9+ YEARS OF CALIOP PSC DATA: AN EVOLVING CLIMATOLOGY

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ABSTRACT

Polar stratospheric clouds (PSCs) play key roles in the springtime chemical depletion of ozone at high latitudes. PSC particles 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, which prolongs the ozone depletion process by slowing the reformation of the stable chlorine reservoirs. However, there are still significant gaps in our understanding of PSC processes, particularly concerning the details of NAT particle formation. 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 on unprecedented vortex-wide scales. In this paper, we examine the vertical and spatial distribution of PSCs in the Antarctic and Arctic on vortex-wide scales for entire PSC seasons over the more than nine-year data record.

1. INTRODUCTION

Polar stratospheric clouds (PSCs) are known to play key roles in the springtime chemical depletion of stratospheric ozone at high latitudes[1]. First of all, heterogeneous reactions on the surfaces PSCs convert the stable chlorine reservoirs HCl and $ClONO_2$ to chlorine radical species that are involved in catalytic ozone destruction. Heterogeneous reaction rates depend on particle surface area and composition, which includes liquid binary H_2SO4/H_2O droplets (background stratospheric aerosol); liquid ternary $HNO_3/H_2SO_4/H_2O$ droplets (STS); solid nitric acid trihydrate (NAT) particles; and H_2O ice particles. PSCs also affect ozone chemistry through the removal of HNO_3 from the polar stratosphere (denitrification) via the formation and sedimentation of large NAT PSC particles. Denitrification enhances catalytic ozone depletion by delaying the reformation of the stable chlorine reservoirs.

In spite of nearly three decades of research, there are still significant gaps in our understanding of PSC processes, primarily concerning the details of how NAT particles form and evolve and to what degree chlorine activation occurs on cold background aerosol prior to PSC formation. These uncertainties significantly limit our ability to accurately represent PSC processes in global models and call into question our prognostic capabilities concerning future ozone loss in a changing climate. This is of particular concern in the Arctic, where winter temperatures hover near the PSC threshold and, hence, future stratospheric cooling could lead to enhanced cloud formation and substantially greater ozone losses.

The PSC observational database has been greatly expanded with the advent of the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite. Launched in 2006 as part of the NASA A-train satellite constellation, CALIPSO offers an ideal platform for studying polar processes since its orbit provides extensive measurement coverage over the polar regions of both hemispheres with an average of fourteen orbits per day extending to 82° latitude. CALIOP is providing a rich new dataset for studying PSCs[2,3,4,5,6] on unprecedented vortex-wide scales and the 9+ years of CALIOP PSC observations are providing considerable new insight into the key remaining questions regarding PSC particle formation and chemical processes.

In this paper, we provide a brief overview of the methodology for detection and composition classification of PSCs in the CALIOP data and then examine the 9+ year CALIOP data record to quantify the seasonal and interannual variability of PSCs in the Antarctic and Arctic.

2. DETECTION AND COMPOSITION CLASSIFICATION

CALIOP is a dual wavelength (532 and 1064 nm), polarization sensitive lidar that measures backscatter from cloud and aerosol particles in the atmosphere[7]. The CALIOP PSC detection algorithm[3,4] utilizes a standard threshold approach where PSCs are identified through enhancements in the 532-nm lidar scattering ratio (R_{532}) or perpendicular backscatter. Detection is performed using a successive horizontal averaging procedure (5, 15, 45, 135 km) that ensures detection of strongly scattering PSCs (e.g., ice) at the finest possible spatial resolution (5 km), while also enhancing the detection of very tenuous PSCs that are found only through additional averaging (up to 135 km). The vertical resolution for detection is 180 m. The inclusion of the perpendicular backscatter channel provides sensitivity to the presence of non-spherical particles, which in the case of PSCs are attributed to NAT or ice particles.

PSC composition classification[4,5,6] is based on comparison of CALIOP 532-nm particle depolarization ratio (ratio of perpendicular and parallel particle backscatter) and inverse scattering ratio ($1/R_{532}$) with theoretical optical calculations for equilibrium STS and plausible non-equilibrium mixtures of spherical liquid (binary aerosol or STS) and non-spherical (NAT or ice) particles. PSCs detected through enhancements in scattering ratio without significant enhancement in perpendicular backscatter indicates liquid particle growth from binary aerosol to STS and are classified as STS. PSCs detected through enhancements in perpendicular backscatter indicate the presence of non-spherical particles and are classified as either liquid/NAT mixtures or ice, depending on their particle depolarization and inverse scattering ratio values. PSCs are separated into five composition classes: two classes of liquid/NAT mixtures (Mix1+Mix2 and Mix2-enhanced) which denote lower or higher NAT particle number density/volumes in the mixtures; STS; H_2O ice; and mountain wave ice.

The standard CALIPSO Level 2 PSC data products are available through the Langley Atmospheric Sciences Data Center (https://eosweb.larc.nasa.gov/project/calipso/ calipso_table).

3. ANTARCTIC PSCs

The Antarctic winter stratosphere is characterized by a large, stable, and cold polar vortex that creates ideal conditions for PSCs to exist. Figure 1 shows examples of the areal coverage of PSCs as observed by CALIOP for a representative subset of four Antarctic winters. The time series represent the total areal extent of PSCs over the Antarctic polar region as a function of altitude and day. Although there are differences in the absolute magnitudes and detailed structure from year to year, the general evolution is similar in terms of season length and PSC vertical extent, and the year-to-year variability is relatively small. The multi-year (2006-2014) mean PSC areal coverage

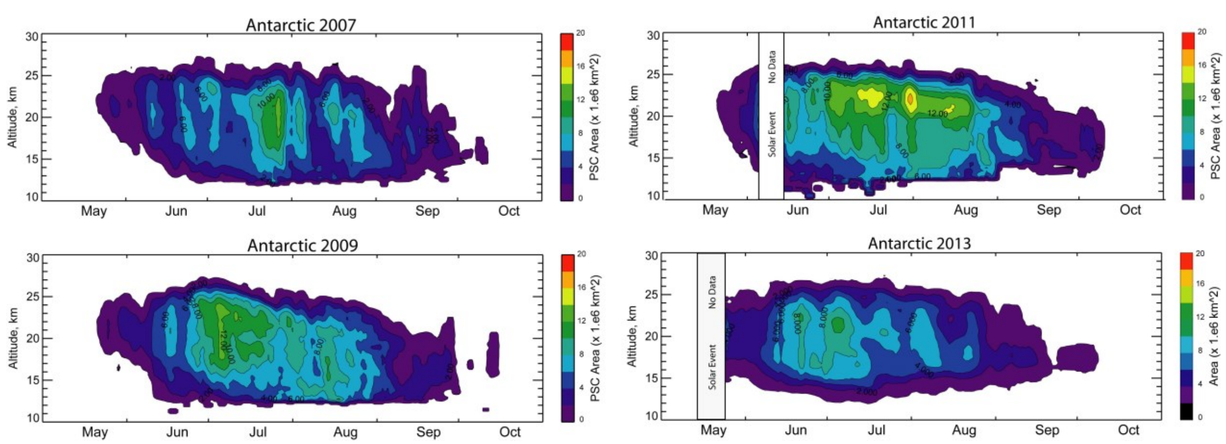

Figure 1. Daily time series of CALIOP PSC areal coverage in the Antarctic as a function of altitude for the 2007, 2009, 2011, and 2013 seasons. Units are in millions of square kilometers.

during the Antarctic season is shown in Figure 2. The multi-year composite is a fairly representative, albeit smooth, rendition of the seasonal evolution of Antarctic PSCs and may be useful for simulating PSC occurrence in global models.

Shown in Figure 3 are the multi-year (2006-2014) mean time series of the fraction of total PSC area

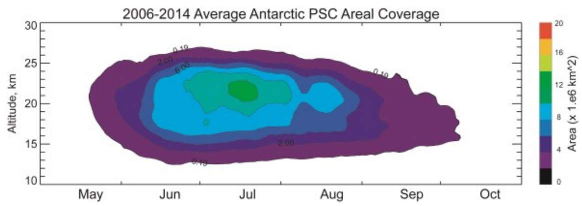

Figure 2. Multi-year mean Antarctic PSC areal coverage based on CALIOP data from 2006-2014.

covered by each composition as a function of altitude and day. STS is the predominant composition early in the season and again late in the season. Lower number density NAT mixtures (Mix1+Mix2) are the predominant composition at the lowest altitudes throughout the season. Ice PSCs occur on relative small scales (never more than about 20% of total PSC area) and their occurrence is typically episodic in nature. Higher number density Mix2-enhanced NAT mixtures make up a large fraction of the PSCs above ~20 km during the period from late June until early September.

4. ARCTIC PSCs

In contrast to the Antarctic, the Arctic polar stratospheric vortex is warmer, more unstable, and prone to sudden stratospheric warmings which disrupt the vortex and raise temperatures above PSC existence thresholds. As a result, PSC occurrence in the Arctic is highly variable from year to year and significantly lower overall than in the Antarctic. The dramatic year-to-year variability is illustrated in Figure 4 which shows the areal coverage of PSCs in the Arctic for a subset of four winters. For instance, CALIOP observed the largest PSC areal coverage to date in January 2010, including synoptic areas of ice PSCs which are very uncommon in the Arctic, but a sudden stratospheric warming ended the PSC season at the end of January. On the other hand, the 2010-11 Arctic season was characterized by persistent periods of PSCs from December through March, resulting in record ozone loss. The 2012-13 winter was another short season with PSCs observed by CALIOP only in December and early January. With such a highly unstable polar vortex, the interannual variability in the Arctic is extremely large with PSC occurrence and even composition varying significantly from year to year. As a result, a multi-year average is not very meaningful in the Arctic as each year is unique.

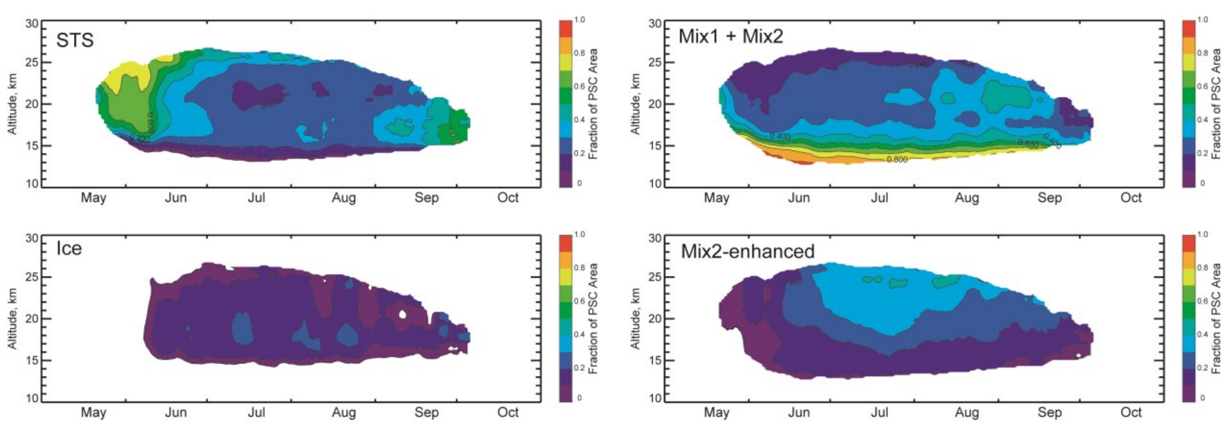

Figure 3. Time series of multi-year (2006-2014) mean Antarctic PSC areal coverage for each of four composition classes: STS, Mix1+Mix2, ice, and Mix2-enhanced. The values have been normalized by the total PSC area to show the relative coverage of each composition class as indicated by the color bars.

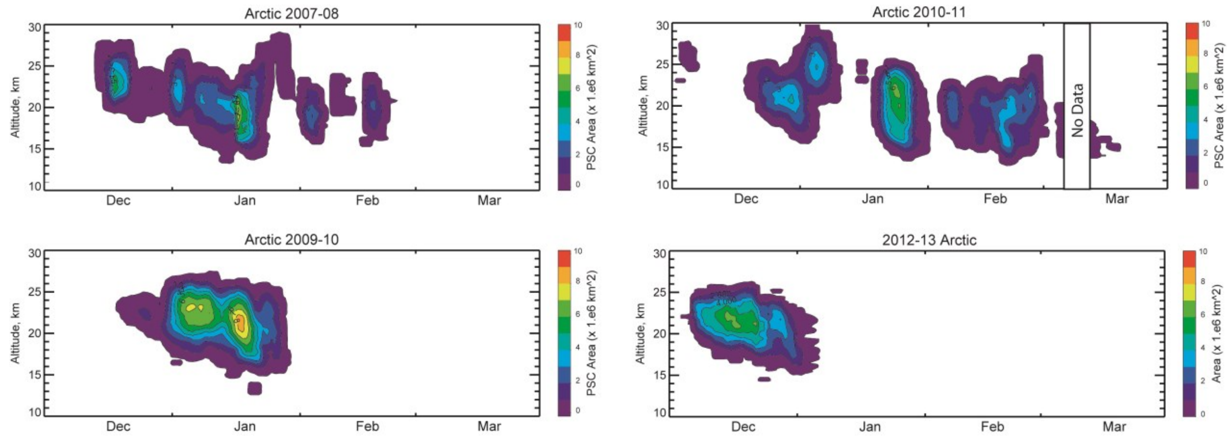

Figure 4. Daily time series of CALIOP PSC areal coverage in the Arctic as a function of altitude for the 2007-08, 2009-10, 2010-11, and 2012-13 Antarctic seasons. Units are in millions of square kilometers.

5. SUMMARY

After more than two decades of research it is well established that PSCs play critical roles in the annual springtime depletion of ozone in the polar stratospheres. However, there are still significant gaps in our understanding of the detailed role of PSC processes in ozone depletion. 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. From the more than nine year CALIOP data record, we can now reasonably quantify the seasonal and interannual variability of PSC occurrence and composition in both the Antarctic and Arctic polar regions. The Antarctic polar vortex is typically stable and cold and, as a result, the evolution of PSCs is similar from year to year. A multi-year mean depiction of the Antarctic PSC season is fairly representative and may be useful in global modeling applications. In contrast, the Arctic polar vortex is relatively warm and unstable, resulting in dramatic variability in PSC occurrence from year to year. A multi-year depiction of the Artic PSC season is not very meaningful as each year is unique.

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