Final Report

Determination of Large-Scale Cloud Ice Water Concentration by Combining Surface Radar and Satellite Data in Support of ARM SCM Activities

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Summary

During the past funding cycle, we have
1. developed, validated and improved the 3-D cloud ice water content algorithm by comparing it with cloud radar (MMCR) retrievals, improving the database used in the retrieval algorithm, and better handling of the non-spherical scattering of ice particles.
2. produced and archived at ARM website as a PI-product of the 3-D cloud ice water contents using combined satellite high-frequency microwave and surface observations for SGP March 2000 IOP and TWP-ICE 2006 IOP over 10 deg. (latitude) x 10 deg. (longitude) area centered at ARM SGP central facility and Darwin sites. The datasets have been used by multiple PIs in the ARM cloud modeling group to their model validations.
3. published 7 papers during this funding cycle.

1. Scope of Work

Single-column modeling (SCM) is one of the key elements of Atmospheric Radiation Measurement (ARM) research initiatives for the development and testing of various physical parameterizations to be used in general circulation models (GCMs). The data required for use with an SCM include observed vertical profiles of temperature, water vapor, and condensed water, as well as the large-scale vertical motion and tendencies of temperature, water vapor, and condensed water due to horizontal advection. Surface-based measurements operated at ARM sites and upper-air sounding networks supply most of the required variables for model inputs, but do not provide the horizontal advection term of condensed water. Since surface cloud radar and microwave radiometer observations at ARM sites are single-point measurements, they can provide the amount of condensed water at the location of observation sites, but not a horizontal distribution of condensed water contents. Consequently, observational data for the large-scale advection tendencies of condensed water have not been available to the ARM cloud modeling community based on surface observations alone. This lack of advection data of water condensate could cause large uncertainties in SCM simulations. Additionally, to evaluate GCMs' cloud physical parameterization, we need to compare GCM results with observed cloud water amounts over a scale that is large enough to be comparable to what a GCM grid represents. To this end, the point-measurements at ARM surface sites are again not adequate. Therefore, cloud water observations over a large area are needed. The main goal of this project is to retrieve ice water contents over an area of 10 x 10 deg. surrounding the ARM sites by combining surface and satellite observations.

Built on the progress made during previous ARM research, we have conducted the retrievals of 3-dimensional ice water content by combining surface radar/radiometer and satellite measurements, and have produced 3-D cloud ice water contents in support of cloud modeling activities. The approach of the study is to expand a (surface) point measurement to an (satellite) area measurement. That is, the study takes the advantage of the high quality cloud measurements (particularly cloud radar and microwave radiometer measurements) at the point of the ARM sites. We use the cloud ice water characteristics derived from the point measurement to guide/constrain a satellite retrieval algorithm, then use the satellite algorithm to derive the 3-D cloud ice water distributions within an 10°

(latitude) x 10° (longitude) area. During the research period, we have developed, validated and improved our cloud ice water retrievals, and have produced and archived at ARM website as a PI-product of the 3-D cloud ice water contents using combined satellite high-frequency microwave and surface radar observations for SGP March 2000 IOP and TWP-ICE 2006 IOP over 10 deg. x 10 deg. area centered at ARM SGP central facility and Darwin sites. We have also worked on validation of the 3-D ice water product by CloudSat data, synergy with visible/infrared cloud ice water retrievals for better results at low ice water conditions, and created a long-term (several years) of ice water climatology in 10 x 10 deg. area of ARM SGP and TWP sites and then compared it with GCMs.

2. Accomplishments

The major accomplishments are described as follows.

(1) *Produce and deliver ice water path and 3-D ice water content as a PI product at ARM Data Center for March 2000 SGP IOP and TWP-ICE 2006 IOP*.

The intention of this product is to provide large-scale distribution of cloud ice water by merging available surface and satellite measurements. The satellite cloud ice water algorithm uses ARM ground-based measurements as baseline, produces datasets for 3-D cloud ice water distributions in a 10 deg. x 10 deg. area surrounding the ARM sites. The approach of the study is to expand a (surface) point measurement to an (satellite) areal measurement. That is, this study takes the advantage of the high quality cloud measurements at the point of ARM sites. We use the cloud characteristics derived from the point measurement to guide/constrain satellite retrieval, then use the satellite algorithm to derive the cloud ice water distributions within a large area, i.e., 10 deg. x 10deg. region, centered at ARM sites.

The ice water retrieval algorithm is based on Baye's Theorem. The main satellite data going into the retrieval algorithm are the high-frequency (89, 150, 183±1, 183±3, and 183±7 GHz) microwave data of AMSU-B (Advanced Microwave Sounding Unit – B), being available on NOAA-15 and later NOAA satellites. One of the most important components in a Bayesian retrieval algorithm is the *a-priori* database that, in this case, connects satellite brightness temperatures (T_Bs) to ice water content (IWC) profiles. The IWC profiles should be realistic and representative of those occurred in the region and season of study. To accomplish this, MMCR radar reflectivity profiles at ARM site during the same time period when retrievals are to be performed are analyzed. The IWC profiles converted from the radar reflectivity profiles are used as the input of radiative transfer model simulations, together with liquid water path (LWP) from surface based microwave radiometer and sounding data observed at the ARM sites. Then, the radiative transfer model simulations produce the required a-priori database for the Bayesian retrieval. In the radiative transfer model, the single-scattering properties of the ice particles are calculated by using realistic non-spherical ice particle shapes and computed by Discrete Dipole Approximation, which are more accurate than those traditionally computed by assuming spherical ice particles. The relationship between IWP/IWC and

T_B's established based on the ARM ground-based measurements at the ARM sites is applied to other satellite pixels over 10 deg. x 10 deg. area centered at the ARM sites.

We have completed the ice water retrievals for March 2000 SGP IOP and 2006 TWP-ICE IOP. These retrievals have been archived at ARM data center as a PI-product. The dataset contains ice water path (vertical integrated ice water content) and ice water contents at 36 levels (from surface to 18 km). The retrievals are given at satellite (NOAA-15/16/17/AMSU-B, NOAA-18/MHS) grid points. The spatial resolution is ~16 km at satellite nadir, but larger toward the edge of satellite swath (~25 km for the outmost pixel). Since NOAA-series satellites are polar orbiters, the temporal resolution is twice daily per satellite. During the 2006 March SGP IOP, there was only one satellite (NOAA-15) is available, while during 2006 TWP-ICE IOP there were 4 satellites (NOAA-15, 16, 17, and 18) available. Further refinement to the retrieval procedure has been carried by sub-setting the a-priori database to include only those data-points having similar cloud top height to satellite infrared observed. This refinement helps the algorithm better determine the ice water location. The end product of the algorithm is 3-D ice water contents, in addition to ice water path, at satellite pixel grid over 10 deg. x 10 deg. area centered at ARM sites. Publications related to the above works are Seo and Liu (2005, J. Geophys. Res.) and Seo and Liu (2006, J. Appl. Meteorol. and Clim.)

(2) *Validate and improve the 3-D cloud ice water content algorithm*

The 3-D ice water contents retrieved in this project using combined data from the satellite and surface measurements is examined with surface radar observations. First, the horizontal distributions of the retrieved ice water path (IWP) are compared to those of NEXRAD-derived IWP. To calculate the NEXRAD IWP, IWCs are first derived from radar reflectivities, Z_e, using Z_e-IWC relation and then integrated vertically to obtain IWP. It is noted that we use the NEXRAD-derived IWP only as proxy of cloud ice water path, since the 10-cm radar is sensitive only to large precipitating ice particles, and has a very coarse vertical resolution and an increasingly large sampling volume with range from the radar. Therefore, the intention of the comparison is only to assess if the retrieval algorithm can produce an IWP horizontal distribution that agrees qualitatively with NEXRAD observations. AMSU-B brightness temperatures from NOAA-15 satellite are available in the vicinity of the ARM SGP site approximately twice a day. Of all the observations during March 2000, we choose three cases on 2, 22, and 18 March 2000, representing clouds with thick, moderately thick, and thin optical depths, respectively. The comparison shows the horizontal IWP structures from the two measurements are in a good agreement; our retrievals capture the main features of the cloud systems shown by the NEXRAD. On the other hand, the NEXRAD shows greater IWPs than our retrievals at locations of optically thick clouds, while it misses ice clouds in the surrounding areas of the cloud systems where usually only thin clouds exist. This discrepancy may partially be explained by the large field of view of satellite measurements and the NEXRAD insensitivity to cloud ice and its vertically coarse resolution at its far range. Secondly, the distance-height cross section of satellite retrieved ice water contents (IWCs) are compared with the time-height cross section of MMCR-derived IWCs for the above 3 cases. The results indicate that the vertical structures retrieved by our algorithm capture the main characteristics retrieved by the surface cloud radar. Detailed comparison results can be found in Seo and Liu (2006).

The mean vertical distributions of ice water contents at SGP site during March 2000 IOP and at TWP Darwin site during TWP-ICE IOP are also compared well between our products and those derived from surface cloud radars (MMCR). The vertical pattern, the peak location and the magnitude of the maxima of the ice water contents are very similar to each other between our retrieval and the MMCR derived values. The mean ice water content peaks near 5 km at ~0.027 g m^{-3} for March 2000 SGP IOP, while it peaks near 9 km at ~0.018 g m^{-3} for 2006 TWP-ICE IOP. However, our analysis showed that the mean ice water content profile and ice water path have a considerable variability within the 10 deg. x 10 deg. area for both SGP and Darwin sites, implying that evaluating GCM model using the point-measured MMCR retrieval, even with an averaging over a month, is not adequate; it is necessary to use averaged values over a large area, too.

We are continuing to improve the cloud ice water retrieval algorithm. Two papers aiming at improving the retrieval algorithm's database and inversion procedures have been published (Seo, Liu and Kim, 2007; Seo, Liu, Tao and Han, 2007), and one is in press (Liu, 2008).

(3) *Understand aerosol indirect effect*

Partially supported by ARM project, we are also actively studying the aerosol indirect radiative effect using a host of data from satellite and numerical model analysis. The aerosol first indirect effect is known to cool the Earth radiatively. However, its magnitude is very uncertain. One of the difficulties in deriving this effect is caused by the coherent variation between aerosol abundance and meteorological conditions. In this study, we demonstrate that evaluation of the aerosol first indirect effect based on comparisons of clouds with different aerosol concentrations suffers an influence of the different degrees of mixing between clean and polluted clouds. By introducing a new method capable to remove this influence, we showed that, for the area off the coast of California, the strength of the aerosol first indirect effect is about half of that estimated by many previous investigators. A paper to describe the above findings has been published in Geophysical Research Letters (Shao and Liu, 2006) and a flow-on paper was published in Journal of Atmospheric Sciences (Shao and Liu, 2009).

3. Publications

Publications (refereed papers during this funding cycle):

(1) Seo, E.-K., and G. Liu, 2005: Retrievals of cloud ice water path by combining ground cloud radar and satellite high-frequency microwave measurements near the ARM SGP site, *J. Geophys. Res*., **110**, D14203, doi:10.1029/2004JD005727.

(2) Seo, E.-K., and G. Liu, 2006: Determination of 3-D cloud ice water contents by combining multiple data sources from satellite, ground radar, and a numerical model. *J. Appl. Meteor. Climatology*. **46**, 667-672.

(3) Shao, H., and G. Liu, 2006: Influence of mixing on evaluation of the aerosol first indirect effect, *Geophys. Res. Lett., 33*, L14809, doi:10.1029/2006GL026021.

(4) Seo, E.-K., G. Liu, and K.-Y. Kim, 2007: A note on reducing systematic errors in a Bayesian retrieval algorithm, *J. Met. Soc. Japan*, 85, 69-74.
(5) Seo, E.-K., G. Liu, W.-K. Tao, and S.-O. Han, 2007: Adaptation of model-generated cloud database to satellite observations. *Geophys. Res. Lett.*, 34 , L03805, doi:10.1029/2006GL027857.
(6) Liu, G, 2008: A database of microwave single scattering properties for non-spherical ice particles. Bull. Amer. Met. Soc., 89,1565-1570.
(7) Shao, H., and G. Liu, 2009: A critical examination of the observed aerosol first indirect effect. J. Atmos. Sci., 66,1018-1032.