Title of Grant / Cooperative Agreement:	Continuation of EOS Clear Sky Infrared Total Precipitable Water Vapor Product Using a Combination of VIIRS and CrIMSS Measurements
Type of Report:	Summary of Research
Name of Principal Investigator:	Dr. Eva Borbas
Period Covered by Report:	11/05/2014 - 05/04/2018
Name and Address of recipient's institution:	The Board of Regents of the University of Wisconsin System
NASA Grant / Cooperative Agreement Number:	NNX15AB95A

Reference 2 CFR § 1800.908 or 14 CFR § 1260.28 Patent Rights *as applicable (abbreviated below)*
The recipient may use whatever format is convenient to disclose subject invention required in subparagraph (c)(1). NASA prefers that the recipient use either the electronic or paper version of NASA Form 1679, Disclosure of Invention and New Technology (Including Software), to disclose subject inventions. Both the electronic and paper version of the NASA Form 1679 may be accessed at the electronic New Technology Reporting Web site https://invention.nasa.gov.
A final new technology summary report listing all subject inventions (or a statement certifying there were none) for the entire award period; which report shall be submitted within 90 days after the end date for the period of performance within the designated system noted within the award document."

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 2 CFR § 1800.907 or 14 CFR § 1260.27 Equipment and Other Property *as applicable* (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 2 CFR § 1800.902 or 14 CFR § 1260.22 Technical publications and reports *as applicable* (abbreviated below)
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.

NNX15AB95A Final Report:
S-NPP IR TPW from a combination of VIIRS and CrIMSS

Project Title: "Continuation of EOS Clear Sky Infrared Total Precipitable Water Vapor Product Using a Combination of VIIRS and CrIMSS Measurements"

Principal Investigator: Dr. Eva Borbas
Co-Investigators: Dr. W Paul Menzel and Dr. Zhenglong Li

Institution: UW-Madison, Space Science and Engineering Center, 1226 W Dayton Str, Madison, WI 53706

Date: Nov 5, 2014 – May 5, 2018

Table of Contents

1. Objectives

We proposed to provide total column water vapor properties from merged VIIRS infrared measurements and CrIMSS (CrIS plus ATMS) water vapor soundings to continue the depiction of global moisture at high spatial resolution started with MODIS. While MODIS has two channels within the 6.5-µm H_2O band and four channels within the 15-µm CO_2 band, VIIRS has no infrared (IR) absorption channels. However, the VIIRS IR windows at 8.6, 10.8 and 12 µm give some indication of low level moisture (which constitutes much of the total column amount) and we proposed to complement this with CrIMSS column moisture determinations. The resulting VIIRS/CrIMSS algorithm follows the approach used for MODIS. A clear sky regression relationship is established between total precipitable water vapor (TPW) and VIIRS IR window brightness temperatures (BTs) and CrIMSS water vapor soundings calculated from a global training radiosonde based profile data set. CrIMSS is added in clear and partly cloudy regions to enhance the TPW depiction and to extend the coverage.

2. Status of the L2 and L3 VIIRS TPW Products

The methodology to generate S-NPP TPW products is based on the operational MODIS TPW retrieval algorithm, MOD07 (Seemann et al., 2003 and 2008). This statistical regression retrieval algorithm is performed using observed clear sky radiances (brightness temperatures) over land and ocean for both day and night. It consists of several steps that include *(1) cloud detection, (2) regression coefficient calculation (this includes forward model calculation), (3) collocation with NUCAPS and (4) TPW retrieval.* The VIIRS water vapor retrieval algorithm has been developed in Fortran using netcdf4 input/output data following the guidelines offered by the Atmosphere SIPS and the Atmosphere Measurement Team. During this work NUCAPS replaced CrIMSS as NOAA's operational CrIS+ATMS sounding products.

The Collection 1 VIIRS Level 2 TPW algorithm has been delivered to the Atmosphere-SIPS and has been used to reprocess data for the whole mission.

Parameters included in the 6-minute VNPWATVP (VIIRS TPW Level-2 water vapor) 750m resolution products are:

(e.g. VNPWATVP.A2014288.2136.001.2018127191505.nc output filename)

- *atmosphere_water_vapor_content_nucaps_bg (NUCAPS retrieval)*
- *atmosphere_water_vapor_content_viirs_nucaps (VIIRS+NUCAPS retrieval)*
- *atmosphere_water_vapor_content_viirs_only (VIIRS only retrieval)*
- *surface_skin_temperature*
- *quality_flag*
  - *1 = good retrieval-VIIRS and NUCAPS data are available;*
  - *2 = filled with VIIRS-only retrieval;*
  - *3 = filled with NUCAPS-only retrieval;*
  - *4 = No retrievals - no VIIRS nor NUCAPS data are available or non-physical retrievals*
- *model_atmosphere_water_vapor_content (from CFSR)*
- *model_surface_pressure (from CFSR)*
- *geolocation and cloud mask data: land_sea_mask, latitude, longitude, sensor_zenith, solar_zenith, clear_sky_confidence*

The VIIRS TPW Level 3 algorithm has been delivered to the Atmosphere SIPS and has been used to reprocess data for the whole emission. The NASA VIIRS Atmosphere SIPS developed the Yori software which has been adapted to generate the Level-3 VIIRS TPW products. The Level-3 VIIRS TPW products are daily and monthly means aggregated to 0.5 degree spatial resolution separated by day and night.

Parameters included in the VNPWATVP (VIIRS TPW Level-3 daily (D3) and monthly (M3) water vapor products:

(e.g. VNPWATVP_M3.A201410.001.2018117134711.nc output filename)

group: night_atmosphere_water_vapor_content_viirs_nucaps (VIIRS+NUCAPS retrieval)
variables: standard_deviation, sum, sum_squares, n_points, mean
group: night_atmosphere_water_vapor_content_ nucaps_bg (NUCAPS retrieval)
variables: standard_deviation, sum, sum_squares, n_points, mean
group: night_atmosphere_water_vapor_content_viirs_only (VIIRS only retrieval)
variables: standard_deviation, sum, sum_squares, n_points, mean
group: day_atmosphere_water_vapor_content_viirs_nucaps (VIIRS+NUCAPS retrieval)
variables: standard_deviation, sum, sum_squares, n_points, mean
group: day_atmosphere_water_vapor_content_nucaps_bg (NUCAPS retrieval)
variables: standard_deviation, sum, sum_squares, n_points, mean
group: day_atmosphere_water_vapor_content_viirs_only (VIIRS only retrieval)
variables: standard_deviation, sum, sum_squares, n_points, mean

3. Summary of accomplishments and results

This final report includes:
Year 1 Progress report is about the L2 algorithm development,
Year 2 Progress report summarizes the L2 validation efforts,
Year 3 Progress report summarizes the L3 development efforts, and
Half Year Extension Report describes the continued L3 development and validation.

The L2 VIIRS+NUCAPS combined products have been compared with the Microwave Radiometer (MWR), AIRS L2 TPW, and MODIS TPW over the SGP Cart site and also with the GPS-based TPW over the United States GPS Network. The VIIRS-only TPW products have similar quality as the simulated VIIRS-like MODIS products (generated using only the MODIS spectral band measurements that are found on VIIRS). When the NUCAPS TPW is added to the VIIRS-only retrievals, the bias and standard deviation and hence the RMS difference of the VIIRS+NUCAPS products has been reduced. The statistical characteristics of the new products became similar to the MODIS MYD07 TPW products.

The VIIRS TPW L3 daily and monthly mean global products have been evaluated with MOD07 L3, AIRS L3, SSMI and NWP analyses data.

The Level-2 and Level-3 comparison with Aqua MODIS showed that VIIRS+NUCAPS TPW quality is better than VIIRS or NUCAPS only. To improve the spatial coverage of VIIRS+NUCAPS TPW, values missing in the NUCAPS only due to failed retrievals are filled by using VIIRS-only values. Values missing in VIIRS-only due to interference by clouds are filled by using NUCAPS values. Both VIIRS and NUCAPS only values are modified to reduce biases before they are used to fill in coverage gaps.

The VIIRS+NUCAPS combined TPW algorithm is producing near-MODIS quality TPW in the comparison between 2012-2016 with r2 values greater than 0.95 over land and ocean both day and night.

The research findings and results have been presented in various Science Conferences such as the AGU Annual Fall Meetings and the International TOVS Study conferences. The project won the first place for The Best Poster Presentation at the International TOVS Study Conference, Nov 29-Dec 5, 2017, in Darmstadt, Germany.

4. Recommended future improvements

Recent developments indicate that there is the potential to generate supplementary narrowband radiances at imager resolution from sounder measurements using a fusion approach (Weisz et al., 2017). This fusion of CrIS radiances convolved with MODIS spectral response functions and mapped to the VIIRS spatial resolution with the fusion approach offers the possibility of adding more information to the VIIRS+NUCAPS TPW derivation.

The VIIRS regression algorithm, the radiative transfer calculation of the VIIRS emissive spectral band radiances is performed using the JCSDA CRTM model. Switching to another forward model called Radiative Transfer for TOVS (RTTOV, https://nwpsaf.eu/site/software/rttov/) offers much broader application and user support. It remains to investigate the VIIRS-only retrieval noise (spiky TPW values) that occurs mostly over land at the edge of the clouds (not shown). The noise over land may suggest it is emissivity related. For IR emissivity estimation the current VIIRS algorithm uses the UW Baseline Fit Emissivity Database (Seemann et al 2008). As part of a NASA MEaSUREs project an update of the UW emissivity database has been developed by combining it with the JPL developed ASTER Global Emissivity Database V4 (Hulley and Hook, 2009). The new, improved Combined ASTER MODIS Emissivity Over Land (CAMEL) (Simon et al, 2017, Borbas et al, 2017) is integrated as part of the RTTOV Version12, which makes it easy to update emissivity.

References:

Seemann, S. W., J. Li, W. P. Menzel, and L. E. Gumley, 2003. Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances. *J. Appl. Meteor.,* 42, 1072-1091.

____, Borbas, E.E., Knuteson, R.O., Stephenson, G.R., and Huang, H-L., 2008: Development of a global infrared emissivity database for application to clear sky sounding retrievals from multi-spectral satellite radiances measurements. *J. Appl. Meteorol. and Clim*., 47, 108-123

Weisz, E., B. A. Baum, and W. P. Menzel, 2017: Fusion of Satellite-Based Imager and Sounder Data to Construct Supplementary High Spatial Resolution Narrowband IR Radiances. J. of Applied Remote Sensing, 11(3), 036022 (2017). https://doi.org/10.1117/1.JRS.11.036022

5. Year 1 Progress Report

NNX15AB95A : S-NPP IR TPW from a combination of VIIRS and CrIMSS
Annual Progress Report – Year 1

Project Title: "Continuation of EOS Clear Sky Infrared Total Precipitable Water Vapor Product Using a Combination of VIIRS and CrIMSS Measurements"
Principal Investigator: Dr. Eva Borbas
Co-Investigator: Dr. W Paul Menzel and Dr. Zhenglong Li
Institution: UW-Madison, Space Science and Engineering Center, 1226 W Dayton Str, Madison, WI 53706

Date: Nov 05 2014 – Nov 04 2015

Objectives
We propose to provide total column water vapor properties from merged VIIRS infrared measurements and CrIMSS (CrIS plus ATMS) water vapor soundings to continue the depiction of global moisture at high spatial resolution started with MODIS. While MODIS has two channels within the 6.5-μm H_2O band and four channels within the 15-μm CO_2 band, VIIRS has no infrared (IR) absorption channels. However, the VIIRS IR windows at 8.6, 10.8 and 12 μm give some indication of low level moisture (which constitutes much of the total column amount) and we propose to complement this with CrIMSS column moisture determinations. This VIIRS/CrIMSS algorithm will follow the approach used for MODIS. A clear sky regression relationship will be established between total precipitable water vapor (TPW) and VIIRS IR window brightness temperatures (BTs) and CrIMSS water vapor soundings calculated from a global training radiosonde based profile data set. CrIMSS is added in clear and partly cloudy regions to enhance the TPW depiction and to extend the coverage.

Task and Key Milestones for Year 1
- Develop the VIIRS+CrIMSS combined statistical regression algorithm
- Prepare associated ATBD concurrently
- Collect locally the Level-2 CrIMSS water vapor data, VIIRS data, and heritage L3 MOD07, L3 AIRS/AMSU TPW, SSMI along with ground-based CART site MWR TPW and GPS TPW data
- Compare VIIRS/CrIMSS TPW with heritage data

Accomplishments:

1. *Software development*

The methodology proposed to generate S-NPP TPW products is based on the operational MODIS TPW retrieval algorithm, MOD07 (Seemann et al., 2003 and 2008). This statistical regression retrieval algorithm is performed using observed clear sky radiances (brightness temperatures) over land and ocean for both day and night. It consists of several procedures that include *(1) cloud detection, (2) regression coefficient calculation (this includes forward model calculation), and (3) TPW retrieval.* We are

developing our water vapor retrieval algorithm in Fortran using netcdf4 input/output data format following the guidelines offered by the Atmosphere SIPS and the Atmosphere Measurement Team.

For cloud detection, the MVCM (MODIS VIIRS Cloud Mask) is used. The cloud mask files are produced in hdf4 format at the moment but a converter script has been developed to create the netcdf4 format.

The regression coefficient code has been developed. It provides the regression coefficient data (in netcdf4 format) for S-NPP/VIIRS. The forward model calculation is performed by the Version 2.1 of the JCSDA Community Radiative Transfer Model (CRTM, Han et al., 2005) using the Optical Depth in Absorber Space (ODPS) transmittance algorithm.

Development of the *VIIRS/CrIMSS water vapor retrieval algorithm* is underway. Code has been developed to read all the input data, that includes the (SIPS Internal File Format) IFF format of the VIIRS L1B data, the regression coefficients, the Climate Forecast System Reanalysis (CFSR), the cloud mask MVCM data, the CrIS/ATMS retrievals, and the VIIRS/CrIS collocation data. The collocation files between VIIRS and CrIS/ATMS instruments have been developed with the help of Atmosphere SIPS. The latest estimate of VIIRS instrument noises has been applied (Efremova B., et al, 2004). We still need to integrate the CrIS/ATMS TPW values into our regression algorithm. Meanwhile the *VIIRS-only water vapor retrieval algorithm* has been developed and tested for single pixel and 7by7 averaged VIIRS-only TPW retrievals. The spatial resolution of the 7x7 averaged pixel product is equivalent with the MODIS MOD07 5 km (5by5) product.

Collocation between VIIRS/CrIS was successfully converted to collocation between VIIRS/NUCAPS. The following issues came up: (1) many VIIRS pixels are not collocated with NUCAPS because they are not collocated with CrIS, although they are very close to the center of a NUCAPS Field of Regard (FOR); (2) near scan edge, one VIIRS pixel might be collocated with multiple NUCAPS FORs. The last FOR processed is assigned as the collocated one; it would be preferable to collocate with the closest NUCAPS FOR. Figure 1 illustrates these two problems, which we are planning to fix.

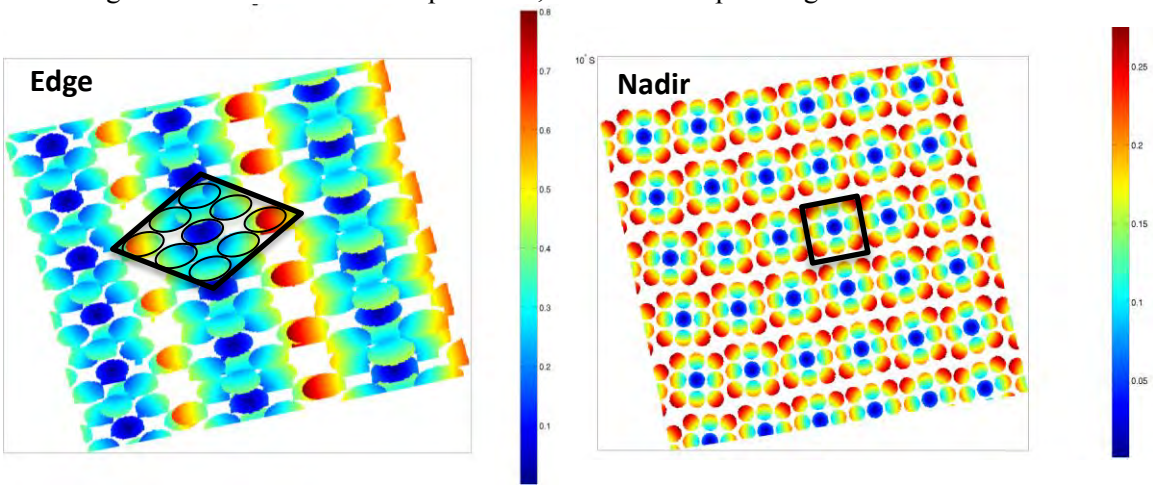

Figure 1: Distance between VIIRS pixels and collocated NUCAPS FOR (deg) at the scan edge (left) and the nadir view (right).

Software delivery to the Atmosphere-SIPS: July 24, 2015, the single and 7x7 average pixel versions of VIIRS-only water vapor algorithm has been delivered to the Atmosphere SIPS.

2. *Data Collection*

To test our algorithm, four days have been selected representing the seasonal changes: Apr 14 2014, Jul 11 2014, Oct 15 2014, and Jan 11 2015**.** These four days were specially chosen to allow maximum overlap between VIIRS and MODIS. The following data has been collected for those four days: VIIRS L1B IFF data, MVCM data, CFSR data, CrIS SDRs, AIRS L2 products, AIRS and CrIS Dual Regression retrievals, NUCAPS retrievals, MOD07 L2 products and the VIIRS-CrIS collocation data from Atmosphere-SIPS.

Figure 2 shows an example TPW comparison for a granule on October 15, 2014 at 08:41 UTC. The TPW data have been derived from the CrIS Dual Regression (top left), the NUCAPS (top right), the CFSR (middle left), the AIRS L2 products (middle right), the Aqua/MODIS TPW (MYD07) (bottom left), the VIIRS-only single pixel (bottom middle) and the VIIRS-only 7by7 averaged TPW product(bottom right). For this granule, the VIIRS split window enables 750 m resolution TPW maps with moderate ability to depict moisture gradients – very wet and very dry conditions are not captured very well. The 7by7 product provides better coverage, although some noise appears over land, which suggests that the VIIRS TPW over land requires careful attention to the surface emissivity, sea/land, BT classification, and clear sky determination. Comparing CrIS DR retrievals to the NUCAPS, the NUCAPS with the help from ATMS has a much better coverage; it shows moisture gradients at 50 km resolution even in the presence of non-precipitating clouds.

a. *CrIS/ATMS*

We proposed to combine VIIRS with CrIMSS moisture Environmental Data Records (EDRs) for generating TPW products that have better quality than the VIIRS or CrIMSS only, in terms of precision/accuracy and spatial resolution. The two available CrIS TPW products are the Dual Regression single FOV CrIS retrievals and the NUCAPS retrievals. While the DR has a better spatial resolution data (single CrIS FOV at 14km), that algorithm provides TPW only over clear or very low cloud scenes. On the other hand the NUCAPS water vapor products are available over clear and most cloudy scenes, but with a much lower spatial resolution (single ATMS FOV at 45km). We have decided to use the NUCAPS TPW for our VIIRS plus TPW products because of its better spatial coverage (see global images on Figure 4).

Figure 3 shows a normalized histogram of MYD07 vs VIIRS (5km) and NUCAPS TPW for the global day in Oct 15, 2014 over water scenes separated by AM and PM. Comparing the VIIRS-only and NUCAPS TPW products to the MYD07 TPW distribution, VIIRS-only product and NUCAPS products appear to be complementary. For example, the VIIRS-only overestimates TPW for both dry scene (smaller than 15 mm) and wet scene (larger than 55 mm) while NUCAPS underestimates. Overall, the VIIRS plus CrIS/ATMS (NUCAPS or the CrIS/ATMS Retrievals if available) show promise for continuing the moisture records established by MODIS. The next step is to include the CrIS/ATMS and its collocation with VIIRS into our retrieval algorithm.

The NESDIS-Unique CrIS-ATMS Product System (NUCAPS) data is only available after August 2014 from NOAA CLASS website; we have been coordinating with the Atmosphere-SIPS group to get the NUCAPS retrievals preprocessed from the beginning of S-NPP launch. As of August 19, 2015, all the NUCAPS data has been processed and is available at the Atmosphere-SIPS site.

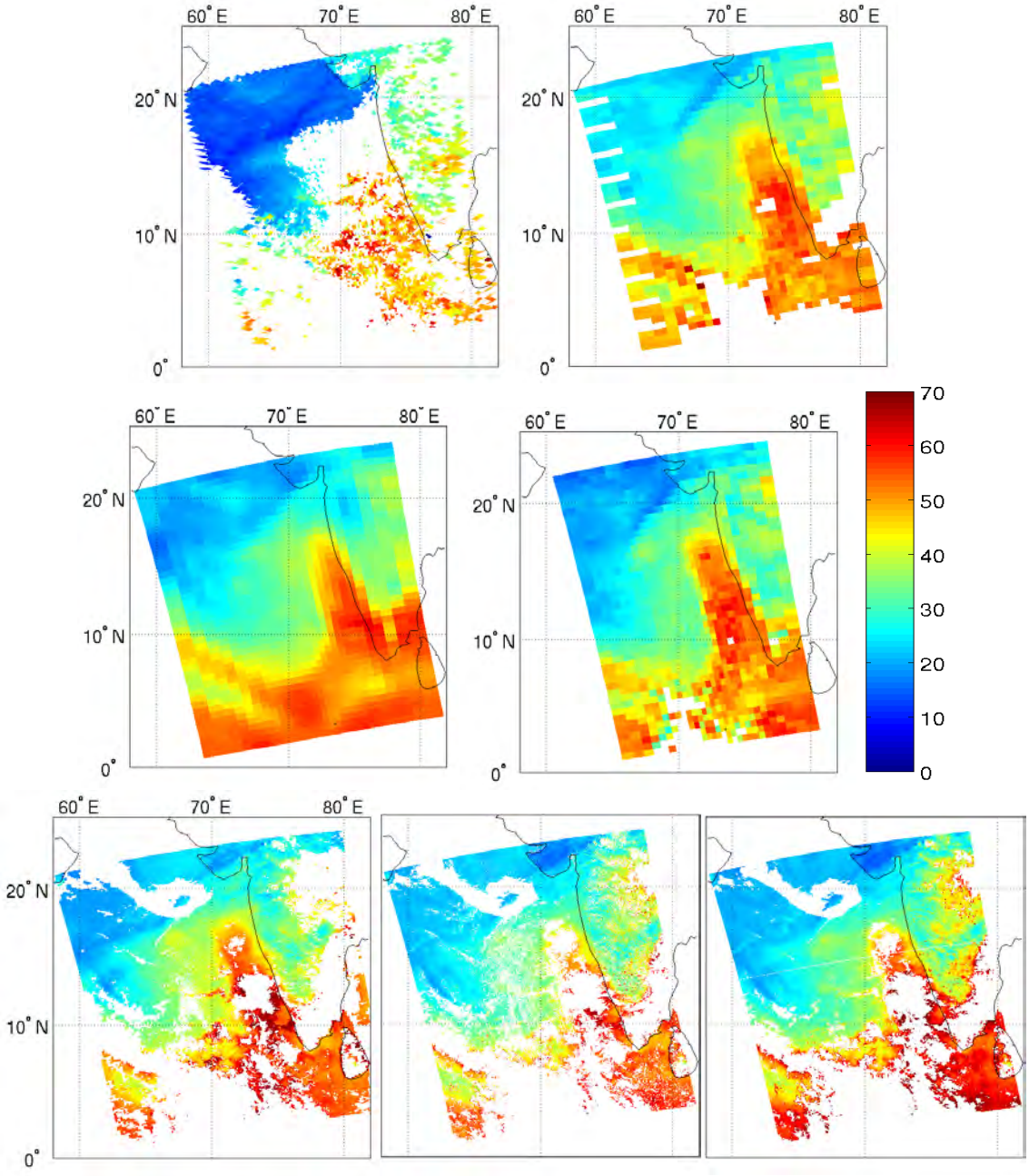

Figure 2: Comparison of the TPW field derived from CrIS Dual Regression (top left), the NUCAPS Retrievals (top right), CFSR data (middle left), the AIRS L2 products (middle right) and Aqua/MODIS TPW (MYD07) (bottom left), the VIIRS-only single pixel (bottom middle) and the VIIRS-only 7by7 averaged TPW product (bottom right). 08:41 UTC on October 15, 2014.

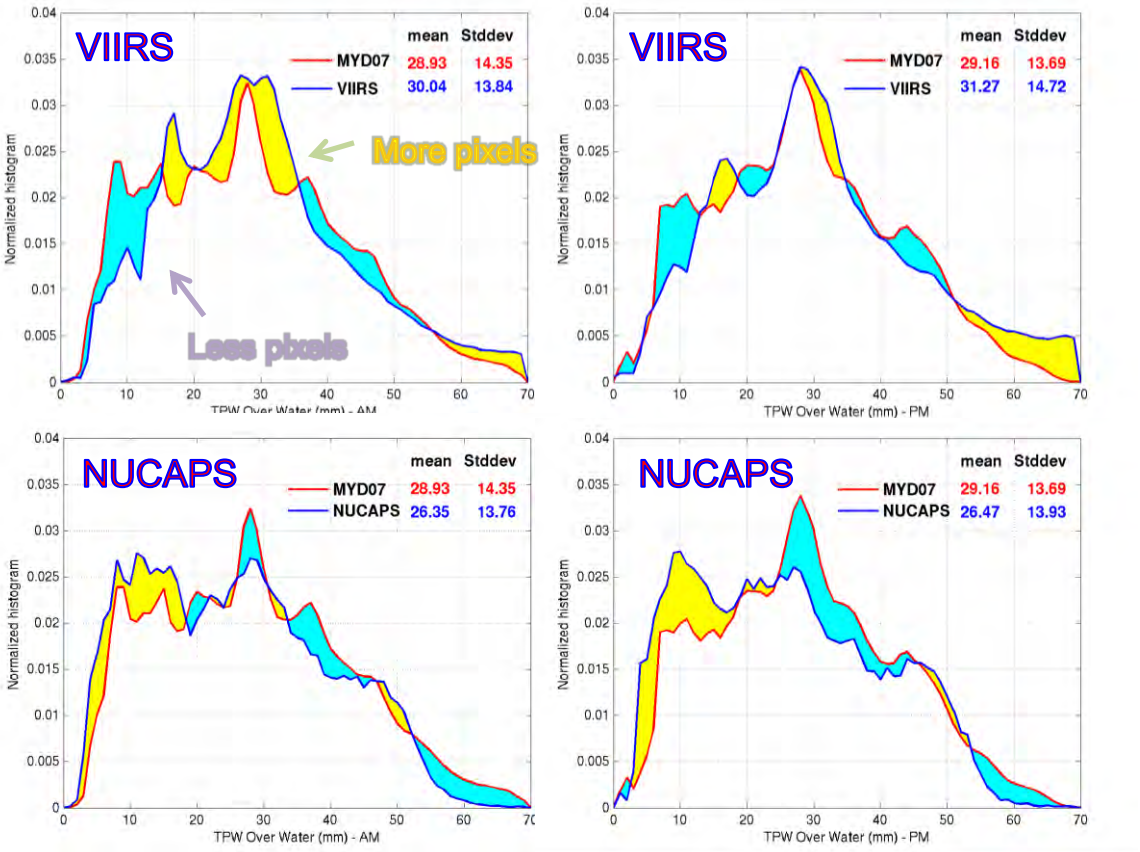

Figure 3: Normalized histogram of MYD07 vs VIIRS (5km) (top panels) and NUCAPS TPW (bottom panels) on Oct 15, 2014 over Water separated by the morning (left panels) and afternoon granules (right panels) .

3. *Evaluation*

The VIIRS TPW product will be evaluated regionally and globally. As was done with the MOD07 TPW products, the VIIRS plus CrIS/ATMS retrievals will be compared regionally to those available from the ARM Cart Sites and the GPS NETWork data. This should provide a good indication of the VIIRS TPW quality. Secondly, the VIIRS plus CrIS/ATMS TPW products will be compared with the MOD07 products, mainly focusing on daily and monthly comparisons. These comparisons will determine if the VIIRS TPW can capture the TPW spatial and temporal variations consistently with MOD07. Global evaluation will also include other retrievals from other satellite instruments such as Aqua/AIRS and the Special Sensor Microwave/Imager (SSM/I) and CrIMSS.

a. *Global comparison*

Figure 4 shows a global comparison of the TPW fields for Oct 15, 2014. TPW values have been derived by the VIIRS only single and 7x7 averaged pixel FOVs version algorithm, the MODIS MYD07, the CrIS Dual-Regression, and the NUCAPS retrieval algorithms. As noted earlier, over land the VIIRS-only retrievals require careful attention to the surface emissivity, sea/land, BT classification, and clear determination. We can also see that NUCAPS shows moisture gradients at 50 km resolution even in the presence of non-precipitating clouds, which gives a promise that the VIIRS plus NUCAPS combination will be able to continue the moisture records established by HIRS and MODIS.

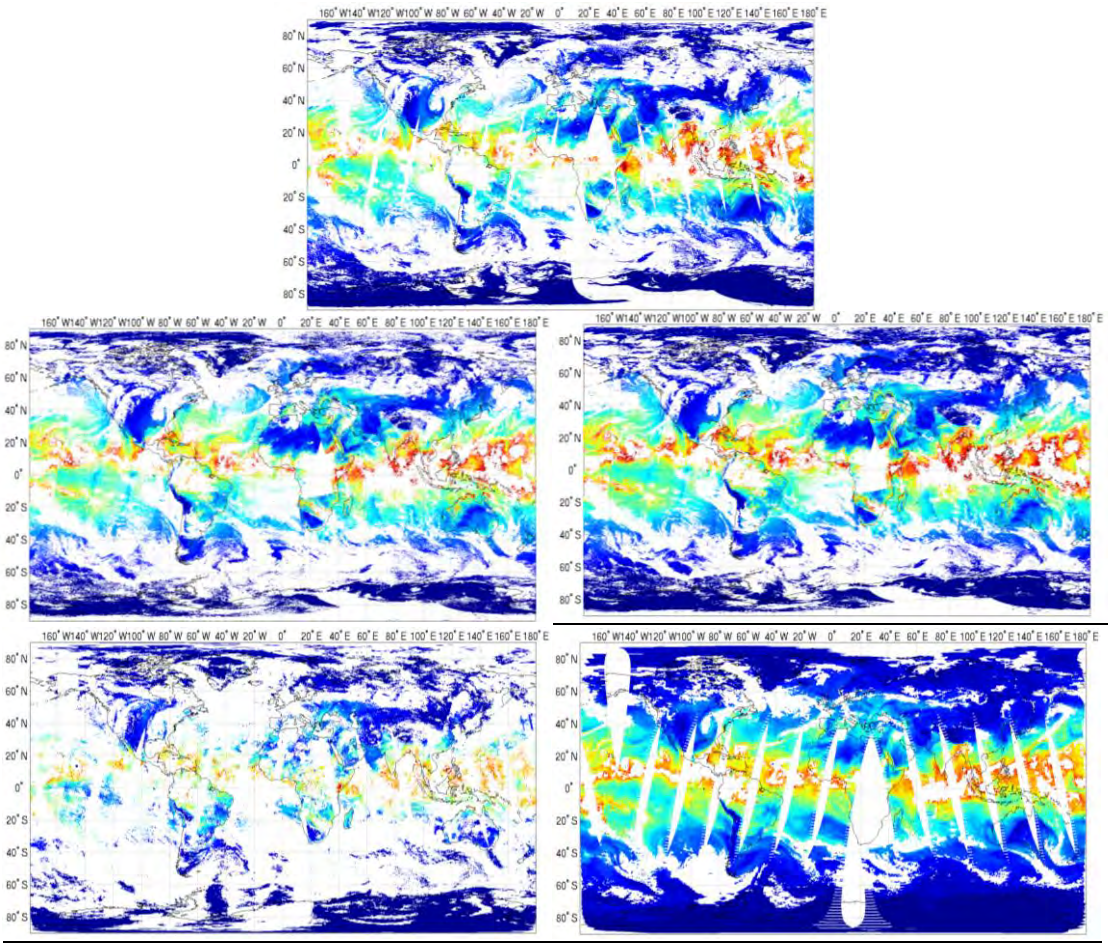

Figure 4: Comparison of TWP fields derived from MOD07 (top), single pixel (middle row, left) and 7x7 averaged pixel (middle row, right) version of VIIRS-only retrievals, the CrIS-only Dual Regression (bottom left) and NUCAPS CrIS+ATMS retrievals (bottom right) for Oct 15, 2014 AM.

b. <u>Regional comparison at the ARM Cart Sites</u>

To evaluate VIIRS TPW products over the ARM CART Sites, the following data has been collected from 2012 January to the present:

- Microwave Radiometer (MWR) TPW
- Radiosonde data
- GPS TPW
- SSMI
- AIRS Level2 TPW
- Aqua/MODIS MYD07
- Data from the Suomi GPS Network

Considerable progress has been made in developing evaluation strategies, collecting the TPW data from various sources, and preparing comparison visualizations. VIIRS or MODIS retrievals are collected and averaged within the 20 km radius of the evaluation sites (ARM CART or Suomi Net) and 80 % of the

pixels are required to be clear. These two thresholds are determined explicitly. The MWR data are averaged for five minutes matching the VIIRS or MODIS granule time. Figure 5 illustrates the collocated TPW data at the SGP cart site since the launch of S-NPP.

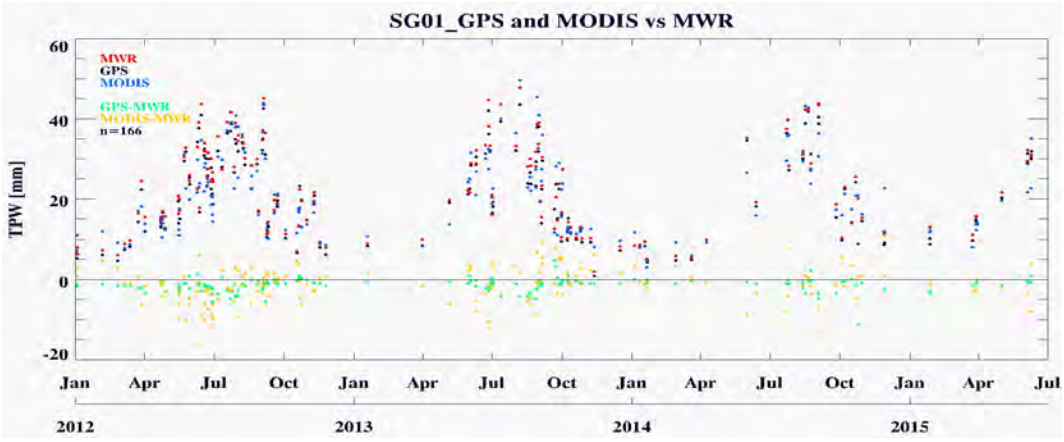

Figure 5: Time series of the collocated MYD07 (blue), MWR (red), and GPS (black) derived TPW over the SGP cart site since Jan 2012, as well as the difference compared with MWR (green for GPS and orange for MYD07). VIIRS TPW will be added soon.

Table 1: Summary of results when using different criteria of collocation radius and clear percentage for evaluating VIIRS-only TPW with MWR TPW data over the SGP and TWP Cart sites on Oct 15, 2014.

site	date	time	VIIRS_ spatavg	VIIRS_ std	numpix	Radius (km)	Clear Needed (%)	clear%	land%	clearland %	MWR	MWR_ num	MWR_ std	VIIRS-MWR
SGP_C1	20141015	920	9.995	0.406	130	5	70.00	96.30	100.00	96.30	9.832	11	0.105	0.164
SGP_C1	20141015	920	10.001	0.368	448	10	70.00	94.72	100.00	94.72	9.832	11	0.105	0.169
SGP_C1	20141015	920	9.963	0.401	1859	20	50.00	96.32	100.00	96.32	9.832	11	0.105	0.132
SGP_C1	20141015	920	9.963	0.401	1859	20	70.00	96.32	100.00	96.32	9.832	11	0.105	0.132
SGP_C1	20141015	1900	16.645	0.657	90	5	70.00	100.00	100.00	100.00	11.02	11	0.119	5.625
SGP_C1	20141015	1900	16.78	0.584	381	10	70.00	100.00	100.00	100.00	11.02	11	0.119	5.76
SGP_C1	20141015	1900	16.791	0.579	1490	20	50.00	100.00	100.00	100.00	11.02	11	0.119	5.771
SGP_C1	20141015	1900	16.791	0.579	1490	20	70.00	100.00	100.00	100.00	11.02	11	0.119	5.771
TWP_C3	20141015	1620	38.899	2.306	138	5	70.00	100.00	67.39	67.39	43.762	11	0.157	-4.863
TWP_C3	20141015	1620	40.839	4.675	513	10	70.00	99.81	42.41	42.41	43.762	11	0.157	-2.923
TWP_C3	20141015	1620	42.493	5.093	2011	20	50.00	97.62	34.56	34.22	43.762	11	0.157	-1.268
TWP_C3	20141015	1620	42.493	5.093	2011	20	70.00	97.62	34.56	34.22	43.762	11	0.157	-1.268

An example of a very good match between the VIIRS-only and MWR TPW data over the SGP Cart Site at Oct 15, 2014, 9:20 UTC is shown in Figure 6. The difference between VIIRS and MWR is 0.13 mm (~1.3%) for a measurement of ~9.8 mm. Figure 7 shows another example from Oct 15, 2014 in the evening when a weather front is going through the area; the VIIRS-only retrievals are not capturing the

TPW values very well. The difference of VIIRS-only and MWR TPW is 5.8 mm which is about half of the MWR-measured value of 11 mm. Figure 8 shows an example over the Tropical Western Pacific Cart Site, where the humidity is high. The difference is -1.27 mm for the 43.7 mm TPW, resulting in a 3 % bias.

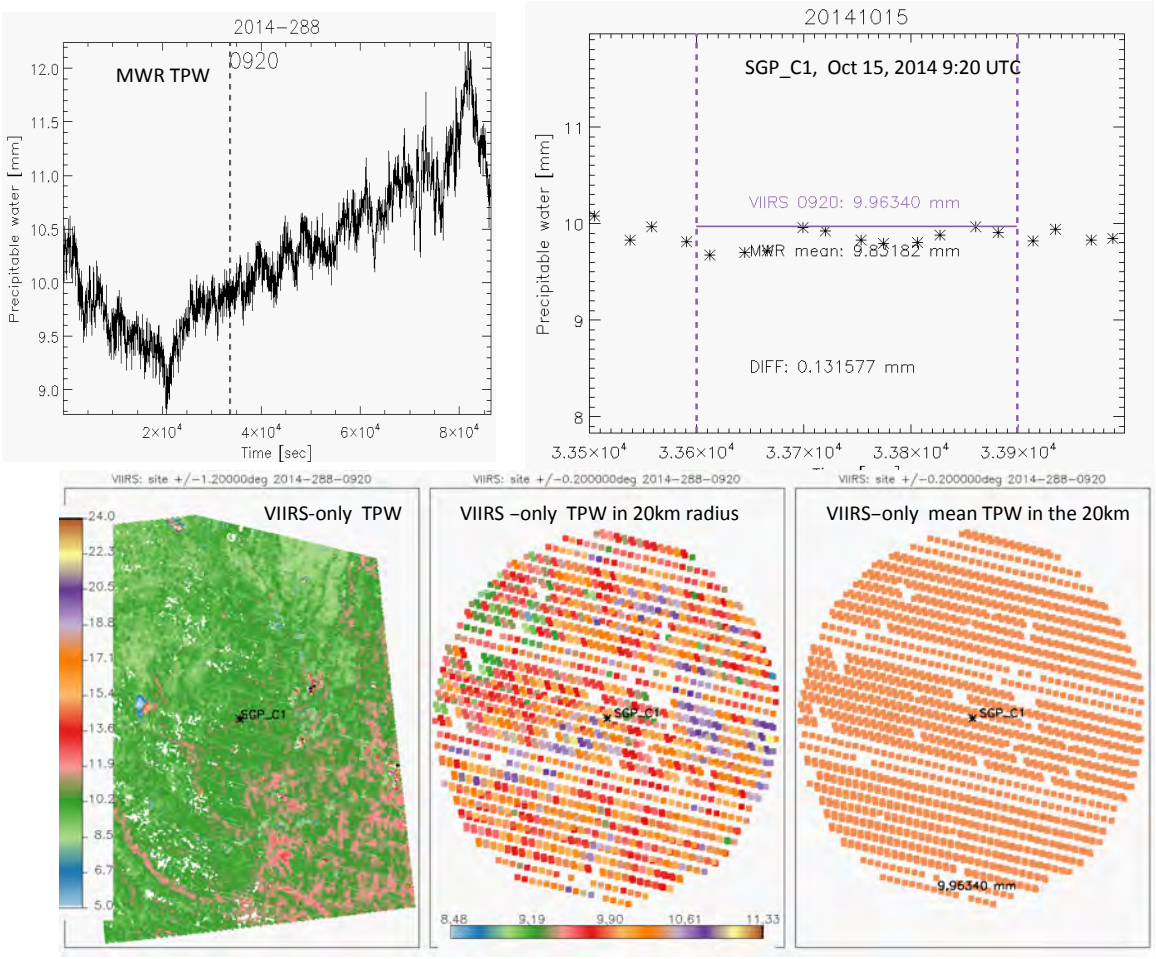

Figure 6: Comparison of VIIRS-only TPW with the MWR TPW over the SGP Cart site on Oct 15, 2014, 09:20 UTC. (Top left) MWR TPW time series for the day. (Top right) subset of the time series at the time of the SNPP VIIRS overpass. (Bottom left) VIIRS-only TPW over the CART site. (Bottom middle) VIIRS-only TPW over the 20 km radius of the CART site. (Bottom right) Average of VIIRS-only TPW retrievals over the 20 km radius.

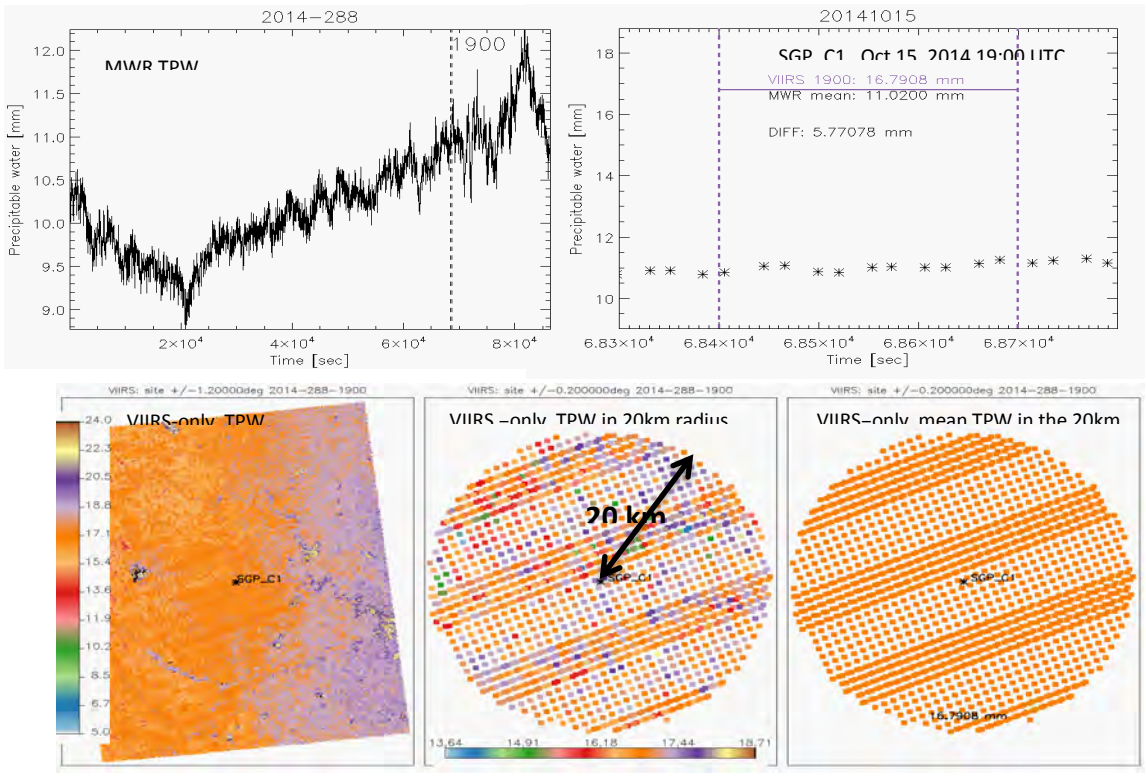

Figure 7: Same as Figure 6, but for Oct 15, 2014, **19:00** UTC.

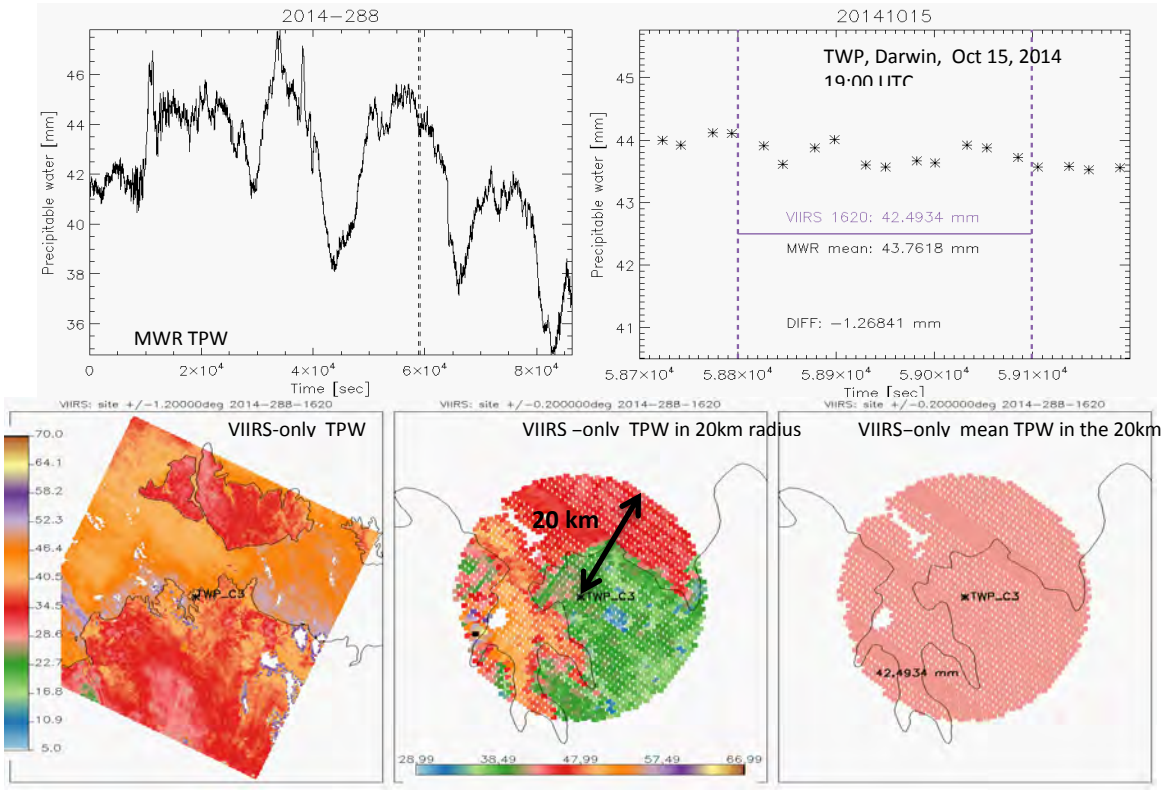

Figure 8: Same as Figure 6, but over the TWP Darwin Cart site on Oct 15, 2014, 16:20 UTC.

Scatterplots of TPW data from Aqua/MODIS MYD07 (Figure 9) and the AIRS L2 Official Retrievals (Figure 10) are plotted versus the MWR measurements over the three ARM cart sites for Jan 1 2012 through July 2015. The VIIRS-only and VIIRS plus CrIS/ATMS TPW values will be added when available.

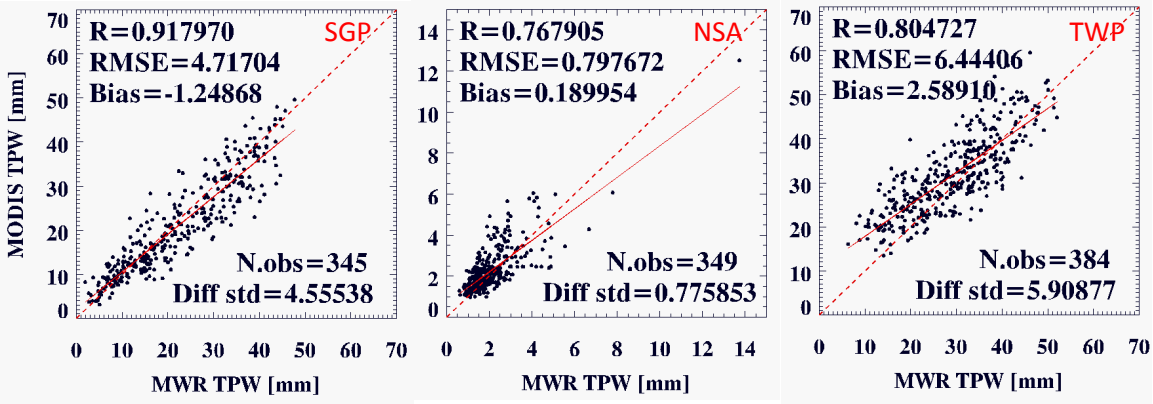

Figure 9: Scatterplots of TPW from **MODIS MYD07** (Y-axis) and MWR (X-axis) at three different CART sites - Northern Slope Alaska (NSA, left), Southern Great Plains (SGP, middle), and Tropical Western Pacific (TWP, right) - along with bias, root mean square differences (rmse), standard deviation of the differences (std) and correlation (R) from Jan 2012 to Jul 2015.

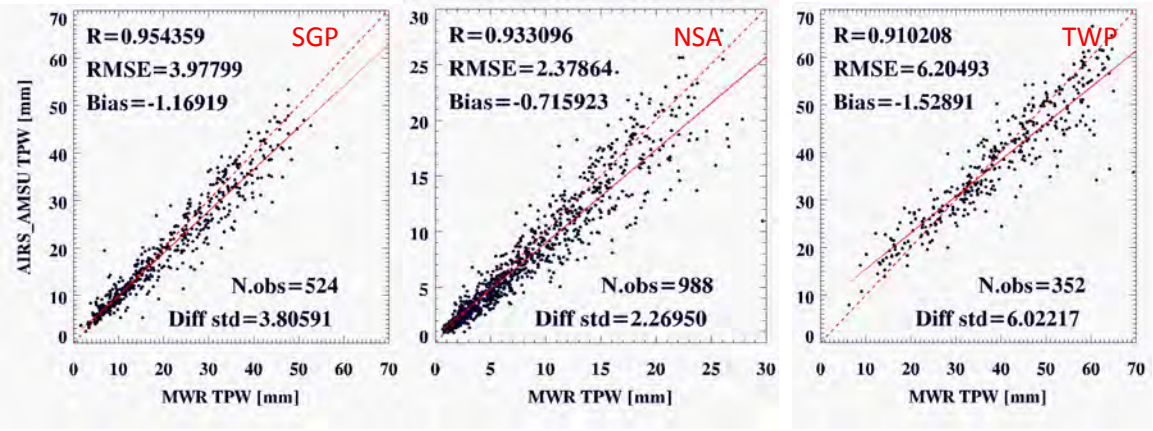

Figure 10: Same as Figure 9, but for TPW from **AIRS+AMSU** L2 products in Y-axis.

Regional comparison at GPS networks

The GPS derived TPW is collected from 401 selected GPS stations (Figure 11). The MYD07 TPW has been collocated to the GPS sites by following the same strategy developed for the ARM cart site study, after additional quality control of the GPS data.

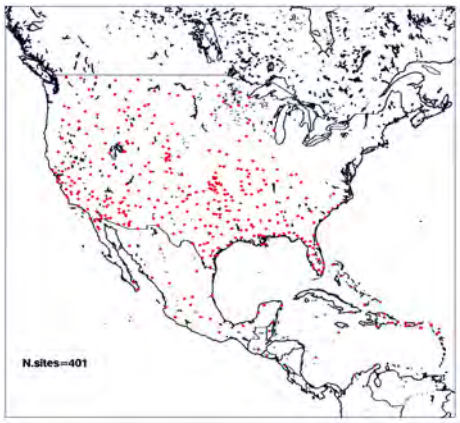

Figure 11: Location of the 401 GPS stations (red) selected for evaluation the VIIRS moisture products.

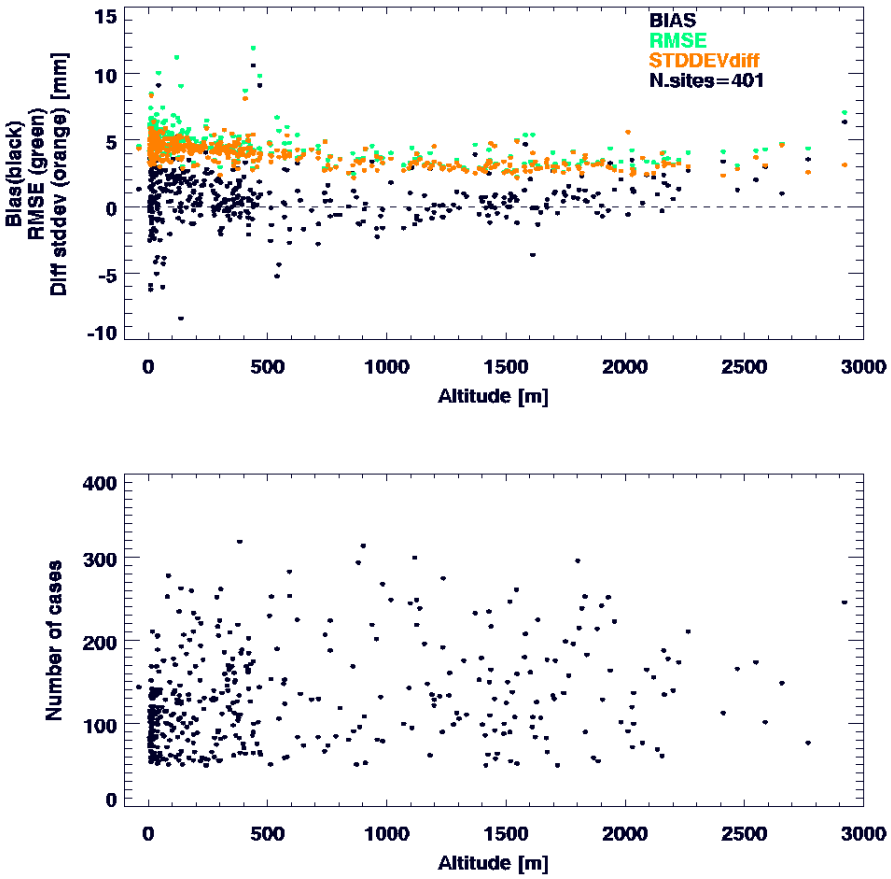

Figure 12: (Top) Bias (black), standard deviation (orange), and root mean square differences (green) of TPW derived from MODIS MYD07 and the GPS network for each of the 401 GPS station locations as a function of the site altitude are shown for Jan 2012 through Jul 2015. (bottom) The number of collocated pairs for each GPS stations as function of the elevation.

The 401 selected GPS stations are located on different elevations providing the opportunity to investigate the accuracy of the TPW retrievals as a function of elevation. The top panel of Figure 12 shows the bias, stdev, and rms differences for each station as a function of the elevation, while the bottom panel gives the

number of collocated pairs for each station. The number of pairs is evenly distributed over the altitude range. The bias, stdev, and rms differences between the MYD07 and the GPS TPW are the largest with the largest variation close to sea level. The smallest bias, stdev and rms differences occur for the stations located between 1000 and 2000m. Above 2000m the bias increases implying that the MYD07 TPWs are wetter. The variation (stdev) is not changing obviously.

The VIIRS-only and VIIRS plus NUCAPS retrievals will be added to the regional evaluation studies when they become available at the Atmosphere-SIPS. The VIIRS-only algorithm has been delivered to the SIPS in July 2015.

Next steps (including Year 2 milestones):

In the coming year we plan to

- Finish the development of the VIIRS+NUCAPS combined algorithm (remaining task for the last two months of year 1)
- Apply STG software to build the global daily, and monthly VIIRS/CrIMSS L3 gridded TPW products
- Compare VIIRS/CrIMSS TPW L3 global products to MOD07 L3, SSMI, and conventional RAOB data
- Continue comparison of VIIRS/CrIMSS TPW L2 products to ground-based GPS network TPW and TPW derived from MWR, RAOB and GPS over the SGP cart site
- Finalize ATBDs and document the findings in Year 2 via relevant conference presentations and peer-reviewed publications,
- Prepare software and documentation for the next transfer to the NASA-Atmosphere SIPS.

Publications/Travel

Eva Borbas participated at the MODIS - VIIRS Science Team Meeting on May 18-22, 2015 in Silver Spring, MD. She gave a talk in the plenary session with the title: MODIS Clear-sky Infrared Total Precipitable Water Vapor Products and its' continuity with VIIRS and CrIS.
http://modis.gsfc.nasa.gov/sci_team/meetings/201505/presentations/plenary/borbas.pdf

The VIIRS_TPW ATBD is under preparation.
A paper is planned for late 2016.

References

Han, Y., P. Delst, Q. Liu, F. weng, B. Yan, and J. Derber, 2005: User's Guide to the JCSDA Community Radiative Transfer Model (Beta Version) http://www.star.nesdis.noaa.gov/smcd/spb/CRTM/crtm-code/CRTM_UserGuide-beta.pdf.

Seemann, S. W., J. Li, W. P. Menzel, and L. E. Gumley, 2003. Operational retrieval of atmospheric temperature, moisture, and ozone from MODIS infrared radiances. *J. Appl. Meteor.,* 42, 1072-1091.

____, Borbas, E.E., Knuteson, R.O., Stephenson, G.R., and Huang, H-L., 2008: Development of a global infrared emissivity database for application to clear sky sounding retrievals from multi-spectral satellite radiances measurements. *J. Appl. Meteorol. and Clim*., 47, 108-123.

Efremova B., et al: S-NPP VIIRS Thermal Emissive Bands; Performance and Calibration Improvements, Slide 11. http://www.star.nesdis.noaa.gov/jpss/documents/meetings/2014/SJASTM/Session4a_Tues.pdf

6. Year 2 Progress report

NNX15AB95A: S-NPP IR TPW from a combination of VIIRS and CrIMSS
Annual Progress Report – Year 2

Project Title: "Continuation of EOS Clear Sky Infrared Total Precipitable Water Vapor Product Using a Combination of VIIRS and CrIMSS Measurements"
Principal Investigator: Dr. Eva Borbas
Co-Investigator: Dr. W Paul Menzel and Dr. Zhenglong Li
Date: Nov 05 2015 – Nov 04 2016 (effective August 5 2015 – August 4 2016)
Institution: UW-Madison, Space Science and Engineering Center, 1226 W Dayton Str, Madison, WI 53706

Date: Nov 05 2015 – Nov 04 2016

Objectives
We proposed to provide total column water vapor properties from merged VIIRS infrared measurements and CrIMSS (CrIS plus ATMS) water vapor soundings to continue the depiction of global moisture at high spatial resolution started with MODIS. While MODIS has two channels within the 6.5-μm H_2O band and four channels within the 15-μm CO_2 band, VIIRS has no infrared (IR) absorption channels. However, the VIIRS IR windows at 8.6, 10.8 and 12 μm give some indication of low level moisture (which constitutes much of the total column amount) and we proposed to complement this with CrIMSS column moisture determinations. This VIIRS/CrIMSS algorithm follows the approach used for MODIS. A clear sky regression relationship has been established between total precipitable water vapor (TPW) and VIIRS IR window brightness temperatures (BTs) and CrIMSS water vapor soundings calculated from a global training radiosonde based profile data set. CrIMSS is added in clear and partly cloudy regions to enhance the TPW depiction and to extend the coverage.

Tasks and Key Milestones for Year 2

- Finish the development of the VIIRS+NUCAPS combined algorithm
- *Update the VIIRS+NUCAPS combined algorithm to use the 6-min input file formats (VIIRS IFF, MVCM Cloud mask and collocation files) instead of the current version which uses the 5-min granule formats*– ***unplanned new task***
- Transfer the new, updated VIIRS+NUCAPS combined algorithm to SIPS
- Apply STG software to build the global daily, and monthly VIIRS/CrIMSS L3 gridded TPW products
- Compare VIIRS/CrIMSS TPW L3 global products to MOD07 L3, SSMI, and conventional RAOB data
- Continue comparison of VIIRS/CrIMSS TPW L2 products to ground-based GPS network TPW and TPW derived from MWR, RAOB and GPS over the SGP cart site
- Finalize ATBDs and document the findings in Year 2 via relevant conference presentations and peer-reviewed publications,
- Prepare software and documentation for the next transfer to the NASA-Atmosphere SIPS

Accomplishments:

In the past year we

- Finalized the development of the VIIRS+NUCAPS combined algorithm by
    - adding NUCAPS (CrIS+ATMS) TPW to the product *****
    - filling the gaps between the collocation index files
    - smoothing the combined VIIRS+NUCAPS products to reduce the blockiness*****
    - filling the remaining holes in the VIIRS+NUCAPS TPW field with adjusted VIIRS only or adjusted NUCAPS only TPWs (after linear fitting) *****
- Updated the VIIRS+NUCAPS combined algorithm to use the 6-min input file formats (VIIRS IFF, MVCM Cloud mask and collocation files) instead of the previous 5-min granule formats– *this was an unplanned new task* *****
    - It required development of new collocation index files and a new collocation method by the NASA-Atmospheric SIPS
    - NUCAPS is now ingested from CLASS (only available CrIMSS product at the moment)
- Validated VIIRS/CrIMSS TPW L2 products to ground-based TPW derived from MWR over the SGP cart site*****
- Assisted the NASA-Atmosphere SIPS as a Jira beta user
- Transferred the new updated VIIRS+NUCAPS combined algorithm onto the SIPS using Jira
    - The 6-min version of the VIIRS-NUCAPS TPW algorithm has been delivered to the SIPS-Atmosphere team in May 2016.
- Prepared software and documentation for the next transfer to the NASA-Atmosphere SIPS
- Provided data to the Science Community:
    - The UW team provided sample products with a Fortran reader to the SNPP VIIRS team lead by Bo-Cai Gao for the VIIRS cirrus reflectance algorithm development.

**See below for more details*

Software Development

Earlier this year the NUCAPS TPW was added to the VIIRS-only single pixel and 7x7 aggregated pixel resolution retrieval algorithm in order to conform with the 5-min VIIRS IFF granule sizes. The Atmosphere-SIPS group preprocessed NUCAPS retrievals for the whole time period using the CSPP software. They also developed and provided the collocation files between the NUCAPS and VIIRS pixels (NUCAPS to VIIRS through CRIS collocation). Figures 1 and 2 show two granules as examples: the VIIRS-only, the NUCAPS and their combined VIIRS+NUCAPS TPW retrievals are shown for October 15, 2012 at 09:20 (Fig 1) and 19:00 UTC (Fig 2). It is evident that the NUCAPS TPW retrievals are helping to reduce the big wet bias over the SGP Cart site especially at the 19:00 UTC time case. Figure 3 shows the SGP Cart site area enlarged. The remaining issue was to reduce/smooth the image blockiness related to the large NUCAPS (45km) footprint.

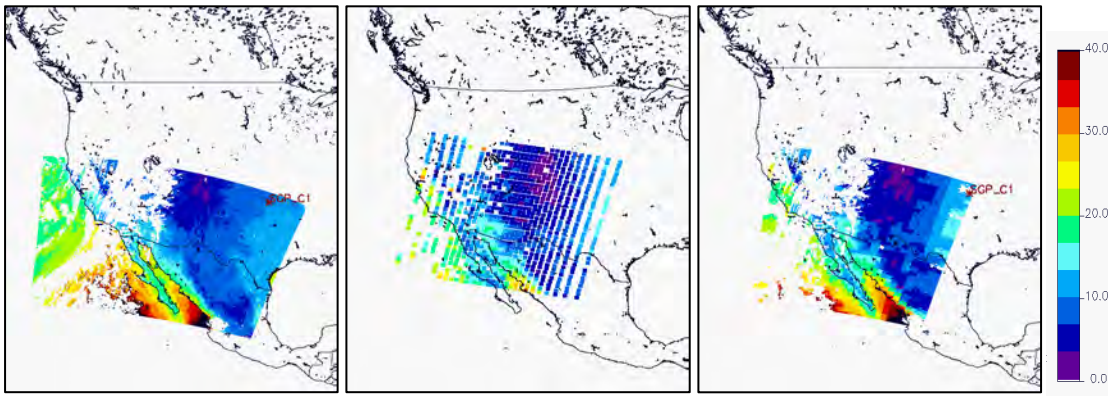

Figure 1: TPW retrievals on 15 October 2012 at 09:20 UTC time produced by the VIIRS-only (left), the NUCAPS (middle) and their combined: VIIRS+NUCAPS (right) algorithm.

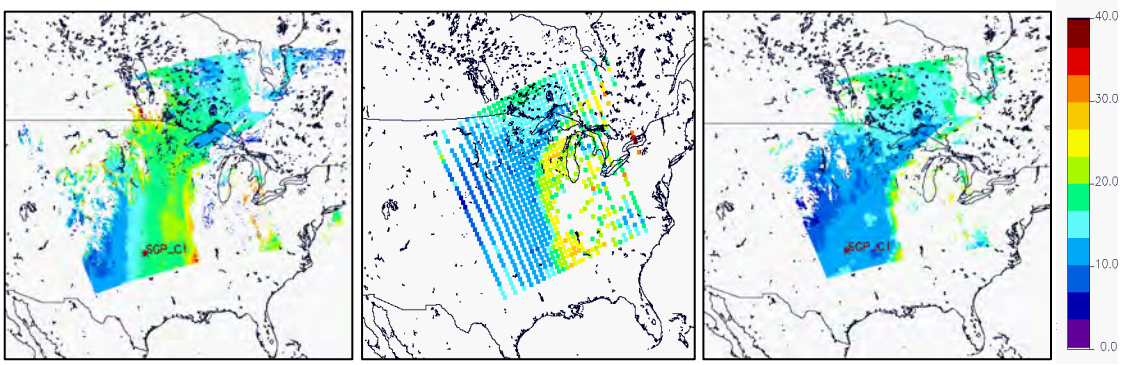

Figure 2: TPW retrievals on 15 October 2012 at 19:00 UTC time produced by the VIIRS-only (left), the NUCAPS (middle) and their combined: VIIRS+NUCAPS (right) algorithm.

Further development included software to fill the gap between the collocation index files (see Figure 1-3) and to smooth the combined VIIRS+NUCAPS products. The smoothing was performed for each VIIRS pixel. Different sets of smoothing radii were investigated (45, 60, 75 and 90 VIIRS pixels) with a weighted (based on distance) average to smooth out the discontinuities. A radius of 60 pixels was found to be optimal for keeping a good balance between smoothing and maintaining moisture gradients. Figure 4 shows an example granule.

Updated the VIIRS+NUCAPS combined algorithm to use the 6-min input file formats

Our VIIRS+NUCAPS TPW algorithm has been updated to accommodate the 6-min VIIRS IFF and MVCM cloud mask data. This transition required a new collocation between the 6-min VIIRS data and the 32-sec NUCAPS products. SIPS-Atmosphere team developed and provided the necessary input 6-min VIIRS- 32-sec CrIS collocation data.

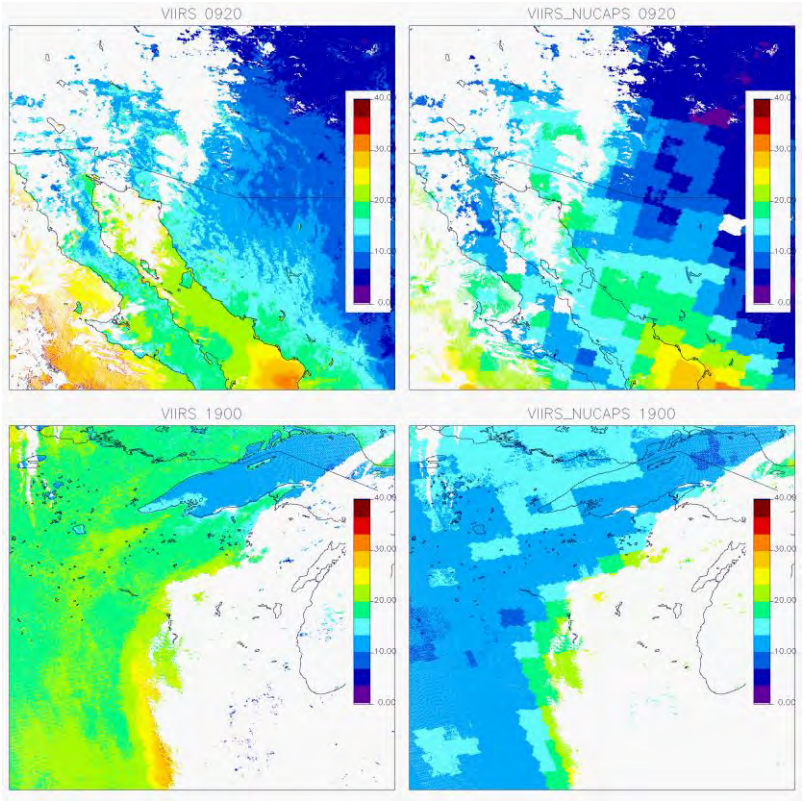

Figure 3: The enlarged center of the images for the two cases showed on Figure 1 and 2. VIIRS-only TPW images are on the left side, VIIRS+NUCAPS are on the right side for 15 October 2014 at 09:20 UTC time (top panels) and at 19:00 UTC time (bottom panels).

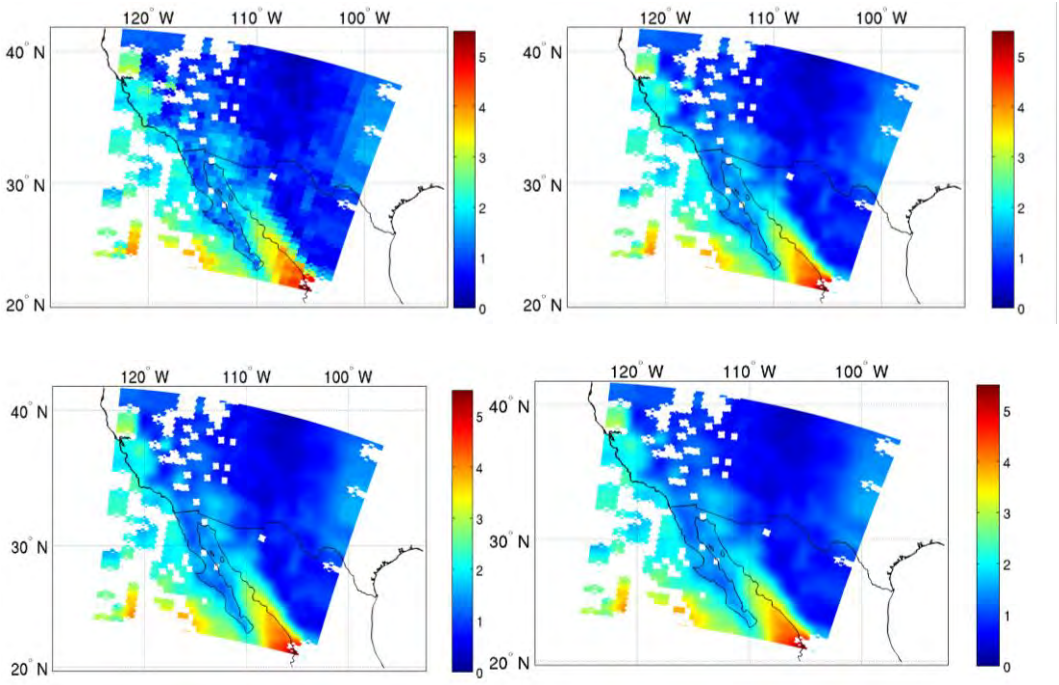

Figure 4: 6-min VIIRS+NUCPAS TPW products for Oct 15, 2014 at 09:20 UTC. Top left: original, without any smoothing. Top right: smoothing applied using 45 pixels radius. Bottom left: 60 pixels radius. Bottom right: 75 pixels radius.

VIIRS+NUCAPS combined algorithm finalized

The final version of the TPW product has been achieved (see Figure 5). As indicated, a clear sky regression relationship is established between TPW and VIIRS IRW BTs (in 8.6, 10.8, and 12 μm) and NUCAPS water vapor soundings calculated from a global training radiosonde based profile data set. The VIIRS cloud mask is used to indicate cloudy VIIRS FOVs. The NUCAPS retrievals are smoothed using a radius of 60 VIIRS pixels. The VIIRS+NUCAPS TPW is generated in clear skies when NUCAPS has determined a TPW (holes exist when surface emissivity or other issues interfere with a NUCAPS retrieval). The remaining holes in the VIIRS+NUCAPS TPW field are filled with adjusted VIIRS only or adjusted NUCAPS only TPWs. The adjustment process for the given 6 minute granule consists of constructing a linear fit of the VIIRS+NUCAPS TPW against collocated the VIIRS only TPW; another linear fit is determined for the VIIRS+NUCAPS TPW against collocated NUCAPS only TPW. The appropriate linear fit is then used to scale the VIIRS only TPW and the NUCAPS only TPW to fill holes where possible. The resulting TPW field shows more detail than VIIRS only, NUCAPS only, and MODIS only. The NUCAPS only holes due to surface emissivity issues are filled by using VIIRS only values and holes in VIIRS and MODIS only due to interference in non-precipitating clouds are filled by using smoothed NUCAPS values.

Validated the VIIRS+CrIMMS Moisture Product

As a routine, the new VIIRS+NUCAPS combined products have been evaluated with the MWR derived TPW over the SGP Cart site and with the GPS-based TPW over the United States GPS Network. Figure 6 illustrates the scatter plots of the VIIRS+NUCAPS TPW vs MWR and its comparison through similar scatter plots of the MODIS MYD07, VIIRS-like MODIS, the NUCAPS and VIIRS-only retrievals. As it is expected, the VIIRS-only TPW products have similar quality as the simulated VIIRS-like MODIS product. When the NUCAPS TPW is added to the VIIRS-only retrievals, the bias and standard deviation and hence the RMS difference of the VIIRS+NUCPAS products has been reduced. The statistical characteristics of the new products became similar to the MODIS MYD07 TPW products. Table 1 summarizes all the statistical results between the available TPW retrievals and MWR TPW over the SGP Cart site and GPS-derived TPW over the United States. The statistical results of the VIIRS+NUCAPS TPW comparison with the GPS-derived TPW will be added and the whole validation will be updated with the 6-min VIIRS+NUCAPS latest products when the whole record will be processed by the SIPS later of 2016.

Next steps (including Year 2 milestones):

- Continue to work on the STG software to build the global daily and monthly VIIRS/CrIMSS L3 gridded TPW products;
- Continue to compare VIIRS/CrIMSS TPW L3 global products to MOD07 L3, SSMI, and conventional RAOB data;
- Continue to compare VIIRS/CrIMSS TPW L2 products with ground-based GPS network TPW and TPW derived from MWR, RAOB and GPS over the SGP cart site;
- Finalize ATBD and document the findings relevant conference presentations and peer-reviewed publications.

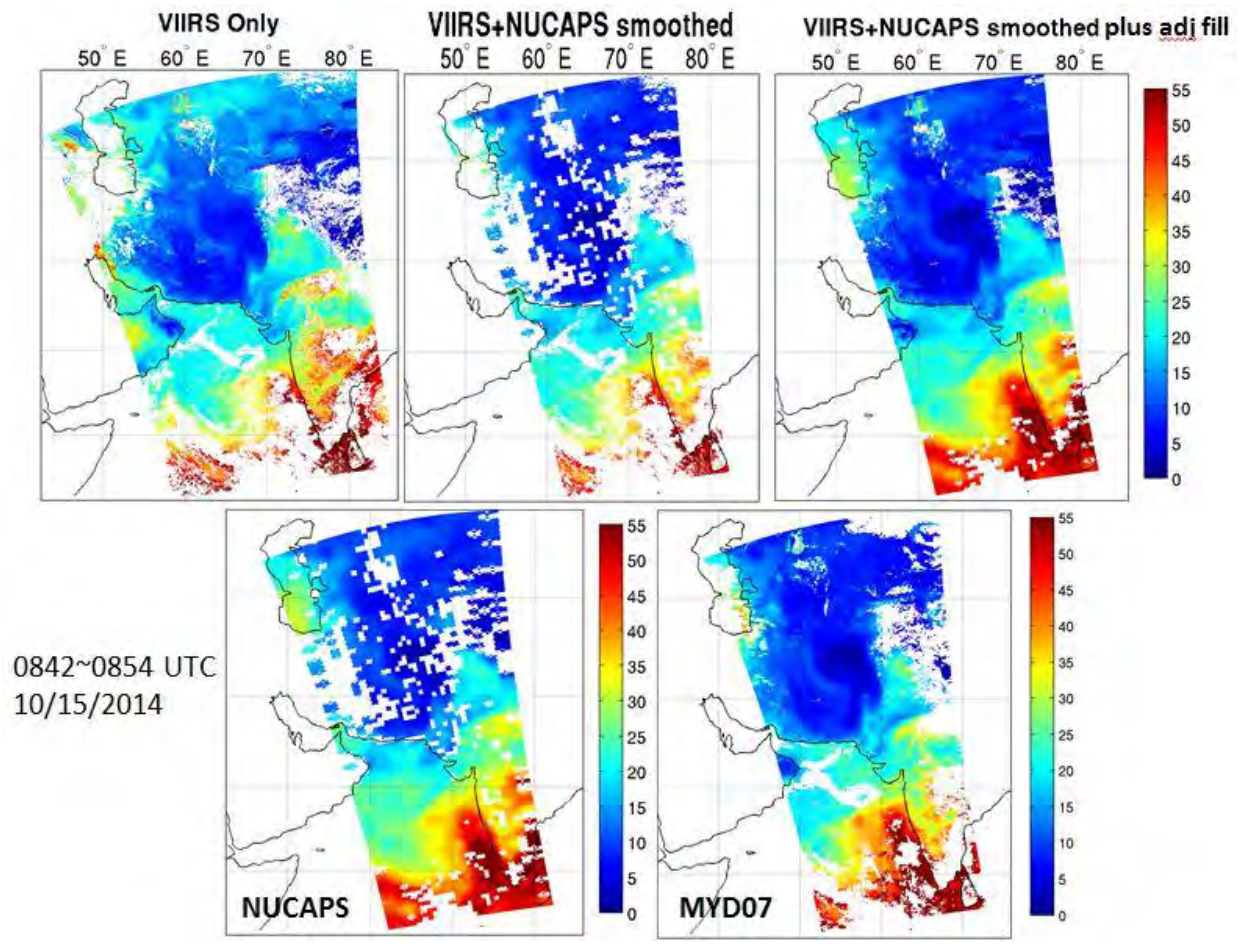

Figure 5: TPW comparison for 15 October 2015 at ~850 UTC. (top left) VIIRS only. (top middle) VIIRS plus NUCAPS with holes. (top right) VIIRS plus NUCAPS with holes filled by adjusted VIIRS only or smoothed NUCAPS only values. (bottom left) NUCAPS only. (bottom right) Aqua MODIS. Notice the better coverage and improved values of VIIRS plus NUCAPS with holes filled over VIIRS only, NUCAPS only, and even MODIS only.

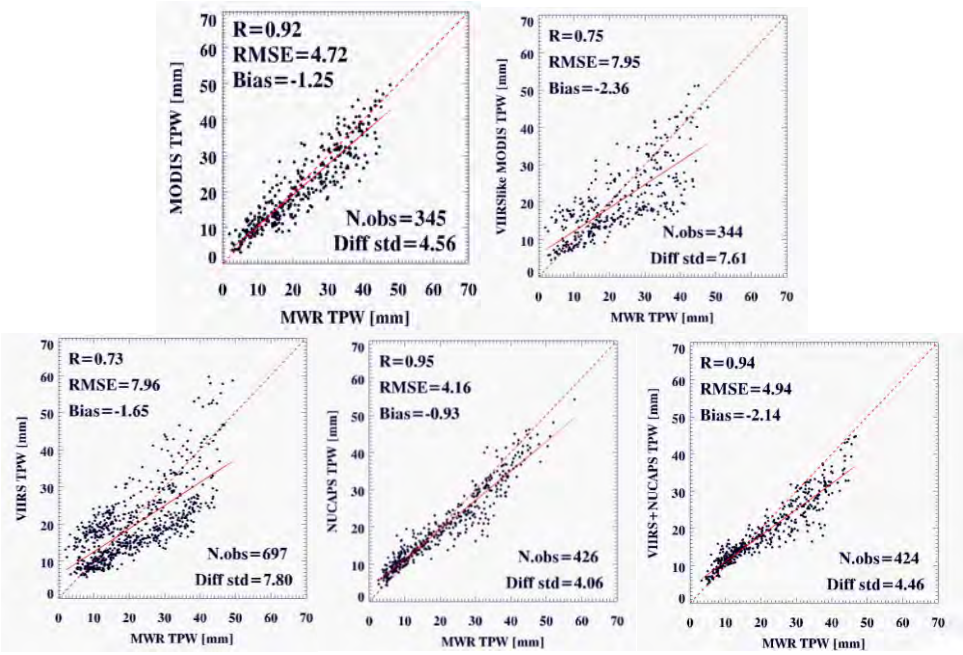

Figure 6: Scatterplots of TPW from MYD07 (top left), VIIRS-like MODIS (top right), VIIRS-only (bottom left), NUCAPS (bottom middle) and VIIRS+NUCAPS combined TPW vs. the MWR derived TPW at the SGP CART sites - along with bias, root mean square differences (rmse), standard deviation (Diff std), and number of observations for the time period between Jan 2012 and Jul 2015.

FINAL STATS	MODIS 5km		VIIRS 750m		NUCAPS 45km		VIIRS+ NUCAPS
	SGP MWR	GPS	SGP MWR	GPS	SGP MWR	GPS	SGP MWR
# of obs.	345	63 565	697	169 927	426	66 705	424
Bias	-1.25	0.89	-1.65	0.99	-0.93	-0.28	-2.14
RMSE	4.72	4.63	7.96	6.86	4.16	4.33	4.94
Std.dev	4.56	4.17	7.8	6.51	4.06	4.16	4.46

Table 1: Statistical comparison of TPW derived from MODIS, VIIRS-only, NUCAPS and the combined VIIRS+NUCAPS retrievals. Bias, standard deviation, root mean square differences are calculated between the TPW retrievals and MWR TPW over the SGP Cart site, and between the TPW retrievals and the GPS sites over the United States.

Publications/Presentations

Dobor et al., 2015: Evaluation of theVIIRS TPW algorithm with ground based measurements (poster) ***20th International TOVS Study Conference*, Lake Geneva, WI, USA, Oct 28-Nov 3, 2015.**

Menzel et al., 2015: VIIRS plus CrIMSS TPW – continuing the record of high spatial resolution moisture determinations (poster). *AGU Fall Meeting, Session: A21C: Earth System Change from Space: Early Results on EOS to Suomi NPP Data Continuity Products II.* San Francisco, CA, USA, Dec 14-18 2015.

Borbas E.E., **Z. Li**, W.P. Menzel and L. Dobor: Developing the VIIRS TPW Algorithm (**poster**); *MODIS/VIIRS Science Team Meeting, Jun 6-10, 2016, Silver Spring, MD.*

Li Z: VIIRS TPW Status Report (**talk**); *MODIS/VIIRS Science Team Meeting, Jun 6-10, 2016, Silver Spring, MD.*

The VIIRS_TPW ATBD is under preparation.
A paper is planned for late 2016.

7. Year 3 Progress Report

NNX15AB95A Progress Report:
S-NPP IR TPW from a combination of VIIRS and CrIMSS

Project Title: "Continuation of EOS Clear Sky Infrared Total Precipitable Water Vapor Product Using a Combination of VIIRS and CrIMSS Measurements"
Principal Investigator: Dr. Eva Borbas
Co-Investigators: Dr. W Paul Menzel and Dr. Zhenglong Li

Date: Nov 5, 2016 – Sept 14, 2017

Objectives

We propose to provide total column water vapor properties from merged VIIRS infrared measurements and NUCAPS (or CLIMCAPS, CrIS plus ATMS) water vapor soundings to continue the depiction of global moisture at high spatial resolution started with MODIS. While MODIS has two channels within the 6.5-μm H_2O band and four channels within the 15-μm CO_2 band, VIIRS has no infrared (IR) absorption channels. However, the VIIRS IR windows at 8.6, 10.8 and 12 μm give some indication of low level moisture (which constitutes much of the total column amount) and we propose to complement this with NUCAPS moisture determinations. This VIIRS algorithm will follow the approach used for MODIS. A clear sky regression relationship is established between total precipitable water vapor (TPW) and VIIRS IR window brightness temperatures (BTs) and NUCAPS water vapor soundings calculated from a global training radiosonde based profile data set. NUCAPS is added in clear and partly cloudy regions to enhance the TPW depiction and to extend the coverage.

Work Progress

VIIRS+NUCAPS combined algorithm update

Versions V1.0 and V1.1 of the VIIRS TPW product were completed last year. But in order to process the whole S-NPP VIIRS life time record, the SIPS needed to reorganize our input data to look like CrIS and ATMS SDR and hence NUCAPS data. The previous version was designed for 32 second ATMS and CrIS granules, with collocation of about 15 CrIS and ATMS SDR files as inputs. The recently developed algorithm V1.2 aggregates CrIS and ATMS files (32 in all) from 6 minute data files (in order to overlap with the VIIRS 6-minute granules). Thus each 6-minute VIIRS granule needs only one collocated CrIS and ATMS SDR file, which makes the processing more time efficient.

The CrIS+ATMS TPW NUCAPS products are now produced on the 6 minute aggregated CrIS and ATMS files by the SCPP V1.2 as part of the SIPS VIIRS TPW processing chain. Figure 1 demonstrates the SIPS SNPP VIIRS TPS data flow with version number.

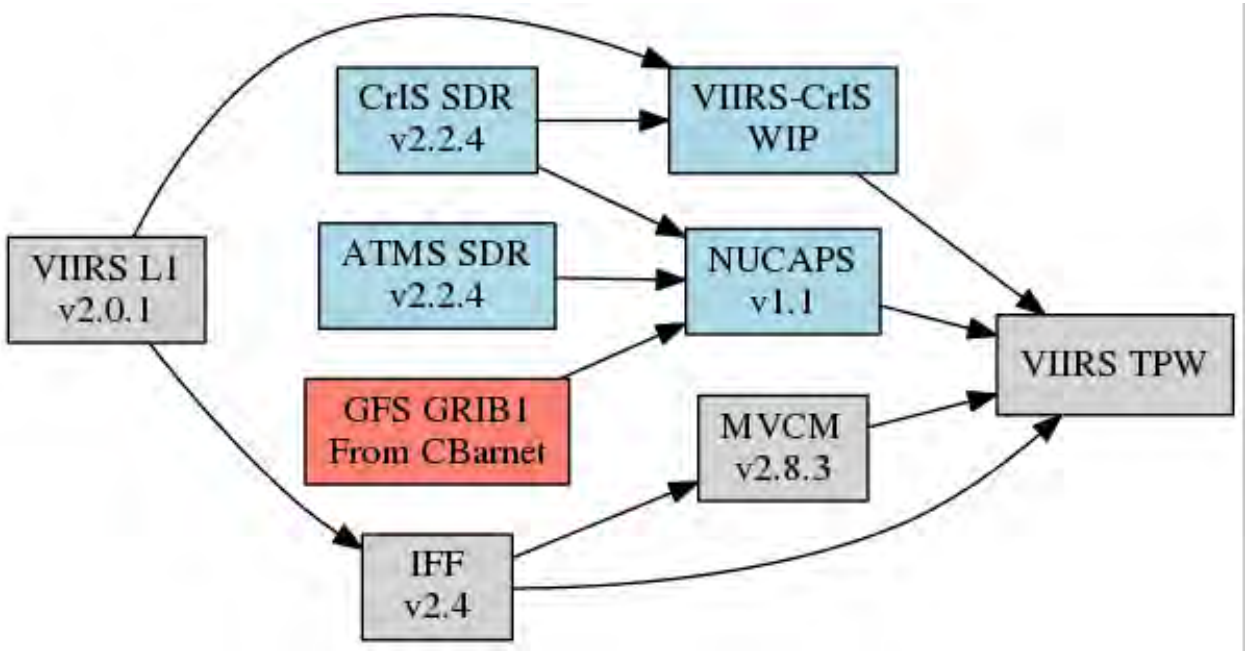

Figure 1: Input data flow of the S-NPP VIIRS TPW processing with the indication of the data version numbers.

The CrIS and VIIRS collocation files have also been changed. Previously only the overlapping CrIS indices were assigned to each VIIRS pixel resulting in missing data between lines and rows. The new collocation is based on closest distance, so each VIIRS pixel has an assigned CrIS index. The CrIS index file is then used to collocate with the NUCAPS (3x3 Cris FOV) data.

The science within the VIIRS TPW algorithm has not been changed. As indicated, a clear sky regression relationship is established between TPW and VIIRS IRW BTs (in 8.6, 10.8, and 12 μm) and NUCAPS water vapor soundings calculated from a global training radiosonde based profile data set. The VIIRS cloud mask is used to indicate cloudy VIIRS FOVs. The NUCAPS retrievals are smoothed using a radius of 60 VIIRS pixels. The VIIRS+NUCAPS TPW is generated in clear skies when NUCAPS has determined a TPW (holes exist when surface emissivity or other issues interfere with a NUCAPS retrieval). The remaining holes in the VIIRS+NUCAPS TPW field are filled with adjusted VIIRS only or adjusted NUCAPS only TPWs. The adjustment process for the given 6 minute granule consists of constructing a linear fit of the VIIRS+NUCAPS TPW against collocated the VIIRS only TPW; another linear fit is determined for the VIIRS+NUCAPS TPW against collocated NUCAPS only TPW. The appropriate linear fit is then used to scale the VIIRS only TPW and the NUCAPS only TPW to fill holes where possible. The resulting TPW field shows more detail than VIIRS only, NUCAPS only, and MODIS only. Holes in the NUCAPS only due to surface emissivity issues are filled by using VIIRS only values. Holes in VIIRS and MODIS only due to interference by non-precipitating clouds are filled using smoothed NUCAPS values (shown in previous reports). Figure 2 shows an example outputs of the granule on Oct 15, 2014 at 8:42 UTC and Figure 3 shows the whole globe on Oct 15, 2014.

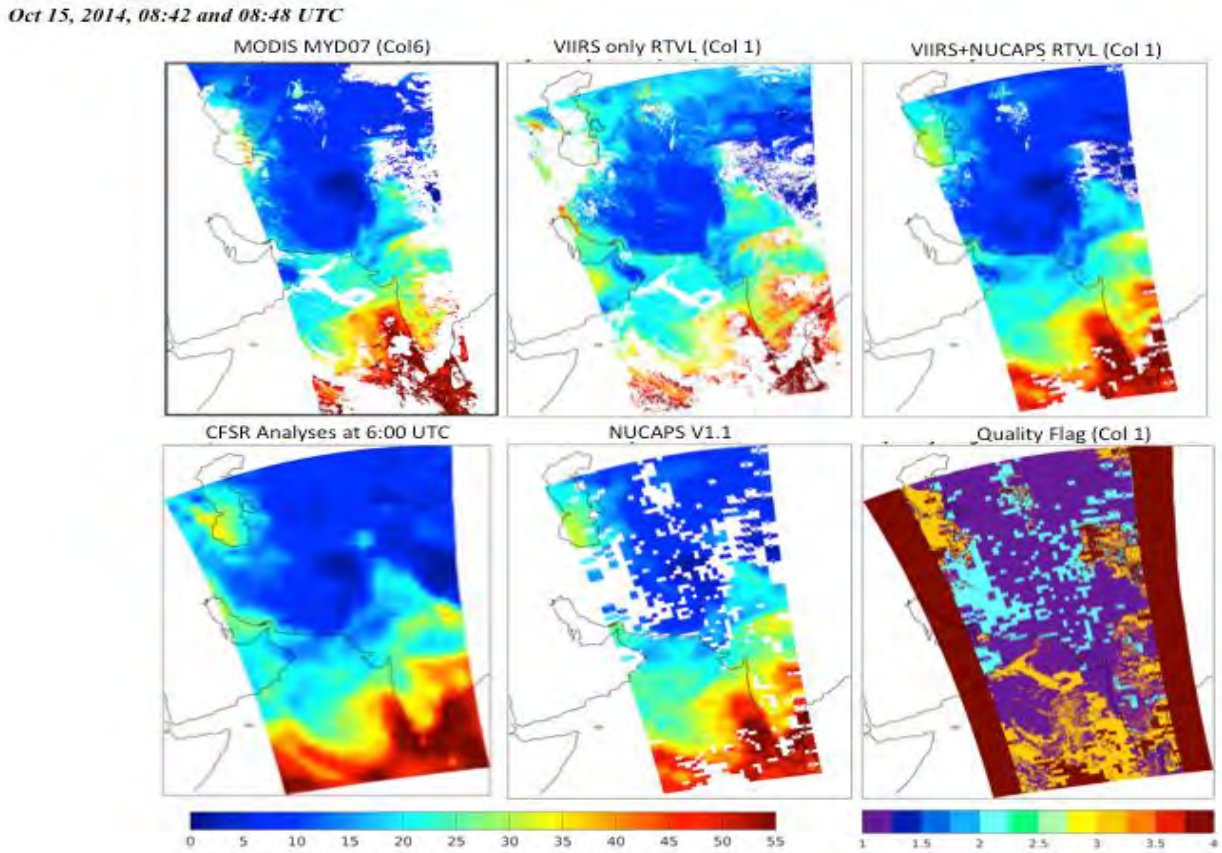

Figure 2: TPW comparison on 15 October 2014 at ~0850 UTC. (top left) Aqua MODIS MYD07. (top middle) VIIRS only (top right) VIIRS plus NUCAPS retrievals. (bottom left) NUCAPS only. (bottom left) CFSR TPW analyses, (bottom middle) NUCAPS v1.1 TWP, (bottom right) quality flag. Note the better coverage and improved clarity for VIIRS plus NUCAPS with holes filled compared with VIIRS only, NUCAPS only, and even MODIS only.

The VIIRS TPW files include the following output now:

VIIRS-only atmospheric water vapor content (TPW),
VIIRS + NUCACPS derived atmospheric water vapor content,
NUCAPS atmospheric water vapor content (used as input data) on the VIIRS resolution,
CFSR model atmospheric water vapor content on VIIRS resolution (used for validation),
Retrieved VIIRS–only Skin Temperature
Quality Flag: 1 = best retrieval-VIIRS and NUCAPS data are available;
2 = filled with VIIRS-only retrieval;
3 = filled with NUCAPS-only retrieval;
4 = No retrievals - no matchup VIIRS and NUCAPS data is available

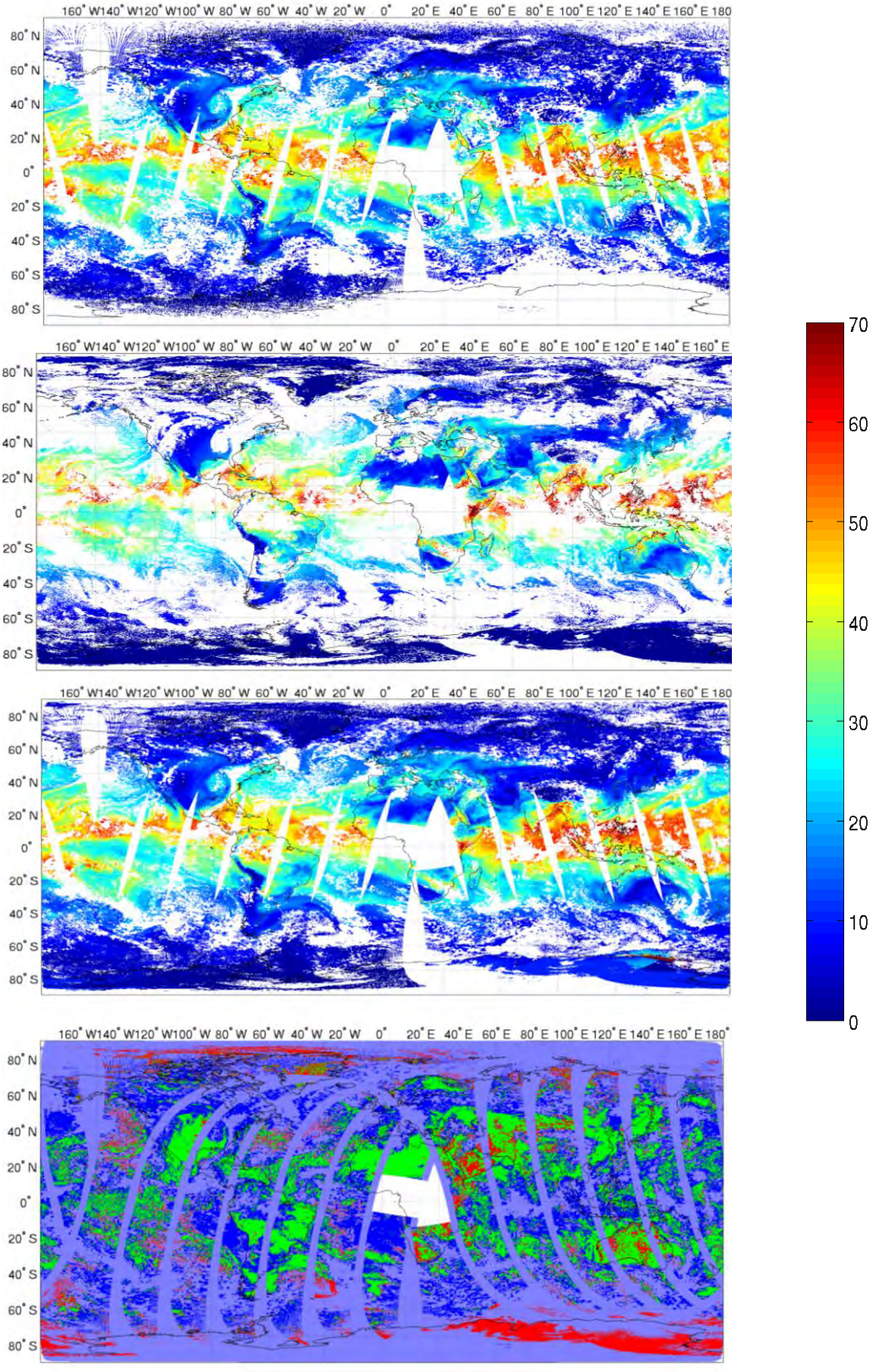
160° W140° W120° W100° W 80° W 60° W 40° W 20° W 0° 20° E 40° E 60° E 80° E 100° E 120° E 140° E 160° E 180
80° N
60° N
40° N
20° N
0°
20° S
40° S
60° S
80° S
70
60
50
40
30
20
10
0

Figure 3: NUCAPS TPW (top), VIIRS-only TPW (second), VIIRS+NUCAPS TPW RTVL (third) and the quality flag (bottom) of the VIIRS+NUCAPS TPW retrievals in the AM on Oct 15, 2014.

VIIRS TPW algorithm update – L2 product processing

The Collection 001 (inhouse version V1.3) VIIRS TPW algorithm and some test data have been delivered following the new code delivery protocol set by the Atmosphere-SIPS. The new system features easier tracking of software versions and easier transitioning between the developers' and SIPS' computer environment.

The Atmosphere SIPS started to process the VIIRS TPW (collection 001) products at the end of May 2017. By August 5, about 90 % of the entire S-NPP VIIRS record has been processed (see Fig 4 for status of processing on July 24, 2017). Investigating reasons for the missing granules is underway now.

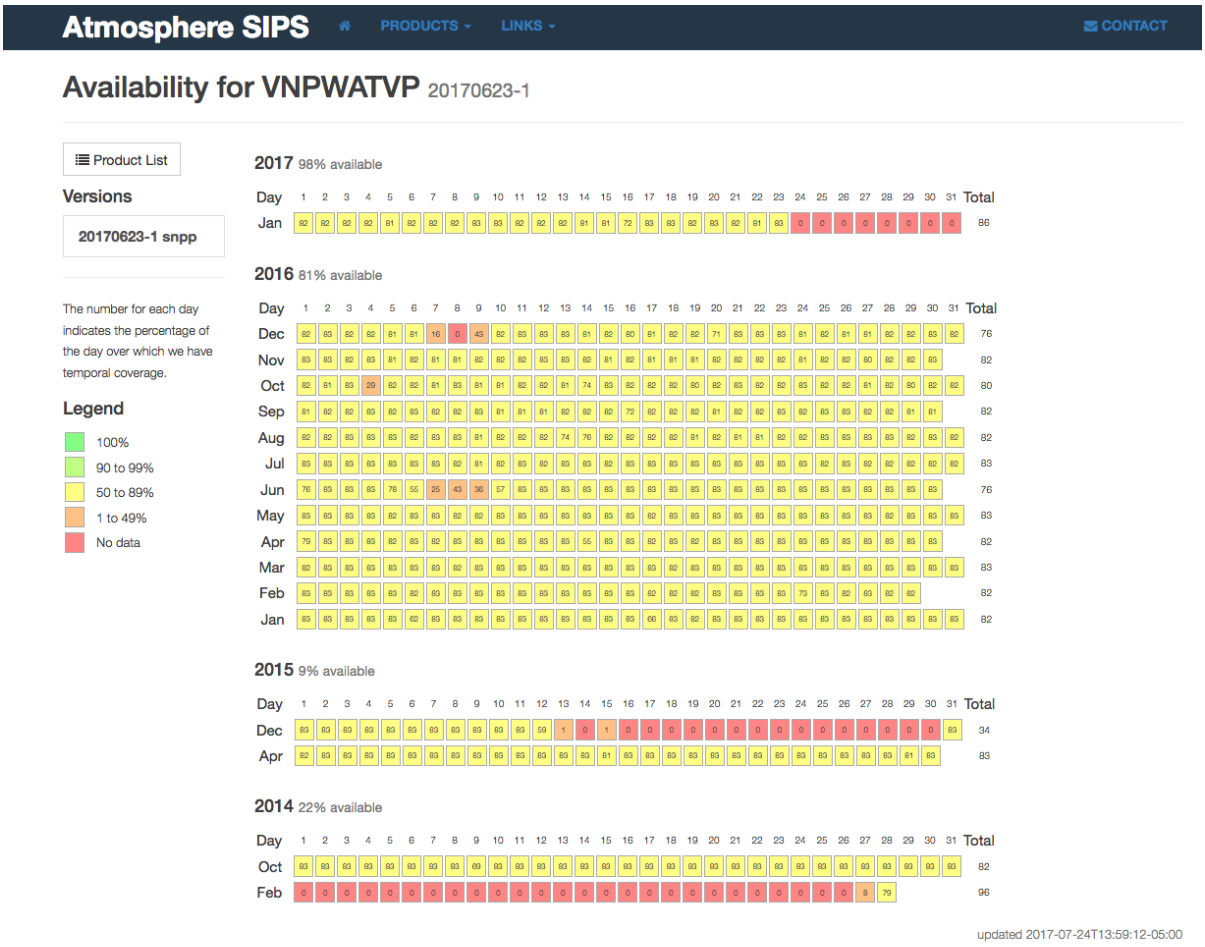

Figure 4: Status of the processing level of the VIIRS TPW product on July 24, 2017

Possible Improvement of the VIIRS TPW by radiance fusion from CrIS

Recent developments indicate that there is the potential to generate supplementary narrowband radiances at imager resolution from sounder measurements (Weisz et al., 2017). This fusion of

CrIS radiances convolved to MODIS-like spectral bands and averaged at VIIRS pixel resolution offers the possibility of adding more information to the VIIRS plus NUCAPS TPW derivation. A brief explanation of the fusion method follows. The first step of the fusion method is to perform a nearest neighbor search using the k-d tree algorithm on both high spatial and low spatial resolution split-window imager radiances as well as the corresponding latitude and longitude values. The k-d tree algorithm provides *N* sounder FOVs that best match each imager pixel. In other words, the indices of the *N* sounder FOVs, that are closest in space and best match the measured imager IR radiances, are provided for each imager pixel. For the second step the sounder radiances are convolved with the spectral response function (SRF) for the band to be constructed. Thus, high-spectral resolution sounder radiances are reduced to match narrow-band (i.e., imager-like) radiances while retaining the sounder spatial resolution. The final fusion radiance results are obtained by computing the mean of the convolved radiances for the *N* neighbors (associated with the indices found in the first step). Figure 5 shows a comparison of the VIIRS only, VIIRS plus NUCAPS, VIIRS plus fusion radiances, and VIIRS plus NUCAPS plus fusion radiances

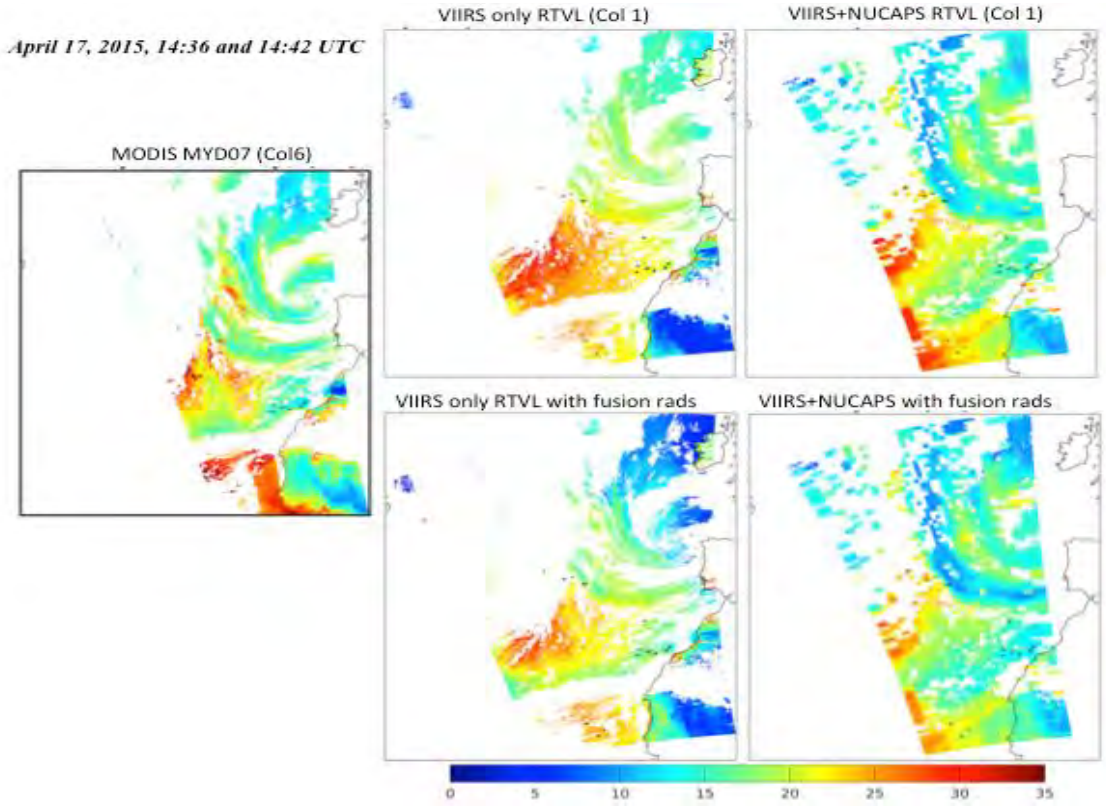

Figure 5: TPW comparison on April 17, 2015 at ~1440 UTC. (left) Aqua MODIS MYD07. (top left) Collection 1 VIIRS only (top right) Col 1 VIIRS plus NUCAPS retrievals. (bottom left) VIRS only (bottom right) VIIRS plus NUCAPS retrievals with MODIS-like B27 and B28 fusion channels added.

The VIIRS plus fusion radiances show a broader range of moisture values and significant drying northeast and south central with some moistening southeast. VIIRS plus NUCAPS plus fusion radiances does not show much difference from VIIRS plus NUCAPS. The optimal use of the supplementary fusion radiances from CrIS needs to be explored; that will be future work within another proposal.

Developing the Level 3 VIIRS TPW Products

To build global daily and monthly VIIRS TPW L3 gridded TPW products, we adopted the Yori L3 aggregation software developed at the Atmosphere-SIPS. To be able to run the Yori L3 software, the VIIR TPW L2 files must be converted into an intermediate file format and a configuration file must be provided explaining where the filtering and gridding parameters are set. Figure 6a shows the monthly mean Level 3 VIIRS TPW (VIIRS only TPW and VIIRS+NUCAPS TPW) for October 2014 compared to the MODIS MYD08 products. The difference fields (shown in Fig 6b) with respect to the Aqua MODIS IR TPW products illustrate a significant underestimation in the VIIRS-only TPW products. This is improved by adding the NUCAPS TPW field as an additional predictant to the algorithm especially over the Tropics. The difference maxims of -30 mm and +13 mm between the VIIRS-only and MODIS products have been reduced by adding the NUCAPS TPW to the range of -14 mm and 11mm. The statistics of the differences between the VIIRS TPW and MODIS products are summarized in Table 1.

Differences [mm]	**mean**	**Stdev**	**RMS diff**	**Number of samples**
VIIRS-only – MYD08	-0.02	3.1	3.1	64800
VIIRS+NUCAPS – MYD08	0.6	1.9	2,0	64800

Table 1: Statistics of the differences between the VIIRS TPW products and the MODIS MYD08 Aqua monthly mean Water Vapor products for October 2014.

Matyas Rada, a visiting scientist at SSEC during the summer 2017 adapted the L3 Yori software on the VIIRS TPW products and provided feedback to the developers. He is currently working on analyzisng the L2 processing status and validating the L3 daily and monthly mean products.

Accomplishments:

- The Collection 1 VIIRS Level 2 TPW algorithm has been developed and delivered to Atmosphere-SIPS.
- The Atmosphere-SIPS processed the ~90% of the VIIRS TPW granules (Collection 001) over the whole S-NPP VIIRS mission.
- Finish creating the level 3 algorithm for the global daily and monthly VIIRS L3 gridded TPW products.

Pending:

- Evaluate the VIIRS TPW L3 global products with MOD07 L3, AIRS L3, SSMI and NWP analyses data.
- Update the comparison of the VIIRS/CrIMSS TPW L2 products with ground-based GPS network TPWs and TPWs derived from MWR, RAOB and GPS over the SGP cart site.
- Finalize the ATBD, document the findings, present at relevant conferences, prepare a peer-reviewed publication.

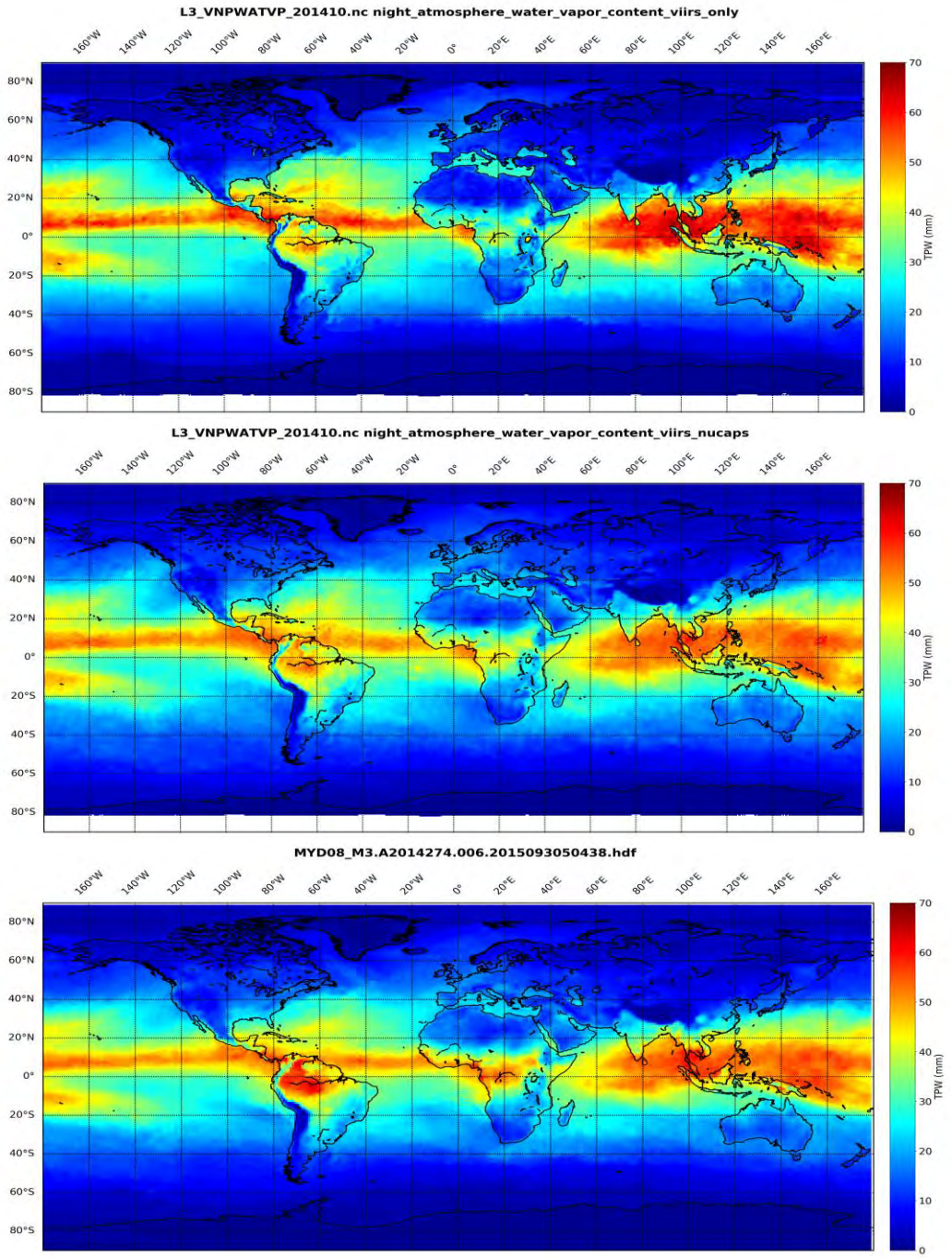

Figure 6a: Monthly Level-3 VIIRS only (top) and VIIRS plus NUCAPS TWP field (middle) compared to the Aqua MODIs MOD07 (bottom) for October 2014 at nighttime.

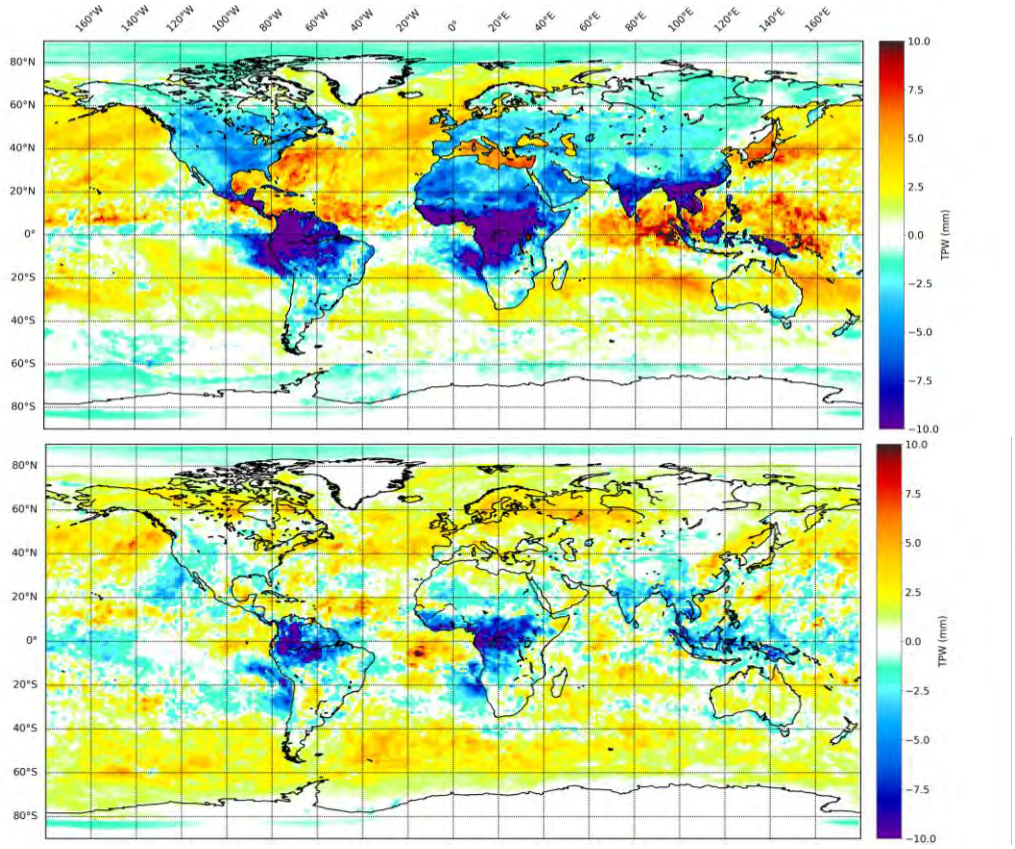

Figure 6b: Difference fields of the VIIRS only (top) and VIIRS plus NUCAPS (bottom) monthly mean Level-3 TWP products, and the Aqua MODIS IR TPW for October, 2014 at nighttime.

Publication/Travel:
The VIIRS_TPW ATBD is under preparation. Version 1 is planned for delivery by Nov 1 2017.

Oncoming Travel:

- International TOVS Study Conference, Nov 29-Dec 5, 2017, in Darmstadt, Germany
- AGU 2017 Fall Meeting, Dec 11-15, 2017, New Orleans, USA

References:
Weisz, E., B. A. Baum, and W. P. Menzel, 2017: Fusion of Satellite-Based Imager and Sounder Data to Construct Supplementary High Spatial Resolution Narrowband IR Radiances. *J. Appl. Remote Sens.* 11(3), 036022, doi: 10.1117/1.JRS.11.036022.

8. The 6-month Extension Report

NNX15AB95A Progress Report:
S-NPP IR TPW from a combination of VIIRS and CrIMSS

Project Title: "Continuation of EOS Clear Sky Infrared Total Precipitable Water Vapor Product Using a Combination of VIIRS and CrIMSS Measurements"
Principal Investigator: Dr. Eva Borbas
Co-Investigators: Dr. W Paul Menzel and Dr. Zhenglong Li

Date: Nov 4, 2017 – May 5, 2018

Objectives

We propose to provide total column water vapor properties from merged VIIRS infrared measurements and NUCAPS (or CLIMCAPS, CrIS plus ATMS) water vapor soundings to continue the depiction of global moisture at high spatial resolution started with MODIS. While MODIS has two channels within the 6.5-μm H_2O band and four channels within the 15-μm CO_2 band, VIIRS has no infrared (IR) absorption channels. However, the VIIRS IR windows at 8.6, 10.8 and 12 μm give some indication of low level moisture (which constitutes much of the total column amount) and we propose to complement this with NUCAPS moisture determinations. This VIIRS algorithm will follow the approach used for MODIS. A clear sky regression relationship is established between total precipitable water vapor (TPW) and VIIRS IR window brightness temperatures (BTs) and NUCAPS water vapor soundings calculated from a global training radiosonde based profile data set. NUCAPS is added in clear and partly cloudy regions to enhance the TPW depiction and to extend the coverage.

Work Progress

VIIRS+NUCAPS combined algorithm update

During processing the L3 daily and monthly products, we have found occasionally the Level-2 nucaps_bg and hence the viirs_nucaps products containing extremely high values in pixels, which are inherited into the Level-3 gridded products as well. A new delivery to the SIPS-Atmosphere was made in the package of viirstpw: 20180504-1 (see Table 1a), which contains a sanity check now by filtering out the 90 mm or higher water vapor products (viirs_only, uncaps_bg and viirs_nucaps) and also has a constrain for the VIIRS-only and NUCAPS-only (nucaps_bg) retrievals to be inside the minimum and maximum values of the granule. Figure 1 and Table 1 summarizes the latest SIPS process flow with the up-to-date version number of the inputs.

The Atmosphere SIPS started to reprocess the VIIRS TPW (Col 001) products in May 2018. Investigating reasons for the missing granules is underway now.

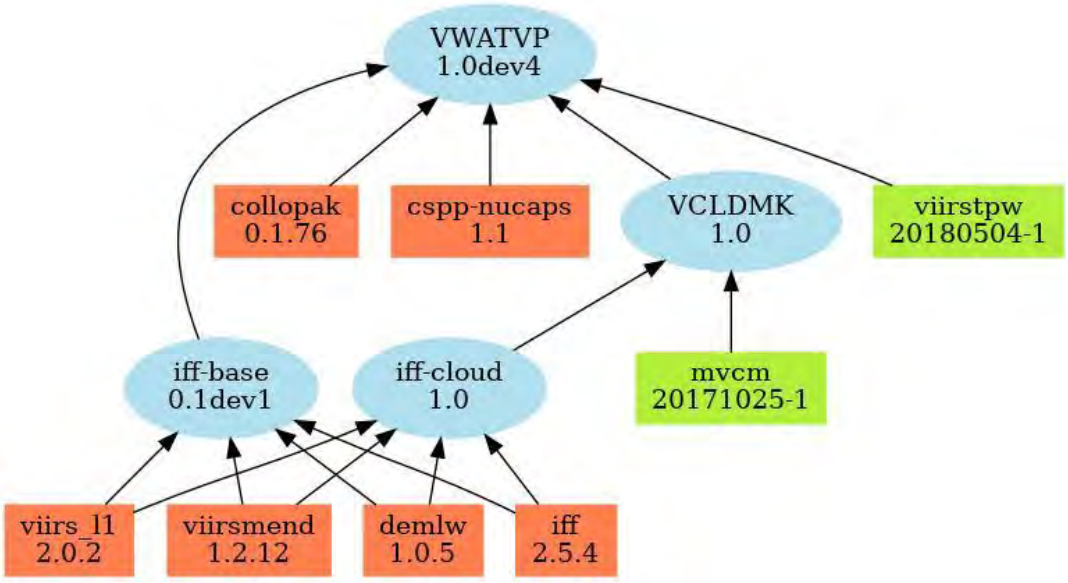

Figure 1: Input data flow of the S-NPP VIIRS TPW processing with the indication of the data version numbers.

Table 1a: Direct inputs required directly by the VIIRSTPW product.

Name	Package	Type
VIIRS TPW	viirstpw: 20180504-1	delivery
Collocation	collopak: 0.1.76	support
IFF: base config	iff-base: 0.1dev1	product
VIIRS Cloud Mask	VCLDMK: 1.0	product
CSPP NUCAPS	cspp-nucaps: 1.1	support

Table 1b: Indirect Inputs not directly required by the product but part of the input graph.

Name	Package	Type
Land-water mask generation	demlw: 1.0.5	support
VIIRS L1B bowtie restoral	viirsmend: 1.2.12	support
NASA VIIRS Level 1	viirs_l1: 2.0.2	support
Intermediate File Format	iff: 2.5.5	support
MODIS/VIIRS Cloud Mask	mvcm: 20171025-1	delivery
IFF: CLoud Team Config	iff-cloud: 1.0	product

The VIIRS TPW L3 Products

Level-3 global 0.5° by 0.5° daily and monthly mean data products were developed by using a gridding software (called *Yori*) developed at UW-Madison SSEC. The development of Yori is framed by NASA VIIRS Atmosphere SIPS. Yori has been adapted for the VIIRS TPW products and has been processed by our team (not by SIPS) from May 2012 to December 2016 based on the SIPS processed L2 (Version 01r03) data.

The Level-3 processing workflow using the Yori software can be structured in five separate steps:

1. Preparing the YAML file (configuration file for our products)
2. Preparing the transitional/intermediate input netCDF files
3. Gridding the Level-2 input granule (see Fig 1)
4. Aggregating a day
5. Aggregating a month (see fig 2).

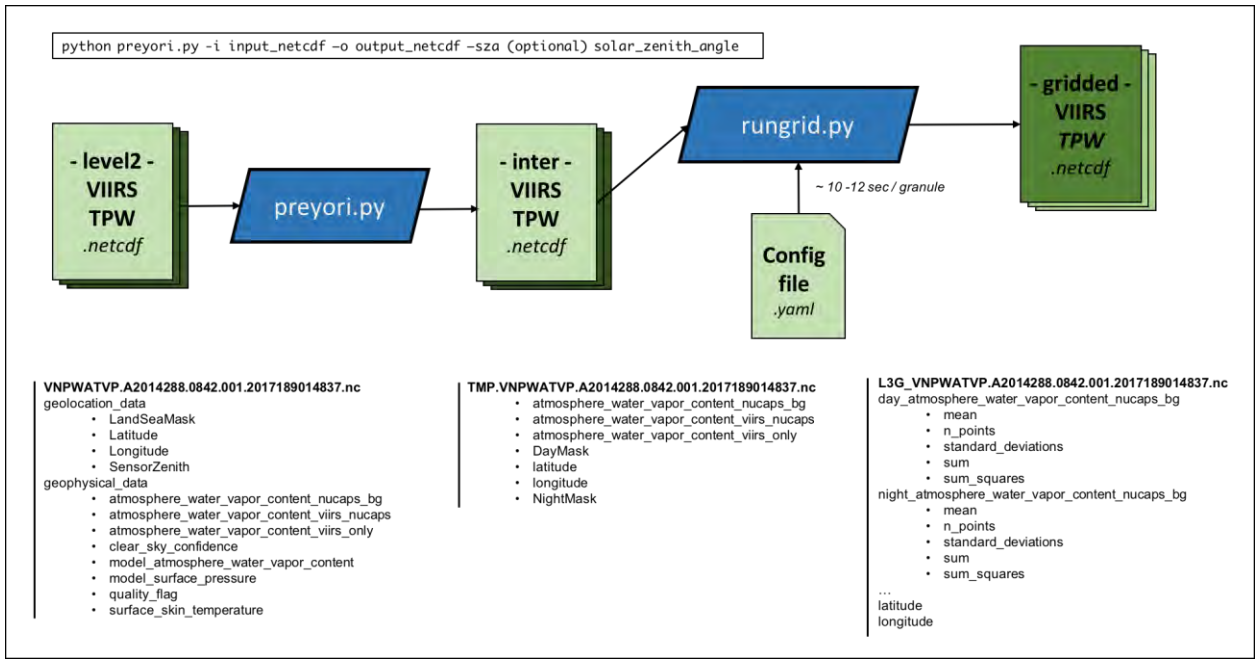

Figure 2: Work flow of VIIRS TPW L3 Processing (step 1-3) to create L3 gridded granule products.

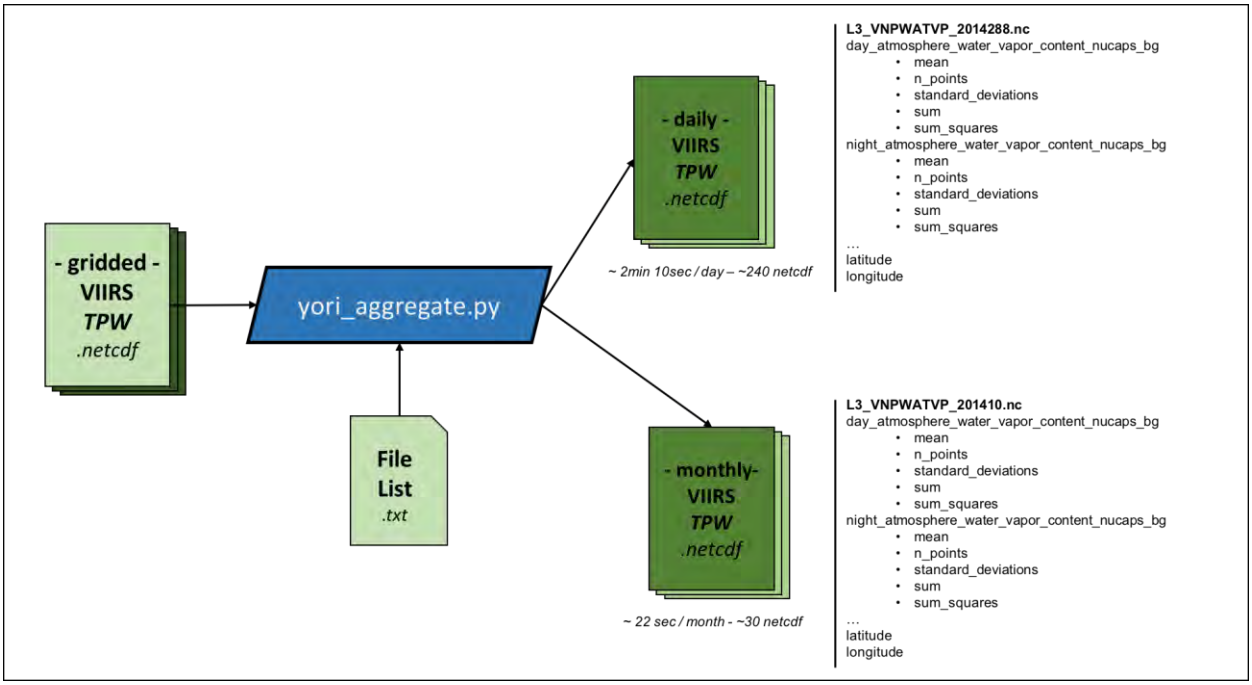

Figure 3: Work flow of VIIRS TPW L3 Processing (step 4-5) to create L3 gridded daily and monthly mean products.

Figure 4 illustrates the results of the step 3 process, when the L2 VIIRS TPW granule products (Fig 4 top panels) have been converted into the corresponding 0.5° resolution gridded products (Fig 4 bottom panels). As an example, the L3 daily and monthly aggregated products have been shown on Figure 5 for Oct 14, 2018 and Oct 2014 respectively and compared to the MYD08 products. Please note a better VIIRS coverage, because of 1) using the all sky NUCAPS TPW products and 2) filling with modified NUCAPS or VIIRS only TPW values.

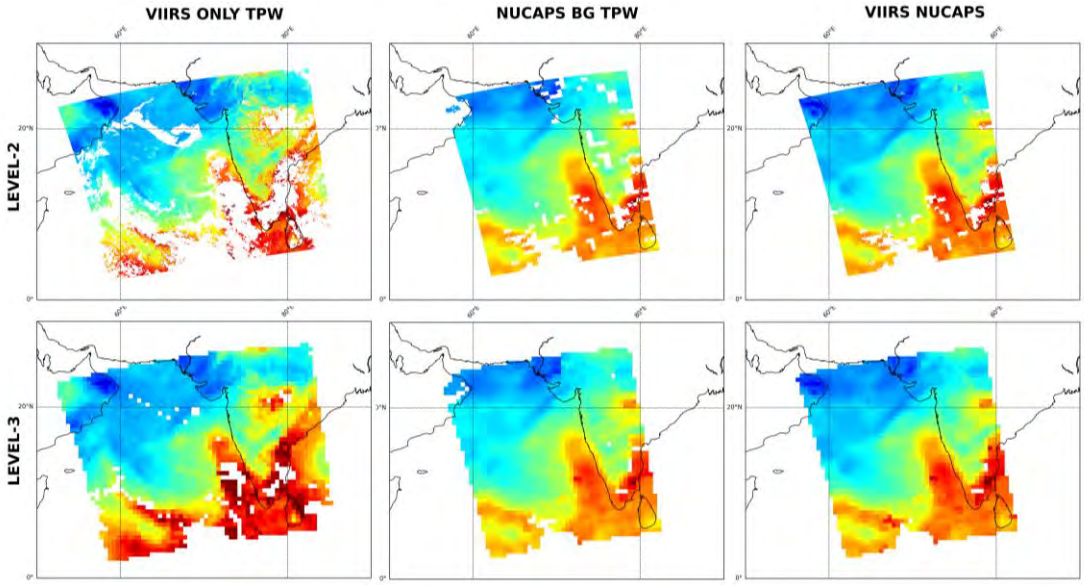

Figure 4: Processing a VIIRS TPW granule to a gridded granule (15 October 2014 at ~08:50 UTC).

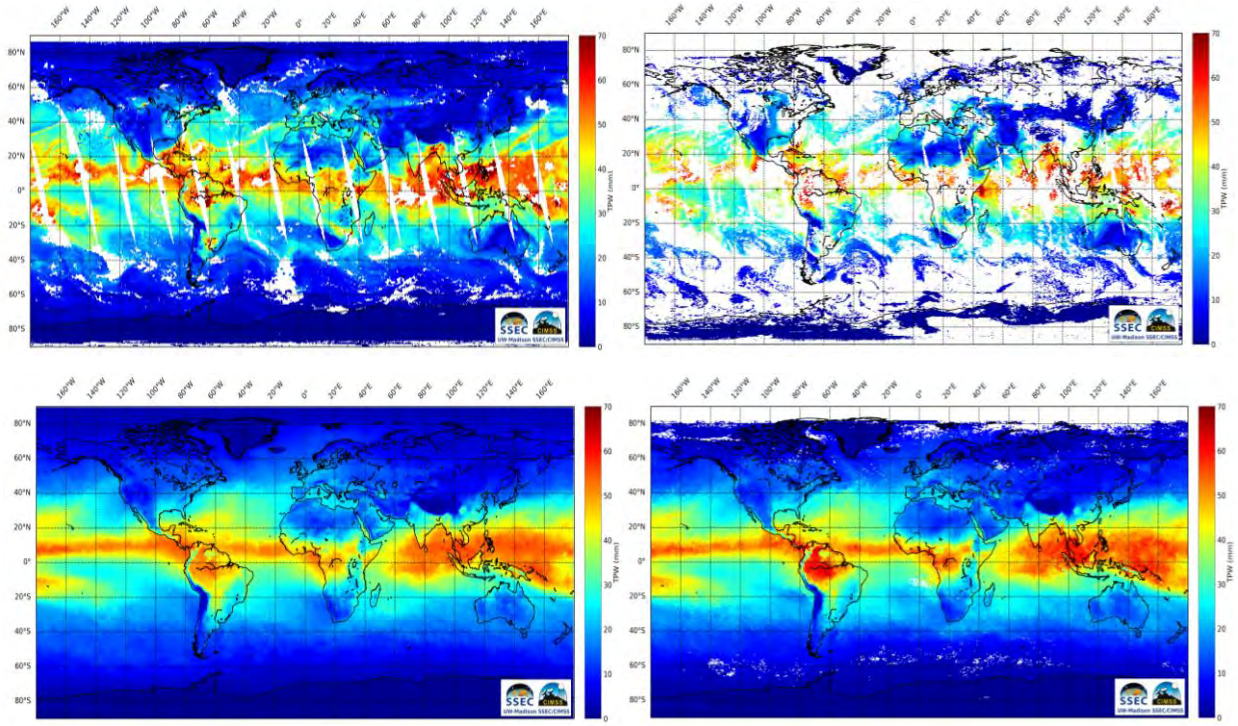

Figure 5: Daytime Daily (Oct 15, 2014, top panels) and monthly (Oct 2014, bottom panels) mean 0.5 degree gridded VIIRS/NUCAPS (left) and AQUA/MODIS MYD07 (right) TPW products.

Evaluation of the VIIRS TPW L3 products

The L3 VIIRS TPW daily and monthly mean products have been evaluated with the NUCAPS, AIRS L3, Aqua/MODIS MYD08, the in-house Aqua/MODIS MYD07_L3 and the SSMI products (see Table 2 for more details about these reference datasets).

Table 2 TPW Products used for the zonal cross comparison

TPW data products		Res.
VIIRS	VIIRS ONLY (day / night)	0.5 °
CrIS + ATMS	NUCAPS BG (day / night)	0.5 °
VIIRS + NUCAPS	VIIRS NUCAPS (day / night)	0.5 °
AIRS3STM	TotH2OVap_A, TotH2OVap_D	1 °
MYD08_M3	Atm. Water Vapor	1 °
MYD07_L3	TPW (day / night)	0.5 °
SSMI	TPW	1 °

The TPW comparison between the different products has been classified by land/sea and day/night. The land/sea mask has been calculated from the average of the monthly mean SSMI TPW products between May 2012 and December 2016. The SSMI data product contains measurements only over ocean. Over land it has -999 value as there is no data value while the ice coverage has the pixel value as -500. The above zero pixel values give us a good indication of the ocean hence they have been converted into the land/sea mask.

The day/night classification is defined by the solar zenith angle. The pixels having solar zenith angle less than 95 degrees are considered day while solar zenith angle more than 95 degrees are defined as night.

During the L3 processing we have found that the L2 nucaps_bg and hence the viirs_nucaps products contained a certain overfitting error which has been filtered out from our study and had been fixed in the latest L2 delivery to SIPS.

Zonal monthly mean TPW products have been illustrated for the Mid-North Latitudes (30°N – 60°N) on Fig 6, for Tropical latitudes (30°S – 30°N) on Fig 7, and for Mid-South Latitudes (30°N – 60°N) on Fig. 8 for the 2012 May – 2016 December time period separately by day and night and Land and Ocean. The TPW products are: VIIRS-only (yellow), NUCAPS (green), VIIRS+NUCAPS (red), AIRS L3 ascending/descending (light blue), Aqua/MODIS MYD08 (grey) , inhouse Aqua/MODIS MYD07_L3 (black), and SSMI (darker blue).

Generally, the VIIR TPW (viirs+nucaps) product agrees with all the other types of TPW products very well. Additionally, all the TPW products have a very similar seasonal pattern and all agree within 3mm except

the VIIRS-only product. The VIIRS-only TPW product over ocean has a smaller seasonal variation between summer and winter producing smaller maximum and larger minimum values except over land daytime for Tropical and South-Mid latitudes when the VIIRS-only TPW values are systematically higher with a bias of 3-4 mm over all other products. It has a negative bias (~4mm) over Tropical land for night case. The luck of the VIIRS water vapor channels are obvious.

The SSMI (over ocean only) and the nighttime (descending) AIRS retrievals have about 4mm higher values than all the other IR-derived products due to the microwave instrument nature, which is able to sense the water vapor content in cloudy conditions as well.

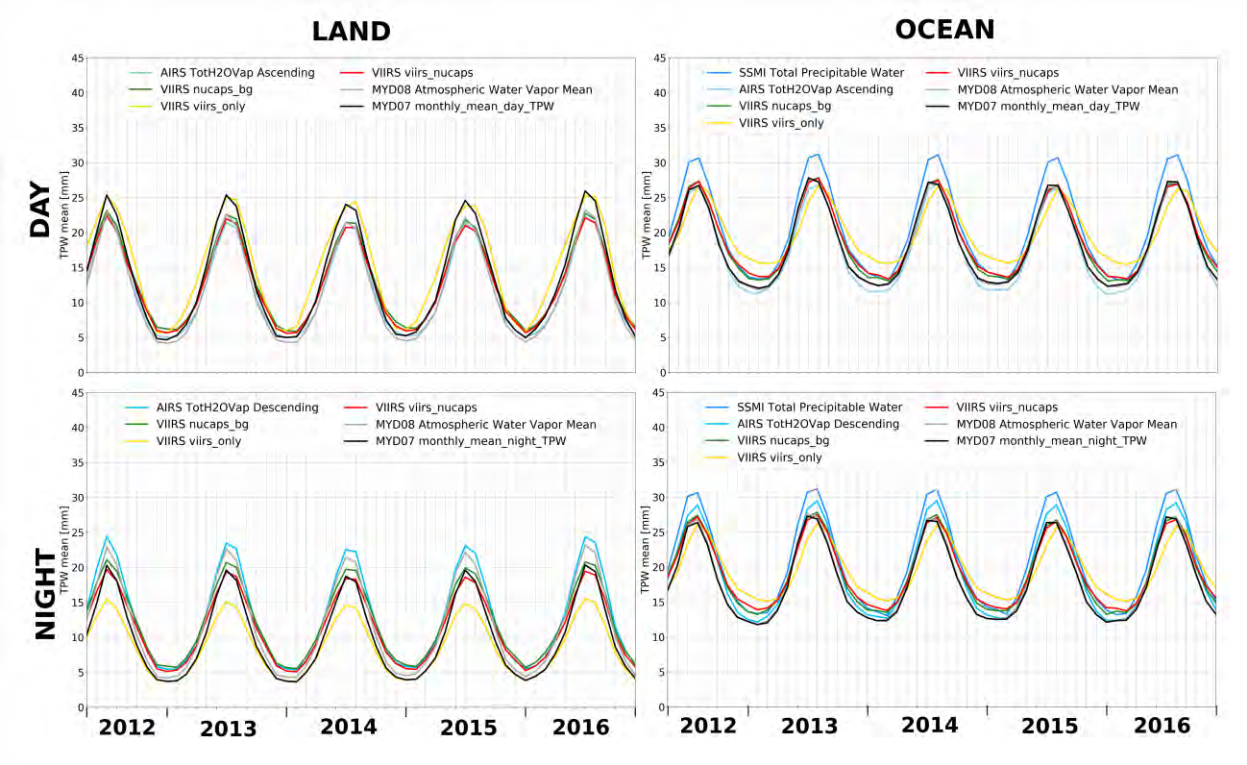

Figure 6: Zonal monthly mean cross-comparisons of different TPW products for the **Mid-North Latitude (30°N – 60°N)** between May 2012 and December 2016. The TPW products are: VIIRS-only (yellow), NUCAPS (green), VIIRS+NUCAPS (red), AIRS L3 ascending/descending (light blue), Aqua/MODIS MYD08 (grey) , inhouse Aqua/MODIS MYD07_L3 (black) and SSMI (darker blue).

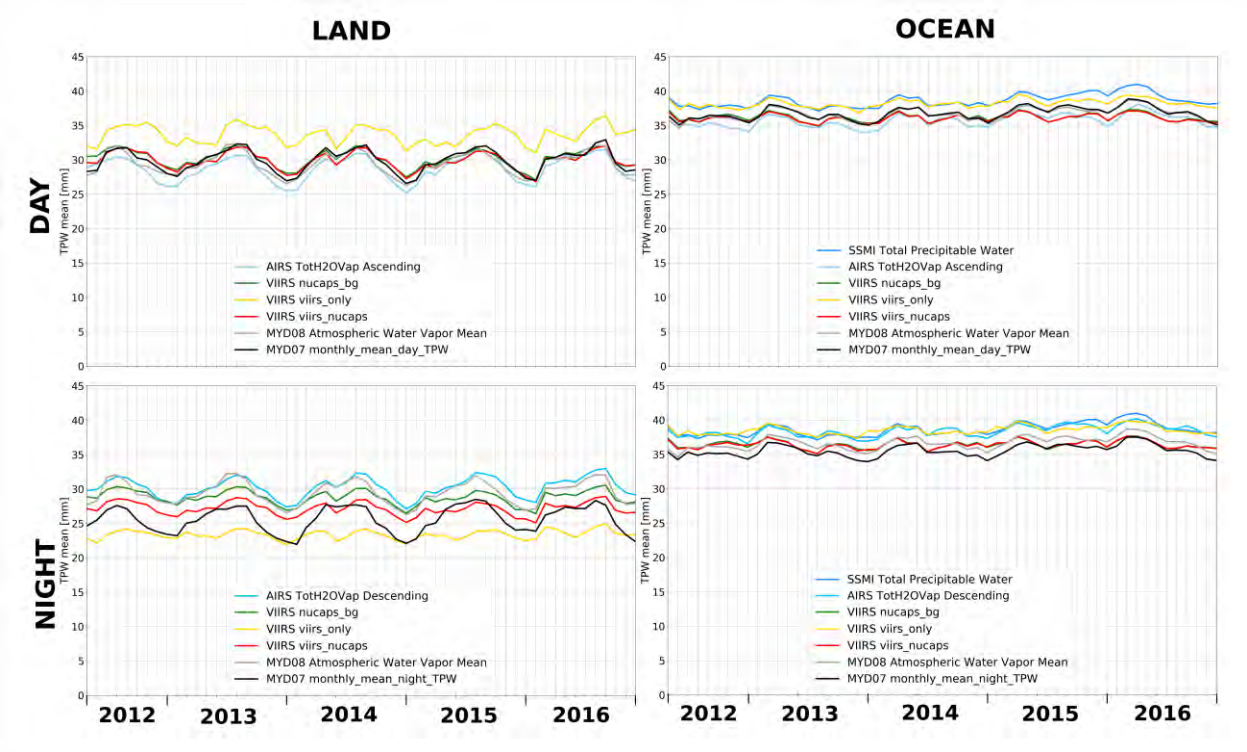

Figure 7: Same as Figure 6, but for the **Tropical Latitudes** (30°S – 30°N).

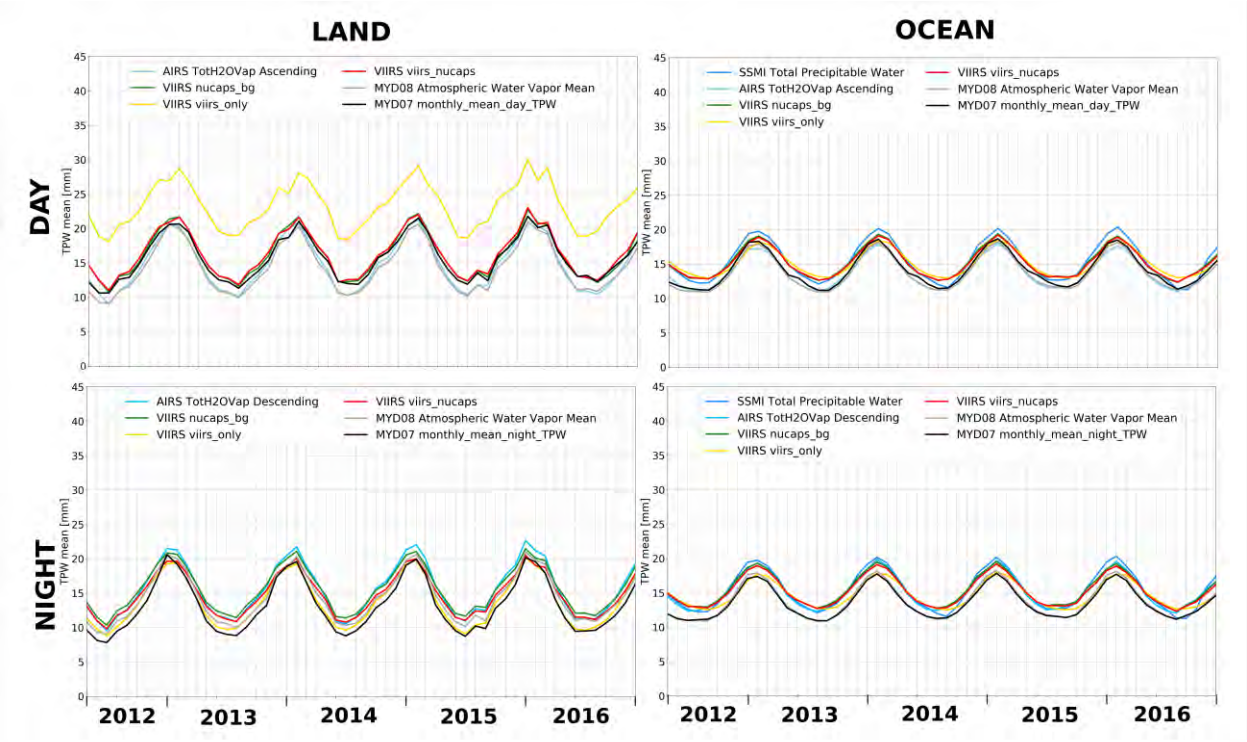

Figure 8: Same as Figure 6 but for the **Mid-South Latitudes** (60°S – 30°S).

Comparison with Aqua/MODIS TPW

The VIIRS TPW monthly mean products (NUCAPS_bg background, VIIRS-only and VIIRS+NUCAPS) have been compared to the in-house processed MYD07 L3 monthly mean TPW product separated by day/night and land/ocean between 2012-2016. Figure 9 shows the scatter plots with RMSE error and correlations. The VIIRS+NUCAPS combined TPW product has the highest correlation with the MYD07_L3 product and the lowest RMSE errors, 2.3mm for ocean and 2.7mm for land respectively.

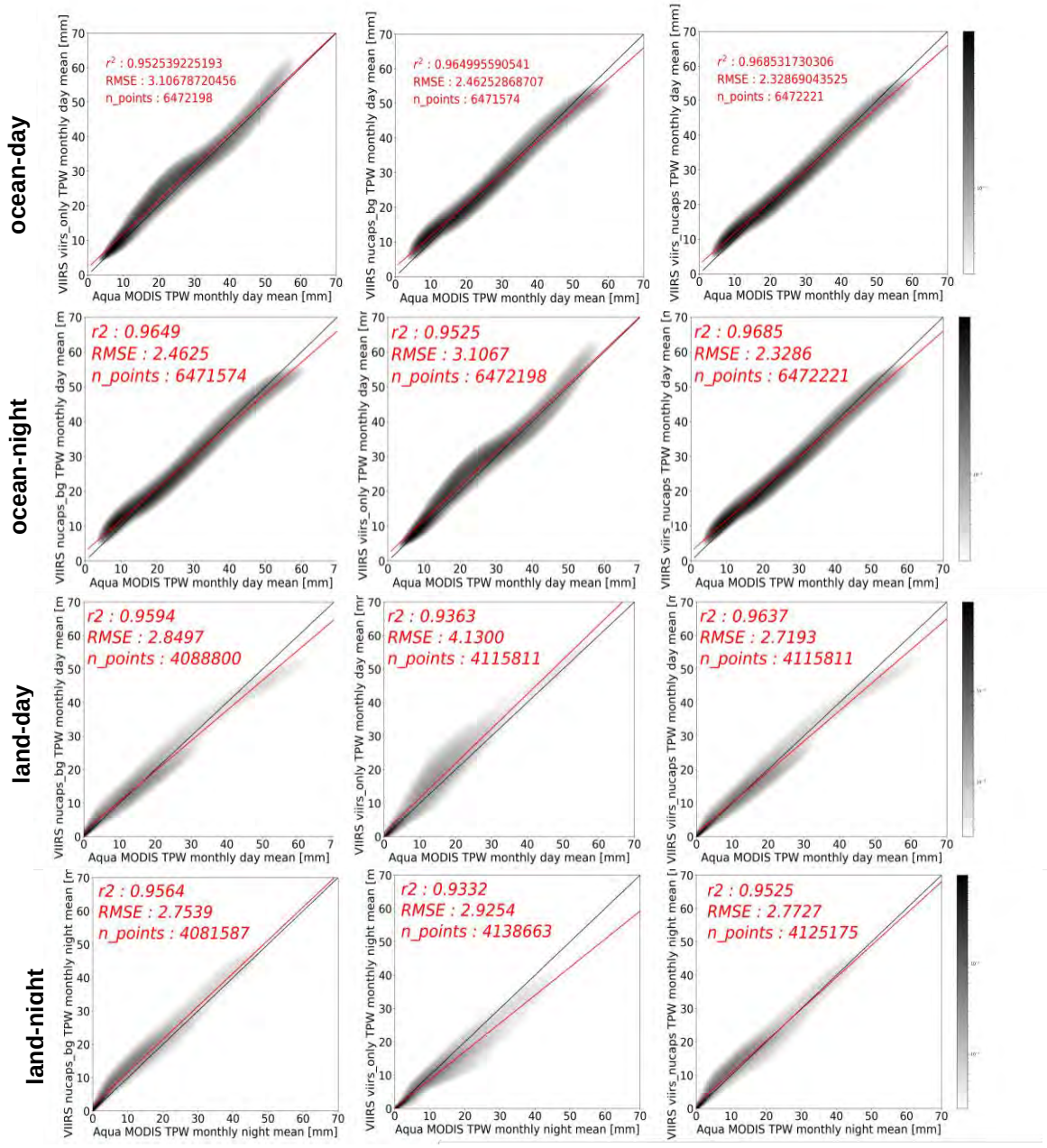

Figure 9: The scatter plots show the day, night, ocean and land separated relationship between the Level-3 MYD07 (x-axis) and the Level3 NUCAPS, VIIRS-only and VIIRS NUCAPS data products.

The timely distribution of the correlation between the three different VIIRS TPW products and the MYD07_L3 is demonstrated on Figure 10. All three products have shown the lowest correlations with the MYD07 L3 TPW products over land, summer daytime. Overall, the VIIRS-only product is the least and the VIIRS+NUCAPS product is the best fit to the MYD07 L3 TPW products. The VIIRS+NUCAPS combined TPW algorithm is producing near-MODIS quality TPW in the comparison between 2012-2016 with r2 values greater than 0.95 over land and ocean both day and night. The Level-2 and Level-3 comparison with Aqua MODIS showed that VIIRS+NUCAPS TPW quality is better than VIIRS or NUCAPS only. Values missing in the NUCAPS only due to failed retrievals are filled by using VIIRS only values. Values missing in VIIRS and MODIS only due to interference by clouds are filled by using NUCAPS values. Both VIIRS and NUCAPS only values are modified to reduce biases before filling in.

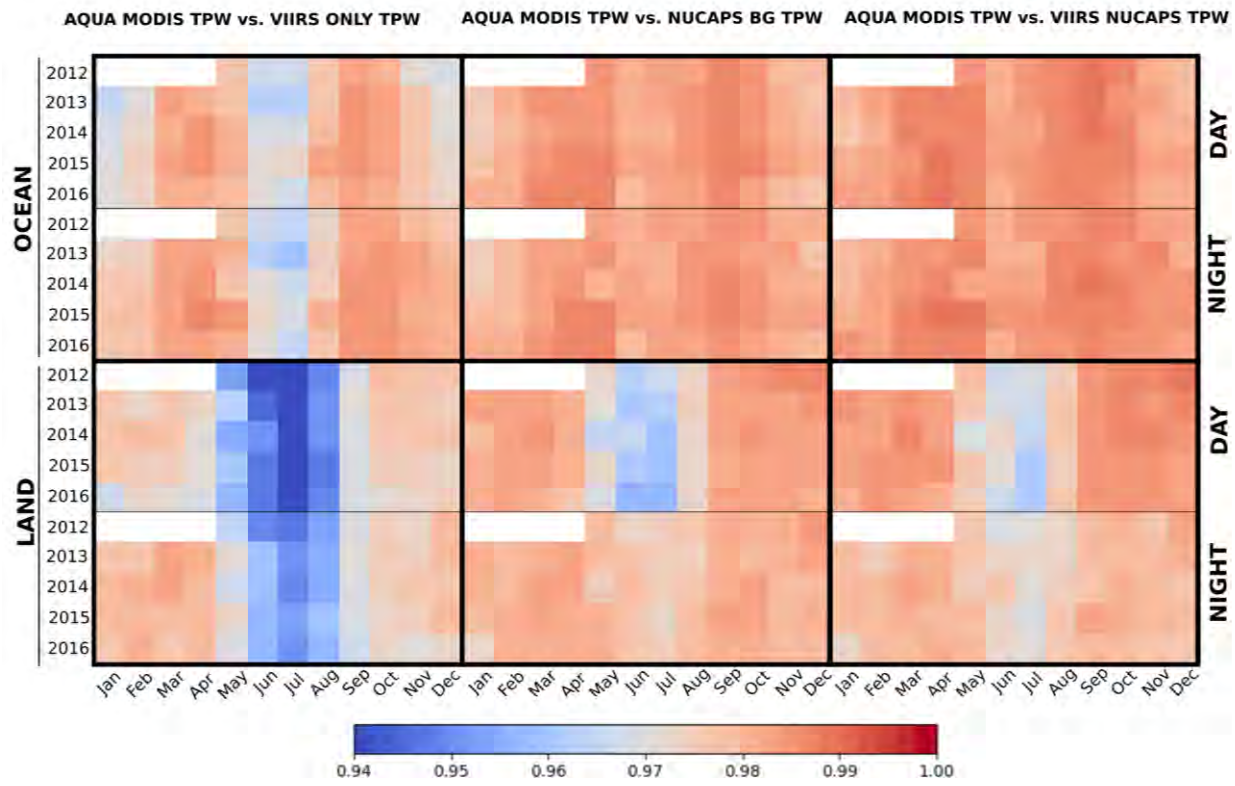

Figure 10: The correlation table shows the relationship between the Aqua MODIS and VIIRS-only(left blocks), NUCAPS(middle blocks) and VIIRS+NUCAPS (right) monthly mean Level-3 data products, separated by day, night, ocean and land.

Summary

- The Level-2 6-minute and 750 m spatial resolution VIIRS TPW product file includes the collocated NUCAPS background TPW, the VIIRS-only TPW, and VIIRS+NUCAPS TPW with a quality flag.
- The Level-3 VIIRS TPW products are daily and monthly means aggregated to 0.5 degree spatial resolution separated by day and night.
- The Level-3 products have been processed for data between May 2012 and December 2016.
- The Level-2 and Level-3 comparison with Aqua MODIS showed that VIIRS+NUCAPS TPW quality is better than VIIRS or NUCAPS only. Values missing in the NUCAPS only due to failed

retrievals are filled by using VIIRS only values. Values missing in VIIRS and MODIS only due to interference by clouds are filled by using smoothed NUCAPS values.

- The VIIRS+NUCAPS combined TPW algorithm is producing near-MODIS quality TPW in the comparison between 2012-2016 with r2 values greater than 0.95 over land and ocean both day and night.

Accomplishments:

- Second release of the Collection 1 VIIRS Level 2 TPW algorithm has been delivered to Atmosphere-SIPS for reprocessing and has been reprocessed from the whole mission.
- The VIIRS TPW Level 3 algorithm has been delivered to SIPS and has been processed for the whole emission.
- The VIIRS TPW L3 daily and monthly mean global products have been evaluated with MOD07 L3, AIRS L3, SSMI and NWP analyses data.
- The ATBD and the VIIRS TPS Users' guide is released.

Travel/Publications/Presentations:

Eva Borbas was attending the 21 International TOVS Study Conference (ITSC21) and the 2017 AGU Fall Meetings.

- Borbas, E., Z. Li, W.P. Menzel, M. Rada and L. Dobor: The Suomi-NPP VIIRS Total Precipitable Water Product, (poster) International TOVS Study Conference, Nov 29-Dec 5, 2017, in Darmstadt, Germany
- Borbas, E., Z. Li, W.P. Menzel, M. Rada and L. Dobor: The Suomi-NPP VIIRS Total Precipitable Water Product, (poster) AGU 2017 Fall Meeting, Dec 11-15, 2017, New Orleans, USA.
- Borbas, E., Z. Li, W.P. Menzel, L. Dobor and M Rada: VIIRS-NUCAPS TPW Algorithm Theoretical Bases Document. V0.5 will be available at ftp://ftp.ssec.wsc.edu/ICI/VIIRSTPW/docs/viirstpw_atbd_v0.5.pdf
- Borbas, E., Z. Li, W.P. Menzel, L. Dobor and M Rada: VIIRS-NUCAPS TPW Users's guide. V0.5 will be available at ftp://ftp.ssec.wsc.edu/ICI/VIIRSTPW/docs/viirstpw_atbd_v0.5.pdf

Award:

- First place for The Best Poster Presentation at the International TOVS Study Conference, Nov 29-Dec 5, 2017, in Darmstadt, Germany