POSSIBLE LINKAGE BETWEEN TROPOSPHERIC AND POLAR STRATOSPHERIC CLOUDS OBSERVED BY SPACE-BORNE LIDAR IN THE ARCTIC?

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ABSTRACT

Measurements performed with the lidar aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite were used to investigate a possible connection between the occurrence of Arctic Polar Stratospheric Clouds (PSCs) and tropospheric clouds. PSCs observed by CALIPSO during the Arctic winter 2007/08 were classified according to their type (STS, NAT, or ice) and to the kind of underlying tropospheric clouds. 172 out of 211 observed PSCs occurred in connection with tropospheric clouds. 72% of these 172 PSCs were observed above deep-tropospheric clouds. Thus, the type of a PSC seems to be connected to the characteristics of the underlying tropospheric clouds. During the Arctic winter 2007/08 PSCs consisting of ice were mainly observed in connection with deep-tropospheric cloud systems while other PSCs than ice was detected above cirrus. No correlation was found between PSC occurrence and the top temperature of tropospheric clouds. This finding suggest that Arctic PSC formation is connected to adiabatic rather than radiative cooling.

1. INTRODUCTION

Polar stratospheric clouds (PSCs) provide the surface for heterogeneous reactions which transform stable chlorine and bromine species into their highly reactive ozone-destroying states. Therefore, PSCs are important for ozone depletion during winter at high latitudes. PSC formation depends strongly on temperature. PSCs are classified into three types according to their composition and physical phase. PSCs of type Ia and Ib form at temperatures below 195 K. PSCs of type Ia are composed of nitric acid di- or trihydrate crystals (NAD, NAT), while those of type Ib include supercooled liquid ternary solutions (STS) that consist of H_2SO_4, HNO_3, and H_2O. PSCs of type II are formed below the ice-frost point and consist of pure-water ice particles. PSCs that cannot be clearly classified by optical measurements are referred to as mixed-phase clouds composed of both solid and liquid particles. Arctic PSCs are mostly formed due to gravity-wave-induced temperature modifications [1]. This effect is also important for Antarctic PSCs formation in early winter when synoptic processes are not sufficient for producing the temperatures necessary for PSC formation [2]. [3] show that more than 50% of the PSCs observed over Antarctica in summer 2006 were associated with underlying deep-tropospheric cloud systems.

Ground-based lidar measurements provide observations for investigating the occurrence and composition of PSCs. However, they are restricted to distinct locations and depend on favorable weather conditions. Space-borne lidars are independent from the situation in the troposphere. This study examines the possible relationship between the occurrence of Arctic PSCs and tropospheric clouds by using observations from the space-borne Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) aboard the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO,[4]) between December 2007 and February 2008.

2. INSTRUMENTATION AND DATA ANALYSIS

The elastic-backscatter lidar CALIOP emits light at 532 and 1064 nm. The system features three detection channels. To allow for depolarization-ratio profiling, the backscattered signal at 532 nm is split into light that is polarized parallel and perpendicular to the plane of polarization of the emitted linearly polarized laser light. A total signal is detected at 1064 nm. An overview of the instrument and the data retrieval algorithms can be found in, e.g., [4]. CALIPSO profiles are provided on a non-uniform altitude and time grid and are available from http://www-calipso.larc.nasa.gov/products/. A combination of the linear aerosol depolarization ratio δ_{aer} and the value of $1 - 1/R$, both measured at 532 nm, was used for PSC classification [5; 6; 7]. R is the backscatter ratio defined as the ratio of total to molecular backscatter. Values of unity refer to an aerosol-free atmosphere while R increases with increasing aerosol load.

Level 1 attenuated backscatter coefficients measured by CALIPSO between 60 and 83°N in the time period from December 2007 to February 2008 were used to identify and classify PSCs. A PSC is identified by $R > 1.06$ which is the threshold used for PSC classification with the Esrange lidar [1]. δ_{aer} is defined as the ratio of cross-to-co-polarized backscatter ratios [7]. The CALIPSO level 2 cloud and aerosol layer product (CAL_LID_L2_05km_CLay-Prov-V3-01) was used to obtain information about underlying tropospheric clouds (e.g., cloud top height and cloud top temperature). Additional meteorological properties were taken from the CALIPSO profile product.

The attenuated backscatter ratio was used to detect PSCs and to identify the altitude range and the spatial extent of possible underlying tropospheric clouds. Tropospheric clouds were classified into five groups: cirrus (above 7 km height), deep-tropospheric clouds (more than 6.5 km in extent, cloud top height above 7 km), mid-tropospheric clouds (below 7 km height), low clouds (at around 2 km height), and no clouds [8].

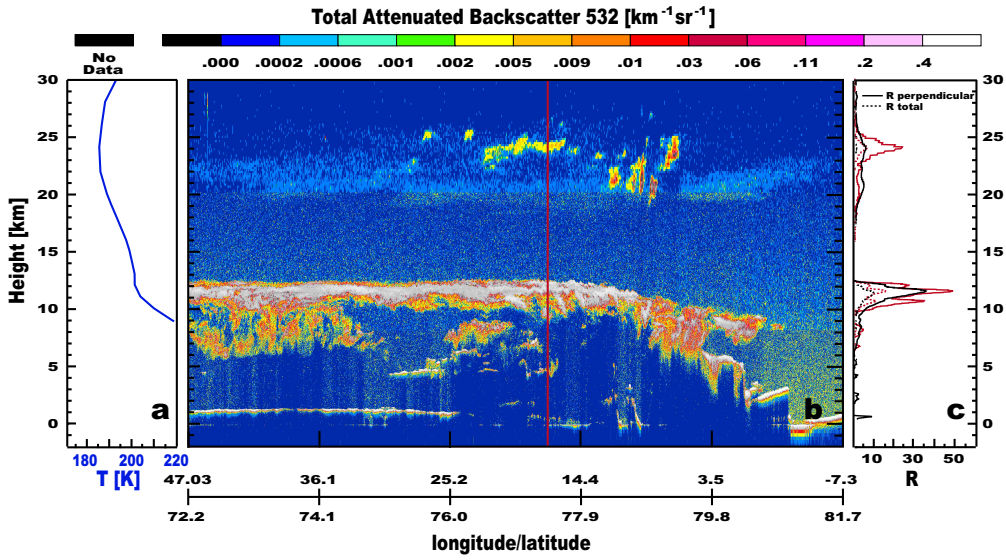

Figure 1: Observation of an inhomogeneous PSC over an deep-tropospheric cloud system as observed by the CALIPSO lidar between 0849 and 0935 UTC on 2 January 2008. (a) The stratospheric temperature averaged over the extend of the PSC. (b) The attenuated backscatter coefficient at 532 nm. The red line shows the center of the averaging window for the calculation of the backscatter ratio. (c) The perpendicular (dotted) and total (solid) backscatter ratio for an along-track longitudinal average of 1.5° (red) and 10° (black), respectively.

Figure 1 shows an example of a CALIPSO observation between 0849 and 0935 UTC on 2 January 2008. An inhomogeneous PSC (different optical characteristics and inferred composition) is visible in the color plot between 19 and 27 km height. This cloud can easily be identified in the profiles of the parallel and perpendicular backscatter ratios (Figure 1c). All kinds of tropospheric clouds considered in this study are present below the PSC in Figure 1b: deep-tropospheric clouds (72.2–79°N), cirrus and mid-tropospheric clouds (79–80°N), low clouds (80–81°N), and no clouds (north of 81°N). Different choices of longitudinal averaging intervals of the backscatter ratios (black and red lines in Figure 1c) do not change the altitude range of the observed clouds. They affect the mean backscatter ratio, which might have an impact on the PSC classification. To prevent this, different longitudinally average ranges as described in [9] were used for cloud classification. The PSC shown in Figure 1 was classified as mixed-phase PSC with STS, NAT, and ice layers according to the method of [6]. The example PSC consisted of liquid and mixed-phase particles below 23 km height and above 25 km height. Both mixed-phase particles and ice were present between these two altitude ranges.

3. RESULTS

Between 15 December 2007 and 6 February 2008 a total number of 211 PSCs could be identified from the CALIPSO lidar observations in the Arctic. A time-resolved display of these observations is given in Figure 2a. These PSCs were analyzed with respect to their composition (Figure 2b) and the type of underlying tropospheric clouds (Table 1). The highest number of PSCs was observed in early January 2008. Mixed-phase (47%) and STS clouds (37%) dominated during the period under investigation. Generally ice PSCs were rather rarely observed during that winter (11%). NAT PSCs were mainly observed during January while February was dominated by pure STS clouds. Most of the observed PSCs were associated with a concurrent occurrence of tropospheric clouds. During the entire period ice PSCs were only once observed during the absence of tropospheric clouds (Figure 2b, shaded light gray).

Table 1: Number of different tropospheric cloud types observed concurrent to the 211 PSCs detected by the CALIPSO lidar during winter 2007/2008. For comparison, the table also gives the number of deep-tropospheric clouds and low/no clouds for which no PSCs were observed.

cloud group/ cloudiness	total number	PSCs present	no PSCs present
deep-tropospheric	124	58.8%	28%
low/no	39	18.5%	41%
cirrus	22	10.4%	
mid-tropospheric	26	12.3%	

All 211 observed PSCs were classified and sorted into four different groups with respect to the underlying tropospheric cloud systems as described in Section 2. Table 1 resolves the connection between an observed PSC and the underlying tropospheric conditions. 172 out of

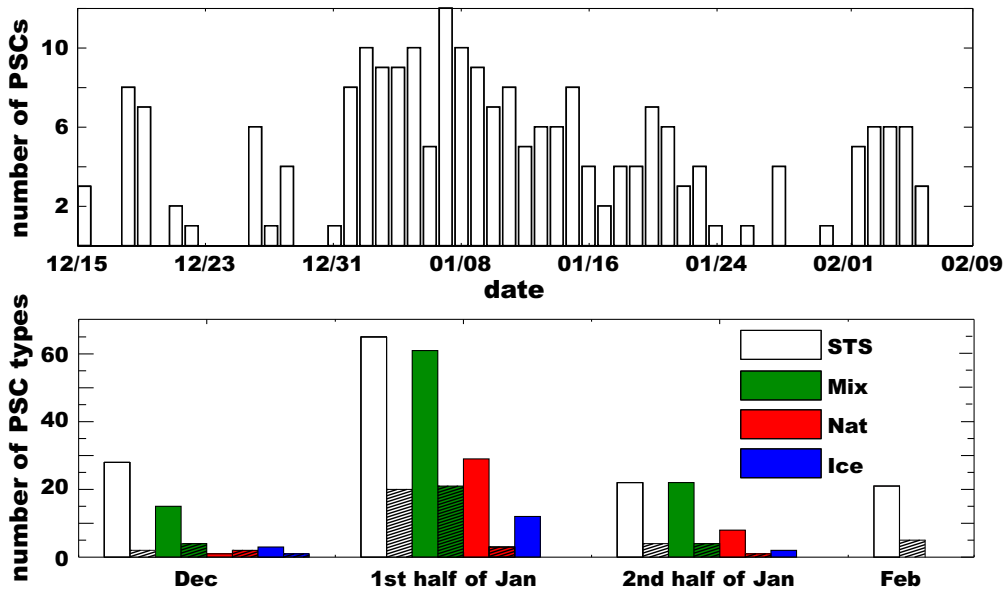

Figure 2: (a) Daily number of PSCs detected in CALIPSO measurements north of 60°N during winter 2007/2008. (b) Analysis of the PSC observations in accordance to their type (colored bars). Unshaded and shaded bars refer to observations over tropospheric clouds or during the absence of tropospheric clouds, respectively. The distribution differs from the display in (a) because individual PSCs might contain areas of different composition.

the 211 observed PSCs (81.5% of all cases) occurred in connection with tropospheric clouds. 72% of these 172 PSCs (58.8% of all PSCs) were observed over deep-tropospheric cloud systems. 26 cases of PSCs were found over mid-tropospheric clouds (12.3% of all cases) while 22 cases of PSCs were oberved over cirrus (10.4% of all cases). The remaining 39 PSCs (18.5% of all cases) showed an absence of tropospheric clouds. For comparison a deep tropospheric cloud without PSC occured during 28% of all observations (CALIPSO over passes during the winter 2007/2008).

PSCs observed during the absence of tropospheric clouds do not show a preferred type of PSC (Figure 2c). Ice PSCs were mostly observed when deep-tropospheric clouds where present. No ice PSCs were found, if cirrus was detected under the PSC. If PSCs were observed above mid-tropospheric clouds, they were mostly consisting of liquid or mixed-phase particles.

4. DISCUSSION

The relative occurrence of different PSC types seems to be affected by deep tropospheric cloud systems though the mechanism behind this remains yet unclear. For instance, deep tropospheric clouds cause radiative and adiabatic cooling in the lower stratosphere [10; 3; 8]. [10] report a linkage between tropospheric synoptic-scale baroclinic waves and PSCs formation. They suggest that PSC occurrence is dependent on tropospheric dynamics rather than mountain-generated small-scale waves. This is in agreement with our observations which show that 81.5% of the observed PSCs occured over tropospheric clouds; thereof 72% over deep-tropospheric clouds. Deep tropospheric clouds without PSCs occurred only during 28% of the CALIPSO overpasses during winter 2007/2008. The PSCs investigated in this study were distributed over the entire Arctic. However, most of them were located south of Svalbard and in the Barents Sea which suggests a rather small orographic influence.

Cooling associated with the presence of tropospheric clouds has an impact on the microphysical properties of PSCs. This is discussed by [8] who show that high and deep-tropospheric cloud systems have an significant effect on the relative occurrence of different PSC types, especially on ice PSCs. This is in agreement with our observation. The effect of additional cooling might be more important for ice particle formation than for STS formation since lower temperature is required to form stratospheric ice particles.

Deep-tropospheric cloud systems are associated with large-scale lifting and/or strong local convective and cyclonic activities. [3] investigated the connection between PSC occurrence and tropospheric clouds in the Antarctic. They conclude that PSC occurrence is strongly linked to tropospheric dynamic and radiative cooling from the underlying tropospheric clouds. To investigate the possible radiative effect on PSC formation we derive the probability of PSC occurrence as a function of the cloud top temperature (CTT) of the underlying tropospheric clouds. CTT of the highest observed tropospheric clouds in each CALIPSO profile was extracted from the CALIPSO level 2 cloud and aerosol layer product. CTT determines

the upwelling thermal radiation from the troposphere to the stratosphere and thus describes a possible radiative control on PSC occurrence. The occurrence probability (f_{PSC}) is defined as the ratio of the number of PSC observations and the total number of observations. f_{PSC} was calculated in CTT steps of 5 K but no correlation was found between the occurrence of PSCs and the top temperature of tropospheric clouds.

5. SUMMARY AND CONCLUSIONS

CALIPSO measurements were used to investigate a possible connection between PSCs and tropospheric clouds in the Arctic. A similar result as from previous studies of Antarctic PSCs was found. More than 80% of the PSCs observed between 15 December 2007 and 6 February 2008 occured in connection with tropospheric clouds. More than 58% of all PSCs were observed above deep-tropospheric clouds. No correlation between PSCs and tropospheric cloud top temperature could be indentified. This indicates that a tropospheric control of PSC occurence would be governed by adiabatic cooling connected to mesoscale cyclonic dynamics rather than by radiative cooling. Furthermore, the type of tropospheric cloud system below a PSC seems to affect their microphysical properties. This effect seems to be most important in the case of ice PSCs, since these were observed only once during the absence of tropospheric clouds. The ice formation temperature is rarely obtained in the Arctic and additional cooling is required. Adiabatically cooling above deep-tropospheric cloud systems might be the trigger for this process.

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REFERENCES

1. Blum et al. 2005: Long-term lidar observations of polar stratospheric clouds at Esrange in northern Sweden. *Tellus*, **57B**, 412–422.
2. McDonald et al. 2009: Can gravity waves significantly impact PSC occurrence in the Antarctic? *Atmos. Chem. Phys.*, **9(22)**, 8825–8840.
3. Wang et al. 2008: Association of Antarctic polar stratospheric cloud formation on tropospheric cloud systems. *Geophys. Res. Lett.*, **35**, doi:10.1029/2008GL034209.
4. Winker, D. M., et al. 2009: Overview of the CALIPSO mission and CALIOP data processing algorithms. *J. Atmos. Oceanic Technol.*, **26**, 2310-2323.
5. Adriani at al. 2005: Climatology of polar stratospheric clouds based on lidar observations from 1993 to 2001 over McMurdo Station, Antarctica. *J. Geophys. Res.*, **109**, doi: 10.1029/2004JD004800.
6. Massoli et al. 2006: Climatology of Arctic polar stratospheric clouds as measured by lidar in Ny-Ålesund, Spitsbergen (79° N, 12° E). *J. Geophys. Res.*, **111**, doi: 10.1029/2005JD005840.
7. Achtert et al. 2011: Investigation of polar stratospheric clouds in January 2008 by means of ground-based and spaceborne lidar measurements and microphysical box model simulations. *J. Geophys. Res.*, doi:10.1029/2010JD014803.
8. Adhikari et al. 2010: Microphysical properties of Antarctic polar stratospheric clouds and their dependence on tropospheric cloud systems. *J. Geophys. Res.*, **115**, doi:10.1029/2009JD012125.
9. Pitts et al. 2011: The 2009/2010 Arctic polar stratospheric cloud season: a CALIPSO perspective. *Atmos. Chem. Phys.*, **11**, 2161–2177.
10. Teitelbaum et al. 2001: Exploring polar stratospheric cloud and ozone minihole formation: The primary importance of synoptic-scale flow perturbations. *J.Geophys. Res.*, **106**, doi:10.1029/2000JD000065.