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Changes in Supersaturation Inside and Around Arctic Cirrus during Warm Air Intrusion Events

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Abstract: Cirrus clouds play a significant role in the radiative processes in the upper troposphere. Depending on the ambient conditions during their formation their micro- and macro-physical characteristics might differ, leading to different and potentially stronger radiative effects. In this study, we use airborne lidar measurements of cirrus clouds performed in the arctic during the HALO-(AC)3 campaign. We distinguish between two cirrus types depending on the ambient conditions during their formation. WAI cirrus, formed during a Warm Air Intrusion and AC cirrus under undisturbed arctic conditions. For these two groups we analyze the distribution of Relative Humidity over ice (RHi) for in-cloud and near-cloud data. We find that WAI cirrus are more frequently detected with high RHi over the threshold for homogeneous nucleation and also reach higher absolute values of RHi, both in the in-cloud and near-cloud regions. This could be indicative of younger clouds where ice nucleation is still ongoing.

1. Introduction

The phenomenon of 'Global Warming', describing the steady increase of the average global temperature has been well-studied since the 19th century and is backed by unequivocal evidence (e.g. [1]). In recent decades, scientists have detected a peculiarity; a much faster warming of the arctic, compared to the global average. This phenomenon has been labeled 'Arctic Amplification' (e.g. [2]). The exact contributions from different atmospheric parameters to this phenomenon are a matter of ongoing science (e.g. [3]).

Cirrus clouds play an important role in the radiative processes occurring at the upper troposphere and lower stratosphere (UTLS) and can strongly affect the weather and climate [4]. They are considered to cause an all-year net warming globally and at high latitudes, thus being a potential contributor to global warming and arctic amplification [5]. Despite that, their exact characteristics and forcing are not yet well quantified. The ambient conditions during their formation and evolution, such as temperature, available water vapor, aerosol concentration, updraft and others, can affect the ice nucleation path and internal processes, thus affecting the microphysical characteristics, which in turn leads to different macrophysical and radiative properties [6]- [9].

Warm Air Intrusions (WAIs) have also been identified as a potential contributor to arctic amplification. [10], [11]. During a WAI event, warm, aerosol- and water vapor-rich airmasses are meridionally transported into the high arctic. This strongly affects the ambient conditions in which cirrus clouds form and persist. Importantly, their effects are expected to become more significant as their amount and duration have been shown to follow a positive trend [12]. Despite the abovementioned, cirrus clouds in the arctic and especially during WAI events are scarcely measured and studied.

A parameter, which connects the micro- and macro-physical properties of cirrus clouds and also the ambient conditions is the Relative humidity over ice (RHi). On the one hand the nucleation process followed during the formation of the cloud is dependent on the ambient RHi and affects the microphysical characteristics of the resulting cloud. Ice supersaturation, i.e. RHi > 100%, is commonly detected inside and in the vicinity of cirrus clouds and is a prerequisite for their formation [7], [9], [13]-[15]. Heterogeneous (HET) nucleation can occur at lower ice supersaturations, while high RHi is necessary for homogeneous (HOM) nucleation [16]- [18]. On the other hand, the RHi is itself affected by the ambient conditions (temperature, water vapor concentration, updraft etc.).

In this work our aim is to study how a prevailing WAIs affect the ice supersaturation within and around cirrus clouds and based on this gain insights on the probable nucleation processes.

2. Data and Method

Our study is based on cirrus cloud data collected in the arctic during the HALO-(AC)3 campaign in Spring of 2022 [19]. For this campaign the German research aircraft HALO [20] was equipped with remote sensing instrumentation including the WALES lidar system [21]. WALES is a combined High Spectral Resolution Lidar (HSRL) and water-vapor Differential Absorption Lidar (DIAL). It provides – among others- measurements of the backscatter ratio (BSR), particle linear depolarization ratio (PLDR) and water vapor mixing ratio (WVMR), which are used in this study.

Regarding the method, first, we constructed a cirrus cloud mask, using the BSR, PLDR and ambient temperature. With this mask we defined three regions for every detected cloud. The in-cloud region containing the cloud itself, the near-cloud region containing data measured at close vicinity of the clouds edge, and the cloud-free region. Then, using the WVMR measured by WALES and model Temperatures we calculated the RHi for each cloud. After, we studied the ambient conditions and airmass origin of each cloud and classified it accordingly as a cloud measured during an active WAI (WAI cirrus) or during undisturbed arctic conditions (AC cirrus). Finally, we performed a statistical analysis of the RHi in the in-cloud and near-cloud regions for both cloud groups. Our findings are presented in the following.

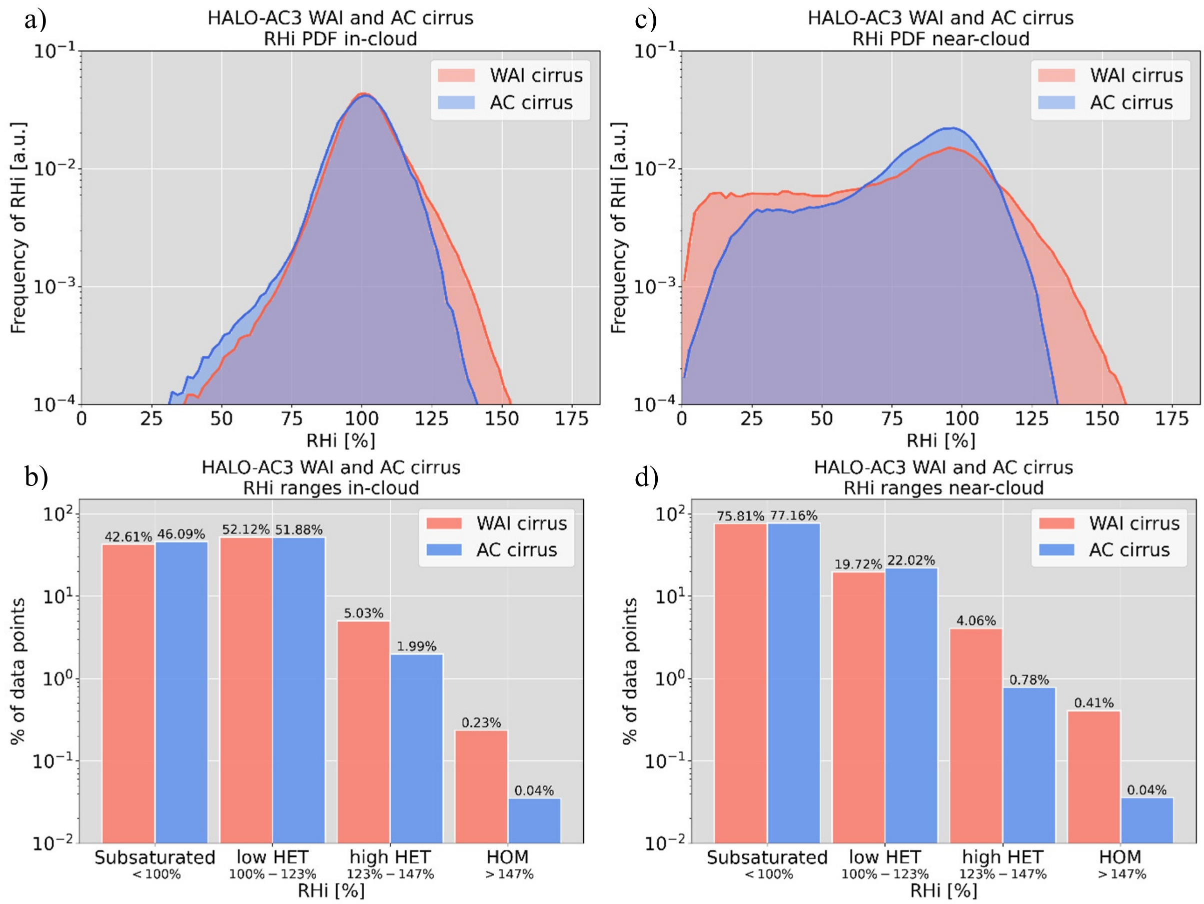

Figure 1: Results from the statistical analysis of the Relative Humidity over ice (RHi) inside and in the vicinity of cirrus clouds measured during arctic (AC) and warm air intrusion (WAI) conditions. **Top**: probability densities of RHi. **Bottom**: probability densities of RHi for both groups in bins of RHi representing different nucleation regimes. **Left**: In-cloud data. **Right**: Near-cloud data.

3. Results and discussion

In Figure 1a we present the probability densities of RHi for the in-cloud data of AC and WAI cirrus. The RHi distribution for both cirrus types has its maximum around saturation. WAI cirrus are more frequently detected at higher supersaturations > 120 % and also reach higher absolute RHi values.

A more detailed analysis of the RHi distribution is presented in Figure 1b. Here we define four bins of supersaturation. The first contains the subsaturated data points (RHi <100 %), the second contains values between 100% and 123% RHi where heterogeneous nucleation (HET) with easily activated ice nuclei (IN) e.g. mineral dust is possible, the third between 123% and 147% where heterogeneous nucleation is possible on not easily activated IN such as coated soot and the fourth with RHi values over 147% where homogeneous nucleation (HOM) is possible.

In the lower HET regime, the two cirrus types have very close probabilities to each other with WAI cirrus being slightly higher. Over the ~123% threshold the frequency of detection gradually drops and the two cirrus types start to differ. In the higher HET regime, the probability of detection is higher for the WAI cirrus. Similarly, in the HOM regime the probability for AC cirrus is close to zero while there are still data points of the WAI cirrus group.

On the right side of Figure 1 the same analysis is performed for the near-cloud regions of the two cirrus types. This region is expected to be very active in new ice formation especially in younger clouds. As seen in Figure 1c, once again the RHi distribution for WAI cirrus reaches up to higher supersaturations and has a higher frequency of detection for RHi values over ~123 %.

In Figure 1d, a more detailed perspective is provided. As is shown, the two cloud types have a similar amount of data points in the low HET regime with AC cirrus actually being slightly higher. In the high HET and especially the HOM regime, on the other hand more data points from the WAI cirrus group are found.

Judging from the fact that WAI cirrus have data points also at very high RHi in the HOM regime, even at the near-cloud region, we speculate that the detected WAI cirrus are in a younger stage and still produce new ice crystals with HOM nucleation playing a significant role. The presence of a stronger updraft, could support aid this explanation.

The AC cirrus on the other hand reach up to lower supersaturations which could be indicative of older clouds, which have already used up all the available moisture to form ice crystals via HET or HOM nucleation.

4. Summary and challenges

In this work we analyzed an extensive data set of cirrus clouds measured in the arctic via airborne lidar. From our analysis we show that WAI events do affect the characteristics of cirrus in the arctic. This can potentially lead to them having a different effect on the radiation budget and in turn on arctic amplification. As can also be seen in the previous chapter many questions still remain open. Measurements of the micro- and, macrophysical and optical properties of cirrus in the arctic are scarce and many studies only focus on lower level clouds. The macrophysical properties of cirrus are an immediate result of the microphysical processes that take place during their formation. It is important to gain a better understanding of these processes and the lifecycles of these clouds in order to better simulate and predict them and their effects.

The proposed next step towards this goal could be to implement data from other instruments and models, allowing for a more detailed analysis of the microphysical properties and cloud evolution. In that regard we have initiated a follow up study where we also use data from the HAMP radar system [22] combined with WALES in order to extract cirrus microphysical properties, and two Lagrangian models in order to calculate the backwards trajectories of the airmasses and the ice microphysics along them, during the evolution of the clouds.

5. References

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