Title of Grant / Cooperative Agreement:	Evaluation of VIIRS Cloud EDRs and Extending MODIS Cloud Data Records into the NPP Timeframe
Type of Report:	Summary of Research
Name of Principal Investigator:	Steven Ackerman
Period Covered by Report:	7/8/2011 - 7/7/2014
Name and Address of recipient's institution:	University of Wisconsin System, 21 N Park St Ste 6401,Madison, WI 53715-1218
NASA Grant / Cooperative Agreement Number:	NNX11AL95G

Reference 14 CFR § 1260.28 Patent Rights *(abbreviated below)*
The Recipient shall include a list of any Subject Inventions required to be disclosed during the preceding year in the performance report, technical report, or renewal proposal. A complete list (or a negative statement) for the entire award period shall be included in the summary of research.

Subject inventions include any new process, machine, manufacture, or composition of matter, including software, and improvements to, or new applications of, existing processes, machines, manufactures, and compositions of matter, including software.

Have any Subject Inventions / New Technology Items resulted from work performed under this Grant / Cooperative Agreement?	No ◉	Yes ○
If yes a complete listing should be provided here: Details can be provided in the body of the Summary of Research report.		

Reference 14 CFR § 1260.27 Equipment and Other Property (abbreviated below)
A Final Inventory Report of Federally Owned Property, including equipment where title was taken by the Government, will be submitted by the Recipient no later than 60 days after the expiration date of the grant. Negative responses for Final Inventory Reports are required.

Is there any Federally Owned Property, either Government Furnished or Grantee Acquired, in the custody of the Recipient?	No ◉	Yes ○
If yes please attach a complete listing including information as set forth at § 1260.134(f)(1).		

Attach the Summary of Research text behind this cover sheet.

Reference 14 CFR § 1260.22 Technical publications and reports (December 2003)
Reports shall be in the English language, informal in nature, and ordinarily not exceed three pages (not counting bibliographies, abstracts, and lists of other media).

A Summary of Research (or Educational Activity Report in the case of Education Grants) is due within 90 days after the expiration date of the grant, regardless of whether or not support is continued under another grant. This report shall be a comprehensive summary of significant accomplishments during the duration of the grant.

EVALUATION OF VIIRS CLOUD EDRSAND EXTENDING MODIS CLOUD DATA RECORDS INTO THE NPP TIMEFRAME

Contract number: NNX11AL95G
Activities: July 8, 2011 – July 7 2014

CIMSS Investigators:
Steven A. Ackerman (PI)
Robert E. Holz (PM)
Richard A. Frey
Andrew K. Heidinger

Table of Contents

Summary of Research Report

This project ported and modified a suite of existing MODIS production cloud algorithms for use with the Visible Infrared Imager Radiometer Suite (VIIRS) instrument. The project was in collaboration with Dr. Steven Platnick of NASA GSFC. Enabling these algorithms to run on the VIIRS spectral channel set allows for direct and meaningful comparisons with the VIIRS contractor cloud EDRs. Leveraging off this approach to EDR evaluation, and potentially with supplemental observations from the Cross Track Infrared Sounder (CrIS), provides a good continuity options for extending MODIS-heritage cloud data records into the NPP timeframe.

With regard to the instruments, several key spectral channels are absent on VIIRS (water vapor and CO2 channels), there is a significant change in the spectral location for the key shortwave infrared band used for cloud microphysical retrievals, and spatial resolutions differ. Further, biases in inter-instrument radiometric calibration and related instrument artifacts (e.g., spectral crosstalk) may be difficult to quantify to the level required for EDR comparisons and for establishing CDR continuity with MODIS. The porting/modification of the MODIS cloud algorithms to VIIRS eliminate instrument-related differences and provides a heritage reference algorithm that can be used to achieve a long term cloud data record.

Cloud Mask and Thermodynamic Phase EDRs

The first step in retrieving cloud or surface properties is to determine if the pixel is clear or cloudy. The VIIRS cloud mask (VCM) is an "intermediate product" (IP) in that it is input to all VIIRS EDRs.

Comparison of key algorithm approaches

The VCM is modeled after the MODIS cloud mask (e.g. Hutchison et al 2005; Hutchison and Cracknell, 2005; and Hutchison et al 2008). As with the MODIS cloud mask, the output of the VCM algorithm is 6 bytes (48 bits) for each moderate resolution pixel. The mask includes information about the processing path the algorithm took (e.g., land or ocean) and whether a view of the surface is obstructed. After the cloud confidence is determined, the VCM tests the pixel for aerosols, and fires. Algorithms to generate the VIIRS cloud, aerosol, land, ocean, surface temperature, and snow/ice Environmental Data Records (EDRs) use the VCM as auxiliary data as mandated by the VIIRS Interface Data Processing Segment's (IDPS).

Cloud mask algorithms for both VIIRS and MODIS use a series of spectral tests on the radiances or their associated brightness temperatures. Cloud detection is based on the contrast (i.e., cloud versus background surface) in a given target area—in this case, at the pixel resolution. Contrast may be defined as differing signals for individual spectral bands (e.g., clouds are generally more reflective in the visible but colder than the background as measured in the thermal IR), spectral combinations (e.g., 0.86-/0.66-μm ratio is close to unity for cloudy skies), or temporal and spatial variations of these. Both the VIIRS and MODIS cloud masks use several cloud detection tests to indicate a level of confidence that the observation is a clear-sky scene. The cloud mask is produced for the entire globe, day and night.

Both cloud masks assess the likelihood that clouds obstruct a given pixel. As cloud cover can occupy a pixel to varying extents, the cloud mask is designed to allow for varying degrees of clear-sky confidence (i.e., it provides more information than a simple yes/no decision).

Evaluation methodology

The first two bits of the mask summarize the results from all individual tests by classifying every pixel of data as either confident clear, probably clear, uncertain/ probably cloudy, or cloudy. To be classified as clear in this analysis, all VIIRS and MODIS pixels within a group were required to be labeled as confidently clear or probably clear. Those labeled as probably cloudy or cloudy are considered cloud contaminated scenes.

Because of the similarity of the VCM and MODIS cloud algorithms; we compare both masking results to collocated observations from CALIOP. We also show some comparisons with the PATMOS-x algorithm, as this historic algorithm set is of unique value to climate studies from satellites.

Evaluation Results

Figure 1 shows the global distribution of cloud amount derived from VCM and PATMOS-x using the VIIRS observations (Heidinger et al 2012) for November 29, 2012 in the ascending node of the spacecraft. As expected, the large-scale patterns are similar to other satellite data sets of cloud amount (Rossow, et al., 1993; Thomas, et al., 2004; Wylie, et al., 1994). The Inter-tropical convergence zone (ITCZ) is clearly evident as are the subtropical high-pressure systems and the marine stratocumulus regions. Figure 2 shows the global map of the difference between the two analysis methods. White regions indicate both VCM and PATMOS-x detect cloud, while green and blue regions are where both methods detect clear over land and water, respectively. Regions colored cyan indicate where the VCM detected clear while the PATMOS-x detected cloud; red pixels are where the VCM assigned cloudy and PATMOS-x clear. The two algorithms are applied to the same data, so differences in the performance arise from the analysis methods. There is generally good agreement between about 60S and 60N, with the VCM producing more clouds in the southern polar region, and less cloud to the north of 60N.

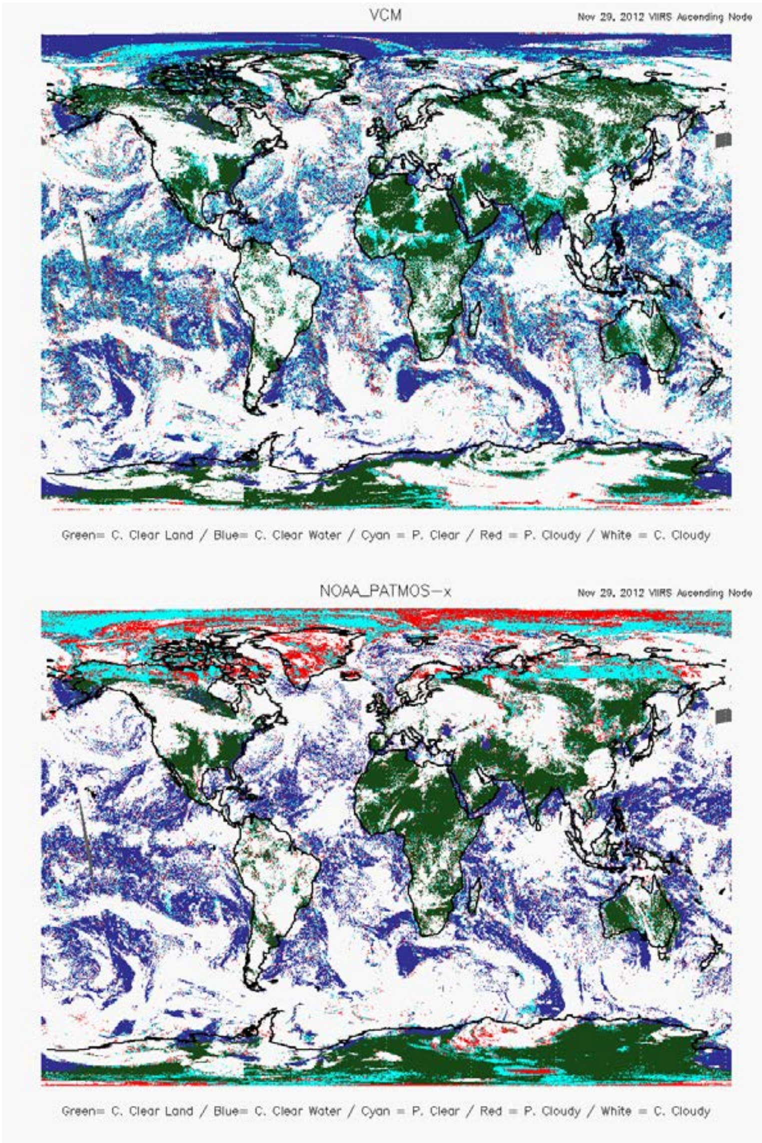

Figure 1. Results from the VCM (top) and PATMOS-x (bottom) cloud mask algorithms applied to VIIRS for data collected in ascending orbit on November 29, 2012.

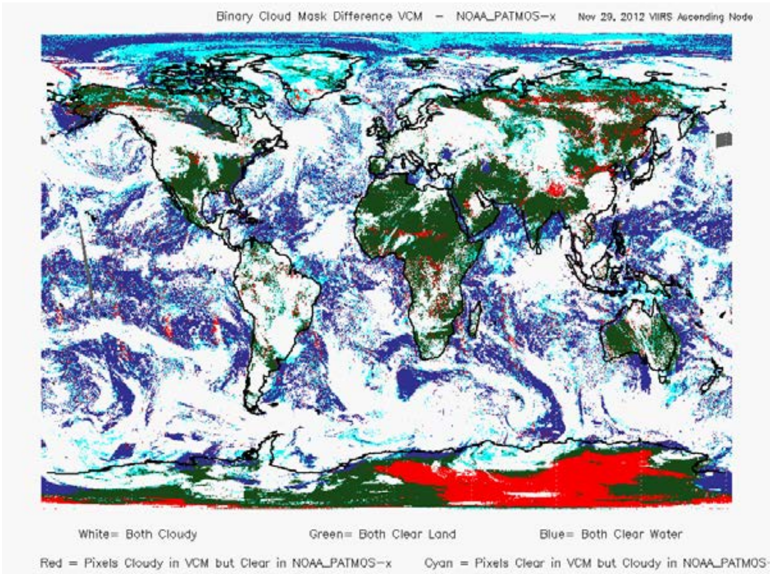

Figure 2. Differences between the VCM (top) and PATMOS-x (bottom) cloud mask algorithms applied to VIIRS for data collected in ascending orbit on November 29, 2012. Green and blue regions are where both methods detect clear over land and water, respectively. Regions colored cyan indicate where the VCM detected clear while the PATMOS-x detected cloud; red pixels are where the VCM assigned cloudy and PATMOS-x clear.

In the next analysis, we compare VCM and PATMOS-x cloud detection results using VIIRS input observations, and also PATMOS-x and Collection 6 MODIS cloud mask (MOD35) results using input MODIS observations for data collocated during the time period 11/10/2012 to 11/29/2012. Only data within ±0.2 hours (±12 minutes) of the collocation window between satellites is used in the comparison (a filter on cloud optical depth was not applied). In the first comparison we focus on scenes where, in general, cloud masks perform the best; ocean only regions between 60N – 60S during the daytime with no surface ice. The results are shown in Table 1, where the first column is the algorithm, the second is the sample size, column 3 is the cloud fraction detected by CALIOP lidar, column 4 is the cloud fraction from each algorithm listed in column 1, 5-6 provide the percent of probably clear and probably cloudy pixels, and the final three columns are more comparisons with CALIPSO. Leakage refers to missed clouds, where CALIPSO is cloudy and others confidently/probably clear. While improvements could be made to the VCM, overall it performs well, detecting 93% of the clouds detected by CALIOP, with false detections and leakages of 1.6% and 5.2% respectively. The differences between the two PATMOS-x indicates that the VIIRS performance suffers from lack of water vapor bands that are available on MODIS.

Polar regions are much more difficult environments in which to discriminate between clear and cloudy pixels, as shown in Table 2 where we summarize results for all scenes pole-ward of 60N. These results demonstrate needed improvements for the VCM.

Table 1. Cloud mask results and comparisons for VCM and PATMOS-x algorithms using VIIRS observations, and also PATMOS-x and C6 MOD35 algorithms using input MODIS observations data collocated during the time period 11/10/2012 to 11/29/2012 for ocean only regions between 60N – 60S during the daytime with no surface ice. The first column is the specific algorithm, the second column the sample size, column 3 is cloud fraction from CALIOP lidar, 4 is the same for each algorithm in column 1, 5-6 provide the percent of probably clear and probably cloudy, and the final three columns show more comparisons with CALIPSO. Leakage refers to the cases of missed clouds where CALIPSO is cloudy and the others confidently/probably clear.

Cloud Mask Algorithm	**Sample Size**	**Cloud fraction**				**Probability of**		
		Active	Passive	Pr. Clear	Pr. Cloudy	Detection	False D.	Leakage
VCM	154160	0.773	0.737	0.062	0.025	0.932	0.016	0.052
NOAA PATMOS-x VIIRS	154160	0.773	0.762	0.009	0.009	0.950	0.020	0.029
NOAA PATMOS-x MODIS	106461	0.781	0.773	0.009	0.010	0.977	0.008	0.015
MODIS_C6	106461	0.781	0.776	0.029	0.016	0.973	0.011	0.016

Table 2. Same as Table 1 except for all scenes pole-ward of 60N.

Cloud Mask Algorithm	**Sample Size**	**Cloud fraction**				**Probability of**		
		Active	Passive	Pr. Clear	Pr. Cloudy	Detection	False D.	Leakage
VCM	23941	0.769	0.412	0.137	0.048	0.613	0.015	0.372
NOAA PATMOS-x VIIRS	23941	0.769	0.714	0.246	0.204	0.803	0.071	0.126
NOAA PATMOS-x MODIS	38637	0.724	0.610	0.246	0.165	0.813	0.036	0.151
MODIS_C6	38637	0.724	0.650	0.016	0.077	0.839	0.044	0.118

We next compare zonal mean of cloud frequencies between the VCM and CALIOP lidar during the 33 day period September 20-October 22, 2012. Figure 3 (top) shows the results as a function of day and night. While the VIIRS and CALIOP instruments have very different scanning methods, Ackerman et al (2008) demonstrated that zonal means can be well represented by both broad swath scanning and near-nadir viewing instruments. In general, the VCM has a lower zonal cloud frequency during both daytime and nighttime. These differences can be particularly large in polar regions where differences can exceed 20%. For reference, we show the same comparison (bottom) but use the Collection 6 MODIS cloud mask. Outside the polar regions, there is excellent agreement. Maximum differences occurring during polar night, consistent with results of Ackerman et al (2008) and Holz et al (2008).

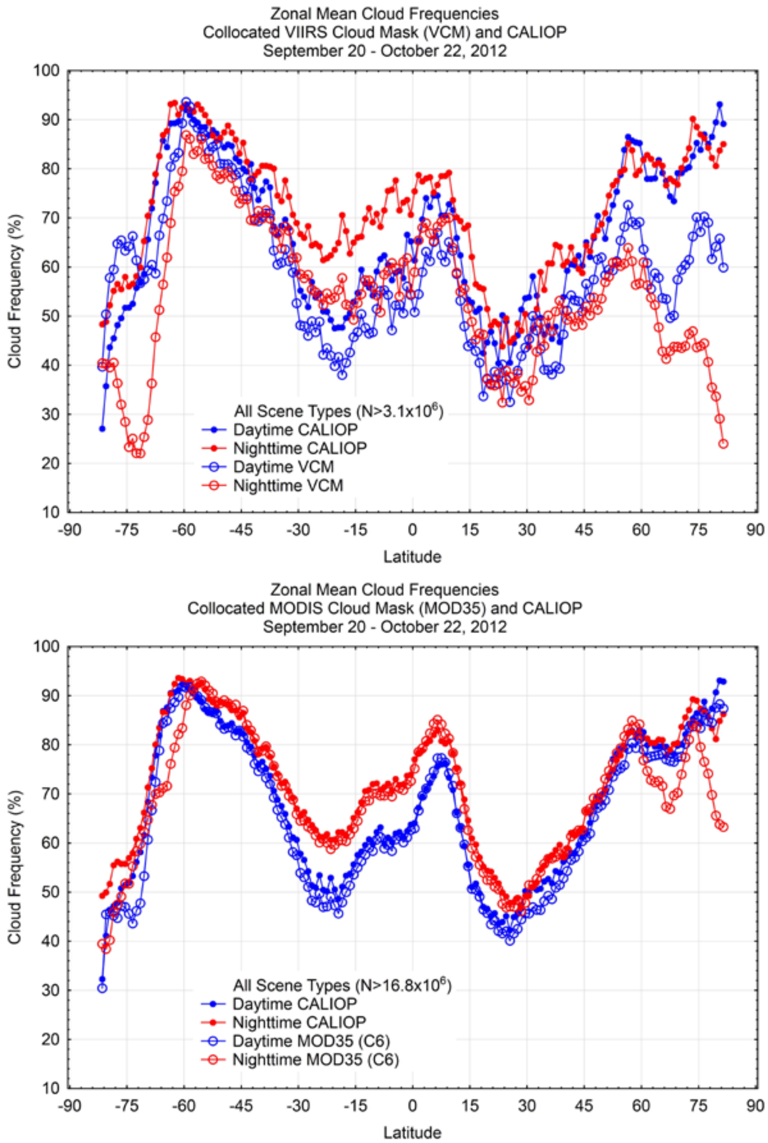

Figure 3 Zonal mean cloud frequency for CALIOP and VCM (top) for the period September 20 through October 22, 2012. The bottom figure shows the same comparison for CALIOP and MODIS MOD35 Collection 6 algorithm.

A global comparison of the CALIOP, VCM, and MODIS cloud mask results for the same 33 day period is presented in Tables 3 and 4. For the comparison, a VCM or MODIS cloud mask result is considered cloudy if the cloud mask returns confident cloud or probably cloudy, while a pixel is defined clear if the cloud mask returns probably clear or confidently clear. Only pixels where all the collocated CALIOP retrievals are identical (i.e. either all clear or all cloudy) are included in the statistics in Tables 3 and Table 4.

Table 3 shows hit rates (in comparisons to CALIOP) for MODIS Collection 6 MOD35 and VCM for CALIOP cloud optical depths of greater than 0.3, while Table 4 shows comparisons for all optical depths. Column 1 in each table lists the scene category, and columns 2-3 show the hit rate for the Collection 6 MOD35 and VCM masks. In table 2, Columns 4-5 shows the Hanseen-Kuiper Skill Score for MOD35 and VCM respectively. The hit rate is defined as:

$$\frac{N_{cld} + N_{clr}}{N} \times 100$$

where N_{cld} is the number of cloud pixels in agreement, N_{clr} is the number of clear pixels in agreement, and N is the total number of collocated pixels. The agreement is also expressed by the Hanssen-Kuiper Skill Score (Hanssen and Kuipers, 1965). The score has a range of -1 to +1, with 0 representing no skill. This skill score expresses the hit rate relative to the false alarm rate, and will remain positive as long as the hit rate is greater than the false alarm rate; it is a useful metric when analyzing phenomena that are not normally distributed.

The global and regional agreement between MODIS and CALIOP is generally greater than 88%, while VCM hit rate for all cloud optical depths is generally less than the hit rate of MODIS by more than 5%. Agreement between the hit rates of MODIS and VCM improves when comparison is categorized to COD> 0 .3, indicating that VCM is missing some optically thin clouds. The skill score of the VCM is always less than the MODIS (Table 4). As expected, both cloud masks have their highest hit rates for daytime ocean scenes between latitude belts of 60 N and S, although the skill score of the VCM is still 10 points below the MODIS algorithm.

Table 3 MODIS MOD35 and VCM hit rates (in comparisons to CALIOP) for CALIOP cloud optical depths of greater than 0.3. Column 1 lists the scene category, and columns 2-3 show the hit rate for the Collection 6 MOD35 and VCM masks.

Scene Category	**MOD35 Collection 6 Hit Rate (%)** N>13.6x10^{6}	**VIIRS Cloud Mask (VCM) Hit Rate (%)** N>2.5x10^{6}
Global	90.7	81.4
60S-60N	93.7	90.9
Global Day	92.5	85.4
60S-60N Day	94.5	91.2
Global Night	89.1	77.9
60S-60N Night	92.9	90.7
60S-60N Water Day	94.8	91.6
60S-60N Water Night	93.3	91.5
60S-60N Land Day	93.8	89.9
60S-60N Land Night	92.0	88.9
Desert Day	93.6	92.5
Desert Night	93.2	93.1

CALIOP COD > 0.3 Sept. 20 – Oct. 22, 2012

Table 4 MODIS MOD35 and VCM hit rates (in comparisons to CALIOP) for all cloud optical depths. Column 1 lists the scene category, and columns 2-3 show the hit rate for the Collection 6 MOD35 and VCM masks. Columns 4-5 show the Hanssen-Kuiper Skill Score for MOD35 and VCM respectively.

Scene Category	**MOD35 Collection 6 Hit Rate**	**VIIRS Cloud Mask (VCM) Hit Rate**	**MOD35 Hanssen-Kuiper SS**	**VCM Hanssen-Kuiper SS**
Global	88.0	76.0	74.7	57.4
60S-60N	90.9	83.7	80.0	70.6
Global Day	89.8	80.7	78.6	62.2
60S-60N Day	91.3	84.7	82.0	71.1
Global Night	86.4	72.0	71.1	53.3
60S-60N Night	90.5	82.8	77.5	70.4
60S-60N Water Day	92.1	85.6	81.9	71.1
60S-60N Water Night	91.0	83.2	76.0	69.4
60S-60N Land Day	89.1	82.0	78.8	65.6
60S-60N Land Night	89.3	81.7	78.3	67.3
Desert Day	88.4	87.9	69.4	56.7
Desert Night	89.1	87.4	76.1	56.5

All Scenes Sept. 20 – Oct. 22, 2012

The assessment of polar regions is summarized in Tables 5 and 6 where the MODIS cloud mask (MOD35) and VIIRS cloud mask (VCM) are compared to the collocated polar CALIOP cloud detection product for September 20 to October 22, 2012. The comparisons are also broken out for Greenland and Antarctica. There is significant improvement needed for the VCM under these challenging conditions.

Table 5. MODIS MOD35 and VCM comparisons to collocated CALIOP observations for all cloud optical depths. Scene category is followed by the total matchups, hit rate and Hanssen-Kuiper Skill Score for MODIS collection 6 and VCM, respectively.

	Collection 6 MOD35			**VIIRS Cloud Mask (VCM)**		
Scene Type	**Total MOD35 Matchups**	**Overall Hit Rate (%)**	**Hanssen-Kuiper SS (%)**	**Total VCM Matchups**	**Overall Hit Rate (%)**	**Hanssen-Kuiper SS (%)**
Polar	5598489	82.1	63.7	1174690	63.2	33.9
Polar Day	2250029	86.2	68.8	487437	72.9	42.4
Polar Night	3348460	79.4	60.4	687253	56.3	28.8
Arctic Day	1048920	90.8	72.5	216309	75.0	60.5
Arctic Night	1751063	81.1	63.3	381092	54.7	41.3
Antarctic Day	1201109	82.2	63.8	271128	71.2	36.9
Antarctic Night	1597397	77.6	56.9	306161	58.3	22.9
Greenland Day	83106	78.3	57.2	17103	62.2	34.4
Greenland Night	174130	73.5	51.2	34837	47.3	15.0
Antarctica Day	517587	67.4	30.5	129403	58.3	20.5
Antarctica Night	833811	75.2	50.1	196390	54.1	8.0

Table 6. VCM comparisons to collocated CALIOP observations for all cloud optical depths and for CALIOP optical depths of greater than 0.3. Column 1 lists the scene category, followed by the total matchups, hit rate and Hanssen-Kuiper Skill Score for VCM in polar regions for data collected from September 20 to October 22, 2012. Left side shows all clouds, right side is CALIOP clouds with cloud optical depth > 0.3.

	All Clouds			**Clouds with CALIOP COD > 0.3**		
Scene Type	**Total VCM Matchups**	**Overall Hit Rate (%)**	**Hanssen-Kuiper SS (%)**	**Total VCM Matchups**	**Overall Hit Rate (%)**	**Hanssen-Kuiper SS (%)**
Polar	1174690	63.2	33.9	1002796	67.2	38.6
Polar Day	487437	72.9	42.4	419673	75.2	46.4
Polar Night	687253	56.3	28.8	583123	61.4	33.9
Arctic Day	216309	75.0	60.5	177473	78.5	64.1
Arctic Night	381092	54.7	41.3	316799	60.4	46.4
Antarctic Day	271128	71.2	36.9	242200	72.7	41.0
Antarctic Night	306161	58.3	22.9	266324	62.6	28.1
Greenland Day	17103	62.2	34.4	15549	66.2	38.6
Greenland Night	34837	47.3	15.0	30626	52.3	18.7
Antarctica Day	129403	58.3	20.5	117731	58.6	25.2
Antarctica Night	196390	54.1	8.0	171761	58.2	12.4

Conclusions

The VCM assessed in this report is the algorithm that was implemented into the IDPS processing in late April, 2012. While it does not meet MODIS capabilities, improvements can likely be made to improve the VCM results. For example, ancillary snow maps used by the VCM should not be static. The problem is that making changes in the IDPS is both time consuming and tedious. Thus, reprocessing the VIIRS data for climate data records is a challenge in the IDPS.

While there are certainly some performance concerns with the VCM, the major concern with using the VCM for climate studies resides mainly with the Interface Data Processing Segment (IDPS) used in the JPSS Ground Segment. Our issues with the IDPS for climate studies are listed below.

The IDPS has not been stable during the first year of NPP operation and shows signs of continued instability. For example, the VCM relies on knowledge of the surface to select appropriate cloud detection thresholds. The IDPS functions that provide information on snow and vegetation cover remain non-functional. Issues also remain with the interaction of the VCM with these background fields. These changes cause large impacts in the VCM performance will certainly destroy the stability needed for climate data records. Presumably this will eventually be solved but their continued presence one year after launch and many years after the development is troubling.

It is clear that the IDPS systems located at the central processing sites are not designed for reprocessing. Our experience is that climate quality data is never generated until multiple passes through the data are accomplished. Our limited experience with the IDPS does not indicate that it provides an avenue for the reprocessing we intend to perform.

ADL is provided as the mechanism to the community to process IDPS algorithms outside of the IDPS. To date, we have found ADL to be slow and cumbersome to use. Tools to acquire the ancillary data for running ADL are lacking and for this reason, large scale processing with ADL is impossible. We don't see ADL as an option for our climate needs.

Given the reasons above, one could still use the VCM outside of the IDPS or ADL. This option has been explored. However, IDPS algorithms are in general written very specifically for the IDPS interfaces. Emulating these interfaces has been very difficult and time consuming. To this date, the Atmosphere PEATE has still not achieved the ability to match the IDPS VCM with enough accuracy to consider exploring using the VCM outside of the IDPS for climate work.

References:

Ackerman, S. A., R. E. Holz, R. Frey, E. W. Eloranta, B. Maddux, and M. McGill, 2008: Cloud Detection with MODIS: Part II Validation, *J. Atmos. Oceanic Tech.*, **25**, 1073-1086.

Hanssen, A. W., and W. J. A. Kuipers, 1965: On the relationship between the frequency of rain and various meteorological parameters. *Meded. Verh*., **81**, 2–15.

Heidinger, Andrew K., Amato T. Evan, Michael J. Foster, Andi Walther, 2012: A Naive Bayesian Cloud-Detection Scheme Derived from CALIPSO and Applied within PATMOS-x. J. Appl. Meteor. Climatol., 51, 1129–1144.Holz, R.E., S. A. Ackerman, F.W. Nagle, R. Frey, R.E. Kuehn, S. Dutcher, M. A. Vaughan and B. Baum., 2008: Global MODIS Cloud Detection and Height Evaluation Using CALIOP. *J. Geophys. Res.*, doi:10.1029/2008JD009837.

Hutchison, K.D., Iisager, B. D., Kopp., T. J., and J. M. Jackson, (2008): "Discriminating between Clouds and Aerosols in the VIIRS Cloud Mask Algorithms," J. Atmospheric & Oceanic Technology, 25, 501-518.

Hutchison, K. D., and A. P. Cracknell, 2005: "VIIRS - A New Operational Cloud Imager," CRC Press, 218 pp.

Hutchison, K.D., Roskovensky, J.K., Jackson, J.M., Heidinger, A.K., Kopp, T. J., Pavolonis, M.J, and R. Frey, 2005: "Automated Cloud Detection and Typing of Data Collected by the Visible Infrared Image

Rossow, W. B., A. W. Walker, and L. C. Gardner, 1993: Comparison of ISCCP and other cloud amounts, *J. Climate*, 6:2394-2418. .

Thomas, S. M., A. K. Heidinger, and M. J. Pavolonis, Comparison of NOAA's operational AVHRR-derived cloud amount to other satellite-derived cloud climatologies. Journal of Climate, Volume 17, Issue 24, 2004, pp.4805-4822. Call Number: Reprint # 3992.

Wylie, D. P., W. P. Menzel, H. M. Woolf, and K. I. Strabala, 1994: Four years of global cirrus cloud statistics using HIRS. *J. Climate*, 7, 1972-1986. .

Conference Presentations

Ackerman, S. A., B. C. Maddux, S. Platnick, A. K. Heidinger, R. Frey, and R. Holz, 2012: What is a Cloud: the Choices People Make and Why They Regret Them (Invited). AGU Fall meeting: Radiation, Precipitation, and Water and Energy Cycles, San Francisco, CA, 3-7 December.

Ackerman, S. A., 2012: Clouds from Satellites: SMONEX to MODIS, Atmospheric Science Department 50th Anniversary Symposium, Colorado State University, July 13-14, 2012.