

Abstract

Polar stratospheric clouds (PSCs) play a crucial role in the springtime chemical depletion of ozone at high latitudes. PSC particles (primarily supercooled ternary solution, or STS droplets) provide sites for heterogeneous chemical reactions that transform stable chlorine and bromine reservoir species into highly reactive ozone-destructive forms. Furthermore, large nitric acid trihydrate (NAT) PSC particles can irreversibly redistribute odd nitrogen through gravitational sedimentation (a process commonly known as denitrification), which prolongs the ozone depletion process by slowing the reformation of the stable chlorine reservoirs. Spaceborne observations from the CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) lidar on the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) satellite are providing a rich new dataset for studying PSCs.

CALIPSO is an excellent platform for studying polar processes with CALIOP acquiring, on average, over 300,000 backscatter profiles daily at latitudes between 55° and 82° in both hemispheres. PSCs are detected in the CALIOP backscatter profiles using a successive horizontal averaging scheme that enables detection of strongly scattering PSCs (e.g., ice) at the finest possible spatial resolution (5 km), while enhancing the detection of very tenuous PSCs (e.g., low number density NAT) at larger spatial scales (up to 135 km). CALIOP PSCs are separated into composition classes (STS; liquid/NAT mixtures; and ice) based on the ensemble 532-nm scattering ratio (the ratio of total-to-molecular backscatter) and 532-nm particulate depolarization ratio (which is sensitive to the presence of non-spherical, i.e. NAT and ice particles). In this paper, we will provide an overview of the CALIOP PSC detection and composition classification algorithm and then examine the vertical and spatial distribution of PSCs in the Arctic and Antarctic on vortex-wide scales for entire PSC seasons over the more than eight-year data record.

PSC Detection and Composition Classification

- PSCs detected using nighttime 532-nm scattering ratio (R_{532}) and perpendicular backscatter ($\beta_{\perp}$); $\Delta z = 180$ m, $\Delta h = [5, 15, 45, 135]$ km
→ $\beta_{\perp}$ sensitive to non-spherical particles: NAT, ice
- 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)
→ $\beta_{\perp}$ outliers: NAT mixtures/ice; R_{532} outliers: STS
- Six composition classes:
→ 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)

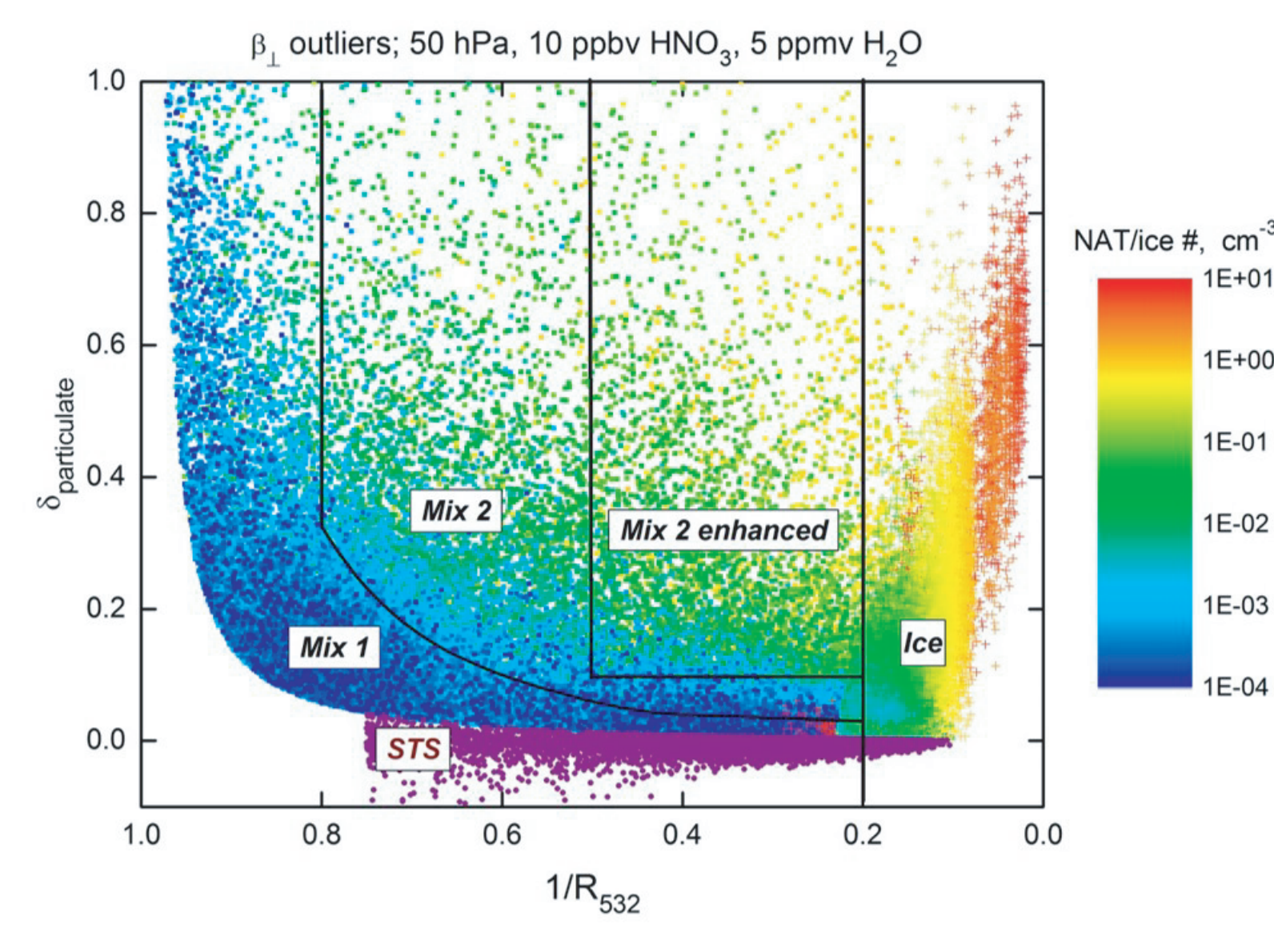


Figure 1. Simulated CALIOP $1/R_{532}$ and δ_p measurements for STS and plausible mixtures of liquid droplets and NAT/ice particles color-coded by NAT/Ice number density.

Instantaneous HNO_3 Sedimentation Flux

- Denitrification potential of NAT mixtures is better characterized by instantaneous HNO_3 sedimentation flux of NAT particles (Consideine et al., 2000; Northway et al., 2002)
→ $J_{HNO_3} = n \cdot v_0 \cdot \exp(8 \ln^2 \sigma) \propto (r_m)^5$
where n = condensed HNO_3 molecules, v_0 = sedimentation speed of particle with lognormal mode radius r_m , and σ = log-normal geometric standard deviation
- Four composition classes:
→ 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 sedimentation flux)
→ Ice, wave ice = H_2O ice (synoptic, mountain-wave-induced)

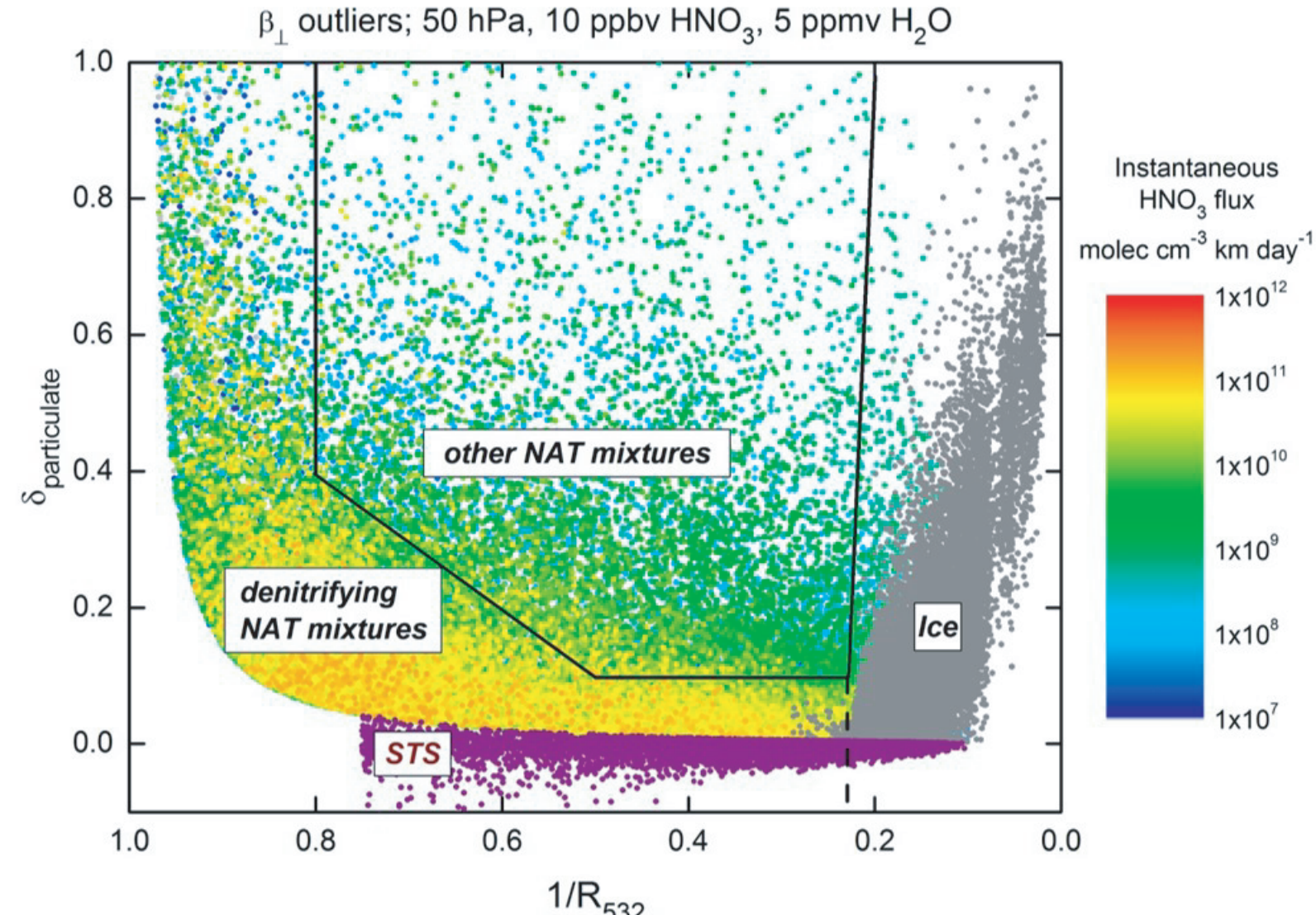


Figure 3. Simulated CALIOP $1/R_{532}$ and δ_p measurements for STS and plausible mixtures of liquid droplets and NAT/ice particles color-coded by instantaneous HNO_3 flux.

Antarctic PSC Area: 2006 - 2013

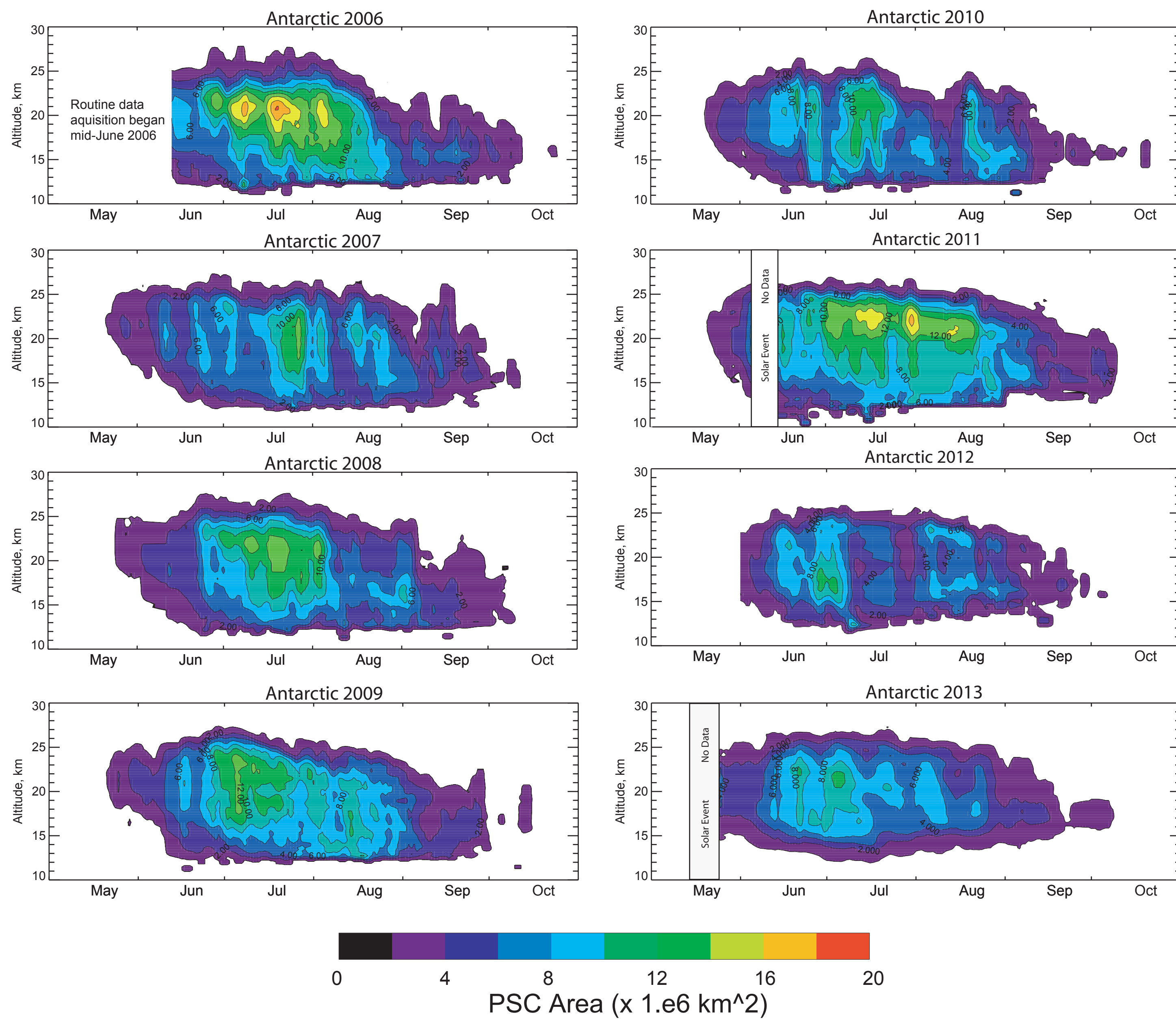


Figure 3. Time series of daily PSC areal coverage poleward of 50° latitude as a function of altitude as observed by CALIOP during eight Antarctic seasons

- Antarctic winter stratosphere is characterized by a large, stable, and cold polar vortex
- General evolution of PSC season is similar year-to-year in terms of season length and PSC vertical extent
- Observed interannual variability of Antarctic PSC areal coverage is small

→ Multi-year average is fairly representative

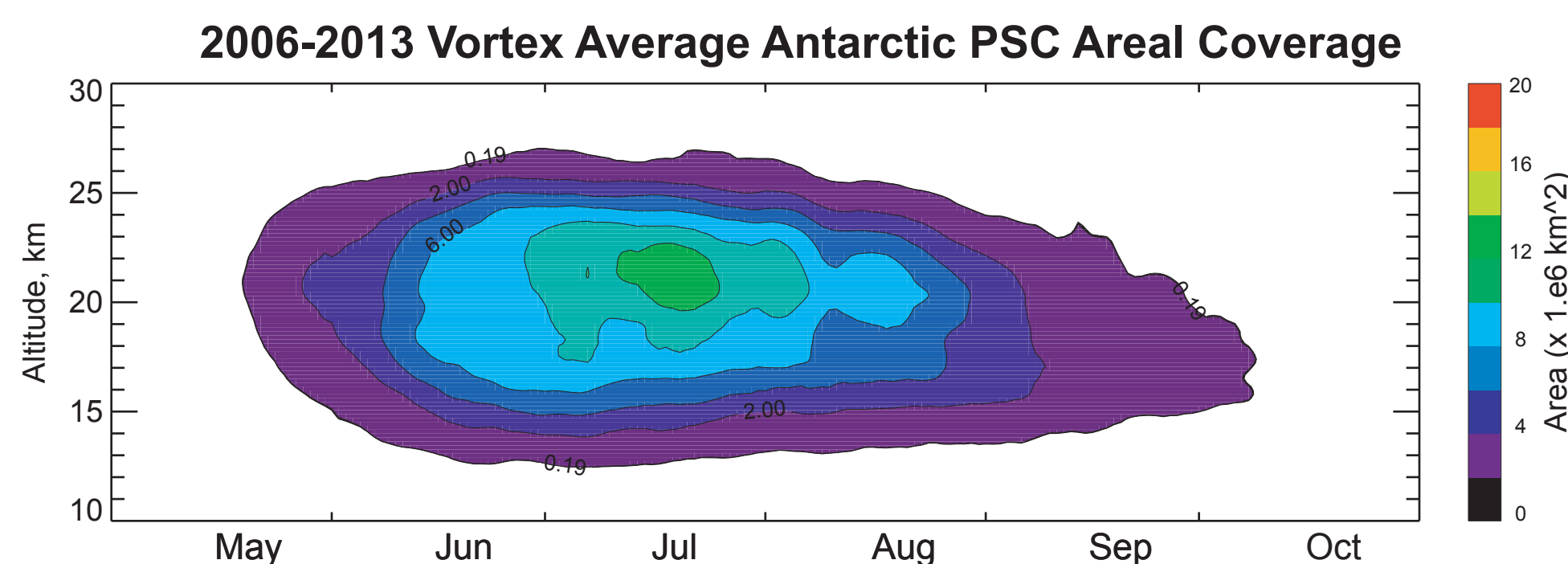


Figure 5. Multi-year mean Antarctic PSC areal coverage based on CALIOP data from 2006-2013.

Antarctic PSC Area Fraction by Composition

Vortex Average: 2006 2013

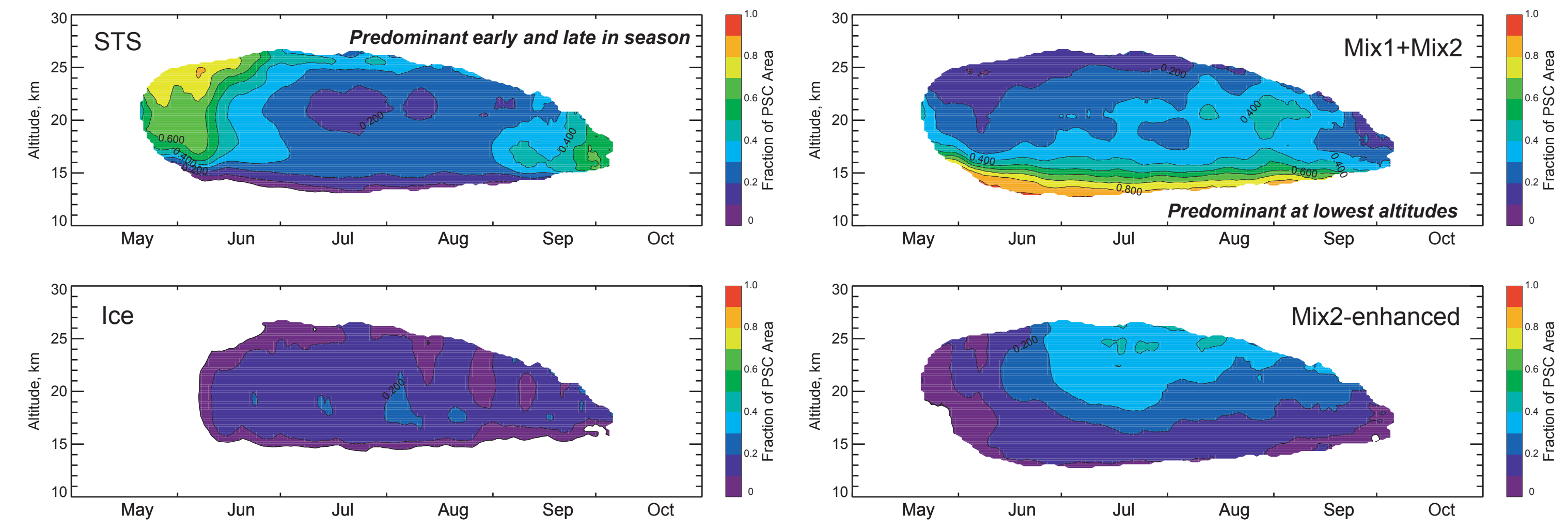


Figure 5. Time series of multi-year (2006-2013) mean Antarctic PSC areal coverage for each of four composition classes: STS, Mix1+Mix2, ice, and Mix2-enhanced. The values have been normalized by the total PSC area to show the relative coverage of each composition class as indicated by the color bars.

Monthly Average Spatial Distributions (2006-2013)

Antarctic PSCs at 20 km Altitude

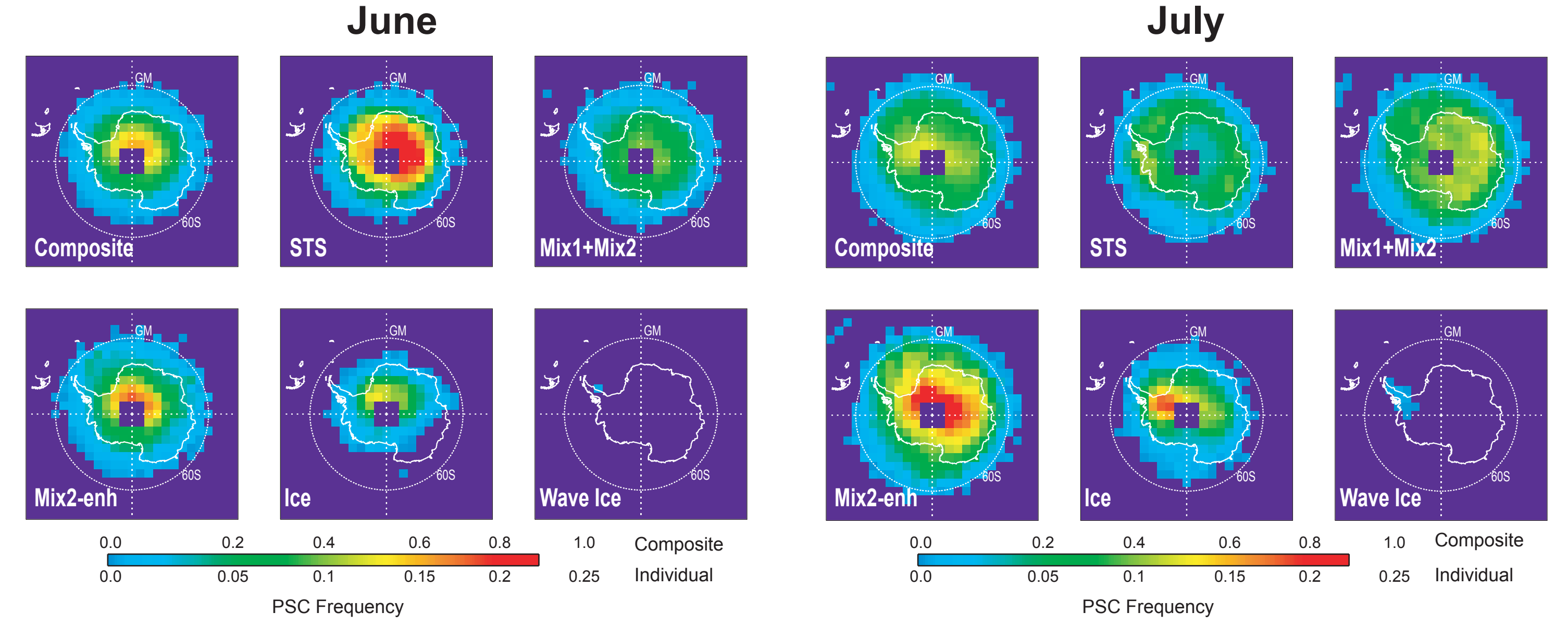


Figure 6. Multi-year (2006-2013) distributions of monthly-averaged Antarctic PSC occurrence frequency at 20 km altitude for the month of June (left) and July (right).

Arctic PSC Area: 2006-07 to 2013-14

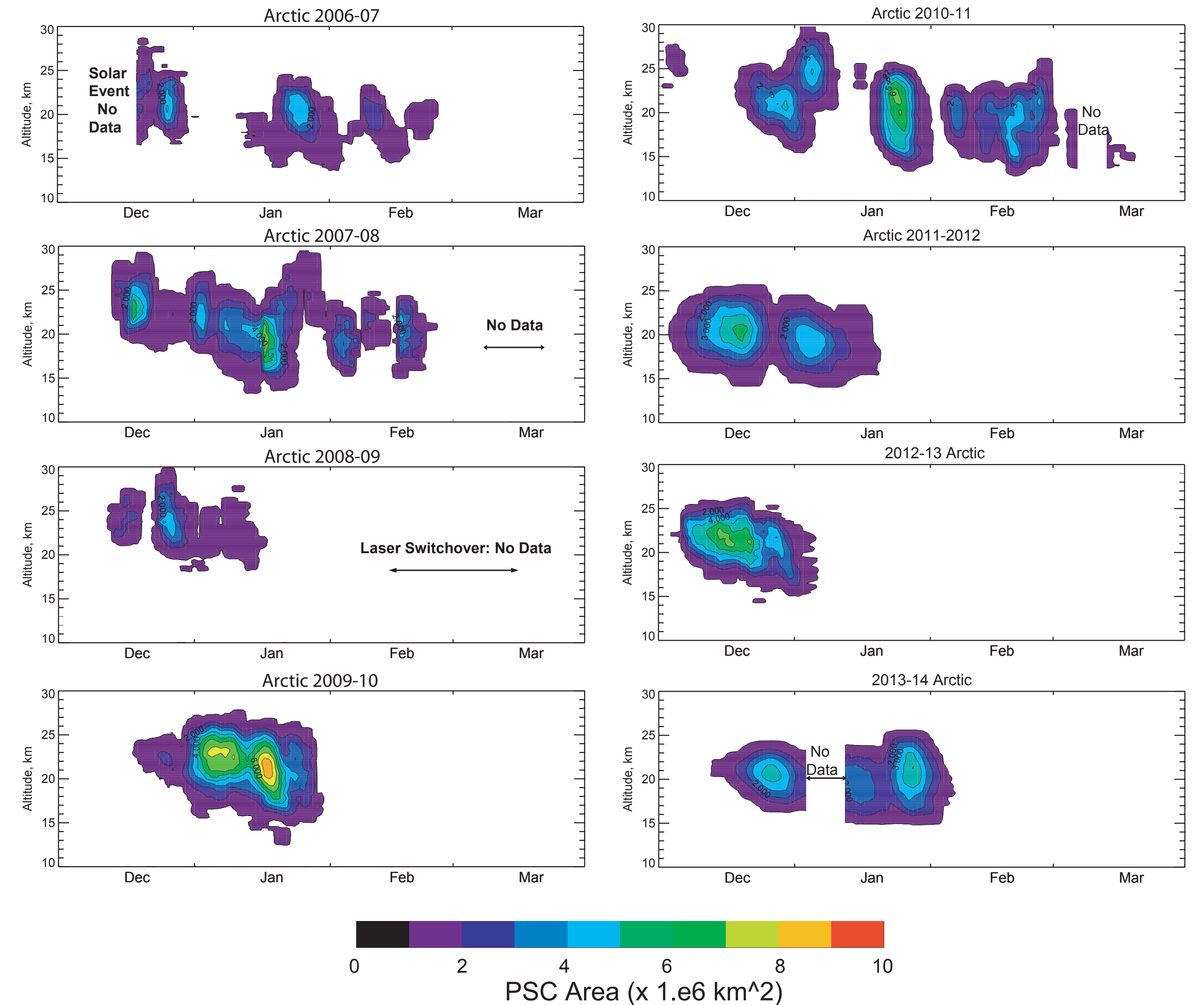
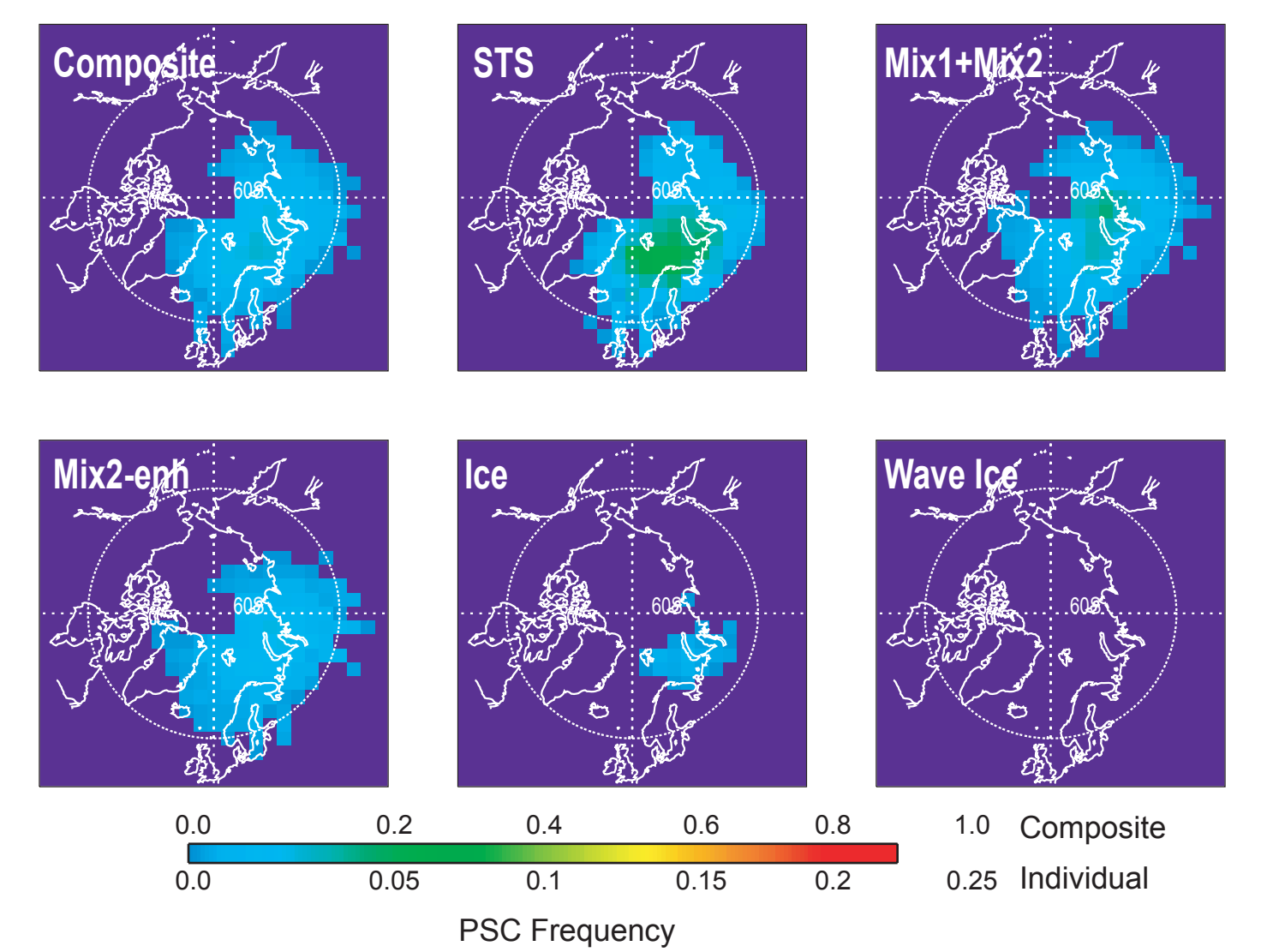


Figure 7. Time series of daily PSC areal coverage poleward of 50° latitude as a function of altitude as observed by CALIOP during eight Arctic seasons

- Arctic winter stratosphere is characterized by a unstable and relatively warm polar vortex that is prone to sudden stratospheric warmings
- Arctic PSC occurrence varies dramatically from year to year and is significantly lower overall than in the Antarctic

→ Multi-year average is not representative

- There is a preferred spatial distribution in Arctic PSC occurrence in the Arctic with PSCs generally confined to longitudes between approximately 30°W and 90°E, which corresponds to the climatologically preferred location of the polar vortex.



Summary

- CALIOP is providing wealth of information on PSC occurrence and composition
- Improved CALIOP PSC composition classification scheme better accounts for effects of measurement noise and denitrification
- Liquid-NAT mixtures now separated into 2 classes based on instantaneous HNO_3 sedimentation flux of NAT particles
- Multi-year averages fairly representative for Antarctic PSCs, but 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