Progress Report on
Investigation of Coupling Between the Large Scale Atmospheric State and Cloud Properties: An Observational Synthesis of the ARM Data Stream

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1. Science Goals

The continuous data stream being produced by instruments operating at the ARM sites is a unique resource that provides information concerning the atmospheric state, clouds and radiation over multiple spatial and temporal scales. Our science team project is using this resource to generate long term databases of the large-scale atmospheric state, cloud macrophysical properties and cloud microphysical properties. These databases, when properly constructed, will allow for investigation of the coupling between the large-scale atmosphere (that resolved by climate models) and the subgrid scale clouds and radiation. To accomplish this goal, we are exploiting the continuous data stream and implementing operational algorithms that combine observations from multiple sensors to generate products useful for this purpose.

2. Summary of Accomplishments (year 3)

- Continued development and validation of cloud property retrieval algorithms to be applied to the operational ARM data stream.
- Planned and implemented Spring 2000 Cloud IOP.
- Acceptance of a paper by *Journal of Geophysical Research* entitled, A Constrained Algorithm for Retrieval of Stratocumulus Cloud Properties Using Solar Radiation, Microwave radiometer, and Millimeter Cloud Radar Data, by Gerald Mace and Kenneth Sassen
- Acceptance of a paper by the *Journal of Climate* entitled, The Composite Characteristics of Cirrus Clouds; Bulk Properties Revealed by One Year of Continuous Cloud Radar Data, by Gerald Mace, Eugene Clothiaux and Thomas Ackerman.

3. Accomplishments

As stated above, our overall research goals are to contribute to the effort to bridge the temporal and spatial scale gap between the observations and the grid scale of climate models. This step is necessary if the vast informational database being generated by the ARM program is to have full impact on climate model validation and parameterization improvement. Addressing our fundamental research goal requires significant effort, and we have been active in many of these areas during the period covered by this progress report. A detailed accounting of our activity is beyond the scope of this report. Therefore, in the following paragraphs, we briefly summarize the bulleted items listed in the previous section.

Cloud Property Retrieval Algorithm Development

We continue to be active in many aspects of this research arena. For instance, currently published algorithms (with the exception of highly uncertain regression-based approaches) can only be applied to optically thin, single layered cirrus. We have been working for several years on an approach that uses only the first three moments of the Doppler spectrum as recorded by the MMCR. In this algorithm, we assume a bimodal distribution of particles where the large mode can be approximated by a modified gamma (Mace et al., 1998) function and the small mode by an exponential distribution (Platt et al., 1998). This modified gamma distribution requires knowledge of three parameters related to the concentration of particles, the mean particle size, and the distribution variance. These unknowns are determined using the radar reflectivity, estimated particle fallspeed and velocity variance. Using Rayleigh-Gans theory, we assume the particles' radar backscatter can be approximated by a collection of prolate spheroids randomly oriented in the horizontal plane (van de Hulst, 1957). The fall speed of the large particle mode is modeled after the characteristics of plane polycrystals as reported by Mitchell (1996). The small particle mode is modeled according to the hexagonal column characteristics reported by Heymsfield (2000). Since the equations relating the three observable quantities cannot be solved analytically, we generate a lookup table by first performing a forward calculation of the three observables using all possible combinations of the size distribution parameters. This table is then inverted so that the distribution parameters can be determined from the observables. With this table, observations of radar reflectivity, Doppler velocity and Doppler velocity variance can be converted directly into estimates of a bimodal size

distribution of cirrus particles. From this size distribution, the optical and microphysical properties can be calculated. We have made extensive use of aircraft data collected at ARM cloud IOPs in the development and validation of this algorithm. Table 1 and Figure 1 show a simulation experiment where 2dc size spectra are converted to Doppler moments, then the retrieval algorithm attempts to derive the input size spectra from three derived Doppler moments. Overall we find that the algorithm is able to reproduce, with reasonable accuracy, the properties of the input size spectra. Use of the bimodal assumption is found to be necessary when considering lower order moments such as particle concentration or count median length but not necessary when considering higher order moments of the particle size distribution such as ice water content.

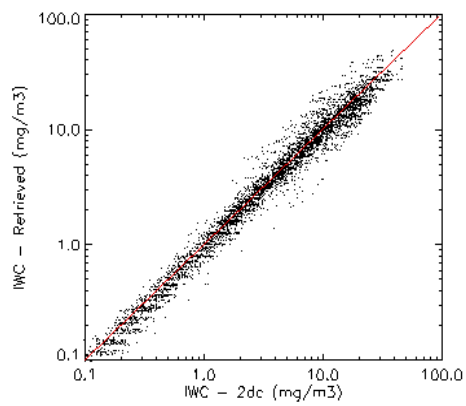

Figure 1. IWC comparison from 2dc simulation experiment. Here we assume a bimodal size distribution. The quantitative summary is in the IWC 2mode row of Table 1.

Table 1. Error Analysis of the moments algorithm from the 2dc simulation experiment. Here we compare assumed bimodal spectra (2mode) with unimodal (1mode) spectra for three parameters of the size distribution, L – count median length, IWC – Ice water content and Conc – particle concentration. The columns show the median (50%), 90%, and 95% error. The values can be interpreted as the fractional error level below which 50%, 90% or 95% of the error occurs. Consider the bimodal median length row. The median error is 8%, the 90th percentile error is 25%. In other words, half of the cases have error less than 8% while 90% of the error lies below 25%. Another interpretation is that there is a 50% chance of error greater than 8% while there is a 10% chance of error greater than 25%. The r column is the linear correlation coefficient.

		50%	90%	95%	Bias	r
L	2mode	0.08	0.25	0.33	-3	0.84
	1mode	0.21	0.45	0.56	64	0.94
IWC	2mode	0.13	0.38	0.58	0.4	0.82
	1mode	0.16	0.40	0.48	0.5	0.95
Conc	2mode	0.3	2.0	4.3	2	0.30
	1mode	0.6	0.8	0.9	-11	0.60

Comparisons of retrievals from radar data to observations by research aircraft are shown in Figure 2. From this preliminary result we find that the uncertainty in ice water content is on the order of 30% while the uncertainty in median size is approximately 15%. Work continues on the algorithm. We anticipate a manuscript will be submitted by the end of this calendar year.

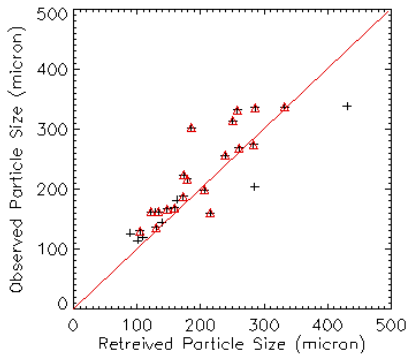

Figure 2. Comparison median particle size derived from aircraft data to that retrieved with the Doppler moments algorithm applied to radar data.

Spring 2000 Cloud IOP

In close coordination with a team of researchers from within the DOE ARM infrastructure and the ARM science team, a considerable portion of our efforts during the past year were devoted to planning and implementing the Spring 2000 Cloud IOP at the Southern Great Plains (SGP) central facility. The IOP was held in conjunction with the ARESE II campaign and the WiscT-2000 ER2 deployment. Quantities related to the three dimensional distribution of cloudiness remain difficult parameters to obtain using the basic observational paradigm of the ARM program. ARM's detailed sensing of clouds occurs in a narrow vertical column using vertically pointing instruments located at single geographical locales. However, knowledge of the cloud field properties are still required to address many important scientific questions including the coupling between the cloud field and the radiative heating profile and the advective tendencies of condensate. With the existing operational instrumentation at the ARM sites, scientific questions related to the volumetric distribution of clouds can be treated only approximately through various assumptions built into algorithms. Our primary goal in Spring 2000 cloud IOP was to generate a dataset that can be used to evaluate these assumptions and quantify the uncertainty of the algorithms into which these assumptions are codified.

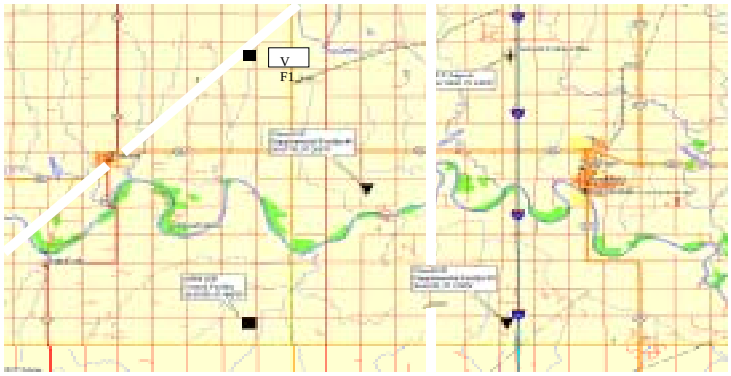

Figure 3. Map of the spatial distribution of observational sites during the Spring 2000 cloud IOP.

The Spring 2000 cloud IOP occurred around a cluster of millimeter cloud radars, lidars and passive instruments that were distributed in an approximate right triangular array with vertices near the SGP central facility (CF), Blackwell Tonkawa airport (~20km), and a supplemental facility ~15 km east of the SGP CF (Figure 3). Within this array were deployed aircraft to collect in situ micro-physical data and an airborne remote sensor platform that collected millimeter radar data and upwelling and downwelling solar fluxes.

Table 2. Spring 2000 Cloud IOPUND Citation Flight Summary

Date	Times (UTC)	Duration	Objective
3/3	1730 – 2011	2.7	Stratus, EOS
3/5	2307 – 0220	3.2	Cirrus
3/9	1841 – 2243	4.0	Cirrus
3/10	1644 – 1949	3.1	Altocumulus, EOS
3/12	1659 – 2011	3.2	Thin Cirrus, EOS
3/12	2233 – 0145	3.2	Cirrus
3/13	1822 – 0230	4.2	Cirrus
3/17	1724 – 2030	3.1	Stratus, ARESE
3/18	1621 – 1837	2.2	Stratus (drizzle)
3/18	2159 – 2348	1.8	Stratus (supercooled)
3/19	1529 – 1855	3.5	Stratus, turbulence (EOS)
3/21	1712 – 1953	2.7	Stratus, ARESE

While only time and hard work will tell if this IOP was as successful as it appears at this early date, the preliminary evidence suggests that a robust data set was compiled that addresses all of our original objectives. We studied pure cirrus, cirrus transitioning to altostratus, altostratus, nimbostratus, stratocumulus and overcast stratocumulus transitioning to scattered cumulus. We coordinated multiple times with the ARESE and ER2 efforts and collected ground-based and in situ data during multiple LandSat 7 and Terra overpasses. Table 2 lists the data collection flights of the University of North Dakota Citation. We are beginning the initial archival of the preliminary data. Our plans call for final submission of the data to the ARM archive by the end of the year 2000.

Journal Papers Accepted

Considerable effort was devoted to preparation of two manuscripts that have been accepted for publication in referred journals. We include here the abstract of these manuscripts:

- A Constrained Algorithm for Retrieval of Stratocumulus Cloud Properties Using Solar Radiation, Microwave Radiometer, and Millimeter Cloud Radar Data, by Gerald Mace and Kenneth Sassen, Accepted by the *Journal of Geophysical Research*

Abstract: Non-precipitating liquid phase clouds of the planetary boundary layer are important components of the earth's energy budget. Modern remote sensors are able to probe these clouds with increasing precision and detail, and extensive boundary layer cloud data sets are being generated at multiple sites around the world. In this paper, we integrate several recent cloud property retrieval algorithms targeted at boundary layer stratocumulus clouds into a single framework that returns the vertical profile of microphysical properties. The new algorithm guarantees consistency between the radar reflectivity profile, the microwave radiometer-derived liquid water path, and the surface solar flux transmission ratio. We demonstrate a 0.9μm RMS difference and 0.89 correlation coefficient when results from the new approach are compared to aircraft-observed volume mean cloud droplet radii. An additional stratocumulus case study observed at an Atmospheric Radiation Measurement site is briefly described.

- The Composite Characteristics of Cirrus Clouds; Bulk Properties Revealed by One Year of Continuous Cloud Radar Data, by Gerald Mace, Eugene Clothiaux and Thomas Ackerman. Accepted by the *Journal of Climate.*

Abstract: The properties of mid-latitude cirrus clouds are examined using a year of continuous vertically pointing millimeter-wave cloud radar data collected at the Atmospheric Radiation Measurement program Southern Great Plains site in Oklahoma. The goal of this analysis is to present the cloud characteristics in a manner that will aid in the evaluation and improvement of cirrus parameterizations in large-scale models. Using a temperature- and radar reflectivity-based definition of cirrus, we examine the occurrence frequency of cirrus, the vertical location and thickness of cirrus layers and other fundamental statistics. We also examine the bulk microphysical properties of optically thin cirrus layers that occur in isolation from other cloud layers. During1997, we find that cirrus were present 22% of the time, had a mean layer thickness of 2.0 km, and were most likely to occur in the 8.5-10 km height range. On

average, the cirrus clouds tended to be found in layers where the synoptic scale vertical velocity was weakly ascending. The mean synoptic-scale vertical motion in the upper troposphere as derived from Rapid Update Cycle model output was +0.2 cm s^{-1}. However, a significant fraction of the layers (33%) were found where the upper tropospheric large-scale vertical velocity was clearly descending ($w < 1.5$ cm s^{-1}). Microphysical properties were computed for that subset of cirrus events that were optically thin (infrared emissivity < 0.85) and occurred with no lower cloud layers. This subset of cirrus had mean values of ice water path, effective radius and ice crystal concentration of 8 g m^{-2}, 35 μm and 100 l^{-1}, respectively. While all the cloud properties demonstrated a high degree of variability during the period considered, the statistics of these properties were fairly steady throughout the annual cycle. Consistent with previous studies, we find that the cloud microphysical properties appear to be strongly correlated to the cloud layer thickness and mean temperature. Use of these results for parameterization of cirrus properties in large-scale models is discussed.

Community Service

Non-Science but ARM-related activities that we participated in during the year include

- Membership by PI on the ARM Science Team Executive Committee,
- Service as co-chair of the cloud working group and now as chair of the cloud properties working group,
- Hosting of cloud working group meeting at the University of Utah during December 1999.

References:

Platt, C. M. R., 1998: A parameterization of the visible extinction coefficient of ice clouds in terms of the ice water content. *J. Atmos. Sci.,* **49,** 2083-2098.

Mitchell, D. L., 1996: Use of mass- and area-dimensional power laws for determining precipitation particle terminal velocities. *J. Atmos. Sci.,* **53,** 1710-1723.

Van De Hulst, H. C., 1957: *Light Scattering by Small Particles.* Dover Publications, New York, 470 pp.

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Mace, G. G., T. P. Ackerman, P. Minnis, and D. F. Young, 1998: Cirrus layer microphysical properties derived from surface-based millimeter radar and infrared interferometer data. *J. Geophys. Res.,* **103,** 23207-23216.

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Year 4 Statement of Work

Gerald G. Mace, P.I.

We plan to use the supplemental fourth year of this grant period to continue toward our original objective of synthesizing the ARM data streams in such a way as to bridge the scale gap between the resolved scales of climate models and the observational scales of the ARM data streams. This fundamental objective was discussed in broad terms in our original science team proposal. Given the progress we and others have made in the past several years, we are able to discuss this objective in much more specific terms. Our goal was to develop three parallel data bases consisting of the large-scale meteorological parameters (those that a climate model might predict), the cloud macroscale properties (cloud boundaries, base and top temperature, cloud fraction as a function of height, etc) and the cloud microphysical properties derived from cloud property retrieval algorithms. From these parallel databases we proposed to search for relationships between the larger scales and the time-averaged cloud properties.

This original goal remains essentially unchanged, and we have made substantial progress toward achieving it. Specifically we now have operational code processing essential portions of the SGP data stream to generate continuous records of the cloud macroscale properties. We have made and are continuing to make advances in development and implementation of cloud property retrieval algorithms (see our previous and current progress reports). We are characterizing the large scale meteorological state with the NCAR/NCEP reanalysis data, ECMWF products and NCEP RUC model output.

To tie these varied sources of information into something like a manageable composite, we have installed state of the art database software (Oracle version 8I) on our Sun workstations and secured the services of a database system administrator under a consulting arrangement. Working with this individual, we have made initial steps toward ingesting a version of out processed ARM data stream into a fully functional relational database. Therefore, our primary goal for year 4 is to construct a scientifically useful prototype database accessible via the internet to the ARM science team.

Beyond the basic mechanics of building the relational database, a useful end product that meets the needs of the general ARM community requires that we continue

- active development of cloud property retrieval algorithms,
- processing of cloud IOP data in order to take advantage of the our growing collaboration with cloud resolving modelers,
- expansion of our local data processing structure to include the TWP and NSA data streams
- continued service as nominal head of the cloud properties working group,
- continued service in the science team executive committee.

We look forward to a busy and productive 4th year.