

GOESR3 Final Report

Reporting Period: July 2017 – June 2020 (full 3-year period)

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Project Title: Using the New Capabilities of GOES-R to Improve Blended, Multisensor Water Vapor Products for Forecasters

Project Number: 444

Executive Summary

Note: Although this is technically called the final report, the project is on a no-cost extension through June 30, 2021. A final report will be written at project completion.

This project began in July 2017 and has the major goal of evaluating and developing techniques to include the new GOES-16/17 Total Precipitable Water (TPW) retrievals into blended TPW products for forecasters. The GOES-R spacecraft provides much higher spatial and temporal resolution for TPW than ever available previously. At project inception, GOES-16 TPW retrievals were new and unproven for forecaster use in blended products for forecasters. The ultimate goal at project completion is to have new methodology and modules using GOES-16/17 data ready to transition to operations to enhance the NOAA operational blended TPW product. This task has been completed and the CIRA team was contacted by Walter Wolf (NESDIS OSPO) in May 2020 for planning on a federal FY21 start to this effort. CIRA would submit a proposal in roughly November 2020 to migrate the blended TPW software with GOES-R additions into the NOAA NDE environment running on Linux in the cloud. Required documentation will also be created. This outcome is a major success of the project.

A second project goal is to create and evaluate the utility of novel cloud-free water vapor channel imagery. This imagery is created from the microwave only Advected Layer Precipitable Water (ALPW) product, which is planned to begin transition to operations in 2021. This imagery is being produced hourly at CIRA for both GOES-16 and GOES-17, and shows promise to “see through” cirrus-impacted water vapor channels (bands 8, 9 and 10, 6.2 to 7.3 μm) and allow forecasters to see whether the underlying atmosphere is moist or dry.

Major milestones for evaluation of the GOES-R TPW merged with polar orbiter microwave retrievals were accomplished in two forecaster-driven experiments:

- Evaluation in the Hazardous Weather Testbed (HWT) 2019 experiment (6 weeks)
- Evaluation in the Flash Flood and Intense Rainfall (FFaIR) experiment in 2019 (4 weeks)

Both of these experiments involved CIRA producing a new blended TPW product, informally called Blended TPW 2020 (BTPW2020), with GOES-16 data and delivering hourly in AWIPS-2 format. 68 % (HWT) and 82 % (FFaIR) of forecasters responded that the new merged TPW product performed better than the current NOAA operational blended TPW product, and a majority said that hourly resolution is sufficient. Near-realtime distribution of BTPW2020 to the NOAA Weather Prediction Center (WPC) continues, and input components and the final BTPW2020 product are available as a six-panel animation at http://cat.cira.colostate.edu/btpw_2020.

The feedback received from the 2019 experiments, as well as CIRA validation against Global Positioning System (GPS) surface sites, radiosondes, and the NASA Orbiting Carbon Observatory-2 (OCO-2) continue to show the stable performance and low error of GOES-16/17 TPW. RMS errors are typically 2-3 mm versus GPS and sonde, in agreement with the recent paper of Schmidt et al. (2019).

Evaluations at CIRA during the summer of 2020 during GOES-17 loop heat pipe interference episodes indicates that the GOES-17 data screening is not of sufficient quality during these times for use in BTPW2020. Better screening of bad GOES-17 TPW retrievals might alleviate this issue and investigation continues. The CIRA code was written in 2018, and new quality flags and interpretations have been posted since then at <https://www.goes-r.gov/users/GOES-17-ABI-Performance.html>. We are using the August and October 2020 periods to investigate this further.

In the remainder of time under the no-cost extension, several important tasks remain:

- Deliver cloud-free GOES water vapor imagery to partner offices. Summarize comments from forecasters. Develop VISIT training module on BTPW2020.
- Develop VISIT training module on cloud-free GOES-R water vapor imagery.
- Submit journal paper, notional title “A New Advectively Blended TPW Product for Forecasters Using GOES-R”. Submit journal paper, notional title “Cloud-Free GOES-R Water Vapor Imagery for Forecasting”.
- Final report and VISIT teletraining sessions.

Project attention is now focused on the simulated cloud-free water vapor channel imagery. Near-realtime animations of simulated cloud free Channel 9 (6.9 μm) imagery from GOES-16 and a “Cirrus Over Dry” product are available at http://cat.cira.colostate.edu/GR3/GOESR_TB09_SIM_Hourly.htm. GOES-17 Channel 9 simulated data is available at http://cat.cira.colostate.edu/GR3/GOES17_TB09_SIM_Hourly.htm. Both of these products are driven by the CIRA Advected Layer Precipitable Water (ALPW) product derived from 7 polar orbiters. These products thus represent a fusion of NOAA’s geostationary and polar satellite data. The expected user audience for these products is in tropical cyclone forecasting, although we expect other uses to be discovered. After the busy Atlantic hurricane season currently in progress, we will begin delivery of the simulated water vapor data to the National Hurricane Center (NHC).

Final Year Milestones (FY19) and Project Deliverables

Note: These items will be completed during the no-cost extension period.

- Deliver cloud-free GOES water vapor imagery to NHC. Summarize comments from forecasters.
- Develop VISIT training module on BTPW2020 with GOES-R.
- Develop VISIT training module on cloud-free GOES-R water vapor imagery.
- Submit journal paper, notional title “A New Advectively Blended TPW Product for Forecasters Using GOES-R”. Submit journal paper, notional title “Cloud-Free GOES-R Water Vapor Imagery for Forecasting”.
- Final report and teletraining sessions.

Discussion of operational transition readiness for any project outcomes

As reported in previously mid-year reports, the BTPW2020 product using GOES-16 has graded out higher than the NOAA operational Blended TPW product in HWT and FFaIR. A summary of forecaster evaluations from HWT and FFaIR is shown in Figure 1. Participation in the experiments in 2020 was planned, but due to the COVID-19 outbreak HWT was cancelled and FFaIR proceeded with more limited evaluations which did not include BTPW2020. An invited seminar on BTPW2020 was presented at FFaIR.

In spring 2020, further independent evidence of the improvement of BTPW2020 over the NOAA operational product, and particularly the strong positive impact provided by GOES-16 TPW, was developed by comparison to coincident radiosondes. Radiosondes are not used in any of the blended TPW products so they represent a truly independent comparison, unlike surface GPS. A summary of the results is shown in Figure 2. There are five components and blended products compared to radiosondes during this time period. These are:

1. Advected polar microwave retrievals
2. GOES-16 TPW
3. Short range (100 km) extrapolation of GPS sites
4. Operational blended TPW
5. BTPW2020

Number of radiosonde matchups (n), correlation coefficient (r^2), and RMS and bias errors are shown. Notice the excellent performance of the GOES-16 component, which has performance only surpassed by the spatially limited GPS network. GOES-16 TPW clearly outperforms advected polar microwave, with an RMS error of 2.7 vs 4.3 mm, an improvement of nearly 60%. Previous validations of GOES-16 against surface GPS showed RMS values of 2.6 mm and a bias of -0.4 mm, in excellent agreement with the radiosonde comparisons. It is encouraging that all the components have minimal bias of < 1 mm, which is key in a blended product as reduction techniques such as histogram matching do not need to be applied. It is also encouraging that all the components of BTPW2020 and the new BTPW2020 product outperform the operational blended TPW. This is strong evidence that the operational product can be improved, and these results support the forecaster evaluations gathered during 2019. The strengths of each product (GOES-R in clear sky, advected polar in cloudy regions, GPS in limited land regions where the network is dense) can be leveraged to make a better blended TPW product.

The BTPW2020 algorithm is hierarchical, and overlays sensors in this priority order: First GOES-16/17, second GPS short range extrapolation, and finally advected polar.

An example of the BTPW2020 product is shown in Figure 3, and a 12-hour loop updated hourly showing a six-panel plot of the components is at http://cat.cira.colostate.edu/btpw_2020. Notice that both GOES-16 and -17 are being used as seen in the date source code panel.

The CIRA team has been exploring the impact of GOES-17 loop heat pipe-impacted retrievals on the product. The key science question is whether the bad retrievals are sufficiently flagged that lines marked as good can be used, or whether during these times the GOES-17 retrievals need to be excluded completely. An example of impacted retrievals is shown in Figure 4, which has the same layout as Fig. 3. It was hoped that a seamless / stripeless final product will be created during this time, but just using the GOES-17 flagged retrievals still generates a product with stripes and artifacts. Either better flagging of bad scan lines or entire full disk images during these times needs to occur, or GOES-17 needs to be excluded completely during the times of this interference. We will continue to investigate this issue during the fall eclipse season.

PI Forsythe was contacted by Walter Wolf (NESDIS OSPO) and Ralph Ferraro (NOAA STAR) in May 2020 for planning on a federal FY21 start the transition of BTPW2020 to operations. Initially OSPO was interested in an FY20 start, which CIRA would have been able to support, but decided to wait until FY21. Currently, CIRA is planning to submit a proposal in roughly November 2020 (assuming a nominal NOAA budget planning schedule) to migrate the blended TPW software with

GOES-R additions into the NOAA NDE environment running Linux on the cloud. Required documentation and technical assistance will be provided for this migration. This work would occur in 2021, and after passing required technical reviews the operational blended TPW would be upgraded to the BTPW2020 approach (it will still be called blended TPW within NOAA) in late 2021 or early 2022. This path is made easier since this is an enhancement to an existing operational product versus a new product, requiring fewer formal reviews.

Additional Information

1. Interaction with operational partners –

John Forsythe presented the talk “Towards the Next Generation of Blended Total Precipitable Water (TPW) for Operations” on June 25, 2020 during week 2 of the 4-week Flash Flood and Intense Rainfall (FFaIR) experiment, nominally at the Weather Prediction Center (WPC) but being performed virtually. There were 31 attendees, mostly operational NWS forecasters. The talk focused on how TPW is increasing in the atmosphere (global mean increase of +1.5% / decade over ocean) and is a key variable supporting flooding rains, and how the current operational blended TPW product is being improved via new sensors (GOES-16/17), advective blending, and a new blending approach. Hats off to the team at WPC for making the experiment happen virtually.

The BTPW2020 product in AWIPS-2 format is flowing into WPC every hour, via the CIRA LDM. Andrew Orrison (WPC) and Michael Folmer (OPC) have acknowledged receipt of the data.

The final major product to be delivered from the project is simulated cloud-free GOES water vapor channel imagery. Channel 9 (6.9 μm imagery) has been the focus, as it shows mid to upper tropospheric moisture and is the most widely used by forecasters, but channels 8 and 10 are also created. CIRA has been producing Channel 9 imagery hourly for GOES-16 and GOES-17, and it is available via the web at:

http://cat.cira.colostate.edu/GR3/GOESR_TB09_SIM_Hourly.htm. (GOES-16) and
http://cat.cira.colostate.edu/GR3/GOES17_TB09_SIM_Hourly.htm. (GOES_17)

An example is shown in Figure 5, from August 26, 2020 when Hurricane Laura was in the northwest Gulf of Mexico. Work remains to write this imagery out in AWIPS-2 (or McIDAS as desired) format and deliver in near realtime to the National Hurricane Center. We will work on rendering and formatting this product at CIRA by November 2020, then deliver to NHC in the off season. A VISIT teletraining session will be created to explain this imagery.

2. Conference/workshop participation –

John Forsythe presented the talk “Recent Advances in Water Vapor Products from Satellites for Forecasters” on July 15, 2020 at the Virtual Alaska Weather Seminar (VAWS), hosted by the University of Alaska-Fairbanks and the Geographic Information Network of Alaska (GINA). There were 61 registered attendees. The talk focused on how the current operational blended TPW product is being improved in BTPW2020 via new sensors (GOES-16/17), advective blending, and a new blending approach. Heavy rain and snow events in Alaska often have a connection to the tropics or decaying tropical cyclones which can be tracked via these products.

“Multisensor Satellite-Driven Water Vapor Products for Forecasters” accepted for oral presentation at National Weather Association annual meeting September 12-17.

The abstract “New Developments in Multisensor Blended Water Vapor Products” was submitted to the “Integrating JPSS and GOES-R Observations to Improve Forecasting” session for the AMS 17th Annual Symposium on Operational Environmental Satellite Systems.

3. Outside project publicity –

N/A

4. Journal articles –

Submitted to *Atmospheric Chemistry and Physics* on July 29, 2020, currently in review:
“Satellite Imagery and Products of the 16-17 February 2020 Saharan Air Layer Dust Event over the Eastern Atlantic: Impacts of Water Vapor on Dust Detection and Morphology” Lewis Grasso, Dan Bikos, Jorel Torres, John F. Dostalek, Ting-Chi Wu, John Forsythe, Heather Q. Cronk, Curtis J. Seaman, Steven D. Miller, Emily Berndt, Harry G. Weinman, and Kennard B. Kasper.

This paper illustrates how water vapor impacts the detection of airborne dust via the widely used Tb (10.35 μm) – Tb (12.3 μm) channel difference from GOES-16. Specifically, dust was detected when values of layer or TPW were approximately 14 mm, but dust was masked when values of TPW were approximately 28 mm. In other words, water vapor masked infrared dust detection if sufficient amounts of water vapor existed in a column. Figures 6 and 7 show Geocolor and channel difference imagery indicating loss of signal in the southern portion of the dust plume.

This study was initiated under this project in year 2 to examine if omitting atmospheric dust from radiative transfer simulations of GOES-16/17 water vapor channels 8-10 caused any errors. As these simulations are driven by passive microwave data which is insensitive to dust, the concern was that if the water vapor channels showed sensitivity the simulations would be in error. Results showed that only a very minor error (0.2 K) would occur from heavy dust in a very dry atmosphere. Output from a simulation with varying water vapor and dust loading between 2 – 4 km is shown in Figure 8. Water vapor increases to the right, and dust mass mixing ratio increases vertically. The nearly vertical line are brightness temperature deviations. A vertical line means no impact. Only the leftmost (driest) lines show any impact, and the effect rapidly asymptotes with higher dust loads. This means that our approach to simulate GOES-16 channels 8-10 without simulating aerosols is appropriate.

Key Graphics

Question	2019 HWT (severe wx experiment)	2019 FFaIR (flash flood experiment)
1. Did the new Merged TPW product perform better than the operational blended TPW?	(responses = 79) 68% YES 32% NO	(responses = 80) 70% - much better 12% - better 14% - same 4% - worse
2. Is <u>hourly temporal resolution</u> sufficient?	(responses = 35) 60 % Yes 40 % No	responses = 25) 68% Yes 12 % No (20 % N/A)
3. Would you like a TPW product that is completely <u>independent of model moisture fields</u> ?	(responses = 35) Yes, but - 45% No, but - 40% No definitive answer - 15%	(responses = 15) Yes - 60% No - 7% Yes and No - 7% No position - 26%

Figure 1: Summary of forecaster rankings from the HWT and FFaIR experiments in spring and summer, 2019.

Radiosonde matchups over CONUS: March 21, 2020 – June 12, 2020

Source	n	r ²	RMS (mm)	Bias (mm)
Advection Microwave:	17485	0.92	4.3	0.17
GOES-16 TPW:	3951	0.96	2.7	-0.40
GPS short range:	710	0.96	2.4	-0.67
Operational Blended TPW:	17632	0.91	4.6	-0.99
BTPW2020:	17632	0.94	3.7	0.20



24% improvement in RMS error from 4.6 mm to 3.7 mm

Figure 2: Validation against radiosonde of r², RMS and bias of different components and the overall BTPW2020 product versus the operational blended TPW product. Radiosondes from March 21 to June 12, 2020 over CONUS and adjacent regions used as independent truth (locations shown on map).

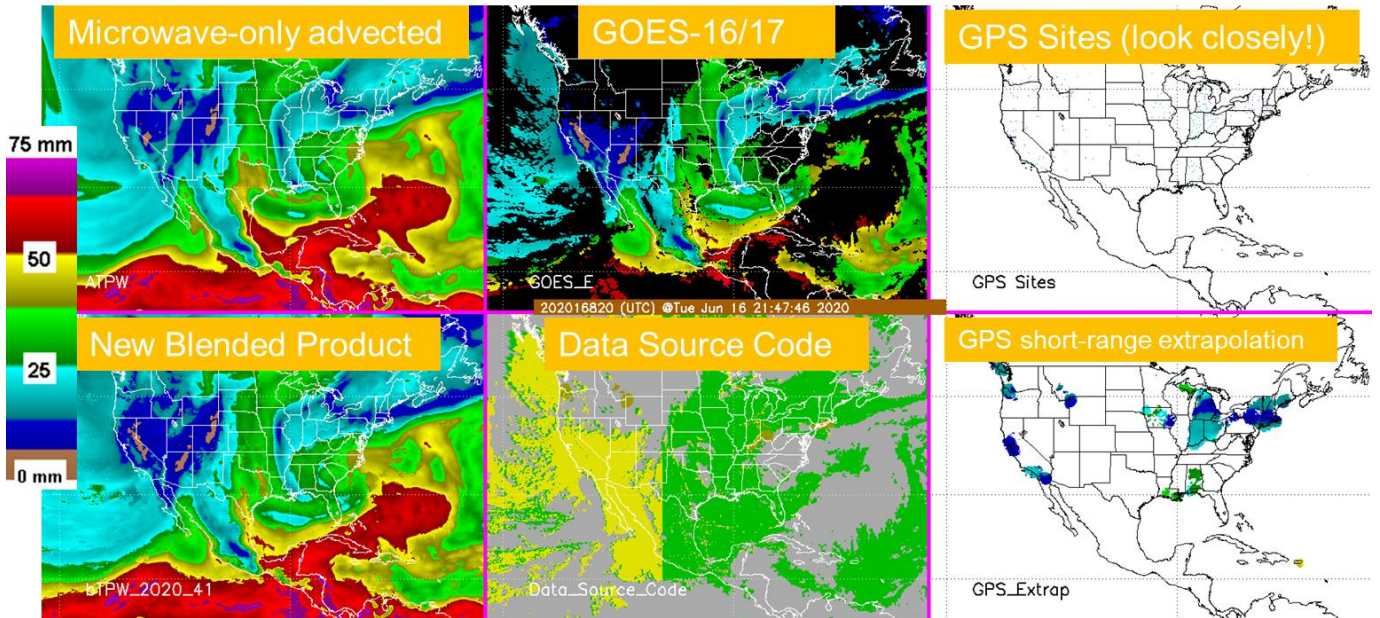


Figure 3: Six-panel plot of the components, new blended BTPW2020 product, and data source code map at 20 UTC 16 June 2020. Data source code color key is GOES-17 (yellow), GOES-16 (green), advected polar microwave (grey) and GPS short range (gold). Near-realtime animations available at http://cat.cira.colostate.edu/btpw_2020/.

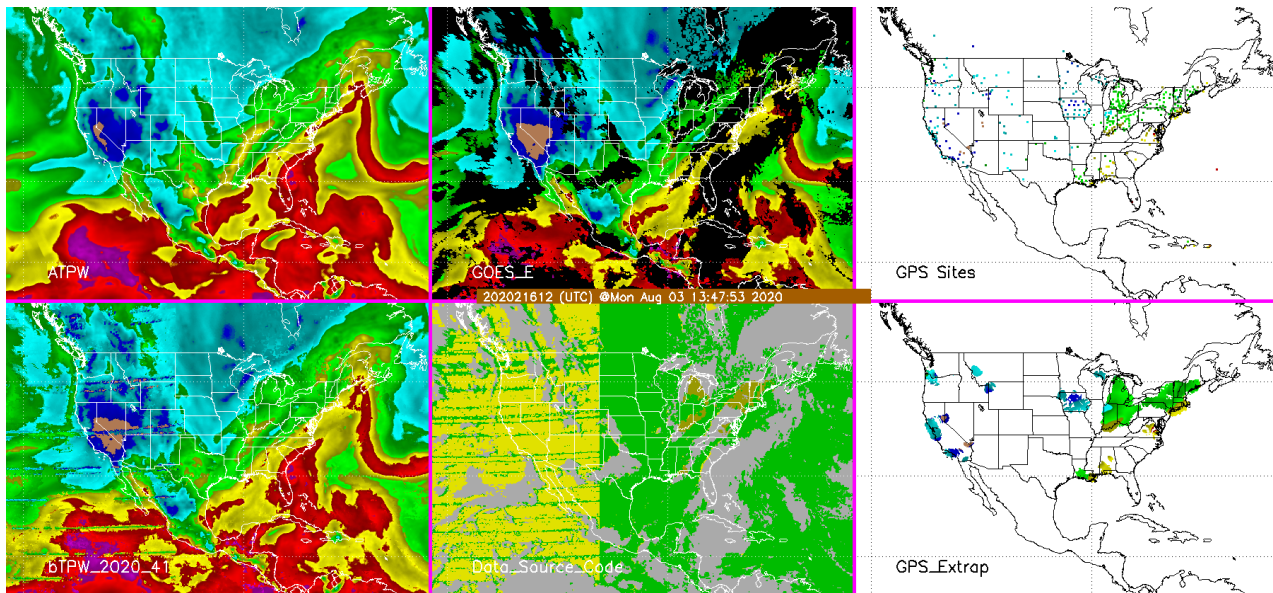


Figure 4: As in Fig. 3, but showing the impact of GOES-10 loop heat pipe-impacted retrievals. GOES-16 retrievals (green data source code) are used where the GOES-17 retrievals are marked as missing. Data from 12 UTC 3 August 2020.

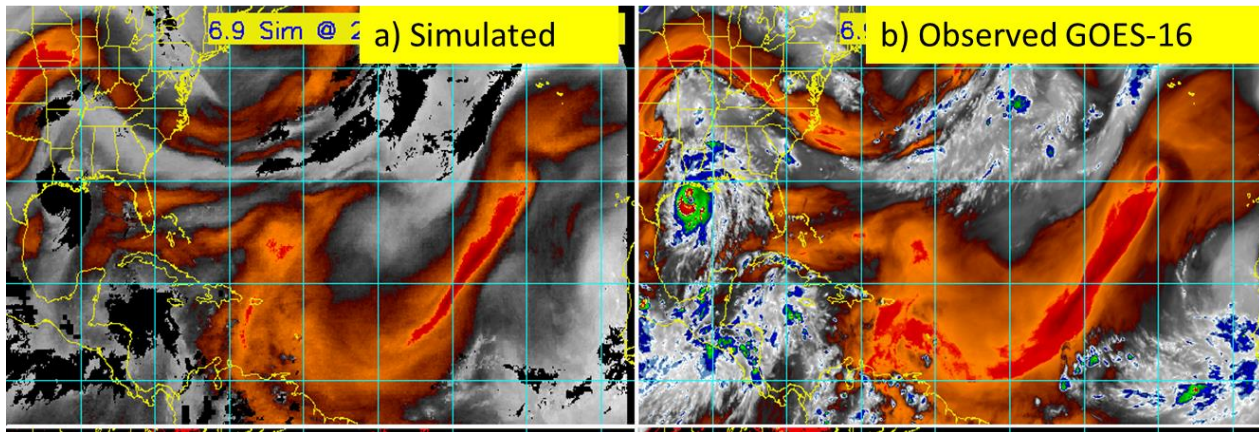


Figure 5: a) Simulated cloud free and (b) observed GOES-16 channel 9 radiance at 2300 UTC 26 August 2020. Major Hurricane Laura visible in Gulf of Mexico.

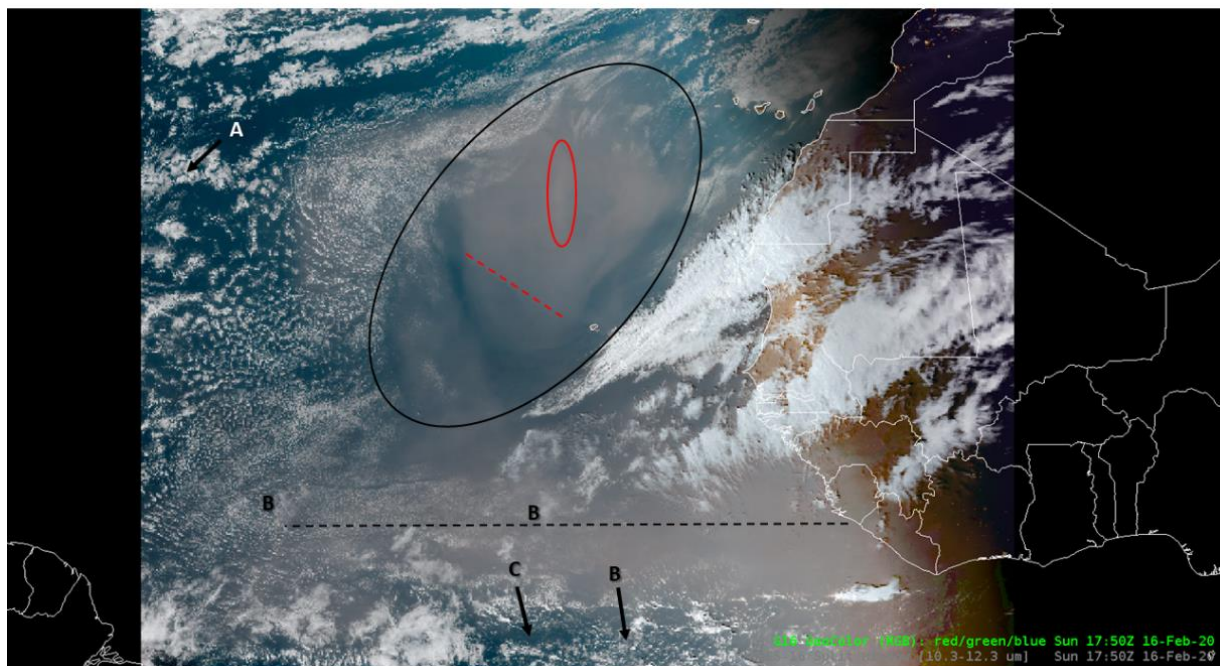


Figure 6: GeoColor imagery diagnosed from ABI on GOES-16, valid 1800 UTC 16 February 2020, along with the following annotations: A black oval bounds dust in the northern dust region while the horizontal, black, dashed line highlights dust in the southern dust region.

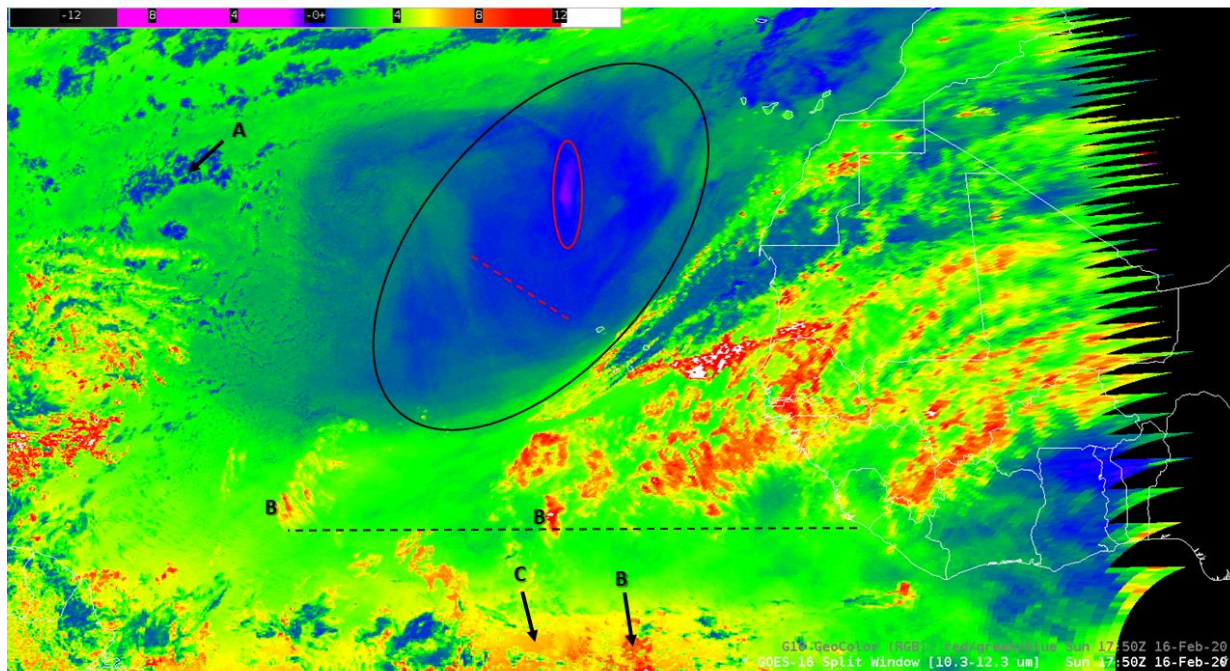


Figure 7: Channel difference, $T_b(10.35 \mu\text{m})$ minus $T_b(12.3 \mu\text{m})$ ($^{\circ}\text{C}$), from ABI on GOES-16 valid at 1800 UTC 16 February 2020. Annotations are the same as in Fig. 6. Dust is indicated by the blue and purple colors within the black oval in the northern dust region. There was a lack of a dust signal in the southern dust region.

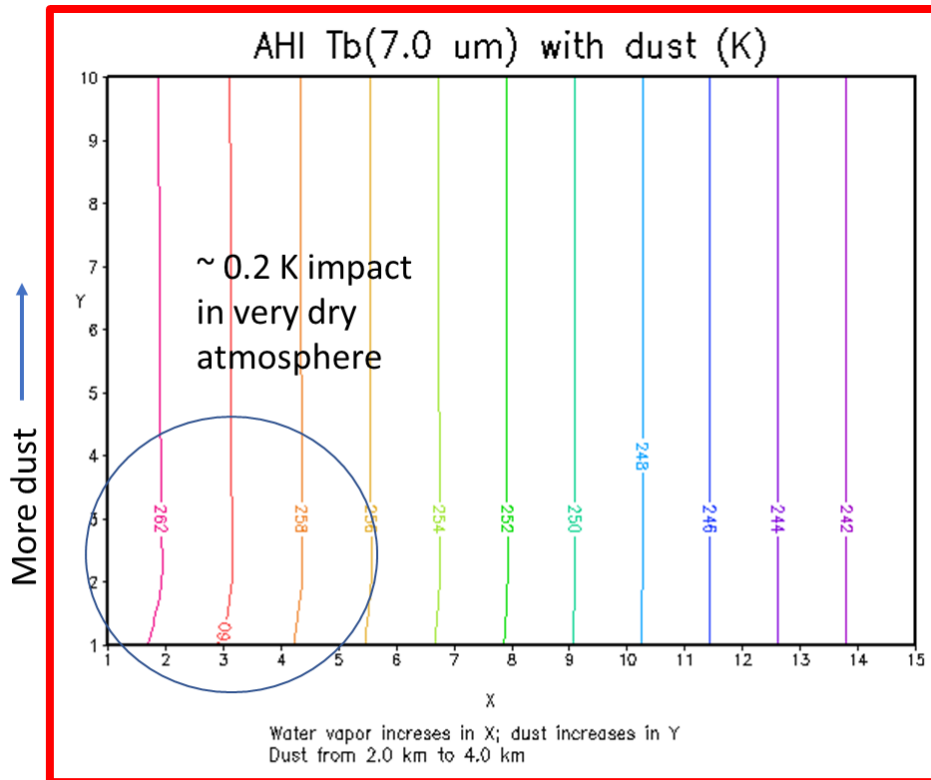


Figure 8: Simulation of dust impact on 7.0 μm data. Dust layer from 2-4 km. Vertical lines indicate no impact. Only at very dry atmospheres (circled) is a small impact seen. From paper in review (Grasso et al. 2020). Simulations show for AHI instrument but ABI is very similar.