Estimation of Cloud Height and Emissivity from METOP/AVHRR and VIIRS

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Introduction

• NGST has implemented a VIIRS Nighttime IR Cirrus Cloud Retrieval Algorithm (Wong et al)* into the NPOESS operational system. Our goal was to evaluate this algorithm using tools we have developed for characterizing cloud products from MODIS and AVHRR.

•With the launch of CALIPSO and CloudSat in EOS A-Train, NASA has provided us a new opportunity to evaluate the characteristics of cloud remote sensing from passive instruments.

•MODIS and other sounder - based systems have demonstrated the advantages of using infrared absorption bands for cloud height estimation. In the development of VIIRS, Raytheon decided to pursue an imager without infrared absorption bands. Part of this work explores the impact of this decision on this algorithm.

* Eric Wong, Keith D. Hutchison, S. C. Ou, and K. N. Liou, 2007: Applied Optics, Vol. 46, Issue 8, pp. 1316-1325

Goals

• Demonstrate the impact of the lack of absorption channels on the estimation of cloud height by VIIRS.

• Validate the microphysical assumptions in the current VIIRS IR cirrus algorithm using CALIPSO observations.

• Show the benefits of adding absorption channels (possibly from CrIS).

Definitions and Methods

A critical parameter in IR remote sensing and in the VIIRS approach is defined by β, which relates cloud emissivities at two different wavelengths (x and y) through the following relationship.

$$(1-\varepsilon_x) = (1-\varepsilon_y)^{\beta_{xy}}$$

As shown by Parol (1991)*, β can be derived from the single scattering properties of two channels (x and y) as follows:

$$\beta_{xy} = ((1-\omega_{o,x} g_x)*Q_{e,x}) / ((1-\omega_{o,y} g_y)Q_{e,y})$$

Where ω_o is the single scattering albedo, g is asymmetry parameter and Q_e is the extinction efficiency.

In Wong et al and the VIIRS ATBD, β is referred to the as the k-ratio. However, the VIIRS formulation ignores scattering. Therefore the VIIRS k-ratio or β values are therefore computed as

$$k_x / k_y = \beta'_{xy} = ((1-\omega_{o,x})Q_{e,x}) / ((1-\omega_{o,y})Q_{e,y})$$

The effects of scattering are evident in the results when we try to match observations which automatically include scattering.

Profiles of derived cloud emissivity, ε(z), can be derived as follows.

$$\varepsilon(z) = (I - I_{clear}) / (I_{bb}(z) - I_{clear})$$

where

I = observed radiance
I_{clear} = clear sky radiance
$I_{bb}(z)$ = TOA radiance for a black body cloud placed at level z.

Profiles of β are derived from the profiles of ε. With CALIPSO-based cloud heights, we can compare derived β values to those predicted by the VIIRS approach.

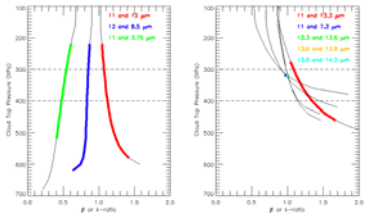
*Parol, F., J.-C. Buriez, G. Brogniez and Y. Fouquart, 1991: Information content of AVHRR channels 4 and 5 with respect to the effective radius of cirrus cloud particles. J. Appl. Meteor., 30, 973-984.

Sensitivity to Cloud Height

The solution space for our cloud height algorithm can be defined as the region of the atmosphere where the derived cloud emissivities are valid and the β values are consistent with our understanding of cloud microphysical properties.

The following figures show the cloud height solution spaces for various channel combinations offered by VIIRS, AVHRR and MODIS. For this example, the valid β range is based on particles of 5 to 100 μm in radius.

The simulations assume an ice cloud is positioned from 300 to 400 hPa with a visible optical thickness of 1. The figure on the left shows results using window channels (AVHRR and VIIRS) and the figure on the right shows results using absorption channels (MODIS)



➢ The solution space offered by window channels spans the upper troposphere

➢ The use of absorption channels limits the solution space and hence the uncertainty

➢ Even the use of multiple pairs of window channels does not significantly reduce the solution space.

➢Window channels still provide reasonable values of emissivity and β even without accurate knowledge of the cloud height.

Use of CALIPSO to Verify the Microphysical Assumptions

This section describes our approach to using the CALIPSO information on cloud height and structure to infer the actual β or k-ratios and to compare these to those assumed in the VIIRS baseline approach.

Methodology

• One night (August 10, 2006) of MODIS/AQUA and CALIPSO/CALIOP was analyzed.

• Clear-sky radiative transfer was performed for each granule using temporally interpolated GFS forecasts, the PLOD RTM and the SEEBOR surface emissivity data-base.

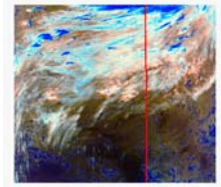
• CALIPSO data co-located to MODIS were provided by Bob Holz at UW/SSEC (see top image on the left for an example track of CALIPSO within a MODIS granule).

• For each MODIS pixel paired with CALIOP data, the cloud emissivity is computed for each MODIS IR channel using the computed clear-sky values and the cloud-top height from CALIOP. (See bottom image on right for an illustration).

• The channel emissivity values are combined to compute the β values for desired channel pairs.

• The values used in the analysis are those for known single-layer ice clouds (determined from CALIOP).

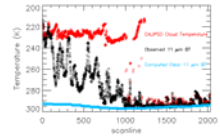
MODIS False-Color Image with CALIPSO Track



Red = 11 - 12 μm BTD, Green = 3.75-12 μm BTD, Blue = 11 μm BT. (Reversed)

Ice clouds are whitish.

Cross section of CALIPSO cloud temperature (mid-layer), clear-sky and observed MODIS brightness temperatures for the above MODIS/AQUA granule. These quantities are used to estimate cloud emissivity in each MODIS band.



Results

• The analysis described in the box to the left yielded roughly 4000 β or k-ratio values for single layer non-opaque ice clouds

• The top image to the right show the distribution of 11/3.75 μm β to the 12/8.5 μm β which are the values used in the VIIRS baseline IR-cloud algorithm.

•Also shown are the theoretical values from Ping Yang's ice scattering property data-base. The values shown are for effective radii from 10 to 50 mm.

• The black line is the predicted curve using the k-ratio parameterizations in the VIIRS ATBD.

• The CALIPSO derived values are given by the grey-shaded contours. The shaded contours represent 10, 50, 90% of the maximum density.

•The bottom figure shows the same analysis but applied to the 11/12 μm β and the 12/8.5 μm β.

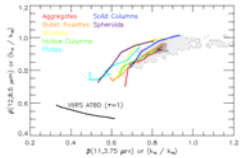
•From this analysis, we can conclude

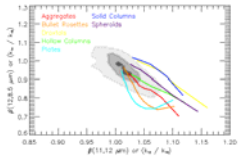
• The CALIPSO values agree better with the Yang scattering properties than with the parameterization used in the VIIRS algorithm.

• Of all the crystal habits, aggregates, bullet rosettes and hollow columns seem to fit the CALIPSO observations the best.

• The 11/3.75 μm β values retrieved from CALIPSO exceed the theoretical values (i.e. values > 1). This may indicate the effects of scattering which are not fully accounted for in this analysis or in the VIIRS algorithm.

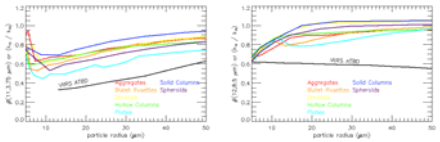
• The distribution of the 12/8.5 β with the 11/12 μm β seems to agree roughly well with CALISPO. These channels may offer a basis for a day/night independent approach. (3.75 μm is heavily affected by reflected solar energy)





Comparison of the microphysical assumptions employed by the VIIRS approach to those from theory

Ping Yang (Texas A&M)* has developed a database of scattering properties of seven ice crystal habits for a wide range of sizes over the entire infrared spectrum. As described previously, the β values can be derived from the single scattering properties and compared to those given in the VIIRS ATBD. The following figures compare values used in the VIIRS approach to those computed from the Yang data-base.



➢Using the formulation of Parol et al (1991), the β values computed from the Yang database include scattering while the VIIRS ATBD values do not. This does account for some of the discrepancy.

➢The 8.5- and 12-μm β values provided in the VIIRS ATBD are very different from those predicted by Yang's data-base (no habit or habit-combination can reproduce the VIIRS results).

➢The 3.75- and 11-μm β values currently used for VIIRS cloud products are in better agreement with theory except for small particles. Here the difference is mainly caused by the presence of scattering in the theoretical values.

➢The VIIRS 3.75- and 11-μm β values in the VIIRS ATBD are a function of optical depth though in theory, they are actually independent of optical depth and are functions only of the single scattering properties.

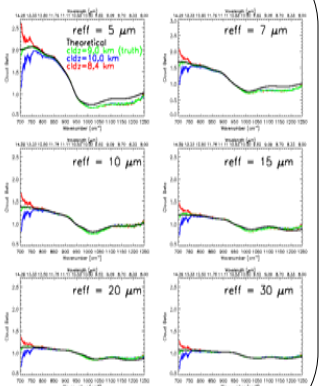
Yang, P., H. Wei, H. L Huang, B. A. Baum, Y. X. Hu, M. I. Mishchenko, and Q. Fu, 2005: Scattering and absorption property database of various nonspherical ice particles in the infrared and far-infrared spectral region. Appl. Opt., 44, 5512-5523.

The Case for Hyperspectral

The NPOESS hyper-spectral sounder, CrIS, can be used to mitigate the weakness of window-based cloud height algorithms. The image on the left shows the spectral variation of the β values referenced to 10.5 μm (where β = 1). The black curve shows the theoretical values from the single scattering properties. The green curve shows derived values when the cloud height is known. The red and blue curves show the results when the assumed is higher or lower than truth. These curves demonstrate two useful properties:

✓ window based measurements of cloud microphysics are insensitive to the assumed cloud height.

✓ β-spectra in absorption lines are very sensitive to cloud height and offer a firmer basis for cloud height estimation than offered by multi-spectral channels on GOES-R and MODIS.



Conclusions

➢ Any IR-only algorithm (VIIRS, AVHRR …) that uses only window channels will exhibit little sensitivity to cloud height for semi-transparent cirrus.

➢The window channels employed by the baseline VIIRS approach should allow for accurate optical depth (emissivity) and particle size estimation even with the lack of height sensitivity. VIIRS should improve greatly on the AVHRR.

➢CALIPSO offers an opportunity to evaluate the microphysical assumptions employed in the baseline VIIRS approach.

➢The CALIPSO analysis indicates that a revisitation of the baseline VIIRS microphysical assumptions is warranted.

➢When possible, merging of VIIRS with CrIS would allow for an IR-only approach that exhibits a large sensitivity to cloud height and benefits from the spatial resolution of VIIRS.