P4.26 **Retrieval of Cirrus Ice-Water Path, Particle Size, and Optical Thickness Using Thermal Infrared Satellite Data**

Robert P. d'Entremont
Satellite Meteorology Group
Atmospheric and Environmental Research, Inc.
131 Hartwell Ave., Lexington, MA 02421-3126

David L. Mitchell
Atmospheric Sciences Center
Desert Research Institute
2215 Raggio Parkway, Reno, NV 89512-1095

1. Introduction

Cirrus ice-water path (IWP) is estimated using a coupled algorithm that simultaneously retrieves IWP, ice-crystal particle size, emissivity, and cirrus temperature using radiances collected in the GOES mid-wave infrared (MWIR), water-vapor (WV), and thermal infrared (TIR) wavelengths, nominally at 3.9, 6.7, and 10.8 μm. From the standpoint of radiative transfer, cirrus IWP, emissivity, effective particle size, and effective temperature (defined here as the temperature of the radiative "center of mass" of the cirrus cloud) are interdependent. For this reason all these cloud attributes are being estimated simultaneously using a first-principles algorithm that numerically solves a set of simultaneous radiance equations.

The cirrus retrieval algorithm uses a simultaneous-solution approach to ensure physical consistency between satellite radiance measurements and theoretical radiative transfer calculations. The fundamental non-uniqueness of the relationship between measured radiance and cloud IWP, emissivity, particle size, and temperature at a single wavelength is resolved by forcing the retrieved parameters to be simultaneously consistent with theory and satellite observations at multiple infrared wavelengths. Retrievals are presented of cirrus cloud ice water path (IWP), effective diameter (D_{eff}) and optical depth (τ). Proof-of-concept retrievals are performed using GOES-8 thermal infrared satellite data.

2. Infrared Radiation Transfer in Cirrus

The cirrus analysis method is newly developed by AER and DRI. It is a thermal infrared (TIR) technique that retrieves the cirrus effective emissivity and temperature that simultaneously predict observed radiances in two or more TIR channels. Since the emissivity depends on absorption efficiency, IWP, and D_{eff}, a knowledge of the ice-crystal size distribution shape N(D) as a function of cirrus environmental temperature is required.

The approach has an explicit dependence of the retrievables not just on IWP and ice-crystal effective size D_{eff} but also on N(D) shape, including the slope parameter and dispersion of bi-modal modified gamma ice-crystal size distributions. These attributes have been related to temperature for tropical and mid-latitude cirrus using ARM and CEPEX in-situ aircraft observations. Comparisons between the ground- and satellite-based retrievals employing the same physics and methodology will reveal the sensitivity of IWP and D_{eff} on the vertical structure of cirrus cloud microphysics. In evaluating these differences, it may be possible to expand our retrieval confidence from small scales (e.g., using ground-based and aircraft data) to larger scales (e.g., satellite-based) for cloud radiative-forcing in climate models.

Analytic approximations to full geometric-scattering theory for non-spherical ice crystals have been developed for use in simulating MWIR, WV, and TIR bands. This section summarizes the theory and its application in our retrieval paradigm.

The infrared upwelling radiance $I_{\lambda,TOA}$ at wavelength λ in a non-scattering atmosphere and for a cirrus-filled pixel is well approximated by

$$I_{\lambda,TOA} = (1 - \varepsilon_\lambda) I_{\lambda,clr} + \varepsilon_\lambda B_\lambda(T_{cld}), \quad (1)$$

where ε_λ is the cirrus emissivity at wavelength λ; $I_{\lambda,clr}$ is the TOA radiance that would be observed in an otherwise cloud-free pixel; and $B_\lambda(T_{cld})$ is the cirrus Planck blackbody radiance, a function of the cirrus effective emitting temperature T_{cld}. Neglecting cirrus reflectivity, absorption optical thickness τ_{abs} is related to cirrus emissivity ε via the expression $1 - \varepsilon = e^{-\tau}$. Cirrus effective temperature is a weak function of wavelength, and in general is not representative of the cirrus cloud top temperature. However, it helps diagnose the wavelength dependence of cirrus emissivity.

The overall retrieval paradigm is to write Eq. (1) for two wavelengths and solve them simultaneously using an iterative numerical approach. At first glance, Eq. (1) has two unknowns in emissivity ε and cirrus temperature T_{cld}, making such a solution possible in a strictly mathematical sense. In practice, the improper choice of the two wavelengths can make the solution unstable and poorly defined.

3. Ice-Crystal Size

Cirrus ice-crystal effective diameter D_{eff} is an important cloud attribute in our retrieval approach, and is directly related to ice water content (IWC). The effective photon path D_{eff} for the entire size distribution is defined as (Mitchell, 2000)

$$D_{eff} = 3\ IWC / (2\ \rho_i P_t), \quad (2)$$

where IWC is the cirrus cloud ice water content (g cm^{-3}), and P_t is the total projected area of all ice crystals in the size distribution (with units of area per unit volume; e.g., $cm^2\ cm^{-3} = cm^{-1}$). Projected area P_t is the geometric cross-sectional area per unit volume of a distribution of ice crystals with random orientations.

4. Absorption by Ice Clouds

If D_{eff} is the appropriate dimension for describing particle-radiation interactions for a size distribution, then it is natural to ask what the consequences might be if the absorption efficiency Q_{abs} were to be taken outside the integral for the absorption efficieny

$$\beta_{abs} = \int_0^\infty Q_{abs}(D,\lambda)\ P(D)\ N(D)\ dD,$$

and solved for in terms of D_{eff}. This results in the following simple equation

$$\beta_{abs} = \underline{Q}_{abs} P_t, \quad (3)$$

where $\underline{Q}_{abs}$ is the absorption efficiency representing the entire size distribution; and where P_t is the geometric cross-sectional area of the entirety of ice crystals in the size distribution N(D).

Both the absorption coefficient β_{abs} and the cross-sectional area P_t of the size distribution are dependent on the amount and shape of the ice crystals that comprise the cirrus cloud. However, the absorption efficiency $\underline{Q}_{abs}$ is a normalized metric of absorption that depends only on crystal size, shape, wavelength, and refractive index. Thus if it is possible to compute β_{abs} and P_t for a "representative" unit volume of the actual ice-crystal size distribution, their ratio will yield that distribution's absorption efficiency. This forms the basis for computing cirrus TIR emissivities in our retrieval paradigm. Mitchell (2000) writes the absorption efficiency as

$$Q_{abs,ADA} = 1 - \exp(-8\pi\ n_i D_{eff} / 3\lambda), \quad (4)$$

where $Q_{abs,ADA}$ is the absorption efficiency representing the entire size distribution based on the anomalous diffraction approximation (ADA) of van de Hulst (1981) and the concept of effective photon path. Equation (4) represents absorption due only to a particle's geometric cross section. It has been expanded by Mitchell (2000) to include the processes of internal reflection/refraction and photon "tunneling," which collectively are well approximated by

$$Q_{abs} = (1 + C_1 + C_2)\ Q_{abs,ADA}. \quad (5)$$

The leading term (the "1") on the right side of Eq. (5) represents absorption via the particle's cross section; the term C_1 represents absorption due to internal reflection/refraction; and C_2 is the photon tunneling term. Tunneling here is a process by which photons beyond the particle's geometric cross-section are absorbed, including large-angle diffraction and wave resonance phenomena. Expressions for the constants C_1 and C_2 are given in Mitchell (2000) and are not repeated here, except to note that they depend only on ice-crystal particle size, shape, wavelength, and index of refraction.

Assuming no scattering at thermal wavelengths,

$$\varepsilon = 1 - \exp(-\tau_{abs} / \cos\theta_{sat}) , \qquad (6)$$

where θ_{sat} is the satellite zenith angle and τ_{abs} is the absorption optical depth. Dividing optical depth by the factor $\cos\theta_{sat}$ accounts for increased path length through the cirrus due to non-nadir views. For a cirrus cloud where the size distribution (SD) is invariant with in-cloud position, the absorption optical depth is given by

$$\tau_{abs} = \beta_{abs} \Delta z ,$$

where Δz is the cloud physical depth (from top to base) and β_{abs} is the absorption coefficient, defined by Eq. (3).

5. Ice Water Path

By definition, and assuming that IWC is the vertically averaged value,

$$IWP = IWC \Delta z$$

and Eq. (2) becomes

$$D_{eff} = 3 \; IWP / (2 \rho_i P_t \Delta z) , \qquad (7)$$

giving

$$IWP = 2 \rho_i D_{eff} \tau_{abs} / (3 \underline{Q}_{abs}) \qquad (8)$$

with the help of Eq. (3) solved for P_t. Substituting for τ_{abs} in (6) using (8), (6) can be rewritten as

$$\varepsilon = 1 - \exp(-3 \; IWP \underline{Q}_{abs} / 2 \rho_i D_{eff} \cos\theta_{sat}) .$$

Solving the above for IWP finally yields

$$IWP = -2 \rho_i D_{eff} \cos\theta_{sat} \ln(1 - \varepsilon) / (3 \underline{Q}_{abs}) . \quad (9)$$

Note that D_{eff} appears both in the numerator and in the denominator, since $\underline{Q}_{abs}$ is dependent on particle size via Equation (4) for absorption efficiency (Mitchell, 2000).

Fortunately, we have exploited a means of estimating D_{eff} in tropical anvil and mid-latitude cirrus as a function of cirrus environmental temperature (Ivanova et al., 2000). The tropical scheme is based on 93 size distributions from tropical anvils observed during CEPEX and other field campaigns. The mid-latitude scheme is based on over 1000 in-situ measurements of cirrus taken during ARM and FIRE campaigns in the central U.S.

With a methodology to compute IWP, emissivity as a function of wavelength, and effective particle size as a function of cirrus environmental temperature, it is now possible to both simulate and solve a simultaneous set of equations as defined by Eq. (1) for two infrared bands using an iterative numerical approach. In application the clear-scene radiance estimate $I_{\lambda,clr}$ in Eq. (1) is made by averaging the radiances of nearby cirrus-free pixels (as determined by a pre-computed cloud mask) on a land-water background basis. Figure 1 illustrates graphically the process of retrieving cirrus emissivity and temperature. Effective particle size is tied to temperature, and also varies throughout the iteration process.

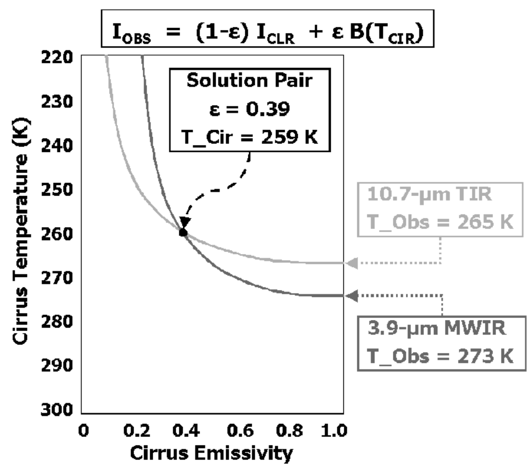

Figure 1. Plots of all mathematically possible pairs of cirrus temperature and emissivity for a given set of satellite radiance observations

In Figure 1 are plots of all mathematically possible pairs of cirrus temperature and emissivity for a given set of satellite radiance observations. The radiance observations correspond to an MWIR brightness temperature of 273 K, and a TIR temperature of 265 K. Note that for a single wavelength the number of theoretically possible pairs (ε,T) is infinite. This ambiguity is resolved, however, by choosing the retrieved pair as that which satisfies satellite radiance observations at two infrared wavelengths simultaneously. This forms the fundamental basis of our retrieval paradigm.

6. Summary

Cirrus ice-water path (IWP) is estimated using a deterministic algorithm that simultaneously models the interdependent effects of IWP, ice-crystal particle size, emissivity, and cirrus temperature using radiances collected in nominal 3.9-μm MWIR, 6.7-μm WV, and 10.8-μm TIR wavelengths. The cirrus IWP retrieval algorithm uses a simultaneous-solution approach to ensure physical consistency between multispectral satellite radiance measurements and theoretical radiative transfer calculations.

Retrieval sensitivity studies indicate that, in general, IWP is underestimated and that the magnitude of the underestimation increases with increasing cirrus thickness. As cirrus thickness and/or IWP increases, the smaller crystals near the top of the cirrus have a larger cross section absorbing area than the larger crystals below. Being more efficient absorbers of upwelling energy, small crystals above tend therefore to "hide" or "subdue" the influence of the larger crystals below. Subsequently the upwelling infrared radiances are not maximally sensitive to the presence of the larger crystals, in turn causing IWP to be underestimated. However it has been shown that the consistent underestimate of IWP is not all bad because the error is systematic and repeatable, suggesting that thermal-IR retrievals of IWP can be adjusted according to our sensitivity results.

7. Future Plans

Retrievals will be performed of cirrus cloud ice water path (IWP), effective diameter (D_{eff}) and optical depth (τ) using our satellite-based technique and a newly developed cirrus analysis method that analyzes ground-based radar data. The radar backscatter technique retrieves ice water content (IWC) as a function of the radar reflectivity factor, given information about the N(D) shape and dispersion, and power-law relations between crystal mass and size. Using ground-based radar backscatter returns it will be possible to integrate the IWC profile from cirrus base to cirrus top to obtain IWP, and compare the result with coterminous TIR retrievals of IWP and D_{eff}.

Proof-of-concept retrievals have been performed with satellite and in-situ data from two ARM cirrus IOPs during March 2000, using GOES-8 thermal infrared data and ground-based radar data. The retrievals coincide with in-situ measurements over the SGP ARM CART site, which will be used to test retrieval performance. Results will be presented at our poster.

References

Ivanova, D., D. L. Mitchell, W. P. Arnott, and M. Poellot, 2000: A GCM parameterization of bimodal size spectra for mid-latitude cirrus clouds. Proceedings, 13th International Conference on Clouds and Precipitation, Reno, Nevada, 14-18 August, 546-549.

Mitchell, D. L., 2000: Parameterization of the Mie extinction and absorption coefficients for water clouds. *Journ. Atmos. Sci.*, **57,** 1311-1326.

van de Hulst, H. C., 1981: *Light Scattering by Small Particles.* Dover, 470 pp.