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# The vertical distribution of thin features over the Arctic analysed from CALIPSO observations

## Part II: Aerosols

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ABSTRACT

Influx of aerosols from the mid-latitudes has a wide range of impacts on the Arctic atmosphere. In this study, the capability of the CALIPSO-CALIOP instrument to provide accurate observations of aerosol layers is exploited to characterize their vertical distribution, probability density functions (PDFs) of aerosol layer thickness, base and top heights, and optical depths over the Arctic for the 4-yr period from June 2006 to May 2010. It is shown that the bulk of aerosols, from about 65% in winter to 45% in summer, are confined below the lowermost kilometer of the troposphere. In the middle troposphere (3–5 km), spring and autumn seasons show slightly higher aerosol amounts compared to other two seasons. The relative vertical distribution of aerosols shows that clean continental aerosol is the largest contributor in all seasons except in summer, when layers of polluted continental aerosols are almost as large. In winter and spring, polluted continental aerosols are the second largest contributor to the total number of observed aerosol layers, whereas clean marine aerosol is the second largest contributor in summer and autumn. The PDFs of the geometrical thickness of the observed aerosol layers peak about 400–700 m. Polluted continental and smoke aerosols, which are associated with the intrusions from mid-latitudes, have much broader distributions of optical and geometrical thicknesses, suggesting that they appear more often optically thicker and higher up in the troposphere.

## 1. Introduction

Aerosol direct and indirect effects constitute one of the largest uncertainties when balancing the radiation budget of the Earth's atmosphere. Although considerable improvements from both observational and modelling perspectives have been made to investigate aerosol effects over the last few decades, there are still large intermodel differences in estimates of aerosol direct and indirect radiative forcing. For example, while highlighting the importance of satellite measurements, the most recent intercomparison of global aerosol indirect effects modelled by climate models and evaluated using satellite data (Quaas et al., 2009) show large discrepancies and significant difficulties in reconciling model and satellite-based estimates. Specifically, for the Arctic region, Shindell et al. (2008) suggested that climate-model uncertainties in describing aerosol–cloud interactions related to physical and chemical, rather than the just transport processes are high. Prenni et al. (2007) argued that the climate model treatment of aerosol–cloud interactions over the Arctic can be unrealistic due to calibration of empirical model parameters in aerosol and cloud descriptions against observations from the lower latitudes.

*Why are aerosols over the Arctic so special*? The Arctic geography and exceptional environmental conditions coupled with synoptic scale weather patterns play a crucial role in shaping the life cycle and distribution of both natural and anthropogenic aerosols. Law and Stohl (2007) and Tomasi et al. (2007) provide a comprehensive overview of aerosols and pollution, trends in concentrations and various processes controlling sources and transport. The surface albedo over the Arctic is often high due to presence of snow and ice. Hence, deposition of absorbing aerosols can contribute to the warming of the surface (e.g. Koch and Hansen, 2005; Eleftheriadis et al., 2009; Hegg et al., 2009; Koch et al., 2009). It has been suggested that a part of the warming observed during the recent few decades over the Arctic may be due to the changes in aerosol regime (Shindell and Faluvegi,

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2009). The high surface albedo also induces a different regime in surface cloud radiative forcing. Another special feature of aerosols over the Arctic is the role of frequent winter surface inversions in temperature in regulating the vertical distribution of aerosols, preventing vertical mixing and trapping aerosols below inversion layer. A third distinguishing Arctic feature is that in the absence of or low solar radiation for a large part the year, long-wave radiative forcing of clouds becomes relatively more important. Aerosols are shown to modulate the emissivity of optically thin water clouds, present in substantial fractions compared to other regions in the world (Garrett et al., 2002; Garrett and Zhao, 2006; Lubin and Vogelmann, 2006). It has also been argued that changes in sulphate aerosol concentrations could have an impact on ice nucleation over the Arctic, altering frozen precipitation, and thereby cloudiness. An increase in precipitation could also contribute to a dehydration of the troposphere (Blanchet and Girard, 1994), thereby reducing the greenhouse forcing by water vapour. Finally, the role of atmospheric circulation in the Arctic is also very important in aerosol distribution (Eckhardt et al., 2003; Sharma et al., 2006) because there are few anthropogenic sources inside the region. Stohl (2006) discussed pathways through which pollution transport and distribution can take place from different regions in the northern hemisphere. Arctic haze is the manifestation of such transport of pollutants from the mid-latitudes during winter and spring seasons. These pollutants are of mainly anthropogenic origin (cf. Quinn et al., 2007, and references therein for a comprehensive overview). However, it is also shown that the air-mass transport alone is not sufficient to explain the observed change from an accumulation-mode (size $>100$ nm) dominated aerosol regime to Aitken-mode (20–100 nm), dominating from spring to summer in the Arctic. Rapid changes in incoming solar radiation in the transition seasons are also suggested to play a crucial role (Engvall et al., 2008). Their analysis of the temporal evolution of the condensational sink and $SO_2$ concentrations suggests that these processes to a large degree compensate each other and that nucleation potential is mainly driven by solar radiation in a relatively short time window of about 10 days. All of these aspects add to the complexities in understanding and modelling aerosol effects in the Arctic.

For a full characterization of the aerosols, the macrophysical properties of aerosol layers are needed in addition to the chemical and microphysical properties of the aerosol. With the launch of the Cloud and Aerosol Lidar with Orthogonal Polarization (CALIOP) instrument onboard NASA's Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite (Winker et al., 2009), it is for the first time possible to investigate vertical structures of aerosols on large scales and extended time periods. This paper is the second of a two-part series where we capitalize precisely on the unique capability of the CALIOP instrument to provide reliable and accurate observations of thin clouds (Devasthale et al., 2011) and aerosols over the Arctic. We here characterize the macrophysical properties of aerosol layers in such terms as vertical distribution and probability density functions (PDFs) of aerosol layer thickness, layer base and top heights. In addition, we present statistical distributions of aerosol layer optical depths and also discuss the seasonal variability of these properties. The analysis cover a large part of the circumpolar Arctic, here defined as 67–82°N (note that the satellite coverage is limited to $<\sim$82°N). The paper is organized as follows. The next section provides a brief description of the data, followed by a discussion of the results. Finally, the conclusions are given in the last section.

## 2. The CALIPSO data

For this study we have used the standard CALIPSO 5 km Aerosol Layer Version 3 Product. Specifically, the retrievals of aerosol layer base and top heights, and optical depth at the 532 nm wavelength are analysed. For a description of all retrieval algorithms and their evaluation for CALIPSO products, the readers are referred to the special issue in the *Journal of Atmospheric and Oceanic Technology* (Liu et al., 2009; Omar et al., 2009; Vaughan et al., 2009; Winker et al., 2009; Young and Vaughan, 2009). The theoretical basis and the evaluation of the aerosol identification procedure can be found in Omar et al. (2005,2009). A rigorous quality control is applied while selecting the data for this analysis. For example, only features classified as aerosol with the classification quality flag set to 'high' are used for this analysis. This ensures that the aerosol/cloud discrimination is accomplished with a high confidence (Liu et al., 2009). The aerosols are further categorized into six different types, based on their integrated attenuated backscatter and volume depolarization ratios along with ancillary information on surface type and altitude. Six aerosol types are analysed; 'clean continental', 'polluted continental', 'dust', 'polluted dust', 'clean marine' and 'smoke'. The theoretical basis and evaluation of the aerosol identification procedure can be found in Omar et al. (2009).

The data used in this study cover the 4-yr period from June 2006 to May 2010 and are analysed for four seasons separately, winter (December, January and February; DJF), spring (March, April and May; MAM), summer (June, July and August; JJA) and autumn (September, October and November; SON). It should be noted that due to the narrow swath of CALIOP and the orbital configuration of the CALIPSO satellite, observations poleward of approximately 82°N are not available. However, it should also be noted that the sampling frequency of CALIPSO is very high compared to other regions of the world, due to multiple passes over this study area, thus providing sufficient samples for the statistical analysis. Figure 1 shows the total number of aerosol layers finally used for the analysis for each season, although at the same time providing an overview of the study domain. It is clear that the data coverage is not homogeneous in space, nor is it the same in all seasons. Most data is available in winter and least data is available for summer, likely an effect of the large cloud cover over the Arctic Ocean during the latter

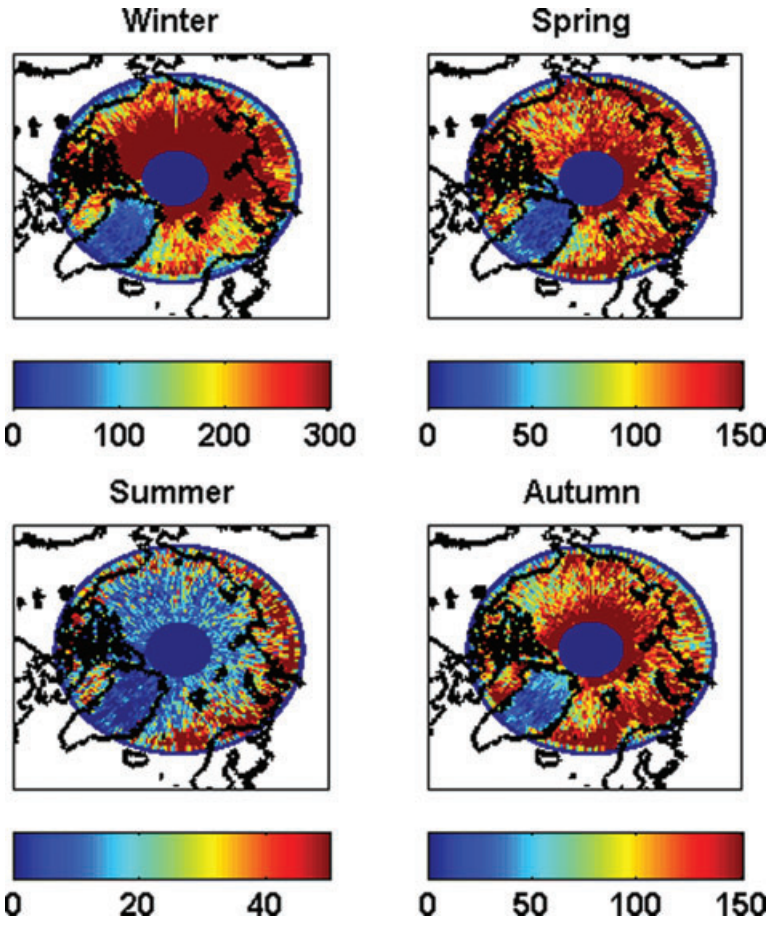


*Fig. 1.* Total number of observations used in the analysis for four seasons after applying high-quality flags mentioned in Section 2.

period. It is possible that the higher nighttime signal to noise ratios of the CALIOP instrument allow the detection of more features during the Arctic winter. It should also be noted that the domain covers different types of surface at different times of the year. For example, in summer most of the area over the northern North Atlantic will be open water whereas in other parts of the domain the ocean will be completely or partially ice covered even in summer. In winter, on the other hand, the same subdomain will have substantial ice cover. There is a bias in summer to more data coming from the southern portions of the domain and particularly over land, whereas in all other seasons there is more data available with increasing longitude, except for over the northern North Atlantic. Differences such as these will affect, for example, any dominance from aerosols with marine or oceanic origin.

## 3. Results and discussions

Broadly speaking, there are three main reasons as to why information on aerosol layer base and top heights, and their thickness is important. First, aerosol chemistry and also various physical processes are, to some degree, governed by the vertical location of the aerosol layer in the atmosphere. For example, the fate of aerosols trapped below a strong persistent inversion layer and of those above is likely to be different. Secondly, aerosol direct and indirect effects are sensitive to the vertical distribution of aerosol layers and their thickness in addition to chemical composition and microphysical properties and their collocation with cloud layers. Thirdly, it is imperative to evaluate whether the global and/or regional climate models, that are used to study aerosol–cloud interactions, can statistically reproduce the observed vertical distribution of aerosols over the Arctic in order to test their fidelity. Statistics such as presented here therefore become an important metric in model evaluation.

In this section, the emphasis is on describing the vertical distribution of aerosol layers over the Arctic for the four seasons along with computing PDFs of aerosol layer base and top height, and geometrical thickness. Figure 2 shows the relative frequency of occurrence of the number of aerosol layers at any given time. It can be seen that single-layer aerosol profiles dominate occurring about 65–85% of the time most common in summer, whereas double layers occur about 10–25% of the time, least in summer. There are also instances when multiple aerosol layers occur. This may be connected to differences in thermal stratification in different seasons. In winter it is more common with strong surface inversion (e.g. Tjernström and Graverssen, 2009) that

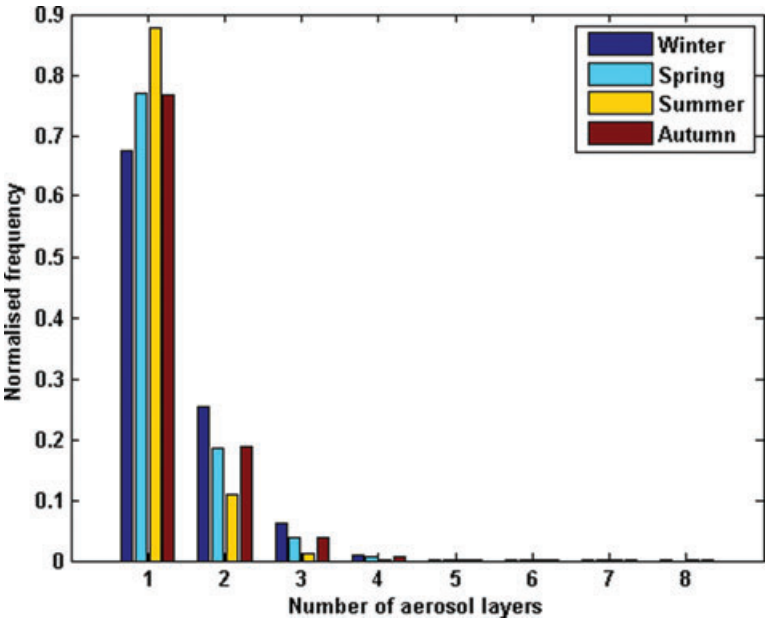


*Fig. 2.* The relative frequency of occurrence of the number of aerosol layers over the study area (180°W–180°E, 67–82°N).

serve to trap aerosols from local and regional sources (e.g. from the Eurasia region) close to the surface and separating them from long-range transported aerosols aloft. Conversely, in summer, vertical mixing is stronger and scavenging of aerosols by wet deposition is very frequent, especially in the marginal ice zone.

Figure 3 shows the zonal-height distribution of aerosol layers for the winter, spring, summer and autumn seasons. Note the absence of observations around 20–60°W in the lowermost troposphere, due to the effect of the topography of Greenland (the altitude scale here is relative to sea level). Strong intraannual variability in the vertical distribution of aerosols is evident. In winter, the bulk of aerosols are concentrated in the lowermost kilometer of the troposphere over the areas corresponding to the Kara, Laptev, East Siberian, Chukchi and Beaufort Seas, and also over the Canadian archipelago (Fig. 1a). Strong surface inversions are common in winter, preventing vertical mixing. Devasthale et al. (2010) using Atmospheric Infrared Sounder (AIRS) satellite sensor data for clear sky cases over the Arctic found surface inversion strength ∼7–9 K, whereas Tjernström and Graversen (2009) found surface inversions from the Surface Heat Budget of the Arctic Ocean (SHEBA) measurements to be ∼8–12 K. This is illustrated in Fig. 4 showing the vertical distribution of the relative frequency of occurrence of aerosols and the corresponding mean clear-sky inversion strength over the Arctic Circle for the winter months of 2006–2010. The temperature profiles were extracted from the AIRS onboard Aqua satellite and the inversion strength is calculated with respect to surface skin temperature. It is clear that aerosol layers in winter are often capped by strong surface inversions.

In spring inversions are weaker and long-range transport of pollutants and biomass-burning aerosols from the European continent (Treffeisen et al., 2007), Russia (Warneke et al., 2010) and consequent Arctic haze contributes substantially to aerosol abundance in the lower and middle troposphere. In summer, when inversion strength is the weakest and long-range transport less effective, a more heterogeneous aerosol distribution is observed. Three features stand out in summer. The maximum concentrations of aerosols: (a) over 0–60°E in the lowermost 2 km, likely due to low-level transport of continental pollution and biomass burning from Europe; (b) over 100–140°E slightly elevated around 1–3 km, likely from forest fires in Siberia (e.g. Generoso et al., 2007), also see the distribution of available observation (Fig. 1) and (c) similarly over 180–80°W from Russia, East Asia and North America (e.g. see O'Neill et al., 2008; Stone et al., 2008; Eck et al., 2009).

The relative vertical distribution of aerosols (Fig. 5a) displays a maximum below 1 km in all seasons. In summer, the vertical distribution is broader in the lowermost 2 km compared to other seasons. These aerosols above the boundary layer may have come from the long-range transport. About 65% aerosol layers in winter and 45% in summer reside below the lowermost 1 km of the troposphere (Fig. 5b). In the middle troposphere (3–5 km), spring and autumn seasons show slightly higher aerosol amounts compared to other two seasons. We also analysed the relative contribution of the layers of six different aerosol types in the Arctic atmosphere to the total aerosol loading, as shown in Fig. 6. In general, clean continental aerosol layers dominate in all seasons except in summer, when clean marine aerosols are almost as large followed by polluted continental. Clean continental and marine aerosols are essentially the background aerosols, which are devoid of any strong biomass or fossil fuel burning signatures (Omar et al., 2009). Continental pollution, manifested as the Arctic haze over the study area in winter and spring, is the second largest contributor to the total

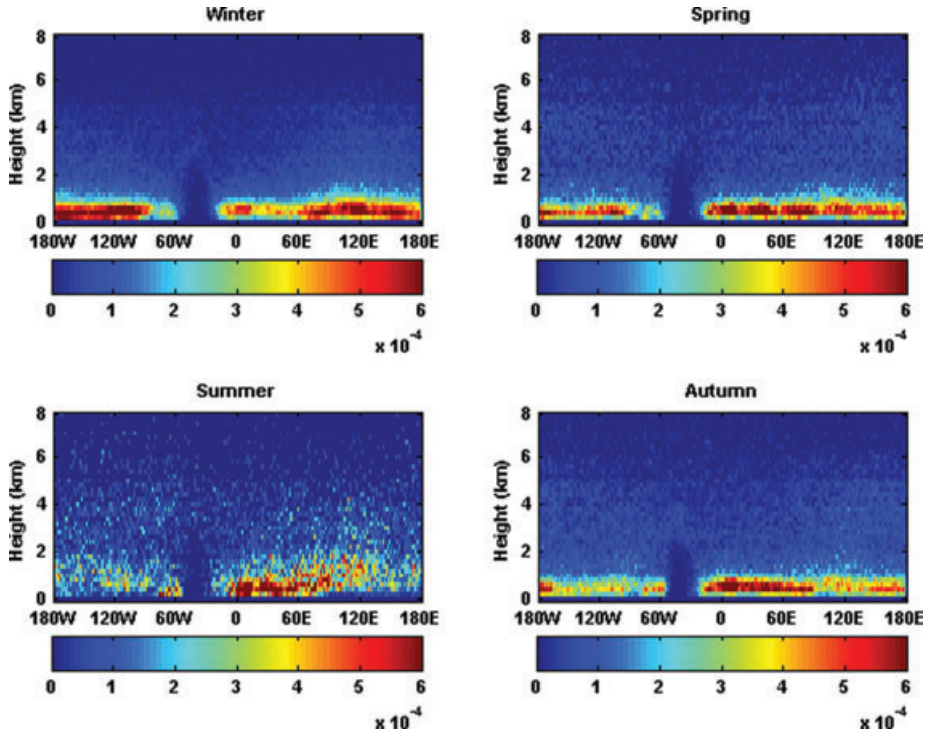


*Fig. 3.* Zonal-height distribution of aerosol layers over the study area. The height on *Y*-axis is in km. Each longitude-height bin is normalized by the total number of aerosol layer observations accumulated over the entire joint histogram.

number of aerosol layers followed by polluted dust layers. In spring, the number of aerosol layers with signatures of polluted dust and smoke increases. However in summer, clean marine and smoke aerosol layers show a dramatic increase compared to other seasons with first being the second largest contributor, only marginally smaller than clean continental. It should be noted, however, that most observations in summer comes from land areas and contributions from marine sources may be underestimated, so that clean marine aerosols may in fact dominate in summer. The peak in the vertical distribution observed near the surface in summer is mainly due to the clean marine aerosols, formed due to biological activity following the abundance of solar radiation (Leck and Persson, 1996). Although solar radiation plays a role, surface winds are also a large driver of the marine aerosol loading.

Figures 7, 8 and 9 show the PDFs of layer base and top heights, and layer geometrical thicknesses respectively for these six aerosols types. These figures also depict seasonal variations in aerosol types as a function of height. It can be deduced from these PDFs that while the clean marine and continental aerosols are mostly observed in the lowermost 2 km dominating the near surface distribution, the contribution from smoke and dust aerosol increases with height at 3–6 km. It is also to be noted that, except for clean marine aerosols, the distributions for other aerosol types are very broad and long-tailed. Seasonality in the peaks of different aerosol types is also visible. Smoke aerosols show the largest seasonal variability in its vertical distribution. Figure 9 shows that the most of the observed aerosol layers have geometrical thickness of about 400–700 m. This narrow range is a consequence of surface-dominated sources combined with limited vertical mixing in the lower troposphere. Polluted continental and smoke aerosol layers have a broader distribution in winter, spring and autumn with a larger average geometrical thickness. Smoke aerosols likely more often emanate from buoyant plumes, for example forest fires, and therefore have a larger likelihood to reach a higher altitude, while polluted continental aerosols typically come from more distant source regions and are therefore more affected by lifting in synoptic weather systems.

In comparison to northern mid-latitudes, aerosol–cloud interactions over the Arctic are tightly constrained by the availability of aerosols. The transmissivity of clean Arctic atmosphere is high and very sensitive to even small changes in aerosol burden. The aerosol optical depth (AOD) is a first-hand metric to monitor changes in aerosol burden. However, the retrievals of AOD from the passive imagers are extremely difficult over the Arctic and monitoring AOD then solely relies on very sparse in situ measurements. CALIOP provides estimates of AOD at unprecedented accuracy over the Arctic and, more importantly, during nighttime conditions that in the Arctic prevail during a large part of winter.

The selection of an accurate lidar ratio (extinction-to-backscatter ratio) for different aerosol types is a key step in estimating extinctions from CALIOP observations. For this study,

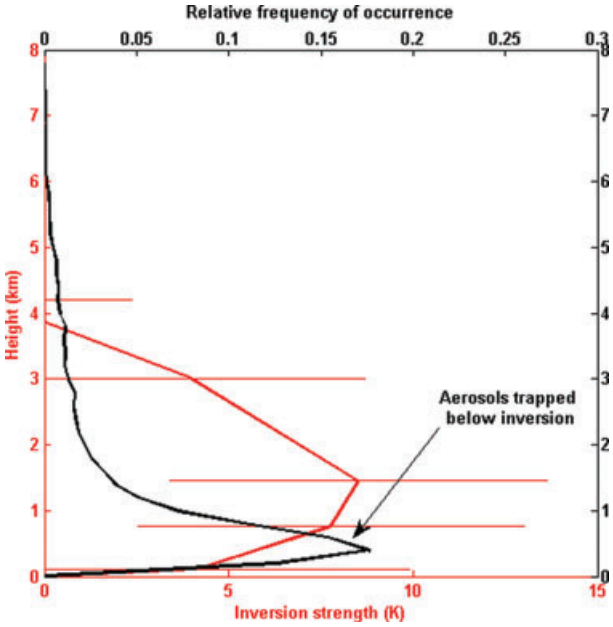


*Fig. 4.* The vertical distribution of the relative frequency of occurrence of aerosols and the mean clear-sky inversion strength over the Arctic Circle for the winter months of 2006–2009. Red horizontal lines are the standard deviation of inversion strength over the same period. The temperature profiles from the Atmospheric Infrared Sounder (AIRS) onboard Aqua satellite are used to compute the inversion strength (with respect to surface skin temperature) for the same period. Note that the both *x*-axes are independent of each other and their range is adjusted to better illustrate the point that the strong inversions in the Arctic during winter season regulate the vertical distribution of aerosols.

the selected lidar ratios at 532 nm were 20, 40, 70, 35, 55 and 70 for clean marine, dust, polluted continental, clean continental, polluted dust and smoke aerosols, respectively. Figure 10 shows the PDFs of aerosol-layer optical depths for the four seasons and for different aerosol types. In general, when compared to the mid-latitudes and tropical regions, aerosol optical depths are small (less than 0.1) in most of the cases for all aerosol types. When compared qualitatively, the range of AOD values is consistent with previous studies (e.g. Quinn et al., 2007; Tomasi et al., 2007). For example, Herber et al. (2002) using long-term record of aerosol optical depth at the 532 nm wavelength at the Koldewey station in Ny-Ålesund, Spitzbergen from 1994 to 2000 show that the optical depths were mostly below 0.1. Observations of very high optical depths associated with the episodes of strong pollution have also been reported in numerous studies (Quinn et al., 2007; Tomasi et al., 2007; Treffeisen et al., 2007; Stone et al., 2008; Eck et al., 2009, and references therein).

The PDFs of polluted continental and smoke aerosol layer optical depths are broad and have higher mean values. This provides an independent confirmation that the influx of aerosols in the Arctic is associated with strong pollution events originated in the mid-latitudes, where the sources of these two aerosol types are located. Recently, Mauritsen et al. (2010) identified two regimes over the Arctic during summer season. Although in one regime, referred to as a tenuous cloud regime with cloud condensation nuclei less than 10 $cm^{-3}$, an increase in the aerosol burden leads to a strong net warming of the surface, in the other regime with cloud condensation nuclei greater than 10 $cm^{-3}$, increasing the aerosol burden further exerts a weak relative surface cooling (note that the clouds in this case are always warming the surface). Based on a summary of results for expeditions in the central Arctic, the tenuous cloud regime is present about 30% of the time in late summer. Transport of aerosols from mid-latitudes and their spatio-temporal distribution over the Arctic will certainly have an impact on the net effect from changes in these two regimes. The broader distribution of aerosol layer optical depth and geometrical thickness of smoke and polluted continental aerosols during all seasons indicates that not only the regimes of liquid water clouds, but also mixed phase and ice clouds would be influenced. For example, polluted continental aerosols are second largest contributor (Fig. 6) to the total aerosol burden over the inner Arctic (Fig. 1) in winter, when

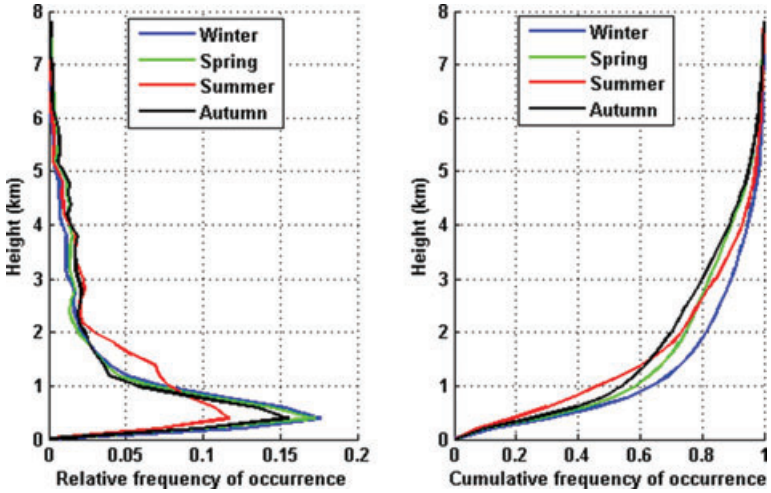


*Fig. 5.* The vertical frequency of occurrence of aerosol layers for four seasons computed over the study area. In the left panel, the frequency of occurrence of aerosols at each height bin on *y*-axis is normalized by the total number of aerosol layer observations accumulated over the *y*-axis for a particular season. The right panel shows the cumulative frequency of occurrence.

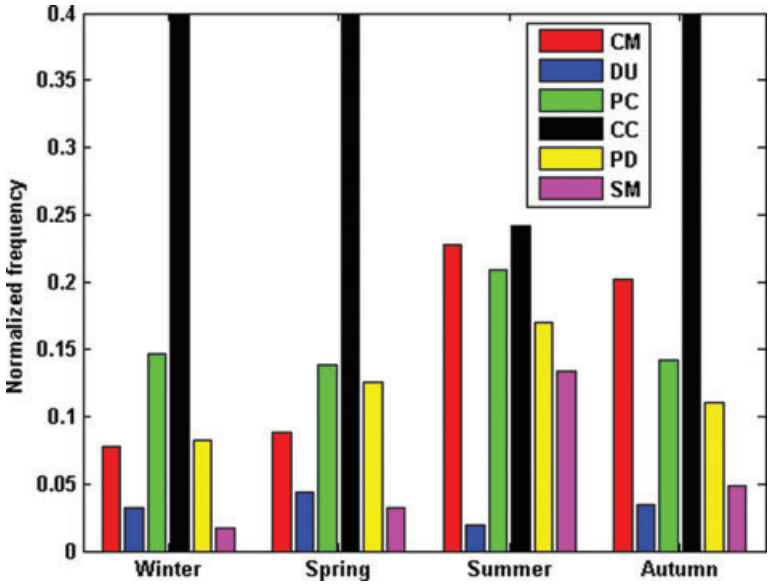


*Fig. 6.* The relative frequency of occurrence of layers of six aerosol types over the study area. For each season, frequency of occurrence of each aerosol type is normalized by the total number of aerosol layer observations in that season. The abbreviations for aerosol types are: CM, clean marine; DU, dust; PC, polluted continental; CC, clean continental; PD, polluted dust and SM, smoke. The histograms for CC in winter, spring and autumn seasons peak at 0.64, 0.57 and 0.46, respectively.

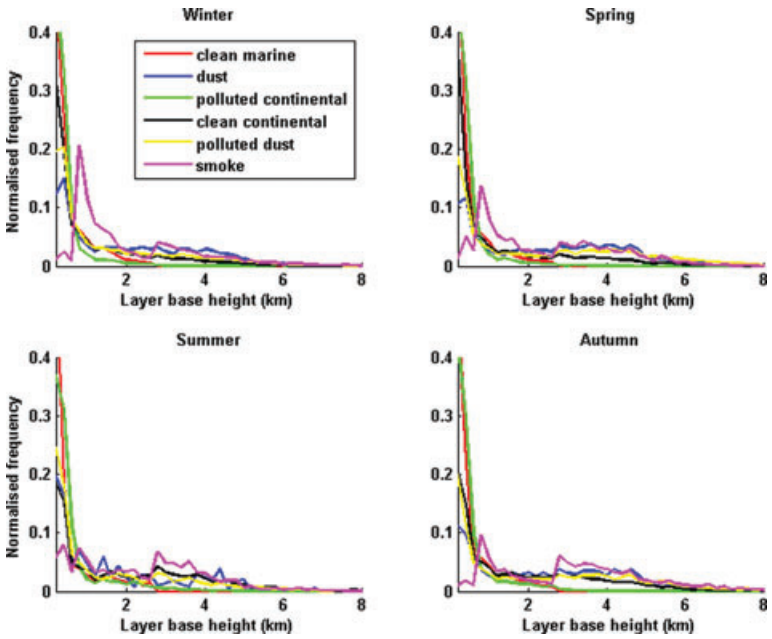


*Fig. 7.* PDFs of aerosol layer base heights for six aerosol types and their seasonality.

ice clouds are predominant. Continuous monitoring of aerosols over the Arctic, the region that has experienced an enhanced surface warming compared to the rest of the Earth over the recent decades, using integrated in situ (e.g. Polar-AOD, Tomasi et al., 2007) and satellite networks becomes important to evaluate and predict changes in atmospheric composition associated with the changes in mid-latitude regions using climate models.

## 4. Summary and conclusions

The CALIOP instrument offers accurate and simultaneous retrievals of three important aerosol characteristics: the vertical structure, speciation and optical depths. This capability of CALIOP is exploited in this study to investigate aerosol layer vertical distribution, layer base and top heights, and their geometrical thickness over the large part of the Arctic (67–82°N, 180–180°E) using 4 yr of data from June 2006 to May 2010. The zonal-height structure of aerosols over the study area is also studied as well as the seasonal variation. Six aerosol subtypes provided in the data set, based on their attenuated backscatter and volume depolarization ratios (sensitive to shape, size and composition), are analysed and the PDFs of aerosol layer optical depths are also investigated.

The intraannual variability in the vertical distribution of aerosols is clearly seen in the observations with the bulk of aerosols confined below the lowermost kilometer due to

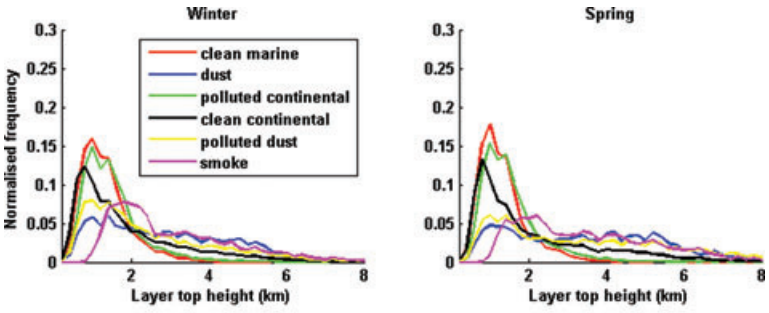


*Fig. 8.* Same as Fig. 7, but for aerosol layer top heights.

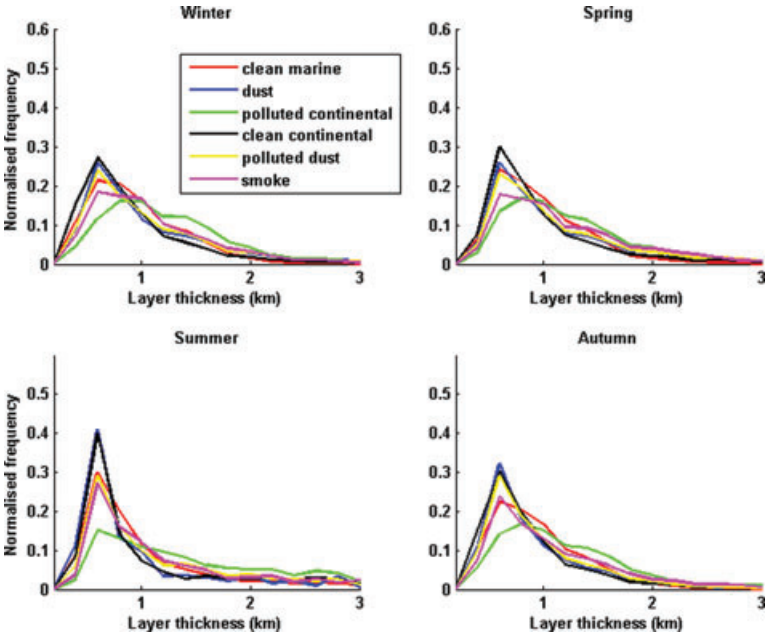


*Fig. 9.* PDFs of aerosol layer geometrical thickness and their seasonal variations.

persistent inversions. About 65% aerosol layers in winter and 45% in summer reside within the lowermost kilometer of the troposphere. In the middle troposphere (3–5 km), spring and autumn seasons show slightly higher aerosol amounts compared to other two seasons. This is likely an effect of the more active synoptic scale activity in these seasons compared to summer, although the frequent strong surface inversions become less prominent compared to winter. The relative vertical distribution of aerosols shows that the contribution of clean continental aerosol layers is the largest in all seasons, although only marginally in summer. In winter and spring, polluted continental aerosols are the second largest contributor to the total number of observed aerosol layers, whereas clean marine aerosol layers are the second largest contributor in summer and autumn; this is likely due to the larger open water surfaces in these seasons. The increase of clean marine aerosols in summer may even be an underestimation due to a selective undersampling of the Arctic Ocean in summer. The PDFs of the geometrical thickness of the observed aerosol layers peak about 400–700 m. Polluted continental and smoke aerosols, which are associated with the intrusions from mid-latitudes, have much broader distributions of both optical and geometrical thickness.

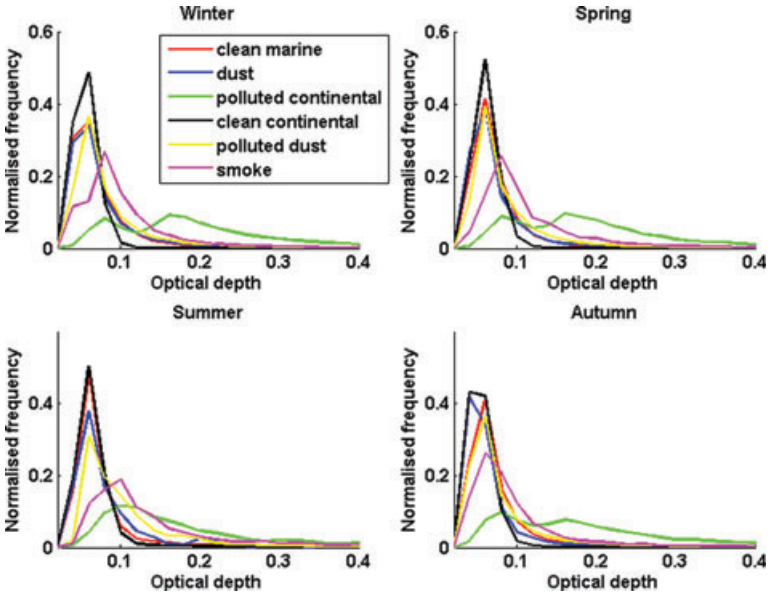


*Fig. 10.* The PDFs of aerosol layer optical depth for different aerosol types. The bin size on *x*-axis is 0.02.

It is to be cautiously noted here that these conclusions are based on only 4 yr of data and thus may not be representative for the Arctic atmosphere in a climatological sense. Neither is it possible from these four years to estimate any trends in time. Nevertheless, they bring out the major macrophysical properties of aerosols over the Arctic. In future, these observations should be integrated with full complexity chemistry transport models to gain further insights into the aerosol–cloud climate interactions over the Arctic.

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