Studying Mixed-Phased Clouds Using Ground-Based Active and Passive Remote Sensors

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Introduction

The impact of a cloud system strongly depends on the cloud microphysical properties and its vertical extent (Stephens et al. 1990; Baker 1997). Although clouds can contain only water droplets when >0°C and only ice crystals when < -40°C, between 0 and -40°C, clouds can be of ice, water, or mixed-phase composition (Rauber and Tokay 1991; Cober et al. 2001). Cloud properties associated with different cloud phases within this temperature range are complicated and not well known. However, properly representing them in general circulation models (GCMs) is very important for climate simulation. Fowler et al. (1996) shows that the variation of glaciation temperature from 0^o to -40^oC in a GCM simulation yielded about 4 W/m^2 and -8 W/m^2 differences in the top of the atmosphere longwave and shortwave cloud radiative forcing, respectively. Other studies (Li and Le Treut 1992; Sun and Shine 1994; Gregory and Morris 1996) have also shown that the treatment of mixed-phase clouds in GCMs affects either their climate sensitivity or their mean climate impact.

Mixed-phase clouds have been mainly studied with in situ measurements, which provide detailed microphysical properties to understand the physical processes controlling mixed-phase clouds. However, it is very expensive to accumulate large in situ datasets over long-time periods and in different climate regions. Existing remote sensing algorithms of mixed-phase clouds (Sauvageot 1996; Vivekanandan et al. 1999) are not practical for many stratiform mixed-phase clouds. Therefore, it is necessary to develop reliable new ground-based and space-based remote sensing algorithms for mixed-phase cloud study.

Recent developments and integrations of remote sensor technologies provide the possible means to achieve this challenging task. The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) Program Cloud and Radiation Testbed (CART) sites have been established in three climatic regimes: the Southern Great Plains (SGP), the Tropical Western Pacific (TWP), and the North Slope of Alaska (NSA). The continuous high-quality data streams from different passive and active remote sensors at these CART sites provide the opportunity to study mixed-phase clouds in these dissimilar climate regimes.

In different dynamical conditions and climate regimes, mixed-phase clouds have different vertical and horizontal structures in terms of the mixing of water and ice and optical and geometrical thicknesses. Therefore, it is hard to develop one algorithm to fit all. According to the cases studied by Fleishauer et al. (2002) and the University of Utah facility for atmospheric remote sensing (Sassen et al. 2001) and CART data streams, supercooled altocumulus with ice virga is a common type of midlevel mixed-phase cloud. Its simple vertical structure provides an ideal scenario to better understand all varieties of mixed-phase clouds. A combined active and passive remote sensing approach was developed to study supercooled altocumulus with ice virga by using data from the SGP and NSA CART sites (Wang et al. 2004). This paper presents more case studies and initial statistics of microphysical properties of this type of mixed-phased clouds at NSA site by using this algorithm.

Summary of the Algorithm

Altocumulus cloud with ice virga can be generally regarded as two connected cloud layers where the top is the 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 profiles (Wang and Sassen 2002). Then a new iterative approach is used to retrieve supercooled water cloud properties by minimizing the difference between atmospheric emitted radiance interferometer (AERI) 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). Case studies demonstrate the capabilities of this approach in retrieving radiatively important microphysical properties to characterize this type of mixed-phase cloud. The good agreement between visible optical depths derived from lidar measurement and those estimated from retrieved liquid water path (LWP) and effective radius provides a closure test for the accuracy of mainly AERI-based supercooled water cloud retrieval.

Case Studies

The algorithm is applied to more data from NSA CART site. Four cases are showed in Figure 2. These examples show large variations of this type of mixed-phase clouds. Ice virga optical depth has the largest variation among different microphysical properties. The comparisons of LWP values retrieved from microwave radiometer (MWR) measurements and that from this algorithm indicates that MWR measurements for low LWP values are not reliable, and the retrieval from the AERI or other IR radiometer provides a good alternative for low LWP measurements.

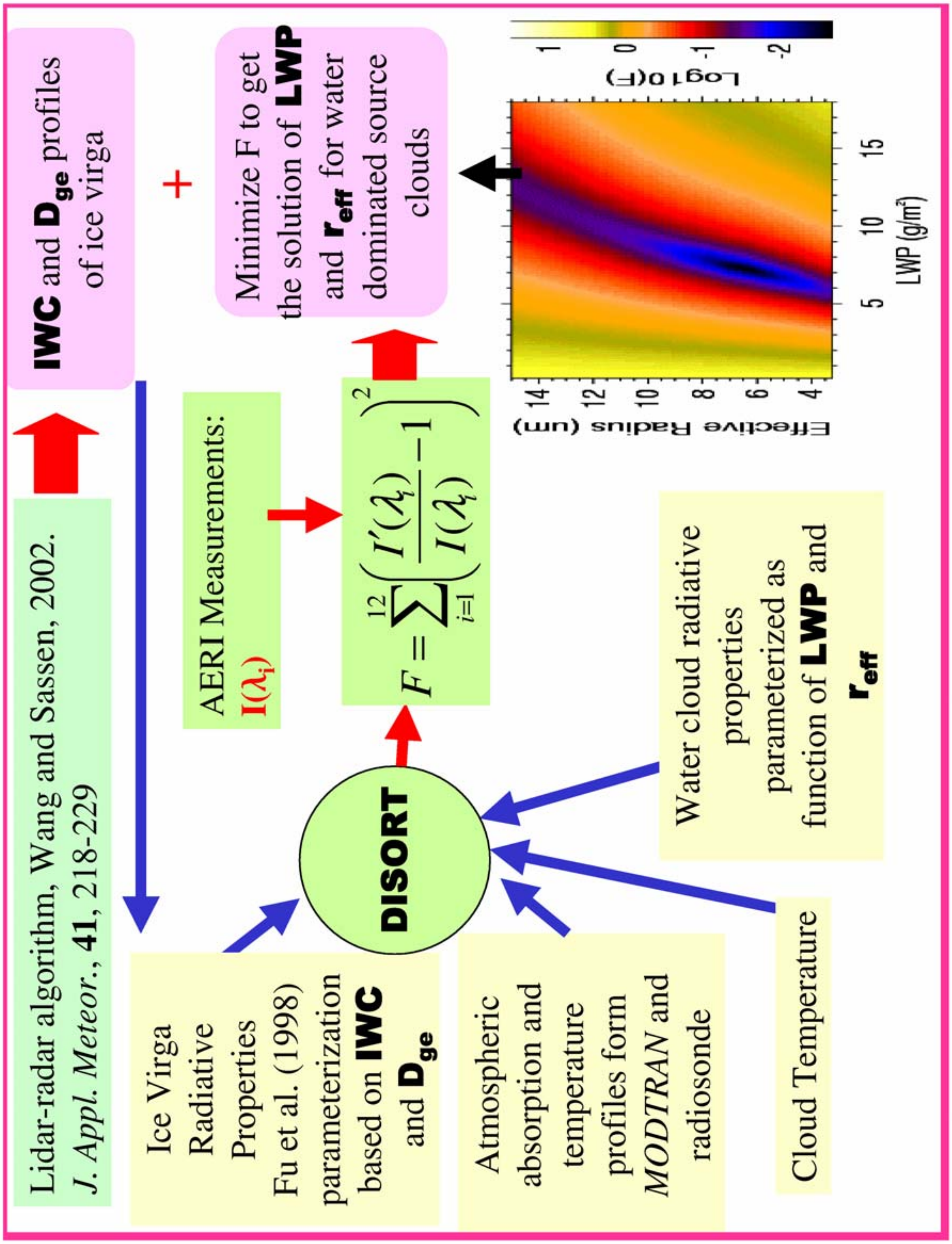

Figure 1. The flowchart of the algorithm.

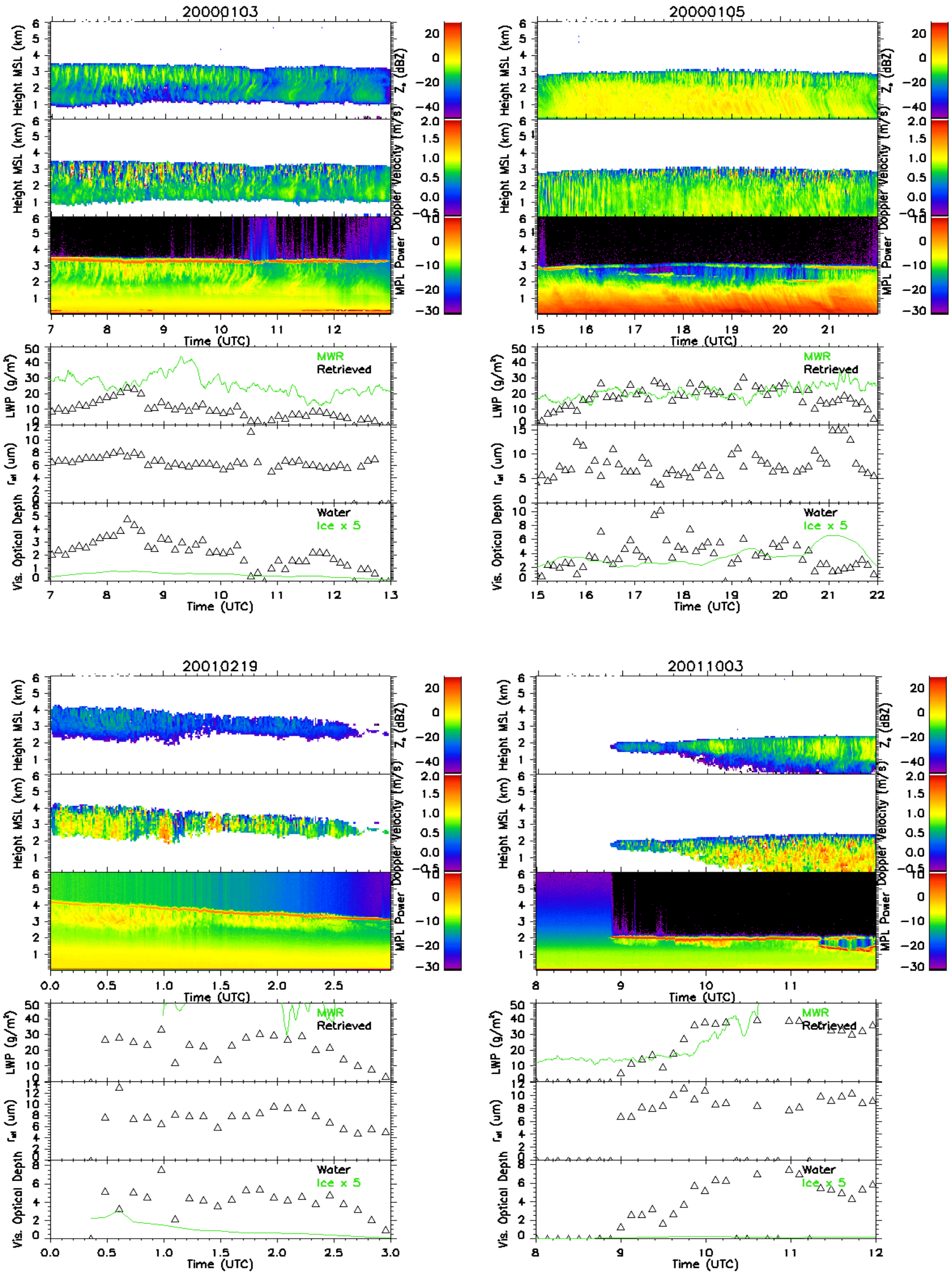

Figure 2. Time-height display of radar reflectivity factor (Ze), Doppler velocity and MPL return power for altocumulus with ice virga on January 3, 2000 (-30°C), January 5, 2000 (-30°C), February 19, 2001 (-24°C), and October 3, 2001 (-8°C). Deep ice virga is clearly indicated by Ze profile and supper-cooled water dominated generating layer is indicated by strong MPL return. The time series of retrieved LWP, r_{eff}, and optical depths for water and ice parts are also presented. Note that LWP from MWR measurement is presented for comparison.

Statistics of Microphysical Properties of Altocumulus with Ice Virga

The algorithm is applied to 30 different cases, and the statistics of microphysical properties of altocumulus with ice virga based on them are presented in Figures 3 and 4. Figure 3 shows the frequency distributions of LWP, r_{eff}, and visible optical depths for ice and water. These results indicate a larger variation of microphysical properties of this type of mixed-phase cloud properties. Compared with boundary-level water, the LWP is small, and it is also true for r_{eff}. The optical depth of ice is much smaller than that of water in this type of clouds in general, but it shows a large variation at different stages of cloud lifecycle as indicated by the case studies.

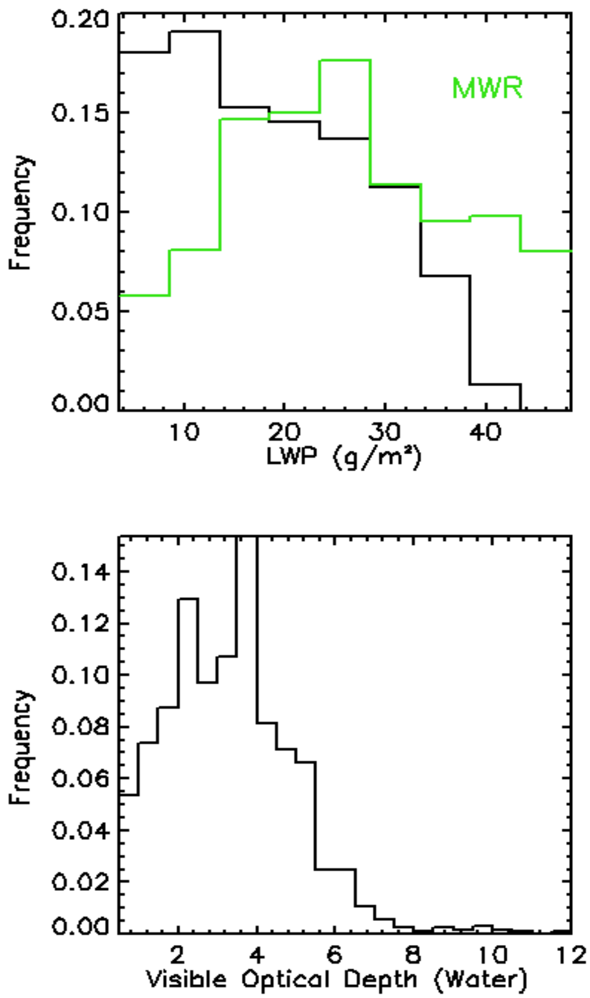

Figure 3. Frequency distributions of LWP, r_{eff}, and optical depth of supercooled water and ice. The frequency distribution of LWP derived from MWR during the same period is plotted in green color.

The temperature dependencies of LWP and r_{eff} are presented in Figure 4.

Both of them increase with the increase of cloud temperature. The standard deviations of them are given with vertical lines, which indicate large variations of them at given temperatures because many other parameters control cloud microphysical properties. In the mixed-phase clouds as we studied here, the competition between ice and water phases makes the situation more complicated.

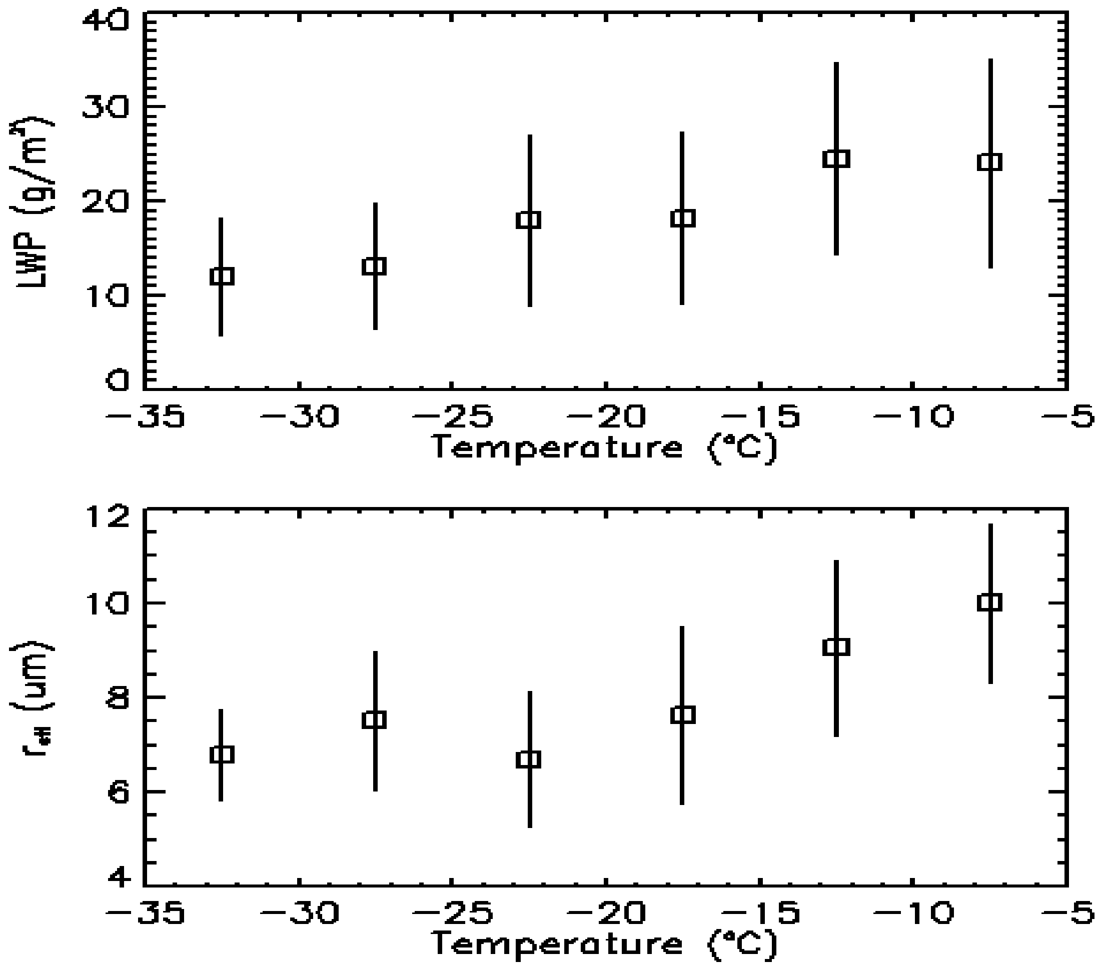

Figure 4. The temperature dependency of LWP and r_{eff}. Vertical lines represent standard deviations.

Summary

An approach of combining lidar, radar, and radiometer measurements to retrieve the microphysical properties of Altocumulus with ice virga was developed. The approach can retrieve the microphysical properties of water and ice in the cloud layer, which are necessary to better understand cloud microphysical processes in this type of mixed-phase cloud. The algorithm can also be applied to boundary layer mixed-phased clouds in NSA CART site, which have similar vertical structure like supercooled altocumulus with ice virga.

The accuracy of LWP and r_{eff} for water in this type of clouds is ~15%. Comparison of retrieved LWP with that retrieved from MWR indicated that MWR is unable to provide reliable low LWP measurements for supercooled altocumulus with ice virga. The mean biases of MWR retrieved LWP can up to 20 g/m^2, which is significant in terms of resulting radiative impacts.

The initial statistics of microphysical properties of this type of mixed-phase clouds based on 30 cases is presented. The analysis of long-term NSA CART observations is in progress. The ultimate goal of these studies is to better understand the physics processes of mixed phase clouds and to improve the parameterization of mixed phase clouds in GCMs.

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