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Retrieval of effective microphysical properties of clouds: A wave cloud case study

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Abstract. One of the important objectives of the SUbsonic aircraft: Contrail and Cloud Effecs Special Study (SUCCESS) field campaign data analysis is to investigate retrieving cloud microphysical properties using remote sensing observations. This paper presents the results of an infrared based retrieval of effective particle radius R_e using brightness temperature observations near 8.5, 11 and 12μm. The retrieval method relies on comparing 8.5-11 and 11-12μm observed brightness temperature differences to theoretical simulations. During SUCCESS, conducted in April-May 1996 out of Salina KS, the MODIS Airborne Simulator (MAS) on the NASA ER-2 made observations of contrails, cirrus and mountain lee wave clouds. Observations indicate that contrail and cirrus clouds are distinguishable by their radiative properties. Retrieval of R_e for the lee wave cloud case on 2 May agrees with in situ observations from probes mounted on a NASA DC-8 aircraft, validating the infrared retrieval. The addition of the 8.5μm information to the R_e retrieval greatly enhances the sensitivity of the retrieval at small particle sizes ($<$ 10μm).

1. Introduction

Increasing aircraft traffic over the last 25 years has raised the issue of the impact of jet aircraft exhaust on global cloud cover. Beginning in the late 1940's [*Weickmann*, 1950] and continuing to the present [*Parungo*, 1995] the microphysical properties of aircraft condensation trails (contrails) and associated cirrus cloud have been of scientific interest. Contrail characteristics including particle size, shape, density, and chemistry are under study for their effect on contrail persistence and role in initiating cirrus development, with implications for regional and the global radiation budget. Modeling studies indicate the effect of high clouds on the energy budget is a function of the ice water path, temperature, and particle size distribution in a cloud [*Stephens et al.*, 1990]. It is therefore important to characterize the microphysics of different types of contrails (i.e., short lived, persistent and spreading) as well as other global cloud types.

In situ sampling provides important validation observations of the particle size distribution for a limited number of clouds. By coupling in situ with broad geographic monitoring by satellites an improved understanding of cloud and contrail impact on the radiation budget can be attained. Already, algorithms for contrail detection using satellite observations have been developed [*Lee*, 1989; *Engelstad et al.*, 1992; *Gothe et al.*, 1993]. This paper investigates the retrieval of cloud effective particle size, R_e, using infrared (IR) remote sensing observations from the MODIS (MODerate resolution Imaging Spectroradiometer) Airborne Simulator (MAS) [*King et al.*, 1996]. MAS flew on a NASA ER-2 as part of the Subsonic Aircraft: Contrail and Cloud Effects Special Study (SUCCESS) in April-May 1996 [*Toon et al.*, 1996], which also included an instrumented NASA DC-8 aircraft for in situ measurements of cloud and contrail microphysics. MAS was developed and tested as a prototype of MODIS, an instrument being developed for the Earth Observing System (EOS) [*King et al.*, 1996]. MAS data are providing the fundamental visible and infrared observations to develop cloud and aerosol detection techniques for MODIS as well as investigate relationships between the microphysical and radiative properties of clouds.

2. Retrieval and Validation of Effective Particle Radius R_e

Split-window brightness temperature difference techniques rely on the spectrally varying cloud optical properties and the non-linearity of the Planck function to detect and study the radiative properties of clouds [*Inoue, 1985; Lee, 1989; Parol et al., 1991*]. Methods of estimating the particle size distribution using IR observations have been developed by *Parol et al.* [1995], *Gothe and Graßl* [1995], and *Duda and Spinhirne* [1996]. These techniques retrieve an effective particle size through comparison of observed brightness

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temperature differences between 11 and 12 μm (BT_{11}-BT_{12}) with model simulations of the same. The effective radius is defined as the third moment of the size distribution divided by the second moment. The sensitivity of the split window retrieval to inaccurate estimates of cloud temperature, cloud particle shape, cloud inhomogeneity, and clear sky radiance is discussed by *Parol et al.* [1995], *Takano et al.* [1996], *Gothe and Graßl* [1995], and *Duda and Spinhirne* [1996]. While providing valuable sensitivity studies, these studies have not compared the retrieved effective particle size with cloud in situ measurements. This study extends the split window approach to include observations at 8.5 μm, creating a tri-spectral retrieval. The retrieval is validated through a direct comparison with cloud in situ measurements.

The tri-spectral combination of 8.5, 11 and 12 μm bands was suggested for detecting cloud and cloud properties by *Ackerman et al.* [1996]. *Strabala et al.* [1996] further explored this cloud retrieval technique by utilizing high (50 meter) spatial resolution data from the MAS. Tri-spectral observations during SUCCESS suggest that contrails have different radiative properties than other cirrus clouds. In the tri-spectral diagram of Figure 1, a contrail and near-by cirrus cloud are compared. Data points with BT_8-BT_{11} < -2K and BT_{11}-BT_{12} < 0.5K are clear scenes (lower left). The presence of transmissive ice cloud increases both BT_8-BT_{11} and BT_{11}- BT_{12} (upper right). In Figure 1, the brightness temperature differences change as a function of the cloud ice water path and the particle size and shape distribution. Sensitivity studies with radiative transfer models indicate that the distinction between the contrail and cirrus points in Figure 1 is due to differences in the microphysical properties of the two clouds, suggesting the contrail has smaller particles. Validating Re for contrail scenes is complicated by the nonhomogeneous nature of contrails. Therefore no Re retrievals are presented herein for contrail scenes; however, a retrieval validation is presented for a uniform wave cloud case.

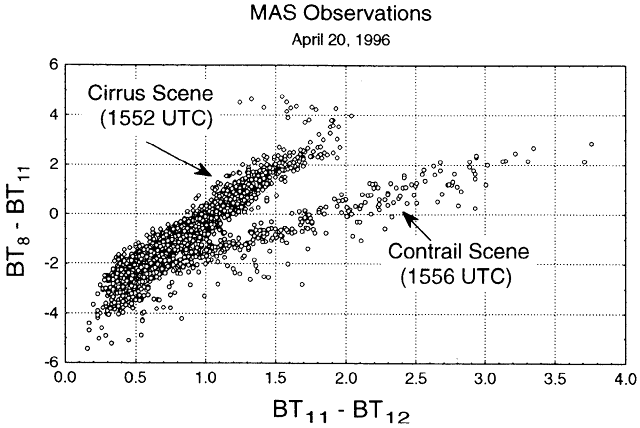

Figure 1. MAS tri-spectral observations from a SUCCESS April 20, 1996 scene containing isolated contrail and cirrus cloud. Contrail and cirrus cloud radiometric signatures are distinguishable from one another. Data points with BT_8-BT_{11} < -2K and BT_{11}-BT_{12} < 0.5K are clear scenes (lower left).

Figure 2. MAS visible (left) and 11μm (right) imagery of mountain lee wave cloud near Berthoud, Colorado on May 2, 1996 from the ER-2 platform. Each image is about 35 km across and 50 km long. This wave cloud case was chosen to validate MAS retrieved Re with co-incident DC-8 in situ measurements. DC-8 flight pattern indicated by contrail in imagery.

In the retrieval process, the MAS brightness temperature differences are compared with radiative transfer model calculations. A doubling/adding model is used to simulate the MAS 8.5, 11 and 12 μm observations, with the model output then being compared back to the MAS observations for determining R_e. Knowledge of the clear sky integrated temperature is required by the model and is obtained by adjusting clear sky theoretical calculations (using near-by radiosonde data) to agree with MAS clear scene observations. This important step "calibrates" the model to the MAS observed radiometric conditions. The sensitivity of the R_e retrieval was tested by varying four cloud properties in the doubling/adding model: cloud top and base altitude, cloud ice water content, and the cloud particle effective size distribution.

On 2 May the ER-2 and DC-8 aircraft collected coincident radiometric and in situ measurements of a quasi-homogeneous wave cloud over Colorado (Figure 2). Near-nadir MAS observations and model simulations of BT_8-BT_{11} (Figure 3) and BT_{11}-BT_{12} (Figure 4) indicate the clear sky 11μm brightness temperature is approximately 297 K. As the ice water path (IWP) in the cloud increases, BT_{11} decreases. As the cloud IWP increases, the BT_8-BT_{11} and BT_{11}-BT_{12} increase to a

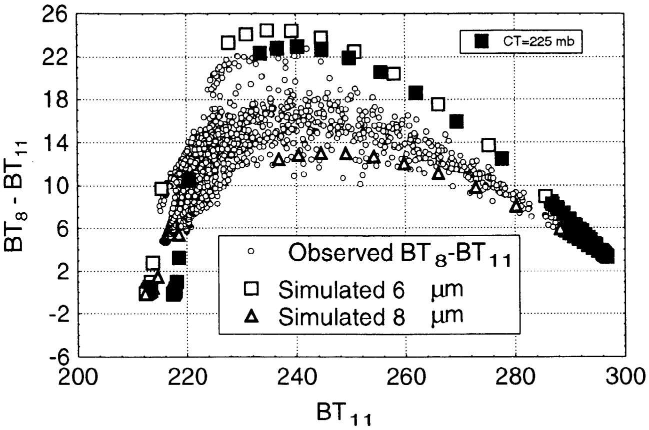

Figure 3. Brightness temperature difference between 8.5 and 11 μm as a function of the 11 μm brightness temperature. The small circles represent MAS observations of the May 2 wave cloud. Model simulations shown for cloud top at 200 mb and an effective radius of 6 (m (open squares), cloud top at 225 mb and an effective radius of 6 μm (filled squares), and cloud top at 200 mb and an effective radius of 8 μm (open triangles). The model simulations bracket the MAS observations.

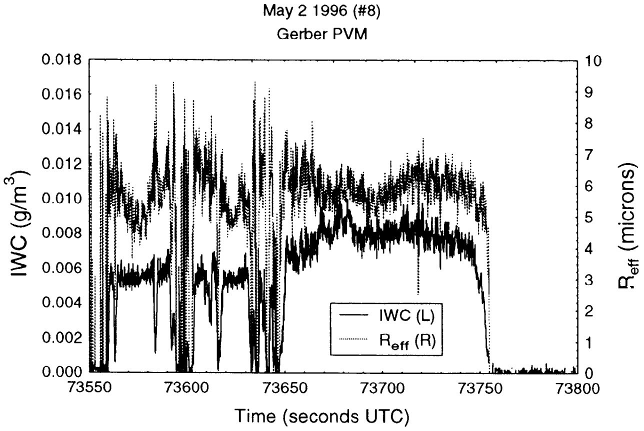

Figure 5. Particulate Volume Monitor (PVM) data co-incident with MAS observations of May 2 wave cloud. Near zero values of effective radius Re and ice water content (IWC) indicate observations outside of cloud. Within-cloud average Re for ER-2, DC-8 overlap region is 5.8 μm.

maximum value and then decrease, forming an arch. The steepness of the arch that bridges the clear sky values with the optically thick cloud case is a function of particle size and the difference between the clear sky and opaque cloud brightness temperatures. The BT_8-BT_{11} model output shows the best match to the observations; importantly, the BT_{11}-BT_{12} Re retrieval does not directly contradict the BT_8-BT_{11} Re retrieval. Figures 3 and 4 indicate cloud particle Re in the range of 6 to 8(m. For these model runs, ice spheres were used (in situ measurements indicated spherical to quasi-spherical particle shape); model runs using aspherical particle shapes (not shown) caused the BT_8-BT_{11} and BT_{11}-BT_{12} estimates of Re to diverge. In addition, using a spherical particle shape for this wave cloud is reasonable as the small ice particles composing wave clouds are quasi-spherical in shape [*Heymsfield and Miloshevich* 1993]. Model runs using different cloud top temperatures (i.e. changing cloud top altitude) did not appreciably alter the retrieval results (Figure 3). In agreement with the model, scatter in the MAS brightness temperature observations is greatest in transmissive cloud scenes (BT_{11} 230-270K). Largest brightness temperature differences tend to occur near the transmissive boundaries of the wave cloud, with smaller differences occurring in the mature, thicker portions of the cloud. Figures 3 and 4 demonstrate quite graphically that inclusion of an 8.5 μm channel increases the sensitivity of the Re retrieval to small particles as compared to the traditional split window (BT_{11}-BT_{12}) approach.

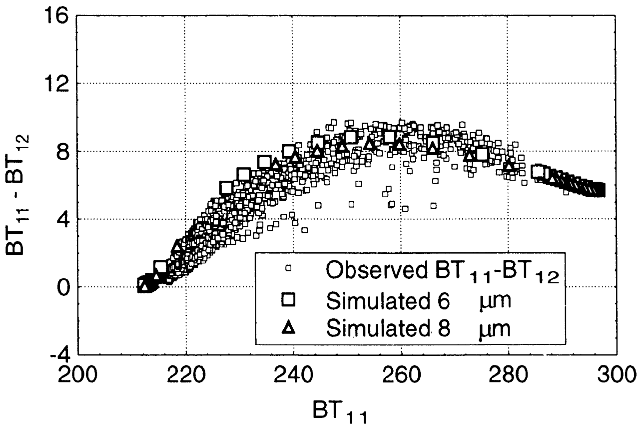

Figure 4. Brightness temperature difference between 11 and 12 μm as a function of the 11 μm brightness temperature. Small squares represent MAS observations of the May 2 wave cloud. Other symbols as in Figure 3. Model simulations show less sensitivity in BT_{11}-BT_{12} to small particle sizes, allowing other factors such as clear sky background or cloud temperature variation to dominate scatter in observed data.

The MAS R_e retrieval indicates particle sizes between 6 and 8 μm with a cloud top between 9 and 10 km. This result is in good agreement with in situ sampling provided by two new microphysical probes on the NASA DC-8 aircraft, the Particulate Volume Monitor (PVM) [*Gerber et al.,* 1994] and the Counter-flow Virtual Impactor (CVI) [*Twohy et al.,* 1997]. During a 2 minute period of sampling (approximately 25 km distance), ER-2 and DC- 8 coverage of the wave cloud spatially overlapped with about a 50 second time separation between the aircraft. The PVM data during this period indicates cloud particle sizes between 5 and 8μm (Figure 5), with an average within cloud effective radius of 5.8μm [*Gerber et al.,* 1997]. CVI in situ sampling indicated an average Re of 8.4μm. As a first attempt, the agreement between retrieved and in situ Re for the 2 May wave cloud case is encouraging and lends credibility to the tri-spectral R_e retrieval for contrails and other cloud types. These results are consistent with the GOES-8 R_e retrievals on 2 May by [*Young et al.,* 1997]. The SUCCESS data set will continue to be used to investigate R_e retrieval for all cloud types, and to validate the retrieval whenever possible.

3. Summary

This study has extended the split-window approach for radiometrically retrieving cloud particle size R_e by including observations at 8.5 μm. It was demonstrated that the addition of this channel improves the sensitivity of the R_e retrieval for small particles. SUCCESS field campaign ER-2 and DC-8 co-incident observations of a mountain lee wave cloud on May 2 1996 showed the retrieved R_e (between 6 and 8 μm) to be consistent with averaged in situ R_e measured by the PVM (5.8 μm) and CVI (8.4 μm) probes. This validation is encouraging and lends confidence to applying the retrieval algorithm to contrails (and other clouds) in various stages of development. As with other approaches, the retrieval algorithm requires an accurate determination of the clear sky radiometric conditions. The wave cloud scenes contained varying cloud ice water path, allowing for a complete definition of the arch that bridges the clear sky values with the thick cloud condition. This facilitated better cloud top temperature estimation for use in the model simulation. In the absence of a complete arch, additional information is required to determine the cloud temperature; in such cases, lidar observations become critical to the retrieval of the cloud effective radius

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