Reply to Referee #2 (anonymous)

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In comparison to the first Reply, we re-considered the terminology concerning haze and droplets.

We would like to thank the anonymous referee for the valuable comments which improved the paper significantly. We re-organized the paper focusing on the new aspects of our observations. The objectives of the paper were pointed out more clearly. Our results are discussed in detail in the context of other articles. A native speaker helped to improve the use of the English language. The detailed replies to the reviewer's comments in quotation marks are given below.

1) focus of the paper

"I do think the paper can be improved substantially by just reorganizing the focus of the material."

We revised the manuscript with a focus on the new aspects of our findings and discussed them more in detail.

2) presentation

"The English presentation is very strained, and could benefit from a thorough review of a technical editor."

A native speaker reviewed the manuscript to improve the English.

"Furthermore, the decision to break up each case into a description, analysis, and then separate discussion makes the paper very blocky and difficult to read. If a central thesis is presented, followed by support for the thesis, the article would read much easier, and hence get read a lot more."

The structure of the manuscript was also revised. Now each case study is presented and discussed in one separate section without further subdivisions.

3) purpose of the article

"After reading through the article several times, I was still left with the question what the purpose of article was. The paper details results from four isolated cases observed by the group, but the best conclusion the very strong group of authors could come up with was that they have show that lidars can detect information of the whole range from subvisible to optically thick clouds. This conclusion came as a surprise considering the multitude of citations in the paper to other work that suggests the same.
The collection of cases clearly represents the spectrum of interesting observations they observed during the experiment. However, the cases are quite distinct, and the authors make no attempt to weave a coherent thesis other than that the lidar can see a whole range of clouds."

We pointed out more clearly the purpose of the article: In the context of the atmospheric conditions of the ASTAR 2007 campaign, we presented different lidar observations of clouds with surprising properties in the boundary layer and in the free troposphere, which are different to what one might expect from studying examples of Arctic clouds in the literature. The findings were analyzed in the light of the meteorological situation. The studies might be a challenge for numerical simulations, which we plan to perform as part of ongoing work. However, these numerical analyses are beyond the scope of this article.

4) Specific comments

Section 3.1.

"It is not clear to me what the significance of this result is that cloud cover change over such a short period. Nor do I see how figure one supports the assertion that it does. This section may easily be deleted."

The section provides an overview of the cloud cover at different altitudes for the whole period of the ASTAR 2007 campaign. As the atmospheric conditions of this time were unusual concerning the aerosol load (no pronounced Arctic haze observations), we do consider it interesting to comment on the general evolution of cloud cover during the same time. Also cloud cover varies substantially from year to year. This has a high impact on the radiation budget, and a significant decrease of cloud cover might even be partly responsible for enhanced melting of sea ice (e.g. Kay et al., 2008). We added this justification in the text.

Section 3.2

"I was intrigued by the first case, and am still not sure exactly what we are looking at there. I have no idea what is meant by pre-condensed liquid droplets. I asked an aerosol scientist and cloud physicist if they knew what a pre-condensation particle was, but also to them it was unknown terminology. The discussion suggests that these are pure liquid drops, with an effective radius of 280 nm. At atmospheric saturation ratios such drops would have to be unstable drop embryos, which I find highly unlikely. Why would such big pure liquid embryos form in a coherent layer? Can you really exclude any hygroscopic aerosol, and hence arctic haze? Why not a swollen aerosol particle slightly different composition than observed before? I do not have a good feel for how sensitive the inversion code is, but it seems to me that if you want to come to the conclusion presented that more prove needs to be provided. The HYSPLIT analysis discussion in this context is pure speculation. If the result can be substantiated, it may be interesting enough to constitute a separate article, but as is I'm skeptical."

As stated in the manuscript, the very low depolarization values indicate the existence of spherical particles. In contrast, the typical Arctic haze observations have revealed a significantly higher depolarization of 2-5 %, as e.g. described in Hoffmann et al. (2009). For this reason, our first guess was that we observed liquid cloud droplets. However, the retrieved particle size is clearly below the typical size of cloud droplets (diameter around 10 micron). Further, the typical Arctic haze is usually observed within dry air (Ishii et al., 1999). Therefore, the high relative humidity measured by the radiosonde suggests a different situation. Our best explanation is that we observed spherical haze droplets. We exchanged the expression "pre-condensation particles" against the more neutral "spherical haze droplets". Further, we added in the text observations of in situ measurements on the nearby Zeppelin mountain of that day, which also showed low values of aerosol, and an overview picture of the MPL lidar which shows the slow dissolution of the layer.

Concerning the sensitivity of the code, we are confident about the results for the following reasons, also mentioned to Referee 1:

The retrieval of microphysical properties from remote sensing data is an ill-posed problem. Hence, small variations in the input data can greatly influence the result (but as Referee 1 states a result is [almost] always obtained). The mathematical concept in finding a stable solution is called regularisation. The theory was carried out by Böckmann (2001) and Veselovskii et al. (2002). A validation was for example given by Wandinger et al. (2002). This quote was added in the manuscript as it demonstrates that a successful inversion from lidar data can be done. Our code uses an improved version of Böckmann (2001). The mathematical approach for a more precise determination of the aerosol number concentration can be found at Böckmann et al. (2006). This information was emitted for brevity as the main idea remains unchanged. We suggest not to quote the latter paper in our manuscript as it is strictly mathematical and not mandatory for the general idea.

Extensive tests were performed to validate our code. Extinction and backscatter coefficients were calculated "forwards" from an arbitrary aerosol distribution, noise was added to the data and the inversion's ability to retrieve the aerosol distribution was analyzed. Moreover, for this work, several inversion runs with lidar data from different altitudes and times were performed from which the given error estimation was derived.

Both Referees mentioned that the HYSPLIT analysis of precipitation is not very convincing. We agree with this opinion. However, our main point of using the trajectory analysis was to obtain information about the path of the air masses and the possible uptake of pollution. We reduced the information concerning precipitation as following:

> HYSPLIT analyses suggest that the probed air masses were confined to the boundary layer until 2 days before their arrival with only minimal precipitation (less than 1 mm). They reached the Siberian coast 6 days before the observation. Hence, a contamination with aerosol from the open sea or Eurasia cannot be ruled out.

5) Minor comments

We thank the referee for pointing out the spelling errors and corrected them.

Page 15141 line 13.

"It is not clear to me what is meant in this sentence."

We changed the sentence to
HYSPLIT analyses suggest that the probed air masses were confined to the boundary layer until 2 days before their arrival with only minimal precipitation (less than 1 mm). They reached the Siberian coast 6 days before the observation.

Page 15144 first paragraph

"There is something peculiar about these clouds (or measurements) that allow the lidar to penetrate through optical thicknesses of 15. In the conclusions you argue for small inhomogeneities in the cloud. Can this be quantified? A cursory look at the arctic HRSL site suggest that this is not a common occurrence."

The referee is right - the lidar penetration of this cloud needs more explanation. We added in the text:

> Assuming pure water clouds, the maximum cloud optical thickness estimated from albedometer data shows values around 13-17 for the more homogeneous cloud deck in the South. In the mixing zone starting at 09:00 UTC, the maximum optical thickness was lower (11-13 assuming pure ice). Despite this high maximum optical thickness, the lidar penetrated the clouds for most time steps due to cloud inhomogeneities and the long integration time of 15 s. For a shorter integration time of 1 s, about every 15th lidar profile reached the ground. This corresponds to "cloud gaps" with a distance of about 1 km. Similar variability of marine stratocumulus clouds with a scale of 1-5 km was reported by Boers et al. (1988).

Page 15149 lines 5 through 20.

"Pure speculation. Remove."

In the text, we mention explicitly that the proposed formation mechanisms of the cloud are possibilities, not facts. However, we consider the analyses of the location and the ECMWF data of the wind field important information to understand the cloud. Hopefully, mesoscale modeling of the clouds can give more evidence of the true processes taking place.

Page 15149 line 26 until Page 15151 line 26:

According to the referee's comment that our conclusions about the capabilities of lidar cloud measurements are "mundane", we removed the very general Section 4. Therefore, the comments have not been answered. In the article, we now focus on the special cloud observations in the last section:

4 Summary: Arctic clouds observed by lidar technique

In this article, an overview of the cloud situation in Ny-Ålesund (Svalbard) during March and April 2007 was presented. In this time period, the cloud cover of low level clouds (cloud top below 2.5 km) increased from 51 % to 65 %. The lidar data of four individual case studies (A - D) of noticeable clouds were analyzed in detail. They showed special properties of Arctic clouds and indicated links between cloud processes and the meteorological conditions.

The observations of case A revealed an optically thin layer of enhanced backscatter and very low depolarization at low temperatures (-30 °C). The inversion of the Raman lidar data provided an estimate of the particle size, which was in the range of 280 nm. This is the typical order of magnitude of aerosol. However, the optical properties suggest differences to the typical Arctic haze. As no strong events of Arctic haze were observed in this time period (Hoffmann et al., 2009, this issue) and only low concentrations of aerosol were recorded by in situ measurements on this day, we hypothesize that we observed hydrophilic aerosol of local origin (e.g. sulfate from sea spray) dissolved in water at the altitude of a dissolving cloud. The observations of case A, a layer consisting of sub-micron spherical haze particles at low temperatures (-30

°C), may be of importance for radiative transfer calculations and climate modeling and an interesting example of cloud and aerosol interaction even in a pristine environment.

Case B describes a mixed-phase cloud system above the open ocean, which experiences a change in air masses. At the air mass intersection, the characteristic vertical structure of a liquid layer on top and an ice layer below was not observed. Instead, the whole cloud consisted of ice only, as evidenced by airborne lidar and confirmed by spectral radiation measurements. The glaciation process remained confined to a small cloud band of about 1-2 km horizontal extent, as was shown by subsequent in situ measurements at the air mass intersection. Our results confirm that a major atmospheric disturbance such as a change in the air mass has a strong impact on the cloud thermodynamic phase.

Case C represents an example of an ice cloud with a highly variable internal structure. The observation of ice cloud layers with very different optical properties seems a special case compared to the microphysical findings of Korolev et al. (2000) and Bailey and Hallett (2002), who describe prevailing irregular structures of ice crystals for a wide temperature range. A high backscatter peak for the 355 nm wavelength, resulting in a low LR was found. Our observations emphasize that even in a pristine Arctic environment without anthropogenic pollution, ice clouds cannot be considered as a homogeneous, simple phenomenon. This poses a challenge for the precise description of pure ice clouds in numerical simulations.

Case D describes the observation of a double-layer cloud at 4 km altitude. At a temperature of about -25 °C, we recorded two geometrically and optically thin individual liquid cloud layers. Below each layer, ice precipitation was found. Multi-layer cloud systems consisting of geometrically thin liquid cloud layers are observed regularly in the Arctic boundary layer (Verlinde et al., 2007, Luo et al., 2008). The temperature inversion plays a key role for the formation processes (Curry et al., 1997). The analysis of the meteorological conditions suggests that the formation of the observed double layer structure was influenced by local orography, which induces lee waves and affects the wind field even in the free troposphere.

Little is known about the frequency of occurrence of subvisible clouds and their radiative impact in the Arctic. Additionally to the two cases provided in this article (case C and D), other examples of optically thin Arctic clouds observed by lidar technique were presented by Lampert et al. (2009, this issue) and Hoffmann et al. (2009, this issue). The study of Wyser and Jones (2005) suggests the frequent existence of optically thin clouds in winter, as the monthly mean cloud cover during SHEBA observed by lidar/radar instruments, which are also sensitive to optically thin and subvisible clouds, exceeded 60 %. In contrast, the satellite based cloud retrieval showed values of only 50 % (Wyser et al., 2005). This leads to difficulties of cloud representation in models (Wyser et al., 2008).

As part of ongoing work, we plan to undertake mesoscale numerical simulations of the optically thin clouds in order to gain a deeper understanding of the factors contributing to the formation of such particular clouds. For future campaigns, we recommend that the formation process and life time of optically thin clouds and haze layers be analyzed and that the lidar observations be compared with the microphysics data obtained from in situ instruments.

General comment

"If the authors significantly reduce the scope of the article by focusing on what they consider the more noteworthy conclusions, presented in a concise manner with a clear focus on the objective of the paper, I may be convinced that the paper is worthy of publication. The amount of data analyses done in preparation for this paper is not insignificant: however, I do not think the authors did a credible job presenting their results."

According to the very helpful suggestions of the Referee, we changed the structure of the article and concentrated on the new aspects of our observations. As the Referee himself states that the data quality is good and the amount of data analyses is large, we hope that the improved presentation of the results also convinces him that the revised version is worthy of publication.

References used in the answer to Referee 2:

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