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DEVELOPMENT OF IMPROVED TECHNIQUES FOR SATELLITE REMOTE SENSING OF CLOUDS AND RADIATION USING ARM DATA

Principal Investigator
Dr. Patrick Minnis
NASA Langley Research Center, Hampton, VA
p.minnis@nasa.gov

Co-Investigators
Louis Nguyen, William L. Smith Jr.
NASA Langley Research Center, Hampton, VA

David P. Duda
Science Systems and Applications, Inc., Hampton, VA

Xiquan Dong
University of North Dakota, Grand Forks, ND

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Abstract

During the period, March 1997 – February 2006, the Principal Investigator and his research team co-authored 47 peer-reviewed papers and presented, at least, 138 papers at conferences, meetings, and workshops that were supported either in whole or in part by this agreement. We developed a state-of-the-art satellite cloud processing system that generates cloud properties over the Atmospheric Radiation (ARM) surface sites and surrounding domains in near-real time and outputs the results on the world wide web in image and digital formats. When the products are quality controlled, they are sent to the ARM archive for further dissemination. These products and raw satellite images can be accessed at http://cloudsgate2.larc.nasa.gov/cgi-bin/site/showdoc?docid=4&cmd=field-experiment-homepage&exp=ARM and are used by many in the ARM science community. The algorithms used in this system to generate cloud properties were validated and improved by the research conducted under this agreement. The team supported, at least, 11 ARM-related or supported field experiments by providing near-real time satellite imagery, cloud products, model results, and interactive analyses for mission planning, execution, and post-experiment scientific analyses. Comparisons of cloud properties derived from satellite, aircraft, and surface measurements were used to evaluate uncertainties in the cloud properties. Multiple-angle satellite retrievals were used to determine the influence of cloud structural and microphysical properties on the exiting radiation field.

1. Introduction

Clouds are the dominant modulators of radiation in the atmosphere. Accurate observations of cloud properties and their relationship to the radiation fields are needed to improve and constrain radiative transfer models (RTM), cloud process models and general circulation models (GCMs). In this role, such observations are critical to the goals of the ARM program. Satellite data can provide quantification of the radiation fields exiting the top of the atmosphere (TOA) and, through remote sensing analysis, can yield many of the bulk cloud properties essential for quantifying atmospheric liquid and ice water and their radiative properties over a variety of scales in a given domain. Additionally, remote sensing can be used to estimate surface radiative properties like albedo and emissivity that are essential for understanding the radiative interaction between the surface and atmosphere. Even more importantly, accurate characterization of the surface radiative properties is essential for deriving cloud properties from satellite data. Cloud properties such as optical depth, particle size, phase, ice and liquid water paths, and cloud height and thickness are necessary to link the atmospheric hydrological cycle to the radiation budget. Thus, increases in accuracy of satellite-derived cloud products and radiative fluxes derived from observations provide the basis for improvements in formulations of the processes that produce clouds in models and interact with the radiation budget. The goals of our proposal are summarized under six broad objectives that apply to ARM surface sites and field programs:

1. *Calibrate sensors used to retrieve satellite cloud and radiation properties for ARM*
2. *Develop techniques for improved characterization of clear-sky radiances for remote sensing and radiative flux determination.*
3. *Test and develop methods to derive cloud properties including cloud ice water path from satellite-observed radiances in all conditions, including multilayered clouds.*
4. *Validate and improve the measurements of broadband radiation at the top of the atmosphere over the ARM sites.*
5. *Provide satellite support for ARM field programs.*
6. *Investigate cloud phenomena related to the ARM surface sites.*

During the period of study, we made considerable broad progress in addressing the problems in remote sensing of clouds and determination of the radiation budget at the top of the atmosphere and at the surface using narrowband data. Some of the work conducted under this agreement was completed and/or published after the end of the study period. Our accomplishments in addressing those goals are summarized below. The full details are documented in our publications. We co-authored 47 published peer-reviewed manuscripts (*A1-A47*). A total of 138 papers were presented at scientific meetings with at least 85 published in proceedings.

2. Data

Our primary satellite datasets for deriving cloud and radiation parameters consist of radiances from the Geostationary Operational Environmental Satellite (GOES) imager (0.65, 3.9, 6.7, 10.8, and 12.0 μm) for the ARM Southern Great Plains (SGP) area, the Japanese Geostationary Meteorological Satellite (GMS) imager (0.65, 10.8, and 12.0 μm), GOES-9, and MTSAT-1R for the ARM Tropical Western Pacific (TWP) domain, Meteosat-8 SEVIRI for the European and African experiment areas, and the Sun-synchronous NOAA series (11, 12, 14, 15, 16) Advanced Very High Resolution Radiometer (AVHRR) 1-km imager (0.65, 0.86, 3.7, 10.8, and 12.0 μm; and 1.6 μm on NOAA-15) over the ARM North Slope of Alaska (NSA) and all other areas. Secondary and supporting datasets include the Tropical Rainfall Monitoring Mission (TRMM) satellite with the Visible InfRared Scanner (VIRS; 0.65, 1.6, 3.7, 10.8, and 12.0 μm) radiances and fluxes from the Clouds and Earth's Radiant Energy System (CERES) broadband scanners (shortwave, SW: 0.2 - 5.0 μm; longwave, LW: 5 - 50 μm) and the Earth Radiation Budget Experiment (ERBE) scanners and wide field of view (WFOV) instruments on ERBS, NOAA-9, and NOAA-10. The TRMM instruments began observing December 28, 1997 between 38°S and 38°N and acquired 9 months of CERES data. The VIRS is still operating. CERES data and multispectral imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) are taken by the Terra and Aqua satellites that have 1030 and 1330 LT equatorial crossing time, respectively. Multispectral data from the second Earth Resources Satellite Along-Track Scanning Radiometer (ATSR-2) were also used in some of the analyses.

3. Research Tasks

3.1 Calibration

Before testing and validating satellite retrievals using ARM and other datasets, it is essential that the satellite data are properly calibrated. Operational satellite imagers, especially their visible channels are generally poorly calibrated. To obtain the best calibrations possible, we calibrated the GOES-8 channels against a variety of research satellite imagers including the VIRS, ATSR-2, and MODIS, which carry onboard calibration systems that are often superior to those on operational meteorological satellites. Our initial study (*A16*) revealed a consistent trend in the GOES-8 VIS calibration. However, the resulting absolute calibration of the GOES imager was different for each satellite. Some of the differences could be attributed to differences in the filter functions for each instrument, but outstanding discrepancies indicate that the three research satellite imagers differed in their absolute calibration. The VIRS calibration was selected as the reference for calibrating the VIS channel on the operational satellites used in our ARM studies prior to 2007. It was selected because the optical depths derived using the ATSR-2 calibration were too low compared to surface retrievals and the MODIS data were still preliminary. The reference calibration may change again if warranted by additional evidence.

The infrared channels were also compared, but the differences between one satellite and another were no greater than the accuracy of the given satellite instrument and the differences expected from the filter functions for each channel (*A17*). A method to rapidly calibrate the various geostationary and Sun-synchronous satellites was also developed by demonstrating that the calibration of GOES to VIRS can be easily and accurately transferred from the GOES-8 to another geostationary satellite using data taken every day (*C96*), thus ensuring that the calibrations between the satellites are consistent and can be used to monitor any sudden shifts in the calibration of one or the other satellite (*C22, C23, C38, C43, C45, C56, C57, C89, C98*). We also developed an independent method to detect trends in the visible channel calibrations using the reflectivity of deep convective clouds (*C95*). These satellite calibrations, which have been supported both by ARM and CERES, represent a significant contribution of ARM to the remote sensing and radiation community. They also have an important positive impact on the derived cloud products and shortwave albedos derived from the VIS data.

3.2 Surface and clear-sky radiance characterization

Bidirectional reflectance distribution functions BRDFs are necessary to describe the anisotropic reflectance patterns from natural surfaces and the atmosphere. They are also critical in the prediction of clear-sky reflectance for cloud detection and for computing the albedo from a reflectance measurements. BRDFs were developed for clear land using radiance measurements from the ARM Unmanned Aerospace Vehicle (UAV) Multispectral Pushbroom Imaging

Radiometer (MPIR; see *A8*) and CERES-ARM Radiation Experiment (CARE) helicopter data (*C2*) taken over the areas surrounding the ARM SGP central facilities. These models along with the GOES and ERBE BRDFs that are currently used in operational ARM and CERES cloud retrievals, and radiative flux inversions were tested using matched intercalibrated GOES-8, GOES-10, TRMM VIRS, NOAA-12 and 14 AVHRR visible channel datasets over the ARM SGP domain (*C11*). The comparisons of the narrowband visible albedos derived from dual, collocated satellite measurements indicated that the ERBE and GOES models, in general, produced the smallest bias and random errors, while the CARE and MPIR models produced the most significant errors in albedo. Although the latter pair were derived directly from central Oklahoma data, they were not as representative as the other models because the atmospheric corrections and angular sampling were insufficient. The comparisons and helicopter measurements indicated that some asymmetric diurnal variations of spectral reflectance occurred for some areas, however the results are not conclusive. All of the models, except CARE, produced acceptable errors in albedos for low solar zenith angles (NOAA-14 AVHRR). The RMS errors ranged from 22 to 35% for high solar zenith angles (NOAA-12). Differences in the filter functions of sensors indicate that UAV imagers can be used to develop useful BRDFs at the TOA if the UAV flies high enough and obtains more complete angular coverage than was possible during the ARM UAV field experiments.

BRDFs were developed for clear snow using theoretical calculations assuming that the snow is similar to an optically thick ice cloud. To simulate the reflectance of clear snow, adding-doubling calculations were performed using a randomly oriented hexagonal ice crystal with an effective diameter of 135 μm in a cloud with an optical depth of 1000. The resulting bidirectional reflectance values were compared to AVHRR and MODIS observations taken over the Arctic Ocean, Greenland, and Antarctica. The theoretical model agreed quite well with the AVHRR observations over the Arctic except for the forward scattering direction where the observations tended to be somewhat greater than the theoretical values at higher viewing zenith angles (*C30*). Initial examination of the data indicates the presence of low-level haze that causes the forward scattering discrepancies. The model calculations for 3.7 and 1.6-μm channels revealed the same trends in clear-snow reflectance as seen from MODIS data taken over both poles. However, the observations show an overall greater reflectance than computed with the model. Some of the differences may be related to the optical depths used and to the MODIS calibrations (*C29*). The theoretical models were adjusted to the observations and have been used to improve the detection of clouds over snow surfaces (*C36*).

As a first step towards improving estimates of surface temperature in cloudy conditions, we examined the relationship between skin temperature and cloud shadowing at the ARM SGP central facility under overcast and partly cloudy skies (*C6*). Surface skin temperature was measured by the down-looking wide field-of-view infrared (9.6 – 11.5 μm) pyrometer, while the up-looking SIRS or BSRN pyranometers measured the total downward shortwave (0.2 – 5 μm) hemispheric irradiance. Skin temperatures derived from 1-min averages of the IR data were compared to the air temperatures measured at a height of 2 m. Under overcast conditions at night, the 2 m air and skin temperatures were within 1 K of each other. In daytime under both overcast and mostly cloudy conditions, the air/skin temperature differences correlated well with the downward shortwave hemispheric irradiance suggesting that skin temperature can be accurately estimated from surface air temperature during cloudy conditions. Partly cloudy conditions are more complex. A comparison of the skin temperature and shortwave irradiance under skies with scattered cumulus showed that the skin temperature at SGP reacts rapidly to changes in solar insolation. The lag between the shortwave irradiance and skin/air temperature differences is less than 1 min. Under such conditions, skin temperature can fluctuate as much as 10 K in 3 min. In nighttime ARESE GOES imagery, the skin temperatures in clear regions were substantially less than those underneath adjacent areas with low cloud cover. The local air temperature provided a good estimate of the cloudy-sky surface skin temperature resulting in a much better analysis of cloud properties at night.

Our follow-on study (*C53*) using 1998 surface-based skin and air temperatures at the SGP central facility (SCF) and skin temperatures derived from clear-sky GOES-8 data over a 0.5° region centered on the SCF generally confirmed the initial results. The maximum skin temperature exceeds the maximum air temperature in clear skies but both temperatures converge near sunrise. The skin temperatures derived from GOES-8 differed substantially from those derived from the surface suggesting that the ARM SCF measurements are not particularly representative of the larger area in general. The greatest differences occurred at night for partly and mostly cloudy conditions when GOES only observed the cold clear areas while the surface radiometer measured both cloud-blanketed and cloud-free scenes. Some of the differences seen in the daytime data can be attributed to anisotropic warming of the surface components. Using dual satellite measurements and matched aircraft and satellite data as well as helicopter measurements, we demonstrated definitively that during the daytime the facets of any land surface warm according to their exposure to the sun and vegetation type resulting in anisotropic emission (*A6, C1*). The derived skin temperature depends on the viewing and illumination angles as well as the surface morphology (terrain and vegetation). Thus, a skin temperature derived from a fixed satellite position will vary considerably relative to that from a hemispheric radiometer at a fixed location. The result is a diurnal cycle in the difference between the two measurements. Similar effects also occur in partly cloudy conditions when cloud shadows cool the surface. A satellite may view various amounts of shadowing depending on the particular time of day. The result may be a diurnally dependent bias in the skin temperature derived from the satellite data and subsequently on any dual angle retrievals that assume a uniform emission that is independent of viewing angles. Methods are needed to correct for anisotropy in the satellite skin-temperature retrievals and for broken cloud conditions. An initial set of methods was determined using CERES data and tested using ARM skin temperature datasets (*C103*).

Surface microwave emissivities in the SGP area were found to vary substantially with soil moisture and time of day, perhaps due to the effects of dew (*A7, C8*). An improved technique for deriving surface emissivity was developed to include, more explicitly, the contributions of downwelling atmospheric radiation to the surface radiation balance need to compute the emissivity (*C46*). The method has been applied to both GOES and MODIS data (*C78*, *C99*).

3.3 Improvement and validation of cloud property retrievals

Algorithm Improvement

Improvement of the various algorithms has progressed considerably. The primary algorithms used for deriving cloud properties include the Layer Bispectral Threshold Method (LBTM), the Visible Infrared Solar-infrared Split-window Technique (VISST), and the Solar-infrared Infrared Split Window Technique (SIST). The last two methods are multispectral and are applied to satellites with the proper spectral complements. The LBTM uses only VIS and IR data and can be applied to most operational satellite imagers. It also serves as the primer algorithm for the multispectral techniques. The SIST is primarily used at night, while VISST is used during the day because it utilizes the VIS data to obtain more reliable estimates of thick-cloud optical depth.

All of these algorithms have been improved and are being used regularly. New infrared emittance models were developed and implemented to improve the interpretation of low clouds that are warmer than or near the same temperature of the surface (*A2*, *C9*). These new models are especially important for deriving low-cloud properties at night (*C24, C25*). A new visible reflectance parameterization was developed (*C58*) that greatly improves the accuracy of the retrievals from clouds over any surface type relative to the older parameterization that was used. The parameterization yields reflectances that are unbiased for all surface albedos and that reproduce adding-doubling results for clouds over surfaces with albedos from 4-10%, 10-50%, and 50-90% to within 0.5%, 0.7%, and 1.0%, respectively for all levels of cloud optical depths, phase, and particle size. The new parameterization can also reproduce the non-monotonic reflectance variation of clouds over bright surfaces, a capability absent from the earlier technique.

The new models and parameterizations were incorporated into SIST and VISST, which were then used together in an operational code to process GOES and other geostationary satellite data in a near-real time fashion (*C20, C24, C31, C44*). This near-real time algorithm ingests hourly 40-km resolution forecast analyses form the Rapid Update Cycle (RUC) numerical weather prediction model, then computes expected clear-sky reflectances and temperatures in all relevant channels using our derived surface emissivity maps and clear-sky albedo maps with the proper BRDFs and atmospheric corrections based on updated correlated *k*-distribution models (*A16, A17*) for each channel. A sophisticated multispectral cloud detection algorithm is employed to determine which pixels are cloudy and then applies either VISST or SIST depending on the solar zenith angle (*C49*). This methodology is currently operating over several ARM domains and producing results that are temporarily archived and displayed within a half hour of receiving the GOES data (see http://cloudsgate2.larc.nasa.gov/cgi-bin/site/showdoc?docid=4&cmd=field-experiment-homepage&exp=ARM). This methodology has replaced the LBTM for operational processing of ARM GOES data.

Detection of low clouds at night and in low-sun conditions is difficult because of variable surface emissivity and because the signal from the 3.7-µm channel is neutralized in low sun conditions (*C49*). We have made progress in improving the cloud mask in near terminator conditions using ARM cloud-radar data at the surface (*C70, C81, C116*). Scattered and broken clouds cause underestimates of cloud optical depth and overestimates of cloud fraction and effective radius. We have demonstrated that combinations of high-resolution visible data can be used with lower resolution infrared data to obtain fractional cloudiness at the pixel level resulting in improved retrievals of cloud properties (*C49, C80*). Detection of clouds over the Arctic was improved using a variety of multispectral techniques and models during both night (*C19, C53*) and sunlit (*A12, C10, C29, C30*) conditions. However, retrieval of cloud microphysical properties is extremely difficult during the winter and early spring even with the many channels available on MODIS (*C59*).

Cloud vertical structure is also important for understanding cloud processes and modeling clouds. Multilayered clouds also affect both satellite detection and retrievals. Using satellite and ARM radar products, we have made progress in identifying those characteristics that can be used to determine which pixels contain overlapped clouds (*C33, C60*). Using matched microwave and visible/infrared sensors, we developed a method for detecting multilayered clouds and deriving the microphysical properties and optical depth of the two ice and liquid water cloud layers comprising the multilayered systems (*A25*, *A36, C69, C85, C104*). We then improved the model using a new ice-over-water multilayered cloud radiance prediction parameterization (*A39*), validating each with ARM radar data. We used ARM radar data to estimate the errors in retrieved cloud thickness and developed a new algorithm for deriving cloud physical thickness from the retrieved cloud properties (*C51*) and validating cloud base heights using ARM and ASOS ceilometer data (*C107, C121*). We used the ARM lidar, radar and ceilometer data along with model and radiosonde humidity profiles to determine the probability of clouds occurring in a given layer (*A30, C83, C102*) to begin the process of developing a 3-D cloud field. We also explored the combination of satellite, retrievals, ceilometer data, thickness parameterization, surface observations, model data, and ARM site data to develop extensive and local 3- and 4-D cloud fields (*C67, C112*, *C114, C126*).

Retrievals of cloud properties are highly dependent on cloud phase and particle size distribution and shape. To help understand these effects, we performed several theoretical and empirical studies. We developed a technique using multiple angle satellite measurements to estimate the ice crystal habit in cirrus clouds (*A19, A29*). With the aid of NSA and MPACE in situ measurements, we developed a method for determining the presence of mixed phase clouds (*C119, C132, C133*). We used observed in situ cloud data to study the sensitivity of the retrievals to the drop size distribution (*C120*) and to the presence of drizzle in low-layer clouds (*C91*).

Validation

Validation studies using ARM surface instrumentation and multi-angle satellite data have helped assess our retrievals using the various algorithms. Over the NSA and Arctic ice pack, radar, lidar, and ceilometer data were used to determine the high accuracy of the cloud fractions and reduced accuracy of the cloud heights derived over the sites (*A12, C4, C17, C58*). ARM fixed and mobile radar and radiometer data were used to validate the cloud optical depths, effective particle sizes, and LWP/IWP derived from GOES, ATSR-2, MODIS, and AVHRR data (*A1*, *A14, A18, A22, A24, A35, A40, A41, A44, C13, C14, C15, C21, C37, C40, C55, C62, C65, C68, C72, C74, C79, C86, C93, C97, C101, C109, C110, C113, C117, C125, C131, C135*). Multi-angle retrievals from two different satellites were used to estimate the instantaneous uncertainties in cloud optical depth and particle size size (*C31, C115, C134*). Aircraft data were used to validate our retrievals of liquid water properties (*A14*, *C27, C56, C108*) and ice cloud properties (*A21, A23, A28*, *A38*). Analysis of time sequences of GOES imagery with VISST and SIST showing the formation of distrails in supercooled clouds provide additional validation of our phase retrievals (*A11*). Ceilometer, lidar, whole sky imager, and radar data were used to validate LBTM cloud amounts and heights over the TWP (*C7, C34, C51*) and SGP (*C32, C52*).

ARM data have also been critical for improving the surface data that are essential for long-term validation of the satellite retrievals. We used ARM microwave radiometers and aircraft in situ data to develop an improved algorithm for retrieving cloud LWP for both warm and supercooled liquid water clouds (*A10, C28, C46*) and determined the sensitivity of microwave-derived LWP to temperature over polar regions (*A20, C75*). Aircraft in situ data were used to validate the radar retrievals of cloud effective particle size and optical depths used to validate the satellite results (*A14, A18, C3, C37*).

Satellite data proved valuable for climate model validation, revealing shortcomings in the models' representation of both low and high cloud cover amounts (*A26*). Comparisons of model calculations of radiative fluxes using ARM retrievals of atmospheric profiles of temperature and humidity and cloud properties with those retrieved from satellite data revealed shortcomings in both the model and satellite retrieval products (*A33, C111*).

3.4 Validation and improvement of broadband flux estimates

One of the most unique features of the satellite retrievals is the TOA broadband flux products that cannot be derived accurately from the surface datasets. The GOES-8, GMS, MTSAT, and AVHRR data can be used to provide the TOA broadband fluxes by careful conversion of the narrowband radiances to broadband fluxes. These conversions require the use of BRDFs and limb-darkening models to translate the observed narrowband radiance into a flux or radiance at some reference condition. Empirical narrow-to-broadband model formulae are then used to convert the narrowband fluxes or radiances into broadband fluxes. The conversion formulae have been based on ERBE data matched with GOES, GMS, or AVHRR data taken during the 1980's. Thus, it is essential to validate and improve the determinations of broadband flux and assess subsequent quantities, such as atmospheric absorption, that are derived from it and other data.

We found significant anomalous absorption of shortwave (SW) radiation in clouds using GOES-8 and ARM surface radiometer data taken during 1995 (*A5*). Subsequent reanalysis of the GOES-8 data using our new VIS calibrations (*A16*) indicated less absorption than originally estimated (*A15*). Use of new aircraft and surface radiometers and data reduction techniques as well as new GOES calibrations, models, and CERES data results in better agreement between the model and observed TOA fluxes and atmospheric absorption (*A45, C35, C39, C42*).

Comparisons of Terra CERES data with the latest GOES-8 broadband fluxes indicate that the old ERBE conversion functions provide relatively accurate albedos for most seasons, but that the derived longwave (LW) fluxes were biased on average during most months over the Arctic (*C53*). Some of the bias is due to different viewing conditions, but the greater part is a lack of seasonal variability in the narrow-to-broadband conversions. New and more specific conversion functions based on the latest CERES data could help minimize errors in both SW and LW fluxes (C63, C64). Aircraft and surface radiometer data have also been used to validate the albedos and LW fluxes derived from AVHRR data over the Arctic (*A13*) resulting in the most accurate cloud radiative forcing data to date over the Arctic (*A13, C12, C16, C18, C26*).

We also explored the use of the ARM satellite retrievals for estimating the surface radiation budget to cover broad areas centered on the ARM sites (*C87, C130, C136*). Tests using the ARM satellite cloud products showed that the quality of the surface radiative fluxes was equivalent in accuracy to using ISCCP cloud data, but could be produced in near-real time (*A43*).

3.5 Participate in and support ARM field programs.

We participated in a minimum of 12 field programs during the study period. In some instances, we provided on-site interactive support providing real time imagery, cloud products, and model output, while, for others, we provided real time imagery and cloud products on the world wide web only. These field programs are listed in Table 1. Some of these programs are summarized in collaborative journal articles (*A3, A8, A42*). In addition to onsite support and participation in mission planning, we also conducted collaborative scientific studies using data taken during the field experiments. Our participation resulted in several collaborative efforts to validate cloud properties (*A18, C37*) and better understand the absorption of SW radiation in the atmosphere (*C35, C39, C42, C61*). Our satellite imagery and many of the cloud products are retained online for future analyses at the links shown in Table 1. Various requests to provide specific web products for other experiments arose from the development of ARM IOP web pages.

Analyses from field studies provided large-scale context for the surface and aircraft measurements (*A12, C71, C73*). They also helped elucidate the impact of aerosols on the microphysical properties of boundary-layer clouds (*A31, C92, C118*). Combinations of airborne and satellite data were used to determine the properties of deep convective anvils (*A34, C82*).

Table 1. Field Program participation and support.

Experiment	Period	Web link URL
SHEBA, ARM, & FIRE Arctic Cloud Exp	May – August 1998	cloudsgate2.larc.nasa.gov/arctic/
ARM UAV Phase III	Spring 1999	N/A
ARM UAV Phase IV	Summer 1999	N/A
TWP Nauru '99	Summer 1999	cloudsgate2.larc.nasa.gov/arm/TWP/nauru.html
Spring Cloud IOP	Spring 2000	cloudsgate2.larc.nasa.gov/armsgp/
Fall Water Vapor IOP & AFWEX	Sept – Dec 2000	N/A
ARM UAV	Fall 2002	cloudsgate2.larc.nasa.gov/armsgp/
MIDCIX	April 2004	cloudsgate2.larc.nasa.gov/midcix/
MPACE	Fall 2004	cloudsgate2.larc.nasa.gov/mpace/
MASRAD	Mar – Sept 2005	cloudsgate2.larc.nasa.gov/cgi-bin/site/showdoc?docid=4&cmd=field-experiment-homepage&exp=MASRAD
TWP-ICE	Nov 2005 – Feb 2006	cloudsgate2.larc.nasa.gov/cgi-bin/site/showdoc?docid=4&cmd=field-experiment-homepage&exp=TWP-ICE
RADAGAST	Jan –Dec 2006	cloudsgate2.larc.nasa.gov/cgi-bin/site/showdoc?docid=4&cmd=field-experiment-homepage&exp=niamey

3.6 Investigate related cloud phenomena

In the process of analyzing the satellite and ARM surface datasets, a variety of related scientific studies arise. The development of a validated radar-radiometer retrieval technique led to the determination of a climatology of stratus cloud microphysical properties, cloud fraction and radiative forcing over the SGP Central Facility (*A4, A27, A32, C123, C124, C127*). These various results should be valuable for modeling studies of boundary layer clouds. Cloud radiative forcing is usually defined in terms of cloud and cloud free cases, but water vapor differs between these cases also, so ARM data were used to determine the contribution of water vapor to the total cloud radiative forcing effect (*A37*). Efforts to properly navigate the GMS data during Nauru99 led to the discovery of a persistent, diurnally varying cloud plume generated by the island that passes directly over the ARM Nauru site (*A9, C5*). This may cause a bias in the cloud properties and radiation budget at the site relative to the surrounding ocean. Identification of this phenomenon led to a 19-month IOP at Nauru. Satellite and model data over the TWP were used to show the impact of breaking Rossby waves on tropical convection (*A46*). Improvement of the LWP values derived from the Arctic microwave radiometers (*A10*) resulted in closer examination of the data and detection of a possible diurnal cycle in cloud LWP over the ice pack (*C41*) and a different dependence of LWP on cloud temperature relative to that observed in the mid-latitudes (*A18, C47*). The ability to determine phase accurately using the VISST in near-real time has potential for detecting aircraft icing conditions (*C27, C55, C76, C77, C94, C105*), an unexpected but potentially very useful spin-off from the ARM satellite retrieval studies. The experience and expertise developed by the Principal Investigator in studies using ARM and other datasets led to a request for him to contribute a chapter on remote sensing to a book focused on cirrus clouds (*A47*).

The improvement of the algorithms and the need for supporting field programs led the development of near-real time retrieval capabilities that have evolved from the ARM domains (C47, C122) to larger areas that include the ARM domain but provide for wider application of the products (C88, C90, C100, C106, C128, 129, C137, C138). These results are provided in near-real time for many areas and over other areas with a lag of a few days. Averages of those properties are also provided on various time scales (C66, C84).

4. Concluding Remarks

Overall, the research conducted under this interagency agreement was quite fruitful and more than satisfied the objectives of the research. The benefits of the research to the ARM Program and the climate and meteorological community are still being felt in additional advances in the remote sensing of clouds and the use of the results for practical scientific applications.

5. Publications and Presentations

All peer-reviewed papers are numbered beginning with "A," while presentations and conferences proceedings are numbered starting with "C."

A1. 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**, 23,207-23,216.

A2. Minnis, P., D. P. Garber, D. F. Young, R. F. Arduini, and Y. Takano, 1998: Parameterization of reflectance and effective emittance for satellite remote sensing of cloud properties. *J. Atmos. Sci.*, **55**, 3313-3339.

A3. Curry, J. A., P. Hobbs, M. D. King, D. A. Randall, P. Minnis, T. Uttal, G. A. Isaac, J. O. Pinto, T. Uttal, A. Bucholtz, D. G. Cripe, H. Gerber, C. W. Fairall, T. J. Garrett, J. Hudson, J. M. Intrieri, C. Jakob, T. Jensen, P. Lawson, D. Marcotte, L. Nguyen, P. Pilewskie, A. Rangno, D. C. Rogers, K. B. Strawbridge, F. P. J. Valero, A. G. Williams, and D. Wylie, 2000: FIRE Arctic Clouds Experiment. *Bull. Amer. Meteor. Soc.*, **81**, 5-29.

A4. Dong, X., P. Minnis, T. P. Ackerman, E. E. Clothiaux, G. G. Mace, R. N. Long, and J. C. Liljegren, 2000: A 25-month database of stratus cloud properties generated from ground-based measurements at the ARM SGP site. *J. Geophys. Res.*, **105**, 4529-4537.

A5. Valero, F. P. J., P. Minnis, S. K. Pope, A. Bucholtz, B. C. Bush, D. R. Doelling, W. L. Smith, Jr., and X. Dong, 2000: The absorption of solar radiation by the atmosphere as determined using consistent satellite, aircraft, and surface data during the ARM Enhanced Short-Wave Experiment (ARESE). *J. Geophys. Res.*, **105**, 4743-4758.

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