Multispectral Retrieval of Nighttime Cloud Properties for CERES, ARM, and FIRE

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MULTI-SPECTRAL RETRIEVAL OF NIGHTTIME CLOUD PROPERTIES FOR CERES, ARM AND FIRE

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Introduction

Knowledge of global and regional distributions of cloud macrophysical and microphysical properties is essential for accurately balancing the cloud water and radiation budget in climate and mesoscale models. A variety of techniques have used spaceborne multi-spectral narrowband radiometers to determine these quantities. Many of these techniques have proven to be quite accurate and robust during daylight hours due to their exploitation of reflected solar radiation at several wavelengths. Nighttime analyses have also been successful but have proven to be less robust due to their reliance on thermal signals only.

This paper presents a new model-based objective nighttime technique that utilizes three narrowband thermal channels: 3.7, 10.8 and 12 µm, available on many geostationary and polar-orbiting platforms. This technique, the Solar-infrared, Infrared and Split-window Technique (SIST) objectively determines cloud phase, optical depth and height, as well as effective water droplet radius or ice crystal diameter for optically thin clouds. This technique is currently being used by the Clouds and the Earth's Radiant Energy System (CERES) program to provide high spatial resolution nighttime cloud properties to improve the interpretation of top of atmosphere broadband radiances. Additionally, the technique is being used for analyzing satellite data collected at the Atmospheric Radiation Measurement (ARM) program's Southern Great Plains (SGP) facility and in polar regions during the First ISCCP Regional Experiment (FIRE) Arctic Cloud Experiment (ACE). This study presents initial results of nighttime cloud properties derived from the Visible Infrared Radiometric Scanner (VIRS) aboard the Tropical Rainfall Measurement Mission (TRMM) satellite.

Data

The cloud properties, derived from the 2-km VIRS imager data, are used in the conversion of broadband radiance to flux for the larger CERES instrument field of view. Similarly, high resolution cloud properties are derived from the Geostationary Operational Environmental Satellite (GOES) and Advanced Very High Resolution Radiometer (AVHRR) instruments over the ARM SGP site, at nominal 4-km and 1-km resolutions, respectively. Analyses of GOES imagery over the ARM SGP and AVHRR imagery during the FIRE ACE will be presented.

Global atmospheric profiles required for the CERES analyses are obtained from the Goddard Earth Observing System (GEOS) four-dimensional data assimilation model produced by the Data Assimilation Office (DAO) at NASA Goddard Space Flight Center as described by Gupta et al. (1995). Profiles for the ARM SGP site are based on National Weather Service rawinsonde data placed on a latitude-longitude grid. Clear-sky radiances and surface emittances used in CERES cloud masking procedures are derived from AVHRR and VIRS data, ISCCP climatological records and DAO model estimates (Minnis et al. 1999, Baum et al. 1995). Clear-sky parameters for the ARM SGP and FIRE ACE analyses are derived from National Weather Service measurements and satellite-inferred surface properties, respectively.

SIST cloud properties are validated by comparison with surface-based measurements using lidar, radar and radiometer data taken at the ARM SGP central facility in Oklahoma. The surface-based optical depths and effective particle sizes are computed using the delta 2-stream model approach of Dong et al. (1997) and Mace et al. (1998). Cloud phases obtained with SIST are also compared to properties derived with a more traditional single channel technique, the Layered Bispectral Threshold Method (LBTM) of Minnis et al. (1995a).

Retrieval Techniques

In order to derive nighttime cloud properties for each cloudy pixel, the SIST utilizes radiances from three thermal channels: 3.7, 10.8 and 12 μm. The technique determines cloud temperature T_{cld}, cloud phase, optical depth τ, and effective cloud particle size with a minimum error, iterative regression method that matches the observations to the parameterized model emittance calculations (Minnis et al. 1998, Minnis et al. 1995b). A 75-term polynomial defines the emittance parameterization which is a function of τ, effective ice-crystal diameter D_e or water-droplet radius r_e, and the temperature difference between the cloud and the surface. Brightness temperature differences (BTDs) are calculated from the satellite radiances such that

$$BTD_{34} = T_{3.7\,\mu m} - T_{10.8\,\mu m}$$

and $$BTD_{45} = T_{10.8\,\mu m} - T_{12\,\mu m}.$$

These same quantities are also computed with the emittance parameterizations assuming that all cloudy pixels are overcast and have a temperature given by an initial estimate of T_{cld} over a background with a known clear-sky temperature for each channel. The phase and a nominal particle size are also assumed for the initial computation. The calculations of BTD_{34} and BTD_{45} are repeated for both liquid and ice clouds by varying D_e or r_e, τ and T_{cld} until the difference between the calculated and observed BTDs is minimized. Specifically, we minimize

$$\Sigma[(BTD_{34}^{obs} - BTD_{34}^{calc})^2 + (BTD_{45}^{obs} - BTD_{45}^{calc})^2].$$

The selected phase is based on which of the two minimum phase errors is smaller. Cloud height is calculated from T_{cld} using the atmospheric profiles. Assuming T_{cld} to be constant permits the retrieval of D_e or r_e and τ at the pixel scale by iteratively adjusting τ and either D_e or r_e in the parameterization until the calculated BTDs best match the observed BTDs for each pixel. For this study, the radiances observed in a cloudy pixel are assumed to be from a single cloud layer, so multi-level scenes may contaminate the retrieval of cloud parameters.

Results

Cloud properties have been derived from VIRS radiances using SIST since mid-December, 1997, when the CERES instrument became operational. Figure 1 contains results from the SIST cloud phase determination procedure for a 512 scan line by 261 pixel region over the tropical western Pacific Ocean. Ice clouds, indicated by the white areas, are most prevalent. Visual inspection of multi-

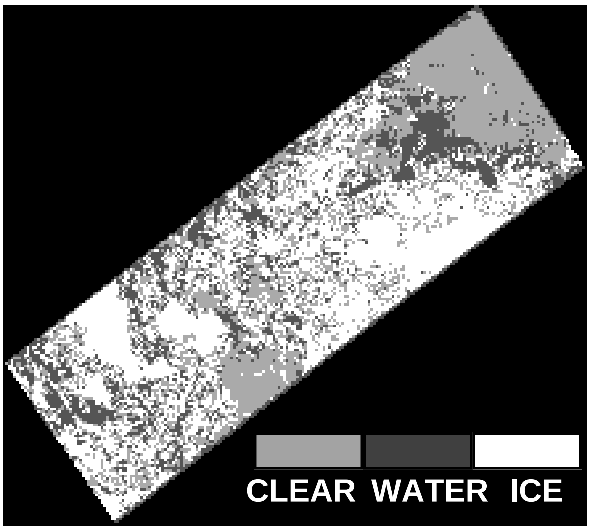

Fig. 1. SIST multi-spectral cloud phase determination from VIRS data over the tropical western Pacific Ocean, January 5, 1998.

spectral imagery of the pixel radiances verifies that a large area of optically thin to moderately thick broken cirrus clouds overlays much of the region. The solid white areas correspond to tops of convective areas. Water clouds, indicated by dark gray, are primarily small areas of scattered cumulus clouds with some larger stratus decks.

The SIST optical depth retrievals for this region ranged from 14.2 over the convective clouds to less than 0.5 in areas with thin cirrus only. The water cloud optical depths were generally around 2.0 with a mean r_e of 7.9 μm. D_e for the ice clouds ranged from 18 μm over the thin cirrus to upwards of 80 μm in the optically thick convective clouds.

Figure 2 presents phase determination results from the same area but using the LBTM. This single-channel technique is able to properly identify many of the larger low level stratus and thick cirrus cloud decks that were distinguished by SIST in Fig. 1, but improperly categorizes much of the variable cirrus as water clouds. The infrared-only technique relies only $T_{10.8\ \mu m}$ to determine T_{cld}, so it is unable to ascertain that pixels filled with optically thin and relatively "warm" cirrus clouds are composed of ice crystals. SIST uses the BDTs between the three channels to extract the cloud emittance rather than assuming that the cloud is a blackbody.

In Figure 3, D_e derived with SIST from VIRS data over the ARM SGP site in Oklahoma is compared with simultaneous surface measurements derived from lidar and radar data. The number of possible validation points is limited both by the relatively low frequency of nighttime TRMM overpasses and to the nights when ice clouds were present, but overall agreement is good.

The surface-derived D_e were averaged over a 1-hour period in an attempt to match the satellite data, which covered a 30-km by 30-km region. The resulting error bars in Fig. 3 approximate the range of mean D_e that could have been retrieved by either method. The two TRMM overpasses on January 20 agree relatively well. The largest error occurs on January 28 when the surface-based D_e is substantially higher than the satellite-derived D_e. This discrepancy is easily explained by GOES satellite imagery and radar data from the same day. A heterogeneous cirrus deck covered the 30-km box for which VIRS data was collected, resulting in a satellite-retrieved mean D_e that was not representative of the portion of the cloud seen from the surface. The surface instruments measure only a narrow column above their location. In this instance, the surface instruments observed the portion of the cirrus clouds that were composed of larger ice crystals.

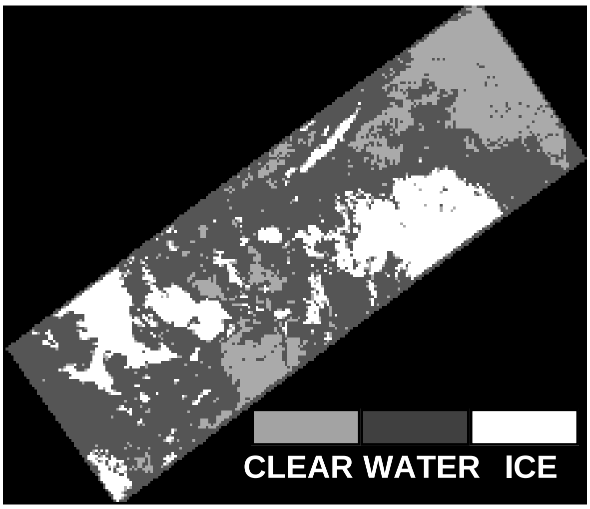

Fig. 2. Same as Fig. 1, but single-channel LBTM method used.

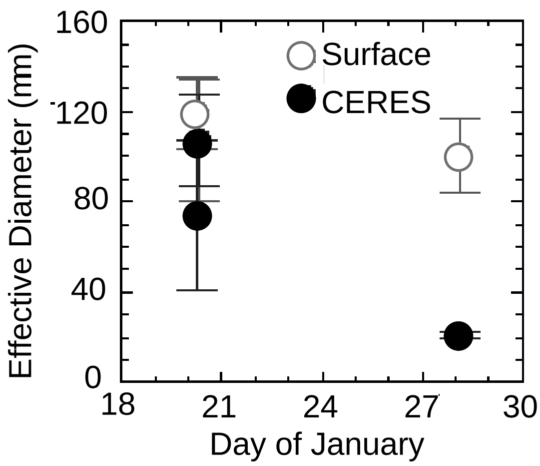

Fig. 3. Comparison of satellite-derived effective ice crystal diameter (closed circles) with surface-derived diameter (open circles) over ARM SGP central facility from January 1 to January 15, 1998. Error bars indicate one standard deviation of spatial average for satellite measurements and one standard deviation of time average for surface measurements.

Discussion

The TRMM satellite's orbit allows for SIST to retrieve cloud properties, such as those discussed in Fig. 1, from approximately 40 degrees north to 40 degrees south latitude. Preliminary validation of the nighttime retrievals over the ARM SGP indicates that the method is performing well. The retrievals have also been checked for consistency with daytime cloud properties derived with a more robust multi-channel algorithm that utilizes solar reflected radiances (Smith et al. 1997). These consistency checks and validation with surface-based instrumentation indicate that the nighttime algorithm is performing much better than infrared-only algorithms and those using two thermal channels.

Improvements to SIST that are in development include identifying multi-layer clouds and more sophisticated treatments of optically thick clouds ($t > 16$) at night. With the current set of commonly available satellite channels, the emittance parameterizations are unable discern optical depth or cloud microphysics for optically thick cases so climatological defaults are used.

This study indicates that the technique will provide much-improved night time retrievals for use in regional field experiments that seek improved cloud microphysics in cloud process models and in global programs that require improved cloud climatologies and more accurate radiative determinations.

References

Dong, X., T. P. Ackerman, E. E. Clothiaux, P. Pilewskie and Y. Han, 1997: Microphysical and radiative properties of boundary layer stratiform clouds deduced from ground-based measurements. *J. Geophys. Res.*, **102**, pp. 23829-23843.

Baum, B. A.., R. M. Welch, P. Minnis, L. L. Stowe, J. A. Coakley, Jr., J. Titlow, V. Tovinkere, P. W. Heck, Q. Trepte, D. R. Doelling, S. Mayor, T. Berendes, Q. Han, S. A. Christopher, K.-S. Kou, M. Penaloza, A. Logar and P. Davis, 1995: Imager clear-sky determination and cloud detection (Subsystem 4.1). "Clouds and the Earth's Radiant Energy System (CERES) Algorithm Theoretical Basis Document, Volume III: Cloud Analyses and Radiance Inversions (Subsystem 3)". *NASA RP 1376, Vol. 3*, edited by CERES Science Team, pp. 43-82.

Gupta, S. K., A. C. Wilber, N. A. Ritchey, F. G. Rose, T. L. Alberta, T. P. Charlock and L. H. Coleman, 1995: Regrid humidity and temperature fields (Subsystem 12.0). "Clouds and the Earth's Radiant Energy System (CERES) Algorithm Theoretical Basis Document, Volume IV: Determination of Surface and Atmosphere Fluxes and Temporally and Spatially Averaged Products (Subsystems 5-12)". *NASA RP 1376, Vol. 4*, edited by CERES Science Team, pp. 163-172.

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**, pp. 23207-23216.

Minnis, P., D. F. Young, D. A. Spangenberg, P. W. Heck, D. R. Doelling, Q. Trepte and Y. Chen, 1999: Cloud mask for CERES from VIRS on the TRMM satellite. *to be published in ALPS99 proceedings*, 4 pp.

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

Minnis, P., W. L. Smith, Jr., D. P. Garber, J. K. Ayers and D. R. Doelling, 1995a: Cloud properties derived from GOES-7 for the spring 1994 ARM Intensive Observing Period using Version 1.0.0 of the ARM satellite data analysis program. *NASA RP 1366*, 59 pp.

Minnis, P., D. P. Kratz, J. A. Coakley, Jr., M. D. King, R. Arduini, D. P. Garber, P. W. Heck, S. Mayor, W. L. Smith, Jr. and D. F. Young, 1995b: Cloud optical property retrieval subsystem (Subsystem 4.3). "Clouds and the Earth's Radiant Energy System (CERES) Algorithm Theoretical Basis Document, Volume III: Cloud Analyses and Radiance Inversions (Subsystem 3)". *NASA RP 1376, Vol. 3*, edited by CERES Science Team, pp. 135-176.

Smith, Jr., W. L., L. Nguyen, D. P. Garber, D. F. Young, P. Minnis and J. Spinhirne, 1997: Comparisons of cloud heights derived from satellite and ARM surface lidar data. *Proceedings of the Sixth ARM Science Team Meeting*, pp. 287-291.