An Integrated Cloud Observation and Modeling Investigation in Support of the Atmospheric Radiation Measurement Program

T. Ackerman, B. Albrecht, D. Lamb, N. Seaman, D. Thomson, and T. Warner
Department of Meteorology
The Pennsylvania State University
University Park, PA 16802

Although the cloud observation and modeling investigation is an integrated project, it subdivides into three components. The first centers on the operations of the Cloud Observing System (COS). This includes instrument development, data acquisition, data analysis, and algorithm development. A large part of our activities in this first year have focused on this particular component. The second focuses on physically-based process models designed to simulate cloud and radiation interactions. During the first year, the activity in this area has been largely developmental. The third component centers on the mesoscale modeling. The focus of this work is on model development and testing, particularly in the area of cloud properties. Again, this work has been largely developmental in the first year.

The natural flow of the project is from the observational database to the process model simulations to the incorporation of cloud parameterizations into the mesoscale model. Our intent is to use the process models, in conjunction with the observations, to expand our understanding of cloud formation and maintenance and interactions with the radiation budget. The model studies, observations, and new insights will form the basis on which improved and new parameterizations will be developed and incorporated into the mesoscale model.

The Cloud Observing System

During the past year, we further developed instrumentation and techniques for the COS and made some initial measurements of continental stratocumulus. The most promising development has been the exceptional performance of the 94 GHz cloud radar for the definition of cloud base and top heights for clouds at all levels.

In December 1990, we started an intensive observing period (IOP) to study stratus and cirrus clouds. Although operational difficulties at the 50-MHz profiler sites prevented us from routinely collecting reliable wind data for divergence calculations, several modifications were made to improve the reliability of these systems. Despite these problems, reliable data were collected during several periods when there was good cirrus development over the observing area. In addition, intensive observations were made with the 915- and the 405-MHz profilers to investigate the structure and evolution of low-level stratus. These data are currently being used to develop techniques for defining cloud structure. We have made initial measurements with our newly acquired 915-MHz profiler and are evaluating its capabilities.

Instrument and Technique Development

During the last year we have been working on a number of projects related to the development of instruments and analysis techniques for COS. These include the following:

1. computation of vertical velocities from profiler arrays
2. automated data collection for the 94-GHz cloud radar
3. definition of cloud-top using the 915-MHz wind profiler
4. vertical velocity corrections for Radio Acoustic Sounding System (RASS) temperatures
5. definition of cloud microphysical properties from the 915-MHz profiler
6. development of Local Area Network for COS.

Starting in midsummer, data were collected from the 94-GHz cloud radar. Mr. Robert Peters has since developed a sophisticated data collection system for the radar to provide time-height displays of the radar return. This system not only offers flexibility in selecting sampling frequency, gate spacing, etc., but also automatically names and saves data and graphics files at fixed intervals. This data collection system allows the radar to be operated unattended for several hours at a time.

Although cloud base for clouds below 4 km is routinely defined with the laser ceilometers that are operated as part of our COS, we have no instrument for routine and continuous measurements of cloud-top height. Data collected from the 915- and 405-MHz cloud are being used to determine if the signal-to-noise ratio, vertical velocity variance, or spectral width from the 915- and the 405-MHz profilers (using the vertical beam) can be used to define cloud top. Although our initial results are encouraging, there is still considerable work to be done before a procedure could be automated to define cloud top. As described below, we have collected the appropriate data sets for the initial development of this technique. Additional measurements will be made to compare cloud-top heights from the 915-MHz profiler with those from the 94-GHz radar. In addition, observations made with the 915-MHz profiler have clearly demonstrated the potential for using this system to discriminate between ice and rain using changes in fall velocity. We are continuing to explore ways to exploit this information.

Temperature is obtained from the RASS by measuring the speed of sound. Thus, vertical velocity fluctuations can result in errors in the RASS temperature. Data collected during the summer and fall of 1990 are being used to evaluate the magnitude of these errors and to develop techniques for correcting them.

A local area network was been developed for the COS. The COS components are now being integrated into this network. This will allow us to combine data from the various COS components in near-real time and to provide a centralized point for saving the data.

Cloud Process Studies

Although all the components of COS have not been operated simultaneously, subsets have been used under a variety of conditions for the study of low-level boundary layer clouds. These studies focused on coupling between the subcloud and the cloud layer; cloud evolution and maintenance; statistics on cloud-base fluctuations; and drizzle events in shallow, continental stratus.

Although studies of cirrus during the IOP were hampered by the lack of the 94-GHz radar, progress has been made on diagnosing vertical velocities from profiler arrays, both at Penn State and using the National Oceanic and Atmospheric Administration (NOAA) demonstration array. The vertical velocity structure has been achieved using satellite imagery to deduce cloud presence and absence.

Future Work

During the next year we plan to continue our development of COS and the analyses of the data collected last year. In addition, we are planning to participate in the First ISCCP Regional Experiment (FIRE) Cirrus II experiment, conduct another intensive observational period from January to April of 1992, and participate in the Atlantic Stratocumulus Transition (ASTEX). In all three of these campaigns, we will rely heavily on the principal components of COS, such as the profilers and the 94-GHz radar. Most important, we expect to collect our first Doppler data with the 94-GHz radar.

Further development of the 94-GHz cloud radar will be given a high priority and will include implementation of a high-speed (150 MFlop) data processor; Doppler capability; scanning capability; and software for processing Doppler and scanning data. The high-speed processor will increase the sensitivity of the radar. With the current processor we are averaging approximately 2000 pulses every six seconds. With the high-speed processor, 10,000 pulses will be sampled every second. In addition, this processor will provide 7 m vertical resolution. With Doppler capability, it will be possible to determine cloud vertical velocities (using the return from the smaller cloud droplets) and the fall velocity (hence, size) of the drizzle droplets. Although the radar is currently operating in a vertically pointing mode, it will be mounted on a pedestal to allow some simple scanning. Initially, we plan to scan off vertical 10 to 15 degrees perpendicular to the cloud-level winds to provide two-dimensional slices of the cloud as a function of time. Additional software will be needed to process and display the Doppler and scanning data.

The ultimate utility of COS will be realized when various components of the system are networked to allow the data from the various components to be combined easily and in real time. For example, we are currently developing a scheme to combine ceilometer cloud-base heights with the real-time cloud radar display. In addition, we plan to develop a technique for automatically defining cloud top from the radar return. When combined with the ceilometer cloud-base height, this would allow for a real-time definition of cloud depth from which the adiabatic liquid water path could be calculated. The adiabatic liquid water path could then be compared with the observed liquid water path from the microwave radiometer. In some cases, it will be desirable to assimilate data into a model to provide variables that could not be measured directly. For example, we plan to use the cloud radar reflectivity, liquid water path, cloud-base height, cloud vertical velocity, and cloud-base temperature as input parameters to a cloud model that will then provide an estimate of the vertical distribution of liquid water.

Future cloud process studies made using the 1991 IOP data and data that will be collected during the 1992 IOP will focus on cloud evolution of both stratus and cirrus; cloud-top entrainment instability; diurnal variability; vertical coupling; spatial and temporal representativeness of point measurement; statistical descriptions of cloud characteristics; and drizzle production.

Process Models

Cloud Model

The cloud modeling effort is designed specifically to improve our understanding of the cloud formation process and to provide a tool for linking the various atmospheric scales. With a minimum of parameterization, the microphysical cloud model permits us to study what happens to the various forms of atmospheric water in response to large-scale forcing (moisture convergence). The results from this detailed model will permit the development of a set of bulk-water parameterizations that can be employed directly in the nonhydrostatic version of the Penn State mesoscale model. The microphysical model also provides the basis for the implementation of the radiative transfer model because cloud particle size distributions, phases, and ice shape factors are all calculated explicitly.

A warm-cloud version of the model is currently operational. This version calculates the distribution of solute mass in much the same way that the distribution of water mass is tracked. This approach was taken because of the strong role that atmospheric aerosols play in the microphysical evolution of clouds. The current model includes the diverse microphysical processes such as condensation, coalescence, breakup, and sedimentation that contribute to determining cloud size distributions. In addition to the warm-cloud model, a conceptual basis for the development of a cold-cloud model has been defined and much of the initial coding has been completed. Various strategies are under consideration for validating the model cloud against observations once the development work is completed.

Radiation Models

The primary focus of the radiation work this year has been on improvements to the coupled dipole code being used for simulations of scattering by ice columns. The current code can be used for a variety of shapes, size parameters from 5 to 10, and for fixed or random orientations. The work in progress is intended to produce parameterizations of scattering properties of hexagonal columns that can be incorporated into multiple-scattering codes. These codes will then be used to compute radiative transfer in cirrus clouds for comparison with data obtained in field campaigns.

A secondary aspect has been the development of a Monte Carlo code that is being used to simulate observations of the reflection and transmission of stratus clouds. The code is capable of simulating cubes and rectangular solids of arbitrary dimension and hemispheric domes. Initial simulations indicate that observed albedo effects in stratus decks cannot be simulated with cloud geometry alone, but must include the effects of variable cloud microphysics.

Future Work

Cloud work over the next year will focus on completing the coding of the cold-cloud model, including the additional processes of ice particle melting and shedding of excess liquid, crystal aggregation, and fragmentation. The ice-specific chemical processes of trace-gas absorption and reaction and entrapment in rime ice will also be included to maintain realism with the calculations of particle solute contents. The warm-cloud model will be used in sensitivity studies, especially with regard to the environmental parameters of updraft speed and aerosol concentration. Spectral outputs from the warm-cloud model will be used with various post-processing programs to aid in visualization and integration into other segments of the Penn State

ARM program. For example, radar reflectivities will be calculated and presented as time-height cross sections for comparison with data from the new 94-GHz radar.

Simulations and parameterization development for the columnar ice crystals should be concluded in the next few months. Our intent is then to use these results to simulate data collected in a wave cloud study. If the application to the study of these well-characterized ice clouds is successful, the same technique will be applied to data from the COS. As an additional task, applications will be made to 94-GHz backscatter to aid in interpretation of radar data.

The Monte Carlo code is currently being modified to account for variable particle distributions. When this is completed, further simulations will be carried out to understand the ramifications of variable microphysics for cloud reflectivity. The long-term goal is to use this model in conjunction with the microphysical model to simulate radiative transfer in simulated stratus clouds. The results will then be compared with observations from the COS.

Mesoscale Model

During this first year, work has concentrated on two major projects:

1. Development of a nonhydrostatic version of the Penn State University/National Center for Atmospheric Research Mesoscale Model (known as MM4) capable of performing four-dimensional data assimilation (4DDA) and using nested grids for real data cases
2. Evaluation of alternative mesoscale convective parameterizations suitable for 15- to 30-km grid resolution models.

Both of these efforts are of critical importance because they directly affect the model ability to simulate the local cloud state and the moisture cycle in the evolving synoptic and mesoalpha scale environment in which the clouds form.

Joint development work by scientists at Penn State and the National Center for Atmospheric Research has led to a working non-hydrostatic code. The model has been tested on a variety of cases, including oceanic storms, mountain wave flow, coastal front development and mesoscale flow over complex terrain in the Grand Canyon area. During the past month, it was merged with Penn State University's 4DDA system and successfully tested. A nested-grid capability has recently been added to the non-hydrostatic code and testing has just begun. After some further evaluation, it will be completely suitable for application to ARM cases.

During the past six months, Penn State has introduced three advanced cumulus parameterization schemes into a single version of the MM4 hydrostatic model. These are the Kain-Fritsch, Betts-Miller, and Grell-Arakawa-Schubert schemes. These three, plus the original Anthes-Kuo scheme used in MM4, have been benchmarked against a test case. The basis for comparison has been 6-hour precipitation rates.

The focus of work in the upcoming year will be to carry out further comparisons of the cumulus schemes for about 10 different cases spread over winter and summer situations. Based on these test results, a suitable parameterization scheme will be chosen for the coarse grid of the nested nonhydrostatic model. Following this, evaluation of the complete nested model for selected ARM cases will begin. A prototype ARM case simulation should be completed by the end of the year.