# The Seasonal Interannual Variations of Mixed-Phase Cloud Properties Observed at the North Shore of Alaska Site

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## Introduction

Curry et al. (1996) gave a comprehensive review of arctic clouds and their role in the Arctic climate system, and clearly indicated that clouds are important to better understand arctic cloud-radiation-surface-dynamics feedbacks. The Surface Heat Budget of the Arctic experiment and long-term North Slope of Alaska (NSA) Cloud and Radiation Testbed site observations indicate that most of Arctic boundary layer clouds are mixed-phase clouds (Intrieri et al. 2002; Wang et al. 2005). Therefore, mixed-phase clouds play a particularly important role in the Arctic climate system.

Combining millimeter wave cloud radar, atmospheric emitted radiance interferometer, and micropulse lidar measurements, a mixed-phase cloud microphysical property retrieval algorithm was developed to provide vertical profiles of ice properties and layer-mean or integrated water properties (Wang et al., 2004). However, the approach only can be applied to single layer clouds with liquid water path (LWP) $< \sim 40$ g/m$^2$. Therefore, it is necessary to include MWR measurements to cover larger LWP mixed-phase clouds. To overcome the current MWR LWP retrieval uncertainties, an improved MWR LWP retrieval algorithm is introduced for the NSA measurements.

These algorithms are applied to long-term NSA Cloud and Radiation Testbed site observations, and we are able to characterize the seasonal and interannual variations of arctic mixed-phase cloud properties. Preliminary results of seasonal and interannual variations observed at the NSA site are presented.

## Summary of the Algorithms

### The Mixed-Phase Cloud Microphysical Property Retrieval

Supercooled water with ice virga is a typical type of mixed-phase cloud in arctic, which can be generally regarded as two connected cloud layers where the top is the supercooled water-dominated source cloud and the bottom is an ice cloud, although it is also necessary to study ice within the water-dominated source cloud. First, we treat ice virga as an independent ice cloud, and apply an existing lidar-radar algorithm to retrieve ice water content and general effective size ($D_{ge}$) profiles (Wang and Sassen 2002).

Then a new iterative approach is used to retrieve supercooled water cloud properties (LWP and effective radius $r_{eff}$) by minimizing the difference between atmospheric emitted radiance interferometer observed radiances and radiances calculated using the discrete ordinate radiative transfer model at 12 selected wavelengths. The flowchart of the algorithm is given in Figure 1, and more information about the algorithm can be found from Wang et al. (2004). Although the algorithm is proved to be able to retrieve the microphysical properties of water and ice phases clouds, it only can be applied to single-layer clouds with LWP < ~40 g/m$^2$. Therefore we needed to combine with MWR measurements to cover mixed-phase clouds with LWP > 40 g/m$^2$.

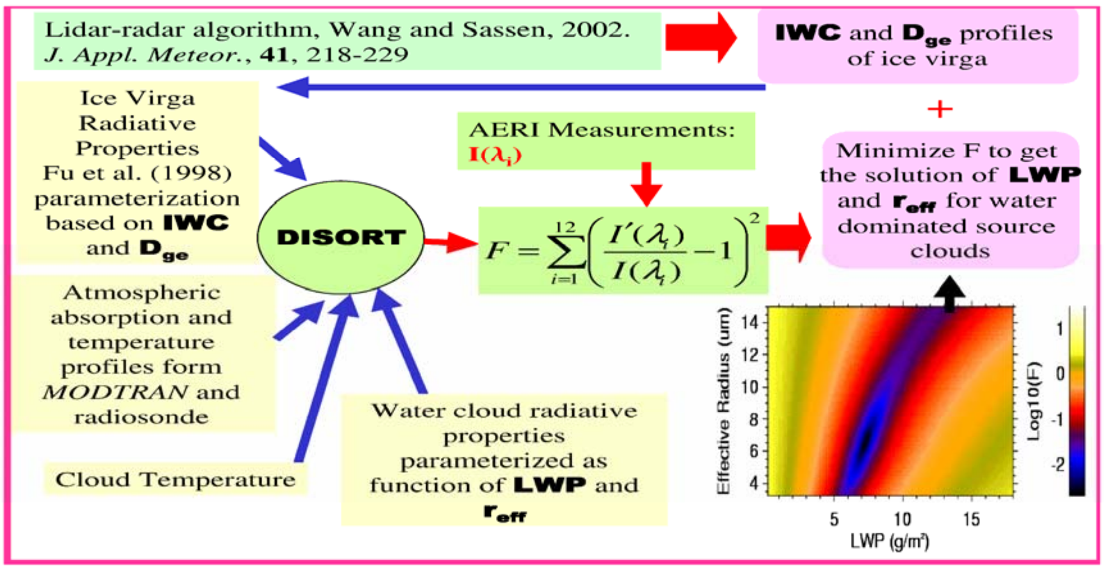



**Figure 1**. The flowchart of mixed-phase microphysical property retrieval algorithm.

## An Improved MWR LWP Retrieval Algorithm

The MWR receives nadir microwave radiation from the sky at 23.8 GHz and 31.4 GHz. Path integrated water vapor and liquid water can be retrieved from MWR measurements. Statistical retrieval methods are usually employed to derive water vapor path and LWP from the total absorption (Liljegren et al. 2001). In current Atmospheric Radiation Measurement (ARM) program data, the regression residual error or 'theoretical accuracy' of LWP is about 0.03 mm (30 g/m$^2$) or 10 times the sensitivity or noise limit (0.003 mm) of the MWR. There are noticeable differences between the ARM archived MWR retrievals and the multi-sensor retrieved LWP (Figure 2a). In order to combining the LWP from the two approaches, we need to resolve these differences. Two improvements are introduced to improve MWR LWP retrievals. First, clear sky observations are used as references to reduce the mean bias and the scattering (Figure 2b). Second, we use the water absorption coefficient of Liebe et al. (1991) to get the slope close to one (Figure 2c).

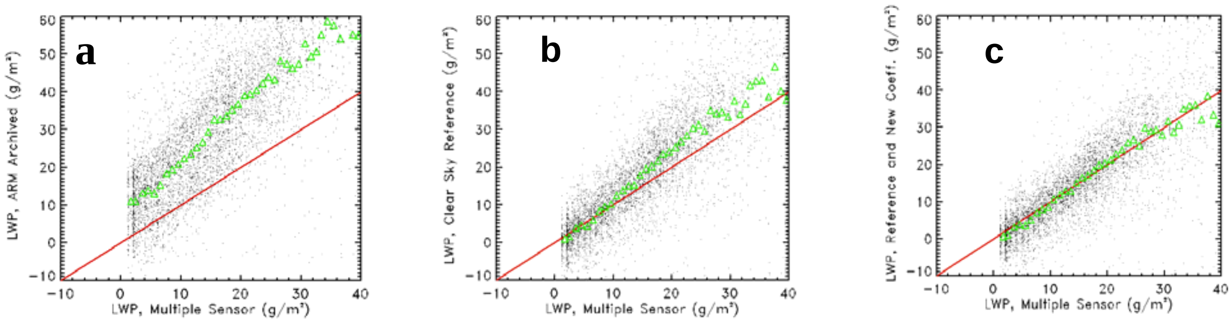
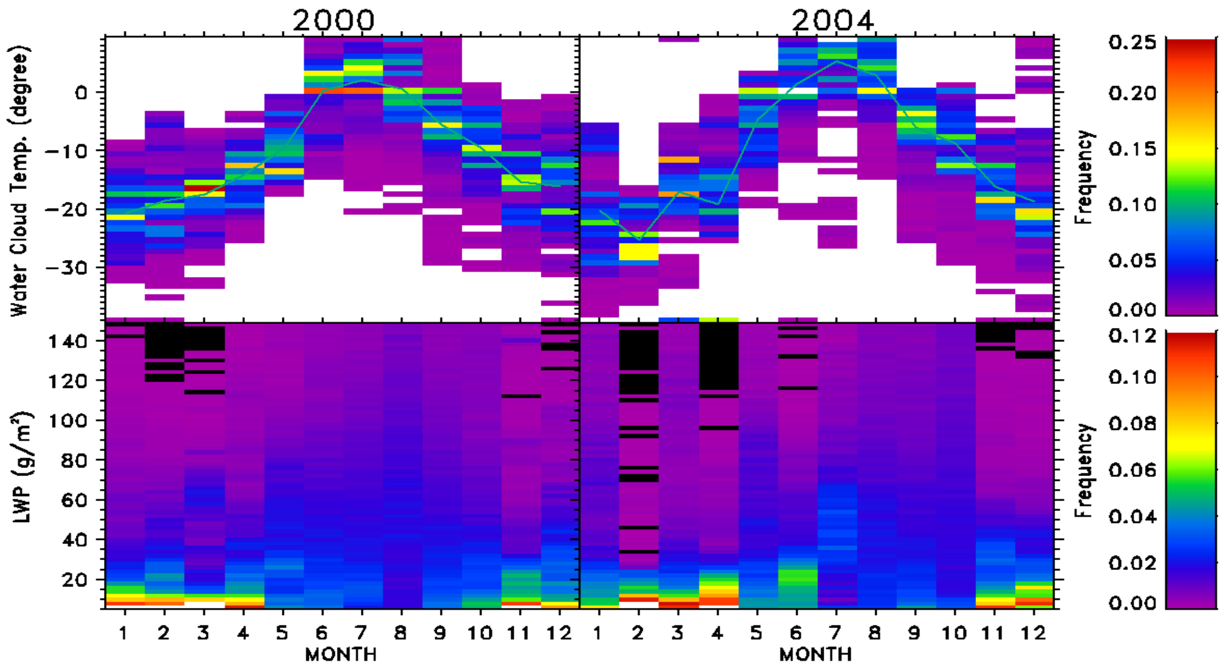



**Figure 2**. The comparisons of MWR retrieved LWP with the multi-sensor LWP. Triangle symbols represent means and solid lines are 1:1 lines. a) the current ARM MWR retrieval, b) MWR LWP with clear sky measurements as references; c) MWR LWP with clear sky measurements as references and new water absorption coefficient.

## Interannual and Seasonal Variations of Mixed-Phase Cloud Properties at the NSA Cloud and Radiation Testbed Site

By applying these algorithms to the long-time observations at the NSA Cloud and Radiation Testbed site, we are able to analyze the interannual and seasonal variations of mixed-phase cloud properties. Some of preliminary results are presented here. Figure 3 presents the annual variation of water layer base temperature and boundary layer cloud LWP. It is clear that most of water layers are supercooled at the NSA site. Compared with year of 2000, the year of 2004 has colder water clouds during the winter season and warmer clouds during the summer season. Following the differences in cloud temperature, there are notice differences in cloud LWP distributions between these two years. Similar, the occurrences of different cloud phases between these two years are slightly different as presented in Figure 4.




1 3 6 9 1 3 6 9
12 12

**Figure 3**. Monthly frequency distributions of water layer base temperature and boundary layer cloud LWP.

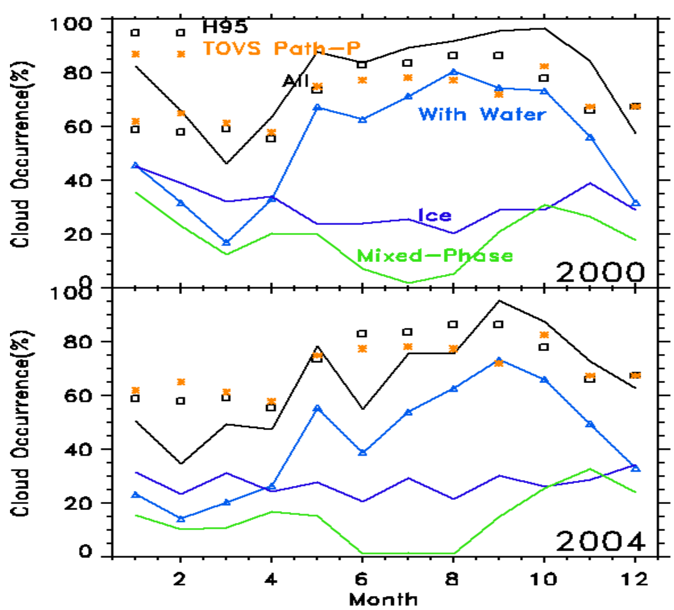



**Figure 4**. Interannual variations of cloud occurrence. Cloud phases are identified with micropulse lidar measurements

So far, we only can retrieval cloud microphysical properties for single layer clouds with LWP < ~40 g/m$^2$. Therefore, we are not able to analyze interannual variation of mixed-phase cloud microphysical properties. Based on 150-day's retrievals with the multiple sensor algorithm, Summer (May-October) and winter (November-April) differences of mixed-phase cloud microphysical properties are presented in Figures 5 and 6.

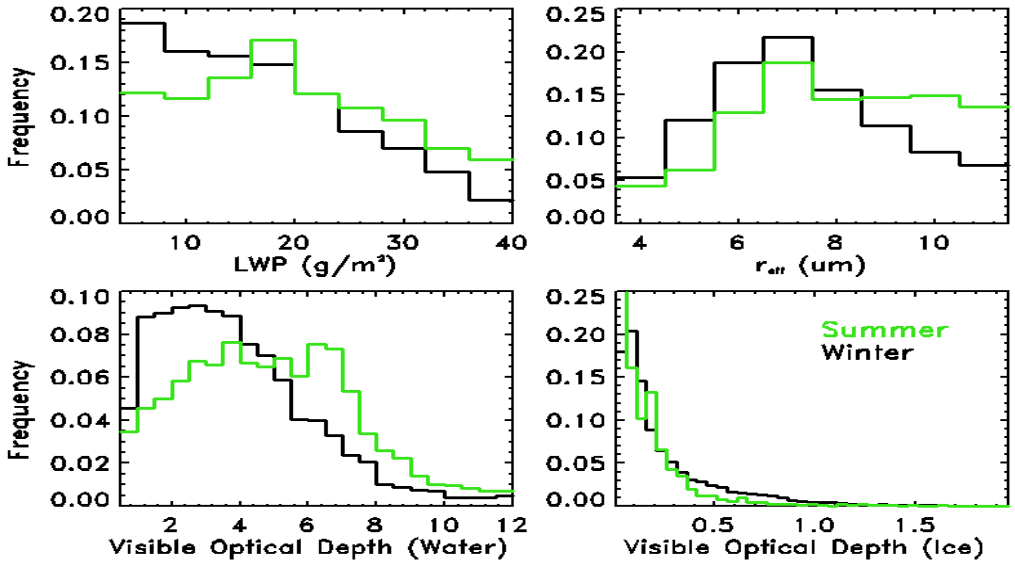



**Figure 5**. Frequency distributions of LWP, $r_{eff}$, and optical depths of supercooled water and ice based on 150-day's retrievals with the multiple sensor algorithm.

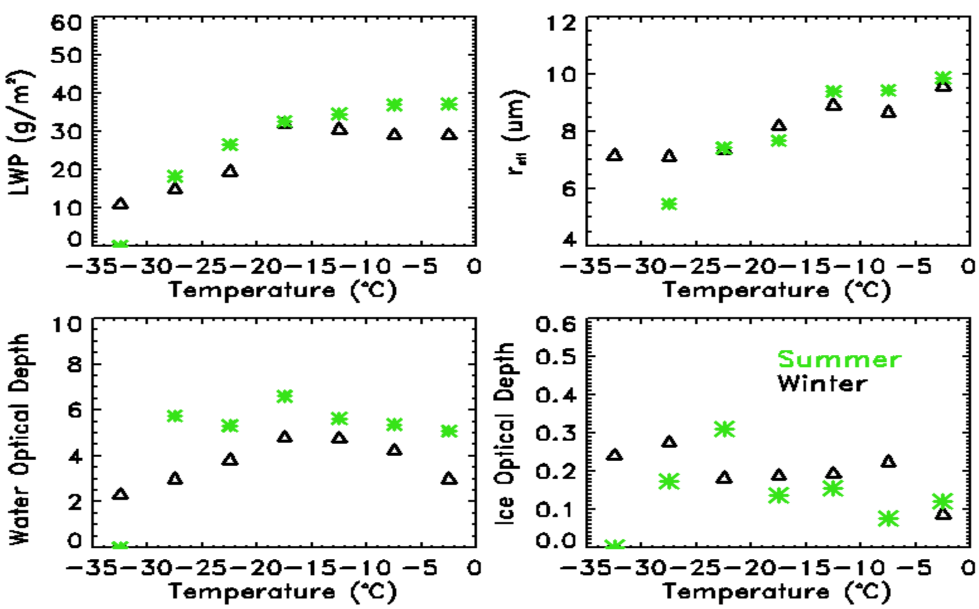



**Figure 6**. Temperature dependencies of LWP, $r_{eff}$, and optical depths of supercooled water and ice.

For mixed-phased clouds, it is important to understand the partition of ice and water phase. Figure 7a presents the optical depth ratio of ice phase to water phase. It is clear that is strongly dependent on cloud temperature. Therefore, the radiative forcing of this type mixed-phase clouds is mainly determined by water phase. However, the ice phase may play an important role in its lifecycle. The ice phase optical depth is dependent on water layer droplet size as showed in Figure 7b. This may share some light on ice generation in these mixed-phase clouds although further detail analysis is needed.

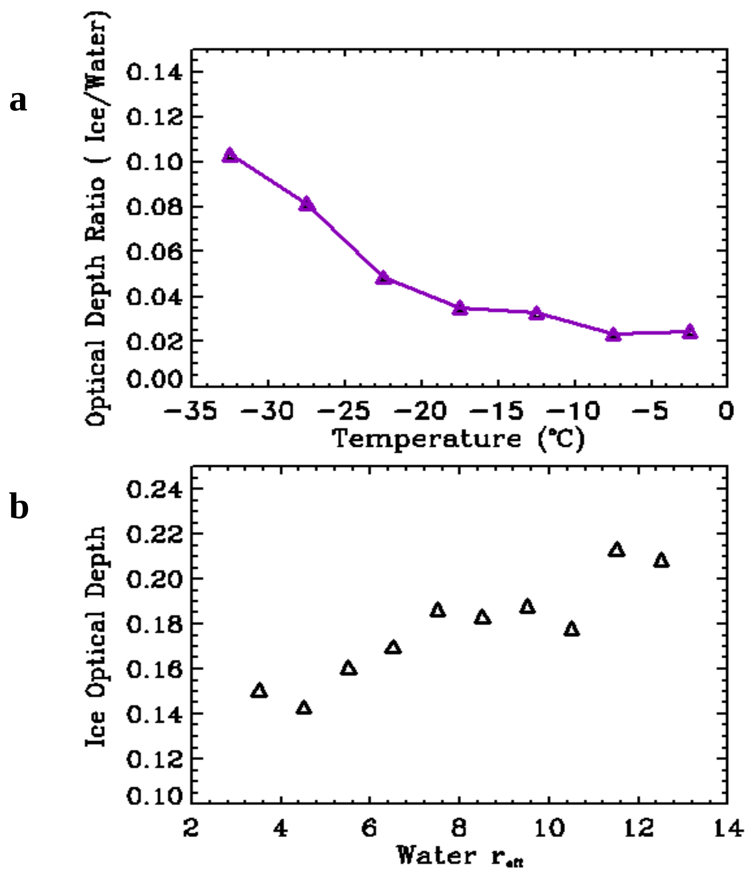



**Figure 7**. The relationship of ice property and supercooled water properties in arctic mixed-phase clouds.

## Summary

The mixed-phase cloud microphysical properties observed at the NSA Cloud and Radiation Testbed site can be well characterized with the multi-sensor algorithm and improved MWR LWP retrievals although *we still need an new approach to retrieve water particle size when LWP >~40 g/m*$^2$. These algorithms are applied to the long-term observations at the NSA site. The preliminary results suggested that there are strong seasonal and interannual variations in the arctic mixed-phase cloud micro- and macro-physical properties.

The next step is to develop an approach to provide water droplet size for high LWP mixed-phase clouds. Then, we will systemically analyze arctic mixed-phase clouds observed at the NSA site to provide a better understanding of arctic mixed-phase clouds.

## Acknowledgements

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