VALIDATION OF A 3-D CLOUD PRODUCT (UW-CAVP) DERIVED FROM NASA ATMOSPHERIC INFRARED SOUNDER (AIRS) RADIANCES WITH MODIS, CALIPSO, AND NCEP GFS USING MCIDAS-V VERSION 1.0

Elise Garms*, Eva Borbas, Robert Knuteson, Paul Menzel, Youri Plokhenko, Henry Revercomb, and David Tobin

Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin, Madison WI

1. INTRODUCTION

The University of Wisconsin-Cloud Amount Vertical Profile (UW-CAVP) is a product currently being developed to provide a three-dimensional view of cloud structure in the atmosphere obtained through passive remote sensing. It uses high spectral resolution infrared data from AIRS (Atmospheric Infrared Sounder) on the A-train satellite Aqua and a model temperature profile to create a cloud amount profile for 25 vertical layers from the surface to the tropopause.

As this is a new product, the validity and accuracy of UW-CAVP must undergo thorough testing. McIDAS-V is an open source, interactive imaging tool released by the Space Science and Engineering Center (SSEC) at UW-Madison in September 2010. It can be used to visualize, manipulate, and assess various types of data including satellite images, grid data, soundings, and hydra files (the format of the CAVP product).

The purpose of this study is to use McIDAS-V to visualize and validate the CAVP product through comparison with collocated MODIS products, CALIPSO lidar cloud retrievals, and NCEP GFS model data. Preliminary qualitative analysis results are presented to identify the benefits and limitations of this new three-dimensional cloud product.

2. AIRS INSTRUMENT

The AIRS (Atmospheric InfraRed Sounder) instrument is a hyperspectral, scanning IR sounder aboard the A-train satellite Aqua. It measures 2378 IR spectral channels over the range of 3.7 – 15.4 μm with a spatial resolution of 13.5 km at nadir, as well as 4 Vis/NIR spectral channels with a spatial resolution of approximately 2.3 km. AIRS attains complete global coverage daily using cross-track scanning, divided into granules of 6 minutes of calibrated radiance data containing 135 scan lines of 90 cross-track fields of view between ±49.5°.

3. MODIS

The MODIS (Moderate Resolution Imaging Spectroradiometer) instrument is also found on Aqua, as well as the Terra satellite. It measures 36 spectral bands ranging from 0.4 μm to 14.4 μm in wavelength with high radiometric sensitivity. Two bands are imaged at a resolution of 250 m at nadir, five bands at 500 m, and the remaining 29 bands at 1 km. MODIS attains complete global coverage daily using cross-track scanning, divided into granules of 5 minutes of calibrated radiance data containing 406 scan lines of 270 cross-track fields of view between ±55°.

4. CALIPSO

The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite is also part of the A-train constellation of satellites, following a few minutes behind Aqua and allowing for coordinated observations. It combines an active lidar instrument with passive IR and visible imagers to obtain the vertical structure and properties of thin clouds and aerosols. CALIPSO is a joint U.S. and French mission that has been in operation since April 2006.

5. AIRS CAVP PRODUCT

The UW-Madison CAVP algorithm uses both spatial and spectral filtering of AIRS radiances to detect cloud amount from the top of the atmosphere to the surface using 25 discrete layers. It compares observed radiances with clear sky radiances and filters horizontally for deviations representing cloud presence using the following formula, described in Plokhenko et al. (2010):

$$
\left.\begin{aligned}
\tilde{J}_v &= (1-a_v)J_v(p_s) + a_v J_v(p_c) + \xi_v \\
J(p_L) &= B[T_s]\tau_s^{\uparrow}(p_L) + \int_{\tau_s^{\uparrow}(p_L)}^{1} B[T(p)]\,d\tau^{\uparrow}(p)
\end{aligned}\right\} \quad (1)
$$

$$
\begin{aligned}
\tilde{f}_v &= \tilde{J}_v - J_v(p_s) = a_v(J_v(p_c) - J_v(p_s)) + \\
\xi_v &= a_v \eta_v(p_c) + \xi_v
\end{aligned} \qquad (2)
$$

$$
\left.\begin{aligned}
&\hat{a}_v(p_c) = \arg\min \left\| \tilde{f}_v - a_v \eta_v(p_c) \right\| \\
&\Psi(\hat{a}_v) : \frac{\hat{a}_v(p_c)}{\Delta(p_c)} > n
\end{aligned}\right\} \qquad (3)
$$

In these equations, the observed top of the atmosphere radiance is compared to a forward model calculation including a vertical cloud profile. The vertical profile of cloud amount is obtained as a minimization of both spectral and spatial variance. The method uses the European Center for Medium-range Weather Forecasting (ECMWF) analysis to characterize atmospheric temperature, moisture, and surface temperature as these properties affect which AIRS spectral channels are used for the cloud profile retrieval. The algorithm assumes cloud presence starts with saturation.

Each AIRS CAVP granule contains 12150 (135x90) latitude/longitude positions, each of which has a vertical profile of CAVP values. A 1-D profile of an individual pixel can be viewed in McIDAS-V using a vertical profile probe, as shown in *Figure 1.* These profiles show a column containing mid-level to high-level cloud, a column with a layer of low cloud below a layer of high cloud, and a column of primarily low cloud.

In addition to the 1-D structure of each pixel, the overall structure of a granule can be viewed in numerous ways using the McIDAS-V software. It can be viewed in traditional 2-D displays, such as in a vertical or horizontal cross-section, both of which are shown in *Figure 2*. McIDAS-V also has options for several types of plan views in the horizontal, which can be displayed at any of the 26 CAVP levels.

Most uniquely, McIDAS-V offers 3-D visualization capabilities that allow the entire cloud structure to be visible at once. For an intuitive cloud-like visualization, the AIRS CAVP product can be viewed as an iso-surface of a user-specified value. In *Figure 3*, the CAVP granule is displayed as an iso-surface of the threshold value for cloud presence, 0.05. By displaying various CAVP value iso-surfaces, one can focus on a specific density of cloud. Another option in McIDAS-V allows for an entire orbit of CAVP granules to be displayed on a globe, which may be rotated. If desired, these displays can be animated to highlight different features or times. Another option available in McIDAS-V for visualization of 3-D products such as the AIRS CAVP product is a volume rendering. This type of display allows a user-specified visible range of values to be displayed and colored by value which allows dense areas of cloud to be immediately apparent. These 3-D capabilities allow for much more visually understandable displays of 3-D products than previously available with traditional 2-D displays and enable validation with several different types of data.

a) b) c)

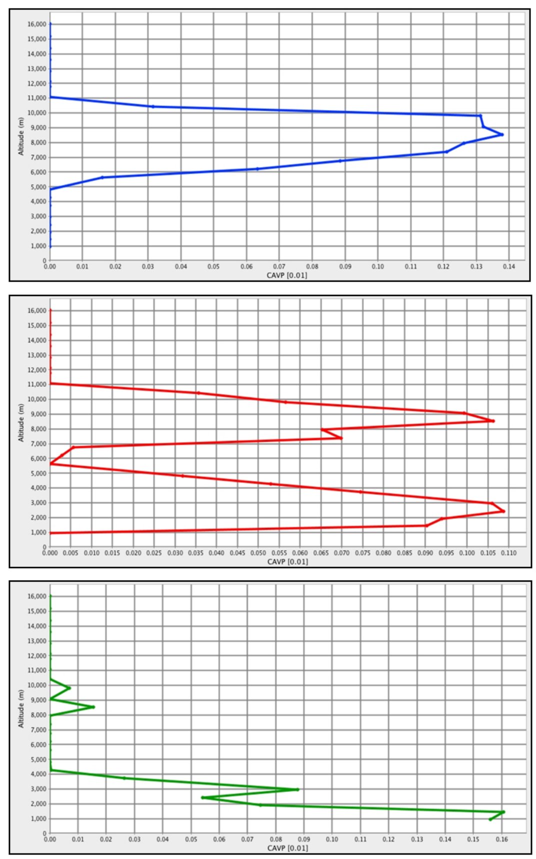

FIGURE 1: CAVP pixel profiles from a) a region of mid- to high-level cloud, b) a region of low cloud below a region of high cloud, and c) a region of low cloud.

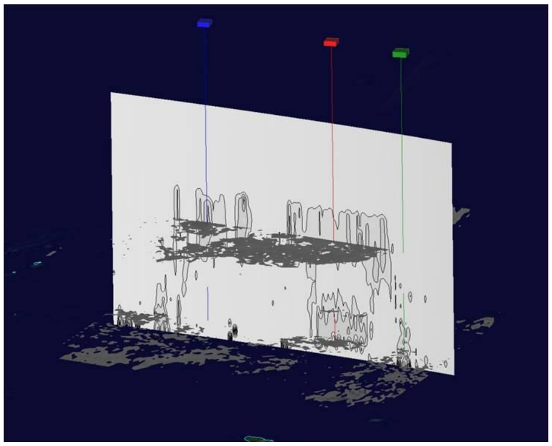

FIGURE 2: Vertical and horizontal cross-sections of CAVP through the AIRS granule centered at [lat/lon] from 28 August 2006. The blue, red, and green markers indicate the positions of the vertical pixel profiles shown in *Figure 1*.

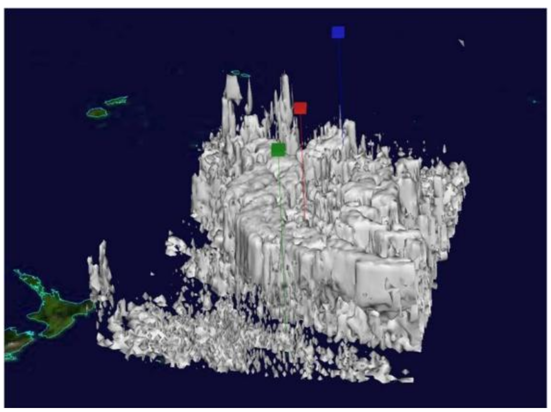

FIGURE 3: Iso-surface of the 0.05 values of CAVP displaying the outer shell of cloud for the same granule as in previous figures. The blue, red, and green markers again indicate the positions of the pixels in *Figure 1*.

6. VALIDATION WITH MODIS

MODIS data provides lots of valuable information about the earth's atmosphere in high spatial resolution. However, it is limited in that it can only give a view from above rather than a complete 3-D depiction of atmospheric makeup. The same 2-D structure is achieved by viewing the AIRS CAVP product from above.

The MODIS level 2 cloud top pressure (infrared) product was used as a means of validating general placement of low, mid-level, and high cloud tops by the AIRS CAVP algorithm. By moving the MODIS cloud top pressure display up vertically through the CAVP 0.05 iso-surface, one can see good agreement between MODIS cloud top pressures and the tops of CAVP-indicated clouds. Comparisons are shown at three levels in *Figure 4*.

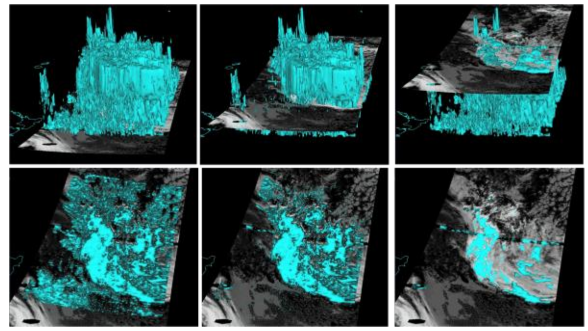

FIGURE 4: Displays of 0.05 CAVP iso-surface (in blue) with MODIS cloud top pressure image display at low, mid, and high levels (left to right). Images are from an angle (top row) and from above (bottom row).

The discrepancy in spatial resolution between MODIS images and AIRS radiances leads to some missing features in the AIRS CAVP product. Small-scale variations in cloud top height are not captured as well by the CAVP product as they are in a MODIS infrared cloud top pressure image due to the coarser spatial resolution of the AIRS infrared data that the product is derived from. There are also resolution effects in the vertical due to the fact that the AIRS CAVP product is calculated using 26 discrete levels. Features falling between levels may get smoothed out, causing cloud tops and bases to appear flatter than in reality.

While the high spatial resolution of MODIS imagery and its coincident observations with AIRS make it useful for comparing cloud top heights, it is restricted by only being able to see the topmost features. For this reason, further comparison with a different data source is required to validate vertical cloud structure.

7. VALIDATION WITH CALIPSO

CALIPSO lidar measurements of total attenuated backscatter provide a profile of cloud structure in the vertical along a nadir track. Because CALIPSO is also a member of the A-train constellation of satellites, it follows the same path as Aqua at a lag of less than two and a half minutes. This allows for a spatially and temporally collocated comparison of vertical

cloud structure between CALIPSO measurements and the AIRS CAVP product.
The method used to compare the CAVP algorithm's detection of cloud presence with CALIPSO measurements was to display contours of AIRS CAVP along the CALIPSO track using McIDAS-V's grid resampling function. This was done for the AIRS granule shown in previous figures which contains an interesting cloud structure that is intersected by CALIPSO.

Several features are visible from CAVP contours plotted over CALIPSO total attenuated backscatter, as in *Figure 5a*. The AIRS CAVP product places cloud tops higher in the atmosphere than CALIPSO. Similar to the vertical resolution effect described in the previous section, some smaller cloud features falling entirely within a layer between CAVP levels can be missed.

One of the main weaknesses of the AIRS CAVP product demonstrated by this comparison is that it seems to be confused by regions of optically thin cloud above layers of optically thick cloud.

Circled in pink, one may notice that the CAVP contours appear to detect the top of the region of optically thin cloud, but ignore the base of the cloud as well as the top of the optically thick cloud beneath. The CAVP product indicates a cloud base at the level that CALIPSO shows as the base of the optically thick mid-level cloud. CAVP also places a layer of low cloud beneath this in a region that has been totally attenuated in the CALIPSO measurements, according to the vertical feature mask (*Figure 5b*). This region, highlighted with a red circle, is likely to also be related to the confusion caused by the optically thick mid-level cloud.

One of the strengths of the CAVP product confirmed by this method of comparison is that the AIRS CAVP product is able to detect low clouds beneath optically thin high clouds. One example of this is circled in yellow in *Figure 11*.

Similarly to MODIS imagery's 2-D limitation, CALIPSO is limited in that it is only a thin 2-D nadir cross-section. A full 3-D comparison requires additional comparison with a fully 3-D data source.

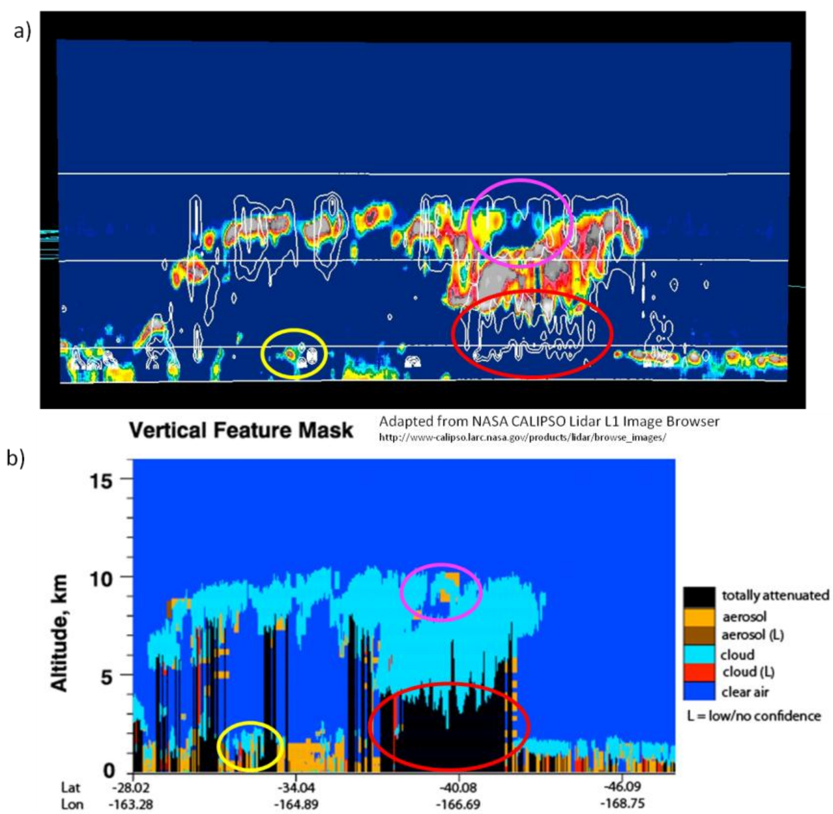

FIGURE 5: a) CAVP contours (white) plotted over collocated CALIPSO total attenuated backscatter. b) A vertical feature mask of the same region (modified from NASA CALIPSO Lidar L1 Image Browser).

8. VALIDATION WITH NCEP GFS

The NCEP GFS model provides global coverage, initialized daily at 00Z, 06Z, 12Z, and 18Z with forecast data available every six hours out 7.5 days. The model used in this study has a resolution of 1°x1°. While the GFS model contains data on tens of different variables in both 2-D and 3-D, it does not contain a product that explicitly describes cloud presence for initialization times. For this reason, cloud water was used as a proxy.

Figure 6 displays a transect of GFS cloud water (grayscale) from the initialization time of the model run corresponding to the center of the AIRS orbit with AIRS CAVP contours overlain (turquoise). The transect was taken through a CAVP orbit from Gulf of Alaska the southern Pacific Ocean between New

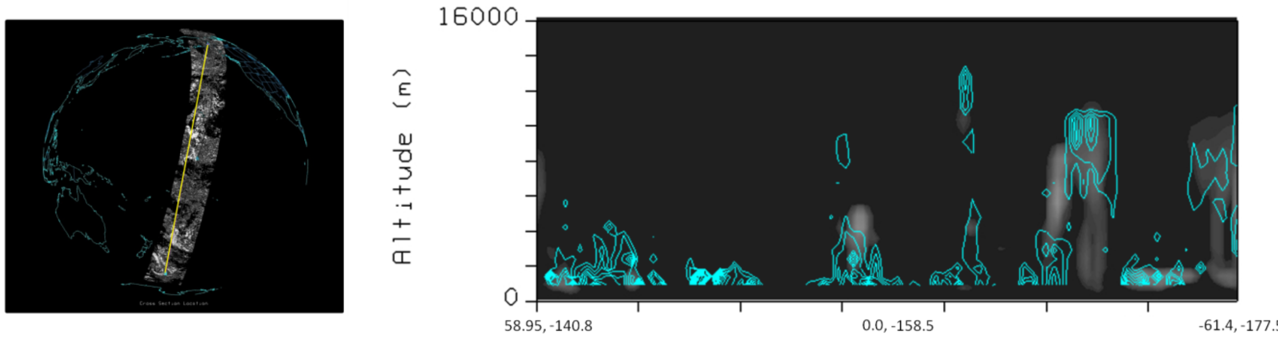

FIGURE 6: CAVP contours (turquoise) over NCEP GFS Cloud Water (grayscale shading) along transect shown in yellow on globe display (left) through CAVP orbit.

Zealand and Antarctica. It displays fairly good agreement for mid-level and high cloud location. There are several regions of discrepancy as to low cloud representation using this method, particularly in the northeastern Pacific Ocean where low-level stratocumulus clouds are climatologically common for the case shown. These low-level clouds do not show up in the GFS cloud water transect, though the presence of these clouds is confirmed in the CALIPSO lidar data.

The NCEP GFS contains several additional products for forecast hours. By using the six-hour forecast data from the model run prior to the time of the AIRS orbit, an average cloud cover over the six-hour period can be accessed. This product exists for low, mid-level, and high cloud, displayed in *Figure 7* with AIRS CAVP contours overlain in red. The same conclusions are reached using this analysis as with the overlain cloud water and CAVP transect: the AIRS CAVP product and the NCEP GFS model show good agreement for both high and mid-level cloud presence but have significant disagreement in the representation of low cloud. Again, a region of particular interest is the lack of low cloud over the northeastern Pacific Ocean in the GFS model. Previous studies have also found that the GFS consistently underrepresents low-level stratocumulus cloud cover, possibly because shallow convection in the model does not produce cloud (Yang et al., 2006 and Sun et al., 2010).

Validation of the AIRS CAVP product with NCEP GFS model data is difficult in that there is no explicit model cloud product for direct comparison. If a variable similar to CAVP can be defined for the GFS and similar model data, a more quantitative comparison fully employing McIDAS-V's 3-D data manipulation and display capabilities may be done in the future. Given the model's failure to represent significant areas of known low cloud however, it may be more useful in the future to use the observation-based AIRS CAVP product to validate the model. Further validation of the CAVP product is necessary before this can be done with confidence though.

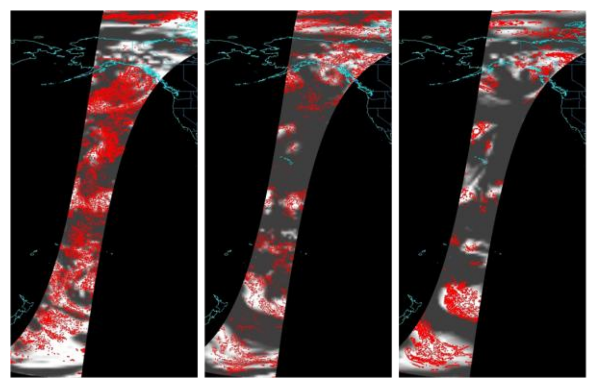

FIGURE 7: AIRS CAVP contours (red) over GFS six-hour average a) low (852.8 hPa), b) mid-level (596.3 hPa), and c) high (300 hPa) cloud cover products.

9. CONCLUSIONS

This study found McIDAS-V to be a flexible, useful tool; it was used to validate a 3-D cloud product against 2-D latitude/longitude MODIS data, 2-D height/orbital track CALIPSO data, and 3-D NCEP GFS model data. Good agreement was found between the AIRS CAVP product and MODIS cloud top pressures for low, mid-level, and high cloud tops; however, MODIS cannot provide cloud base validation. CALIPSO data was used in this study to validate AIRS CAVP cloud base and detection of low cloud below optically thin high cloud. Due to the nature of the CALIPSO track, this validation could only be carried out in a nadir cross-section below the satellite and thus a 3-D product was needed.

Through comparison of the AIRS CAVP product with NCEP GFS model data and confirmed with CALIPSO data, the CAVP product indicated that low stratus clouds in the north Pacific are not well represented in the GFS model. Reasonable agreement was obtained for mid- and high-level cloud. Additional validation of the AIRS CAVP product is required before it can be fully utilized to validate the complete 3-D model cloud fields.

11. REFERENCES

Plokhenko, Y., W. P. Menzel, H. E. Revercomb, E. E. Borbas, P. Antonelli, E. Weisz, (2008), Analysis of multi spectral fields of satellite IR measurements: Using statistics of second spatial differential of spectral fields for measurement characterization. *International Journal of Remote Sensing*, *29*, 2105-2125, doi:10.1080/01431160701268988.

Sun, R., S. Moorthi, H. Xiao, C.R. Mechoso, 1010: Simulation of low clouds in the Southeast Pacific by the NCEP GFS: sensitivity to vertical mixing. *Atmos. Chem. Phys. Discuss.,* **10**, 18467–18505, 2010 www.atmos-chem-phys-discuss.net/10/18467/2010/ doi:10.5194/acpd-10-18467-2010

Yang, F., H. .Pan, S. Krueger, S. Moorthi, S. Lord, 2006: Evaluation of the NCEP Global Forecast System at the ARM SGP Site. *Mon. Wea. Rev.*, **134**, 3668–3690. doi: 10.1175/MWR3264.1