

Grant NNX08AG96G
Final Report
Jan 2008– Dec 2011

Project Title: Development of the Decadal Cloud Climatology from Polar Orbiting (AVHRR and HIRS) Through EOS (MODIS and AIRS) to NPOESS (VIIRS and CrIS)
Principle Investigator: W. Paul Menzel (paul.menzel@ssec.wisc.edu)

Summary

With the advent of the Joint Polar Satellite System (JPSS), the VIIRS (Visible Infrared Imaging Radiometer Suite) imager will offer many advances over previous sensors, but it lacks infrared spectral bands sensitive to absorption by carbon dioxide or water vapor. Those bands offer greater sensitivity to cloud top pressure (CTP) estimation than can be obtained from window spectral bands alone, especially for semi-transparent ice clouds. The CrIS (Cross track Infrared Sounder) on JPSS, with sounding bands in both CO₂ and H₂O spectral regions, has complementary measurements to VIIRS but at lower spatial resolution. This paper reports on an approach to combine the VIIRS horizontal detail (using Moderate resolution Imaging Spectroradiometer, or MODIS, data as a proxy) with the CrIS absorbing infrared spectral bands (using Atmospheric Infrared Sounder, or AIRS, data as a proxy) for cloud detection and cloud top pressure estimation. The cloud structures at CrIS horizontal resolution (13.5 km at nadir) are related to those at VIIRS resolution (880 m at nadir) through a regression relationship of CrIS CTP gradients against gradients of CrIS radiances convolved to VIIRS spectral band response functions. The regression relationship is applied to simulated pre-launch VIIRS radiances to determine CTPs at sub-kilometer resolution. These “merging gradient” CTPs are converted to cloud top heights (CTH) and compared to the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) Version 3 cloud product. The combined imager+sounder CTHs for optically thin ice clouds compare better with CALIOP than those obtained solely from the imager.

This work has provided approaches for combined AVHRR (Advanced Very High Resolution Radiometer) /HIRS (High resolution Infrared Sounder), MODIS/AIRS, and VIIRS/CrIS cloud property determinations. As part of this work, UW tested some improvements to the MODIS CTH algorithm, established the software capabilities to simulate MODIS spectral bands by convolving with AIRS data, to co-locate MODIS radiances and cloud products at 1 km resolution within the AIRS pixels, to test various algorithms for combining MODIS+AIRS, and to compare CALIOP (CALIPSO) cloud measurements with those of MODIS+AIRS. The MODIS/AIRS algorithm was then tested for VIIRS/CrIS.

Improving the MODIS Cloud Top Pressure Algorithm

Cloud properties derived from CO₂ slicing using MODIS data have been compared with co-located CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) observations. The CALIPSO instrument takes measurements about 75 seconds behind that of Aqua MODIS. MODIS cloud top pressures are converted to cloud top heights (CTHs) using the Global Forecast System and are compared to heights from analysis of CALIPSO 0.532 micron

backscatter data. Various adjustments to the MODIS cloud algorithm used in Collect 5 (described in Menzel et al., 2008) were tested and compared with CALIPSO cloud observations. The tests concluded successfully and retained for production runs included: **Test A:** Use "top-down" method with channel pairs 36/35, 35/34, 34/33 in that order to select CTP. **Test B:** Restrict CO2 channel pair solutions to the appropriate portion of troposphere (determined by their weighting functions – 36/35 less than 450 hPa, 35/34 less than 550 hPa, and 34/33 less than 650 hPa). **Test C:** Prohibit CO2 slicing solutions for water clouds; use only IRW solution. Avoid IRW solutions for ice clouds; use CO2 slicing whenever possible. **Test D:** Lower the "noise" thresholds (clear minus cloudy radiances required to indicate cloud presence in bands 33 to 36) to force more CO2 slicing solutions for high thin clouds. **Test E:** Adjust ozone profile between 10 and 100 hPa to GDAS values instead of using climatology (so that CO2 radiances influenced by O3 profiles are calculated correctly). **Test F:** Implement Band 34, 35, 36 spectral shifts suggested by Tobin et al. (2005). **Test G:** Add marine stratus improvement where a constant lapse rate is assumed in low level inversions – lapse rate is adjusted according to latitude region.

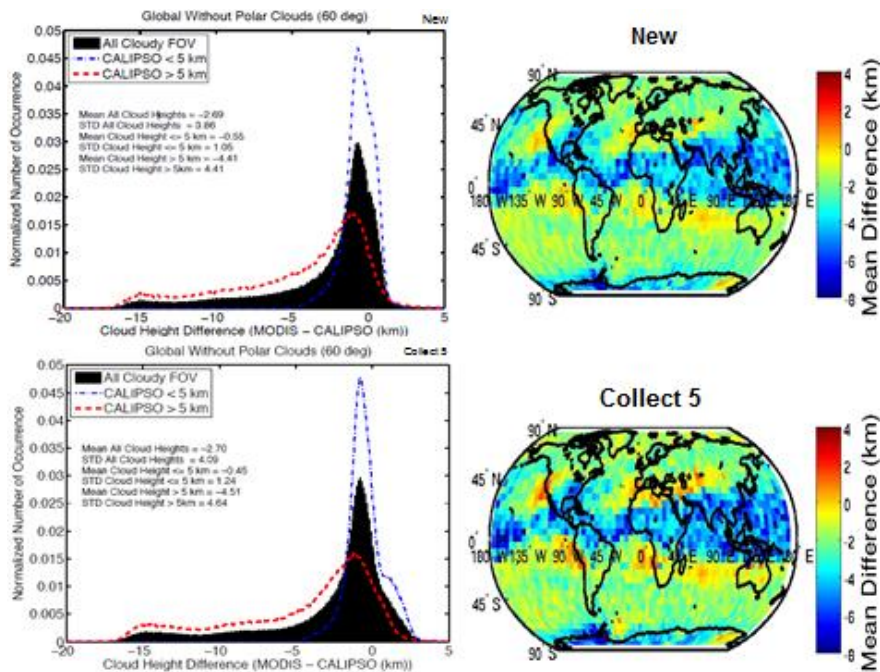


Figure 1: New (left top) and Collect 5 (left bottom) global 60 N to 60 S normalized histograms of MODIS minus CALIPSO cloud top height measurement differences for all (black), higher than 5 km (red), and lower than 5 km (blue). New cloud heights are accomplished after implementing all of the tests described above. Geographical distribution of CTH differences of new (right top) and DAAC Collect 5 (right bottom).

Figure 1 (bottom left) shows the histogram of the cloud height differences of over 2 million MODIS Collect 5 cloud products minus the CALIPSO cloud measurements distributed globally between 60 N and 60 S. In the mean CALIPSO is higher than MODIS by 2.7 km with a scatter of 4.1 km. High cloud determinations from MODIS are hindered by thin cloud heights defaulting to infrared window estimates; MODIS also errs on low marine stratus clouds by placing them above the inversion height. The results of all the tests are shown as New in Figure 1 (top left). The mean cloud height difference dropped by 0.1 km and the scatter by 0.4 km. The

geographical distributions of the differences (Figure 1 right panels) show that the tropics have been improved and that marine stratus problems along the west coasts of North and South America and Africa have been largely mitigated. While these improvements are modest on the global scale, they represent significant improvement for problem regions and for high thin cirrus.

Combining CrIS and VIIRS radiance measurements for improvement cloud property definition

In the VIIRS+CrIS “merging gradients” algorithm, CTP gradients derived from the high spectral resolution sounder measurements are correlated by regression with the associated gradients in broad spectral band imager radiances calculated from the sounder. The resulting regression is then applied to actual imager measurements to infer high spatial resolution cloud properties. This is accomplished in several steps. **First**, high spectral resolution sounder radiance measurements are convolved using imager spectral response functions to calculate imager broad band radiances at sounder single FOV resolution. **Second**, sounder CTP gradients in neighboring FOVs are regressed against the calculated imager radiance gradients. **Third**, the resulting regressions are then used with measured imager 1 km radiances to create combined imager+sounder CTP retrievals at 1 km spatial resolution.

With the use of MODIS+AIRS as a surrogate for VIIRS+CrIS, the merging gradients CTP algorithm proceeds in three steps that are now described in more detail. Step 1: AIRS radiances are convolved to three infrared window spectral response functions (see Table 1) to create MODIS radiances at AIRS resolution (referred to as AMODIS radiances). Figure 1 shows scatter plots of 1 km resolution 11.03 micron (μm) band 31 MODIS radiance differences versus 13.5 km resolution AMODIS radiance differences (between center pixel and its neighbors) for an example cloud scene with polar Nimbo- and Alto-stratus with cirrus; the AMODIS radiance gradients show correlation with the MODIS radiance gradients but have smaller magnitude (roughly +/- 5 versus +/- 10 $\text{mW/m}^2/\text{ster/cm}^{-1}$).

Step 2: Gradients in AIRS CTPs are related to gradients in the three AMODIS radiances in a regression relationship. Written in terms of differences between a reference pixel (the center pixel of a 5 x 5 FOV area) and its neighbors, the regression relationship is

$$CTP_{n\text{nbr-pixel}}(\text{AIRS}) - CTP_{\text{ref-pixel}}(\text{AIRS}) = \sum_{\text{MODIS spectral bands}} a_i [R_{n\text{nbr-pixel}}(\text{AMODIS})_i - R_{\text{ref-pixel}}(\text{AMODIS})_i], \quad (1)$$

where CTP is the AIRS-derived cloud-top pressure, and $R(\text{AMODIS})_i$ is the calculated radiance for MODIS spectral band i using the AIRS spectral measurements within the pixel. This is done separately for high ($\text{CTP} < 440$ hPa), mid ($440 \leq \text{CTP} < 680$ hPa), and low ($\text{CTP} \geq 680$ hPa) AIRS CTPs. Thus three sets of regression coefficients (each containing three elements, one for each of the MODIS spectral bands) are obtained.

Step 3: The regression coefficients a_i are applied on measured 1-km resolution MODIS radiance $R(\text{MODIS})$ gradients calculated with respect to the average of the MODIS radiances within the reference 13.5 km AIRS pixel, $R_{\text{mean-AIRS-ref-pixel}}(\text{MODIS})$, to get the “merging gradients” 1 km resolution $CTP_{\text{MODIS-pixel}}(\text{AIRS+MODIS})$. The equation for Step 3 is,

$$CTP_{MODIS-pixel}(AIRS + MODIS) - CTP_{AIRS-ref-pixel}(AIRS) = \sum_{MODIS \text{ spectral bands}} a_i [R_{MODIS-pixel}(MODIS)_i - R_{mean-AIRS-ref-pixel}(MODIS)_i]. \quad (2)$$

The regression coefficients a are applied to the radiance difference between each cloudy MODIS pixel and the average of all (clear and cloudy) pixels within the reference AIRS FOV to obtain new MODIS CTP retrievals at 1 km spatial resolution. Cloudy pixels are indicated by the MODIS cloud mask (Ackerman et al. 1998; Frey et al. 2008; Ackerman et al. 2008). The regression used (high, mid, or low) is dictated by the reference AIRS CTP. Each MODIS cloudy pixel is regressed with all AIRS FOVs that are within 0.1 degree at nadir (and expanding to 0.2 degrees at the edge of the granule); the resulting multiple CTP retrievals are averaged to generate the final CTP product for that 1 km cloudy pixel.

Thus, the regression coefficients are calculated from AIRS CTP and AMODIS radiance gradients, and are then applied to MODIS radiances for every cloudy pixel within or near an AIRS FOV to obtain 1km AIRS+MODIS combined CTPs. The retrieved CTP in hPa is converted to CTH in kilometers using the NCEP (National Centers for Environmental Prediction) GDAS (Global Data Assimilation System) analysis temperature and moisture profiles.

An Example Case Study- Polar Nimbo- and Alto-stratus with cirrus overlay (AIRS granule 124, 28 August 2006)

Granule 124 is located in the southern hemisphere (southeast of New Zealand) entirely over ocean. The CrIS, VIIRS, and VIIRS+CrIS retrievals in Figure 2 agree on the extent and distribution of the cloud field, but the VIIRS retrievals find higher CTP values (i.e. lower cloud heights) in general.

Comparison with CALIOP's cloud altitude product is shown in Figure 3. For the cloud features (Nimbo- and Alto-stratus) between latitudes -65° and -54° , the heights of the cirrus clouds (as given by CALIOP) agree with the cloud heights retrieved from CrIS and VIIRS+CrIS; VIIRS heights are lower by 4 to 5 km placing the CTHs within the cloud observed by CALIPSO. Biases (standard deviations) for VIIRS, CrIS, and VIIRS+CrIS are 4.2, 1.7, and 1.8 km (3.1, 2.9, and 2.7 km) respectively.

North of latitude -53° , a row of stratocumulus clouds resides very close to the ground. The VIIRS values underestimate the CALIOP CTHs, whereas CrIS and VIIRS+CrIS heights are somewhat too high and show excessive vertical variation; this is likely caused by the CrIS difficulty in capturing these scattered cloud fragments. For latitudes -54° to -52° , a two-layer cloud structure is observed; since our current CrIS retrieval algorithm does not account for two layer situations, the retrieved product from CrIS and VIIRS+CrIS does not capture the lower clouds.

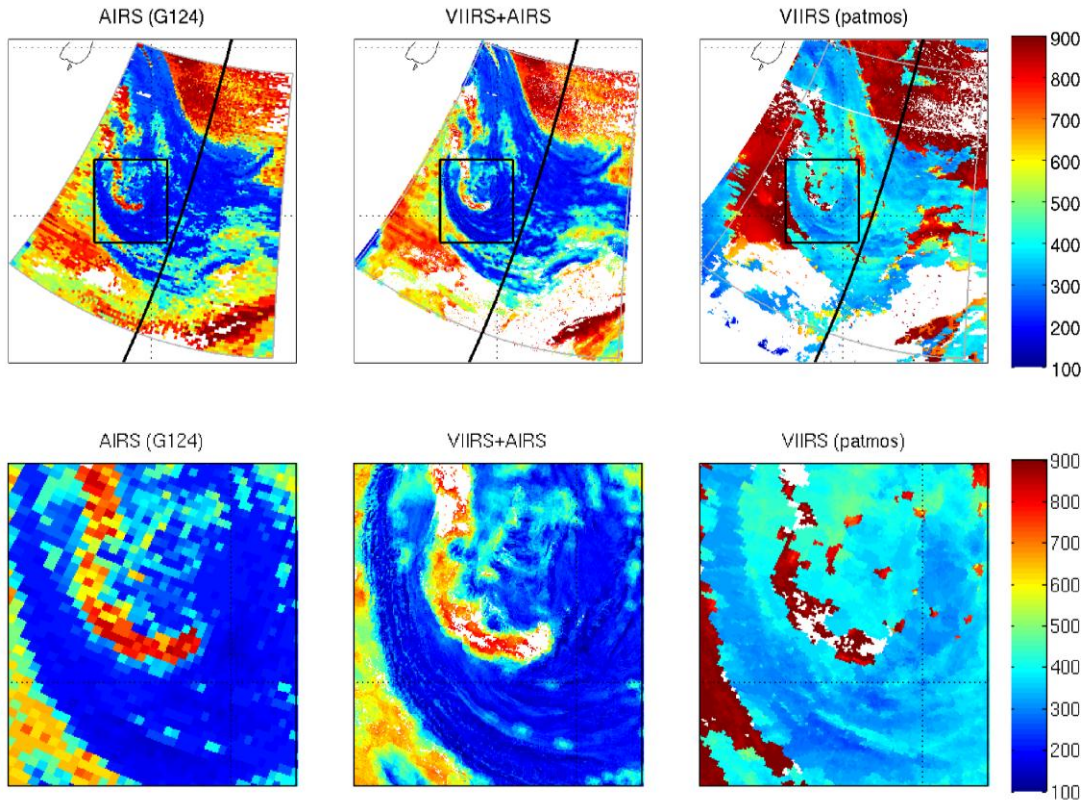


Figure 2. CTP (in hPa) retrievals from AIRS (left), MODIS+AIRS (middle), and MODIS (right) for AIRS granule 124 (28 Aug 2006). Top: Entire granule with the CALIPSO overpass (black line) and the outlines of a selected area (black rectangle). Bottom: Same products as in top figure but for selected area.

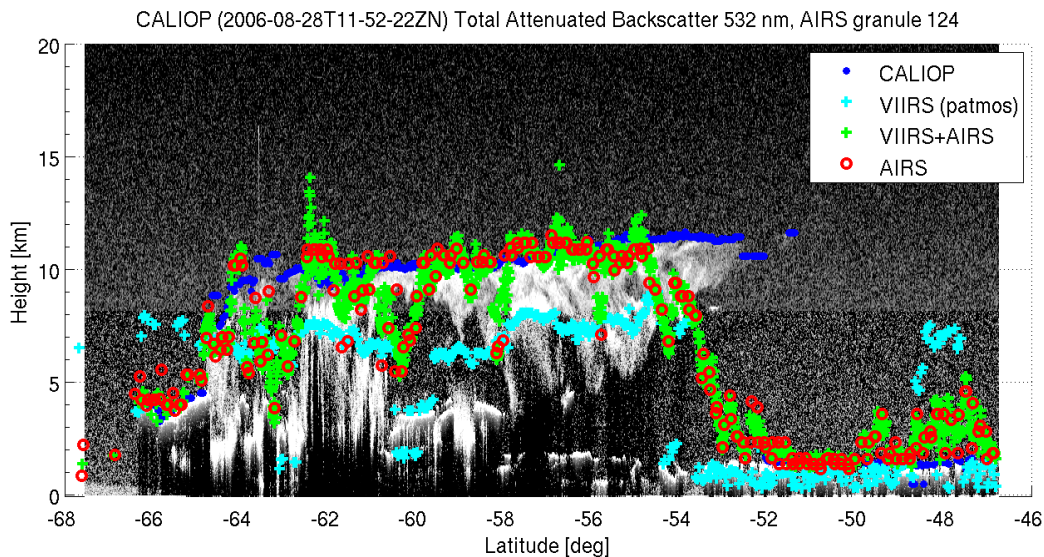


Figure 3. Cross-section along the CloudSat/CALIPSO track for AIRS granule 124 (28 Aug 2006). Top: CALIOP 532 total attenuated backscatter /km/steradian (background). CTHs from CALIOP, VIIRS, VIIRS+CrIS, and CrIS are plotted as blue dots, cyan pluses, green pluses, and red circles, respectively.

Conclusions

Various adjustments to the MODIS CTH algorithm have been tested. The geographical distributions of the differences with respect to CALIOP CTH determinations show that the tropics have been improved and that marine stratus problems along the west coasts of North and South America and Africa have been largely mitigated. These improvements are modest on the global scale, but they represent significant improvement for problem regions and for high thin cirrus. A paper has been submitted to the Journal of Applied Meteorology and Climatology (JAMC) detailing the algorithm performance improvements (Baum, B. A., W. P. Menzel, R. A. Frey, D. Tobin, R. E. Holz, Ackerman, S. A., A. K. Heidinger, and P. Yang: MODIS cloud top property refinements for Collection 6)

Transition of CTH records to the VIIRS sensor has been addressed. While the new VIIRS imager has many advances over previous sensors, it lacks infrared (IR) spectral bands that are sensitive to absorption by carbon dioxide or water vapor. The use of such bands has been relied upon with past sensors (HIRS, MODIS) to provide greater sensitivity to cloud top pressure (CTP) estimation than can be obtained from use of window bands alone. The lack of absorbing IR bands will have the most impact on the inference of cloud top pressure for semi-transparent ice clouds. The CrIS on JPSS with sounding bands in both the CO₂ and H₂O spectral regions, offers complementary measurements to VIIRS but at lower spatial resolution. CrIS is better suited to infer cloud-top pressure for cirrus because of the hyperspectral sounding measurements in the CO₂ and H₂O absorption bands, whereas VIIRS is able to detect clouds of small horizontal extent and describe clouds with large horizontal variations.

This work demonstrates an approach to combine the horizontal detail of VIIRS (using MODIS data as a proxy) with the absorbing IR spectral bands of CrIS (using AIRS data as a proxy) for cloud detection and cloud top pressure estimation. The cloud structures at CrIS horizontal resolution (13.5 km at nadir) are related to those at VIIRS resolution (880 m at nadir) through a regression relationship of CrIS cloud top pressure (CTP) gradients against CrIS measurements convolved to VIIRS spectral band response functions. The regression relationship is applied to simulated pre-launch VIIRS radiance measurements to determine CTPs at sub-kilometer resolution. That is, the VIIRS+CrIS merging-gradient approach provides cloud pressures/heights at 1-km spatial resolution. The “merging gradient” CTPs are converted to cloud top heights (CTH) and compared to the CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation) Version 3 cloud product.

CTHs retrieved from VIIRS+CrIS are compared with CALIOP Version 3 Level-2 CTHs. For optically thin ice clouds and also clouds of small vertical extent, the combined VIIRS+CrIS CTHs compare much better with CALIOP than the individual VIIRS CTHs. The retrieval performance is found to be best for high clouds above 6 km. VIIRS+CrIS biases for ten different cloud scenes with respect to CALIPSO are 1.3 km down from 3.2 km for VIIRS alone, corresponding to a bias reduction of 1.9 km; VIIRS+CrIS biases are similar to those for CrIS, but they are accomplished at 1 km resolution (improving the standard deviations from 3.3 to 2.8 km).

This “merging gradients” approach is expected to have positive impact, especially for cirrus, with an imager that does not have any IR absorbing spectral bands such as VIIRS in combination

with CrIS or AVHRR in combination with IASI. Since the combined retrieval depends on the performance of the sounder retrieval algorithm, the improvement of the latter (e.g. by implementing a physical iterative retrieval scheme and enabling retrieval of multi-layer clouds) is an important part of ongoing studies as are more validations of the combined VIIRS+CrIS retrievals for diverse cloud conditions. In this paper CrIS and VIIRS radiances have been combined on a granule level with regression relationships determined for that or a nearest neighbor granule; it remains to be seen how a regional application affects the retrieval outcome.

A paper has been submitted to JAMC (Weisz, E., W. P. Menzel, R. Frey, E. Borbas, N. Smith, and B. A. Baum: An approach for improving cirrus cloud top pressure/height estimation by merging high spatial resolution VIIRS data with high spectral resolution CrIS data); publication is expected in 2012.