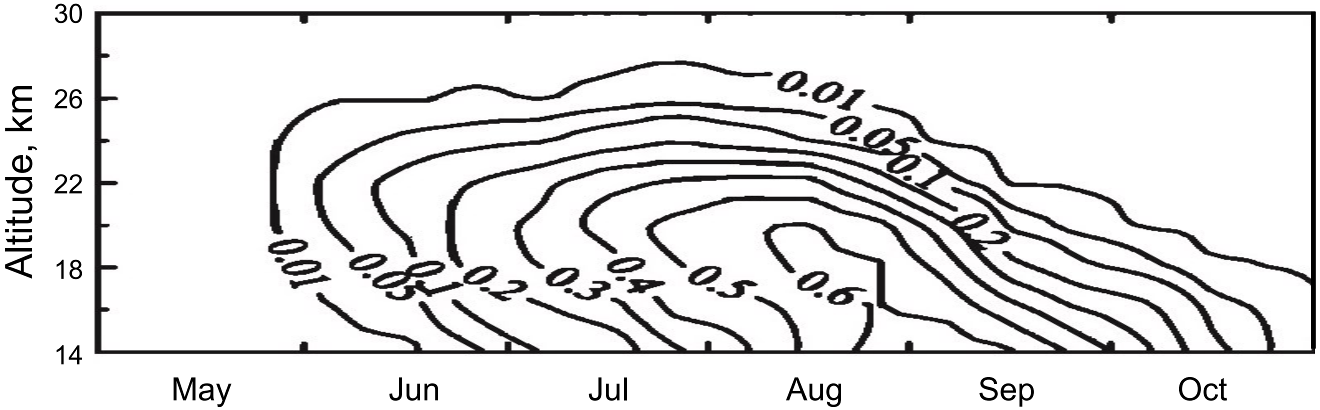
- T=GEOS-5; $T_{eq}=T_{NAT}$, T_{STS}, T_{ice} computed using Aura MLS HNO_3 and H_2O
- All compositions conform well to expected temperature existence regimes
  - Deficiencies understood, to be corrected in next version of algorithm
- STS and ice: peak ~ 1K below equilibrium, possible cold bias in GEOS-5
- Two NAT mixture modes
  1) near NAT equilibrium, long exposure to $T<T_{NAT}$
  2) 4-5 K below T_{NAT}, near STS equilibrium curve, short exposure to $T<T_{NAT}$, HNO_3 uptake dominated by STS droplets

Comparison with Satellite Occultation and Ground-based Lidar Data Records

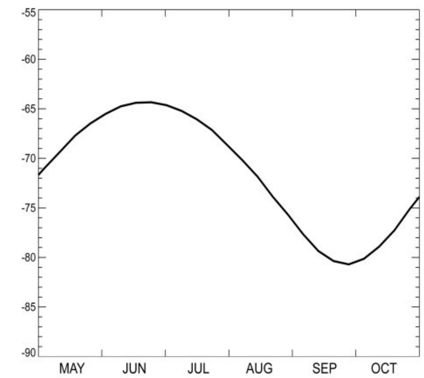
CALIOP Sampling vs Solar Occultation

PSC Climatology based on SAM II Observations from 1978-1989

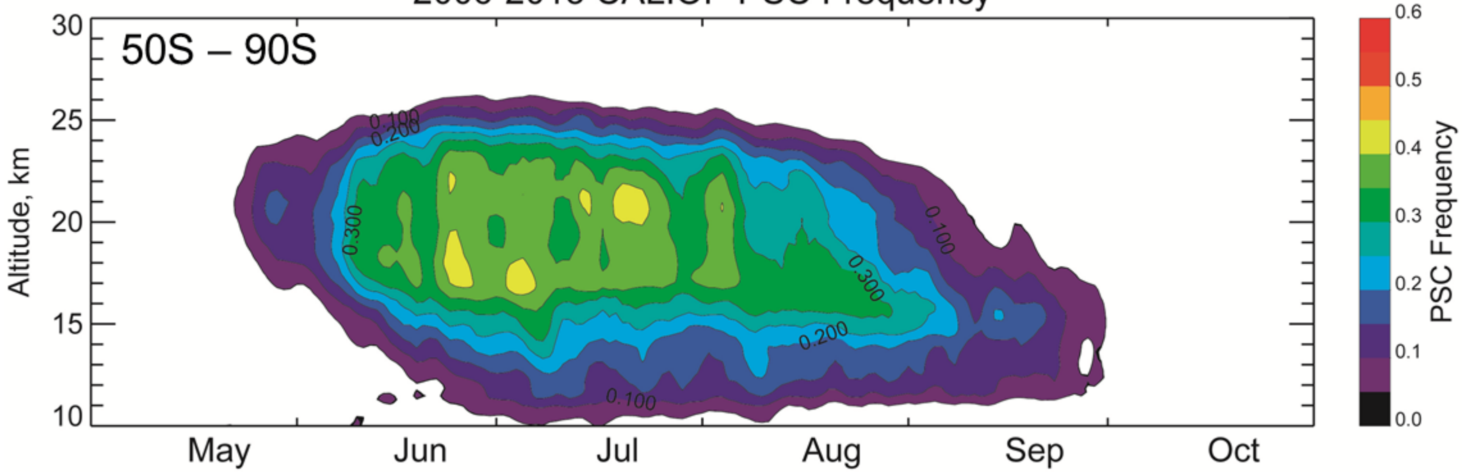
Poole and Pitts, *JGR, 99* (1994)

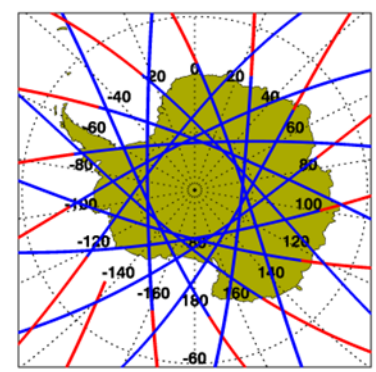


SAM II Measurement Latitudes



2006-2013 CALIOP PSC Frequency

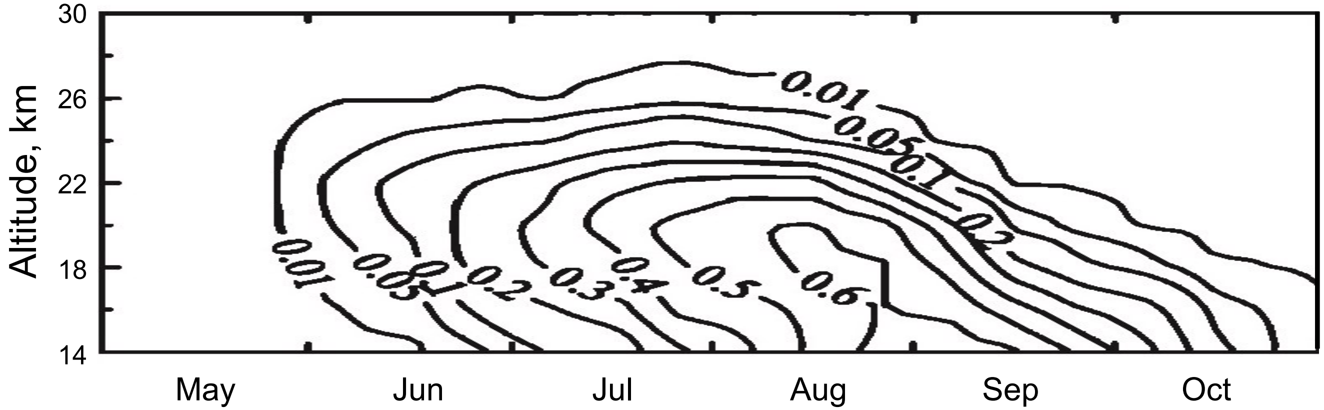




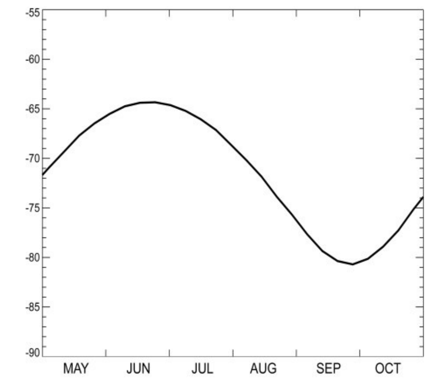
CALIOP Sampling vs Solar Occultation

PSC Climatology based on SAM II Observations from 1978-1989

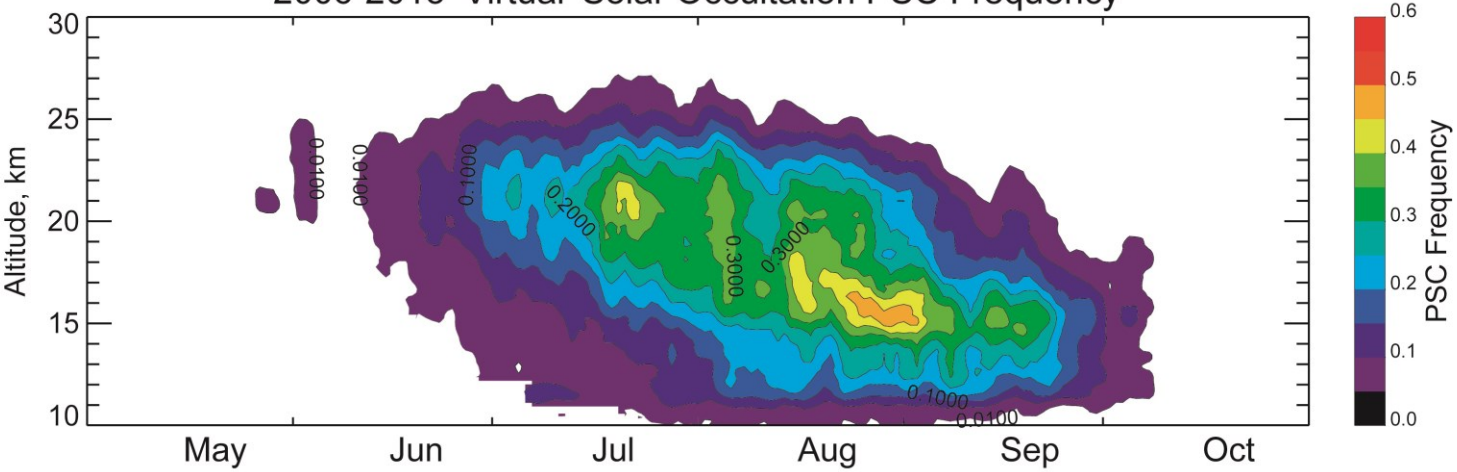
Poole and Pitts, *JGR, 99* (1994)



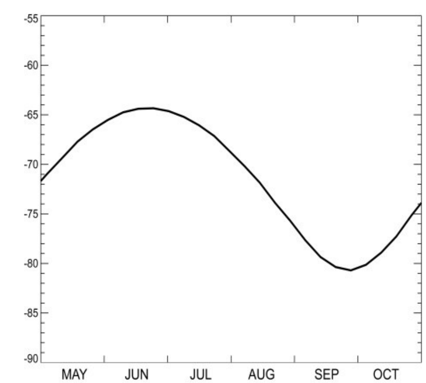
SAM II Measurement Latitudes



2006-2013 'Virtual' Solar Occultation PSC Frequency

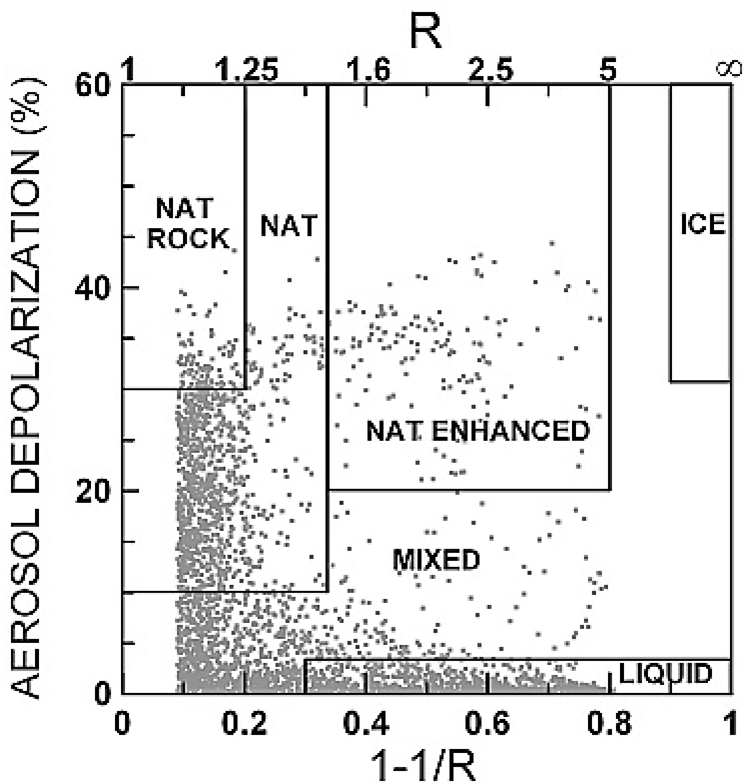


SAM II Measurement Latitudes



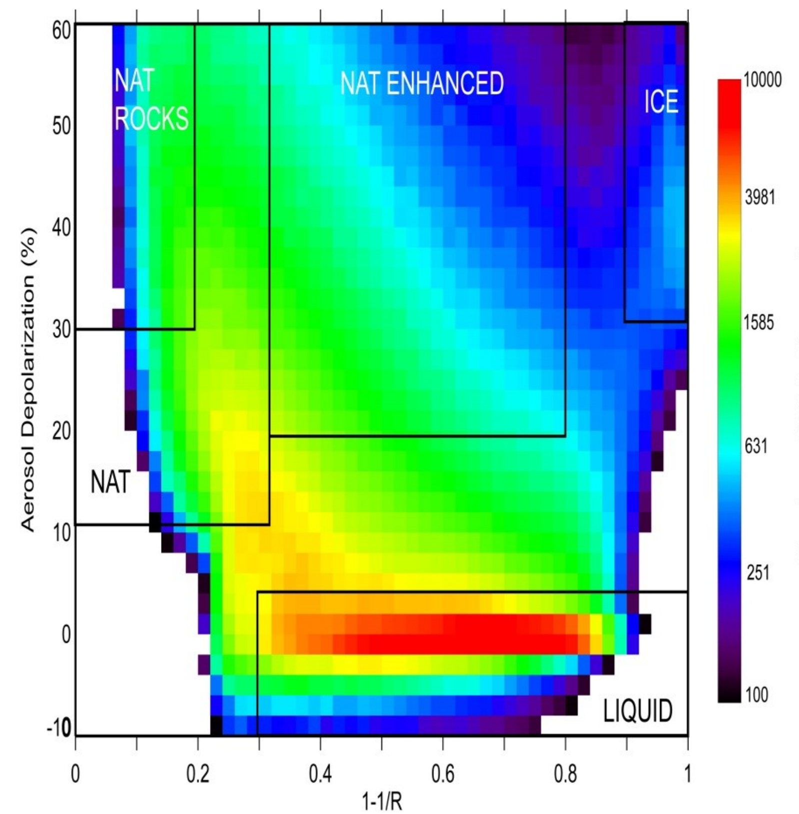
CALIOP vs Ground-based Data Record

Ny-Alesund (79°N, 12°E) Ground-Based Lidar
1994/1995 – 2003/2004



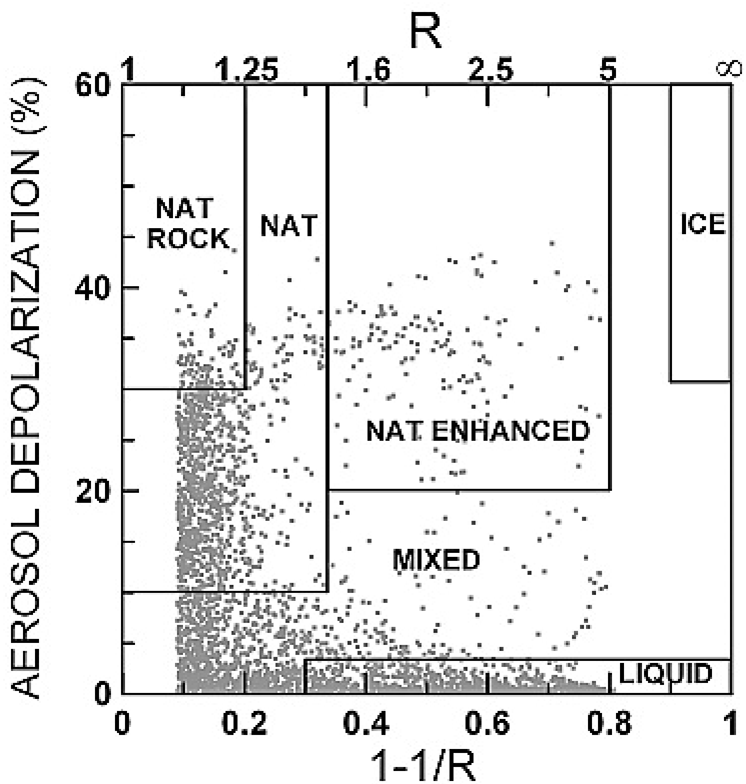
Massoli et al., *JGR, 111* (2006)

CALIOP Vortex-wide Observations
2006/2007 – 2013/2014



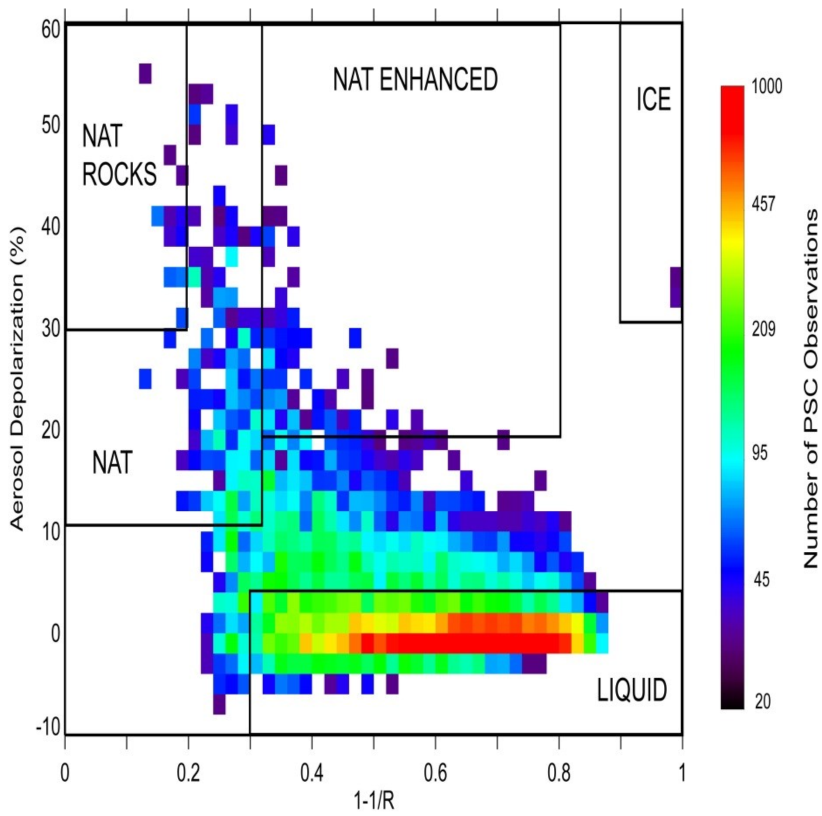
CALIOP vs Ground-based Data Record

Ny-Alesund (79°N, 12°E) Ground-Based Lidar
1994/1995 – 2003/2004



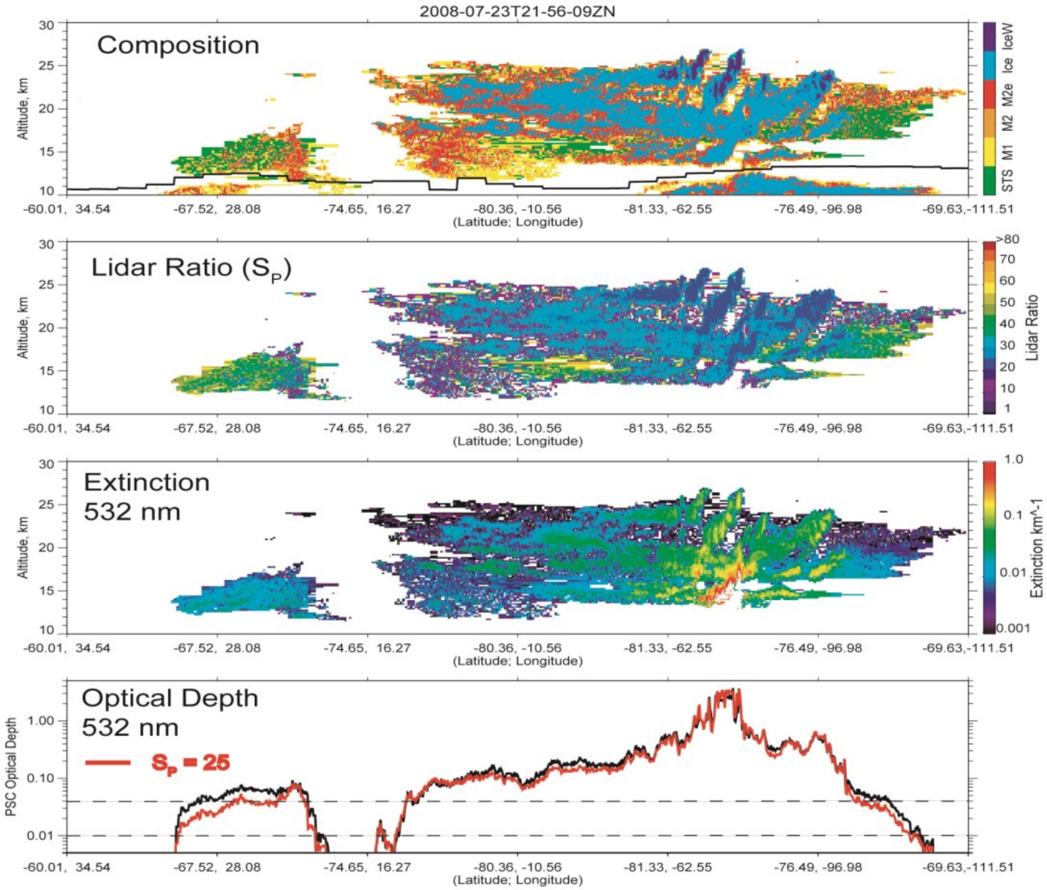
Massoli et al., *JGR, 111* (2006)

CALIOP (within 100 km of Ny-Alesund)
2006/2007 – 2013/2014

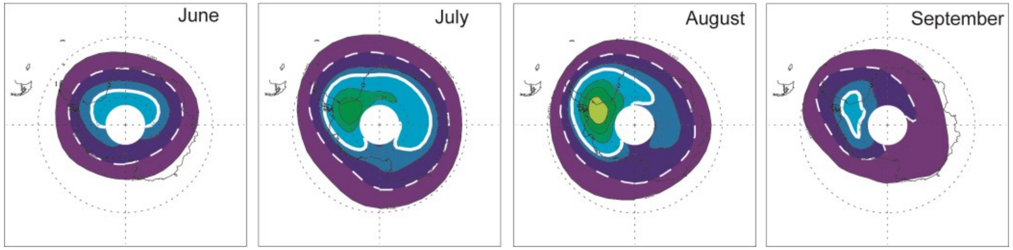


Radiative Impact of PSCs

Single Orbit on 23 July 2008



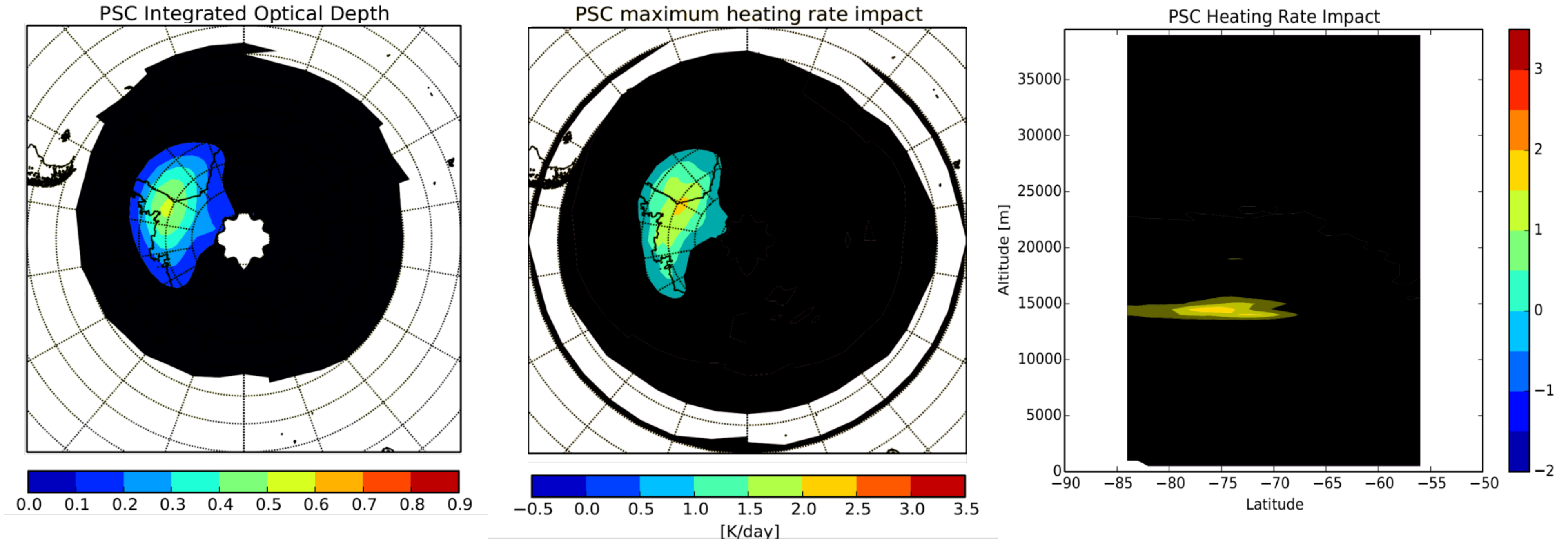
Multi-year Monthly Antarctic Composites



- Past studies have shown that PSCs may affect radiative heating rates- but magnitude and sign of the effect varied greatly from study to study
- Information on PSC characteristics over the entire polar region and throughout complete seasons is required to more accurately evaluate radiative effects (Hicke and Tuck, 2001)
- Comprehensive PSC optical depth database has been produced from CALIOP observations
  - Ice PSCs are dominant component
  - Pronounced maximum over Antarctic Peninsula
- Radiative modeling studies underway to evaluate radiative impact of PSCs

Radiative Impact of PSCs

24 Aug – 6 Sep 2008



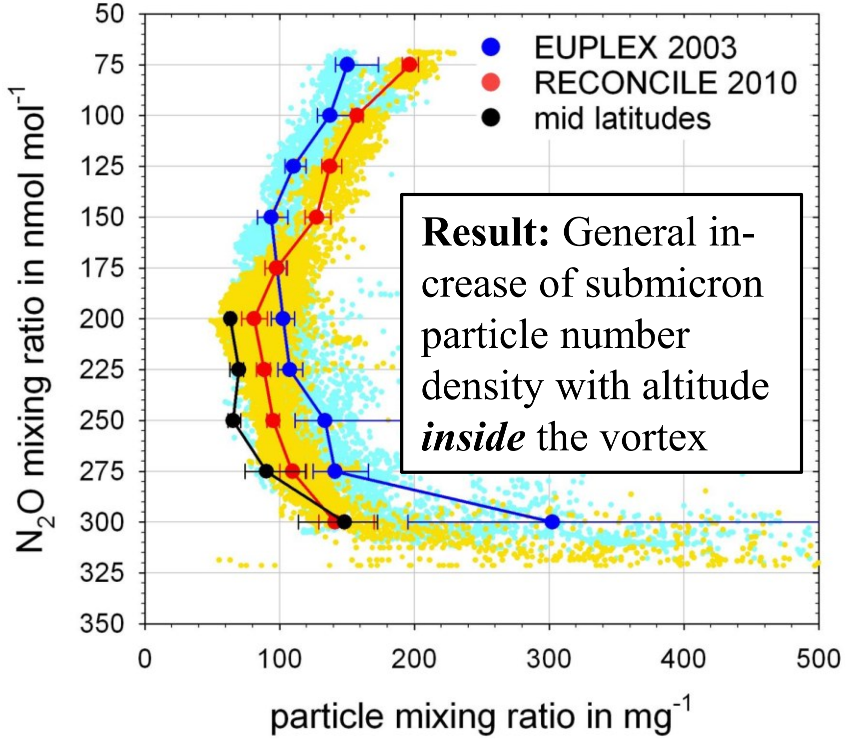
- Heating rates calculated with state of the art line by line radiative transfer model (LBLDIS) using CALIOP PSC and tropospheric cloud as input
  - Maximum optical depth is localized around the Antarctic peninsula
  - Maximum calculated heating rates for PSCs without underlying clouds of up to 2K/day
  - Maximum heating rate located around 15km altitude
- Heating rates decrease significantly in presence of underlying tropospheric clouds
- Potential impact on circulation and PSC formation

Summary/Conclusions

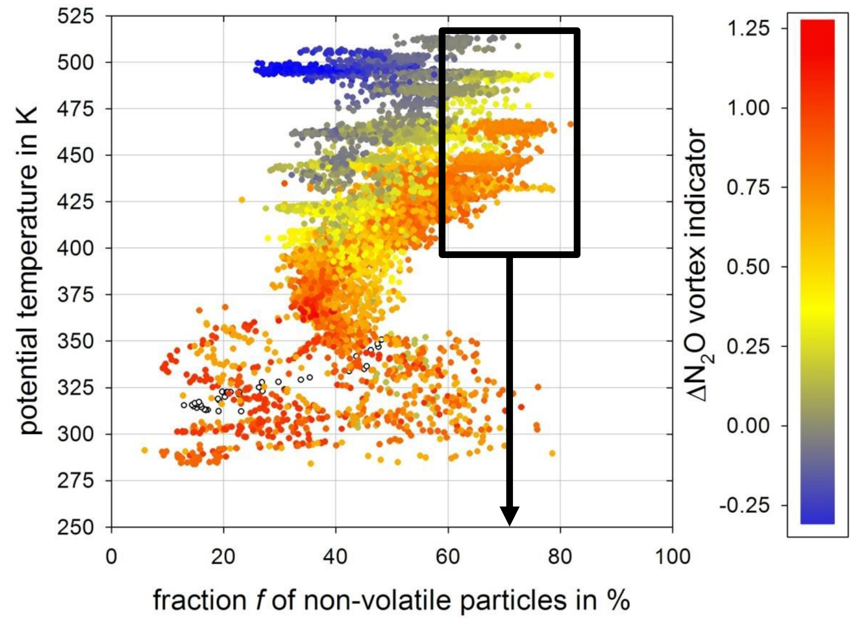
- CALIPSO platform and payload have performed beyond expectations
- CALIOP has ushered in a new era in PSC research and is providing a wealth of information on PSC occurrence and composition on unprecedented spatial scales
- CALIOP 8+ year data record has captured primary aspects of the seasonal and multi-year variability of PSCs in Antarctic and Arctic
  - Small interannual variability in Antarctic: Multi-year averages fairly representative
  - Large interannual variability in Arctic: Each Arctic winter is unique
  - Interesting spatial patterns observed in PSC composition
  - Frequent maximum in ice PSCs over Antarctic Peninsula
- CALIOP data consistent with solar occultation and ground-based data when sampling is similar
- Radiative modeling studies underway to evaluate radiative impact of PSCs
- Next steps: Development of detailed CALIOP PSC climatology

PSC Workshop Science Highlights: Meteoric Particles as Heterogeneous Nuclei (Borrmann et al.)

In situ particle measurements in Arctic lower stratosphere



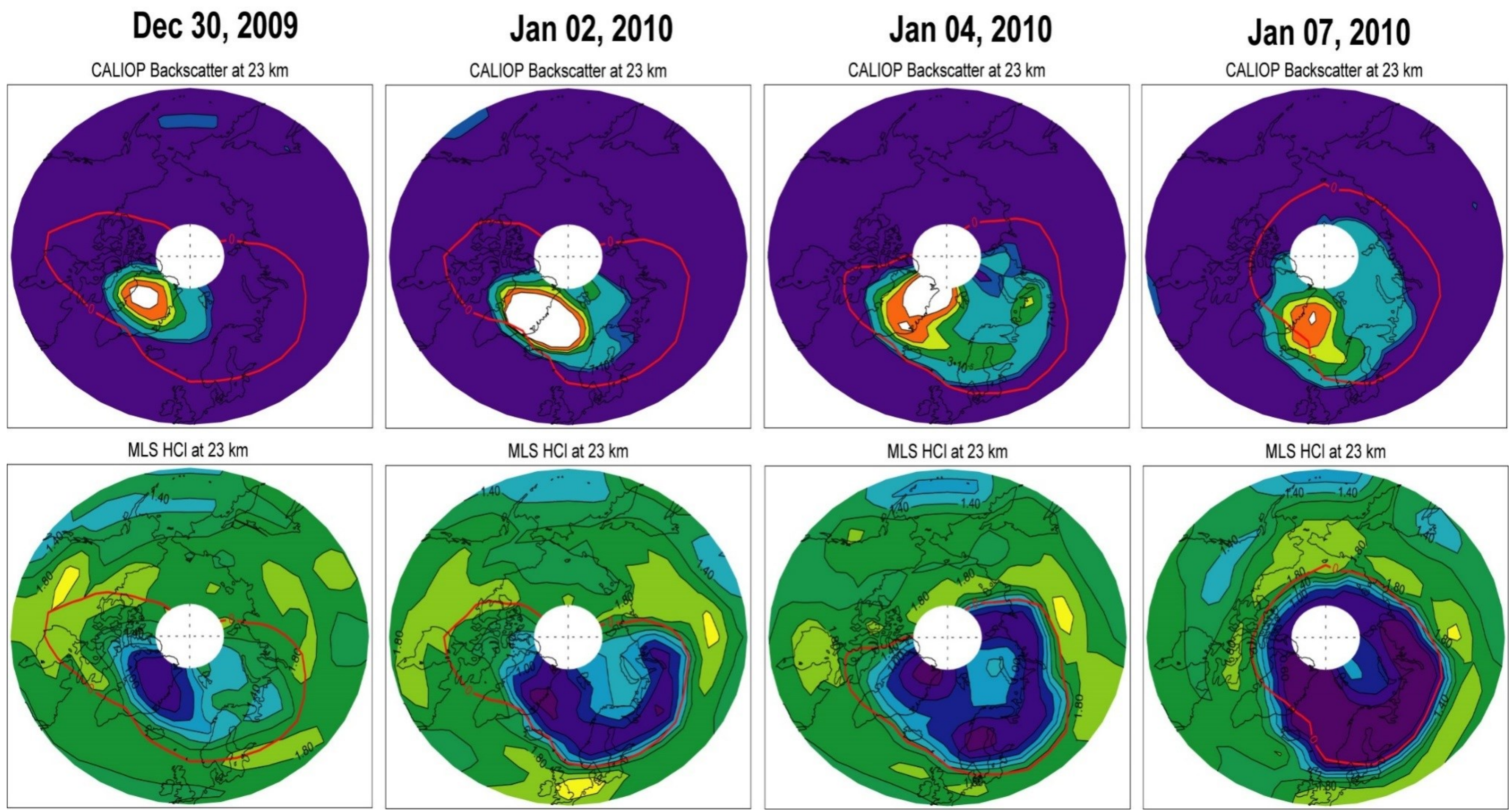
Seven of ten particles inside the vortex are -non volatile- 2003, 2010, 2011



- Submicron particle number concentration increases with altitude in/below the downwelling zone of NH polar vortex consistently in 1990, 2003,2010, 2011.
- Coincides with high fraction of non-volatile particles and thus most likely of meteoric origin.

Weigel et al., *Atmos. Chem. Phys., 14,* 12319-12342, 2014

PSC Workshop Science Highlights:
Vortex-wide Chlorine Activation by Mesoscale PSC Events (Nagajima et al.)



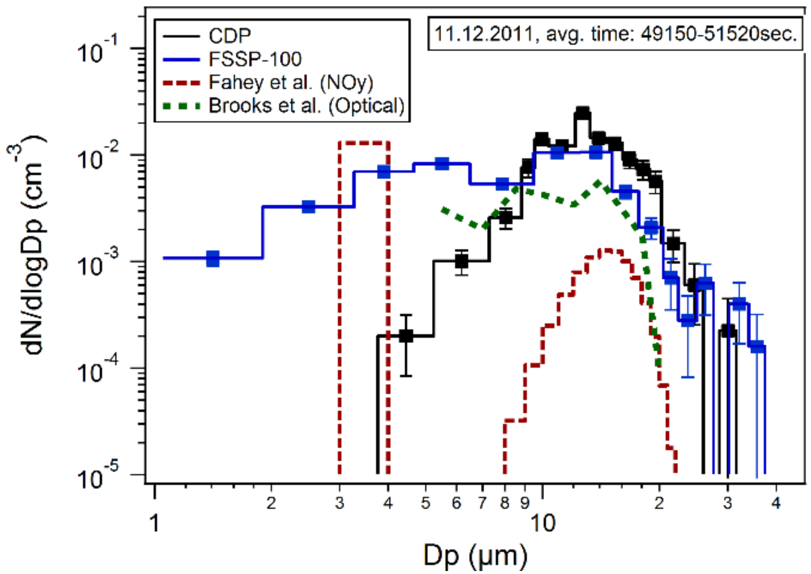
Mesoscale localized PSC events in early winter can rapidly activate chlorine in just a few hours and effectively activate the whole polar vortex in a few days

Wegner et al., *Atmos. Chem. Phys. Disc., in preparation*, 2015
Nakajima et al., *Atmos. Chem. Phys. Disc., in preparation*, 2015

PSC Workshop Science Highlights: Large NAT Particles Unexplained (Molleker et al.)

In-situ measurements of exceptionally large HNO_3 containing particles

- Large PSC NAT particles detected with sizes and concentrations bigger than the previously reported NAT "rocks"
- Such particles seem to be a regular feature in synoptic scale PSCs
- BUT cannot be explained …



- Optically detected NAT particle sizes are not consistent with HNO_3 measurements from MIPAS and SIOUX
- Such large particles cannot grow to detected diameters with given back-trajectories and trace gas fields

- *Hypothesis 1: High asphericity of large NAT particles ("needles") causing high apparent optical cross section*
- *Hypothesis 2: "Empty NAT shells" around evaporated ice*

Molleker et al., *Atmos. Chem. Phys., 14*, 10785-10801, 2014