560 THE ART AND BEAUTY OF GOES-16

Frederick R. Mosher; Professor Emeritus
Chris Herbster
Embry-Riddle Aeronautical University, Daytona Beach, FL

1.0 INTRODUCTION

The new generation of geostationary weather satellites has more channels, higher spatial resolution, and faster scanning rates than previous generations of weather satellites. The various channels were selected as means of providing new products which would be useful in weather forecasting. When NOAA was having meetings of scientists 15 to 20 years ago to determine the requirements for the various channels for the new GOES-R series of satellites, NOAA insisted that each new channel be required for some scientific purpose. When a green channel was suggested so that natural color satellite images could be shown to the public, NOAA's reaction was that they would not spend money just for the sake of making “neat” looking images. After much discussion, the current 16 channels for the GOES-R were implemented. NOAA then formed working groups for the development of scientific products from the GOES channels. Twenty five baseline products were developed to be ready on day one of the GOES-16 operations, and another 30 products were specified to be developed in the future. NOAA funded development of the baseline products and most were ready five years before the launch of the GOES-16 satellite. After the launch of GOES-16, the first image was released by NOAA on Jan. 23, 2017. The release showed images of the 16 individual channels and a full color image of the Earth. None of the official derived baseline products were released.

* *Corresponding author address:* Frederick R. Mosher 1325 Tuckaway Court, Ft. Collins, Colorado 80525; e-mail: moshe774@erau.edu

When the GOES-16 became the GOES-east operational satellite on December 18, 2017, the various NOAA web pages containing GOES-east images and derived products were discontinued to be replaced by a centralized NOAA web location at https://www.star.nesdis.noaa.gov/GOES/index.php. NOAA generates the various baseline derived products, and sends them to the forecasters at the National Weather Service (NWS) via the NOAAport communications system. On the NOAA web page images of the 16 individual channels are available along with a "GeoColor" derived product. None of the official derived baseline products are available on the NOAA web page.

For the past 30 years, the American public have had access to geostationary satellite images of visible, infrared and water vapor channels. Most weather web sites still have these three types of satellite images. While the GOES-16/17 satellites have 16 channels of images, many of the channels look very much like each other. There are minor differences in the appearance of the various channels, but just looking a given image is not sufficient to see the unique information contained in that channel choice. There are 6 visible and near infrared channels which look rather similar, 3 water vapor channels which also look similar, and 7 infrared channels which also look similar. In order to get new information from the various channels, one needs to process multiple images into a new product display. Having a web page with raw images of all 16 channels is rather wasteful of resources, since there is only 3 basic types of unique images that need to be displayed in the raw image format. Beyond that, derived products are needed to show the information contained in the various satellite channels. As an example, look at figures 1a, 1b, and 1c to see

if you can tell any difference. Then look at the derived product (GeoColor) in figure 1d to see the power of generating derived products.

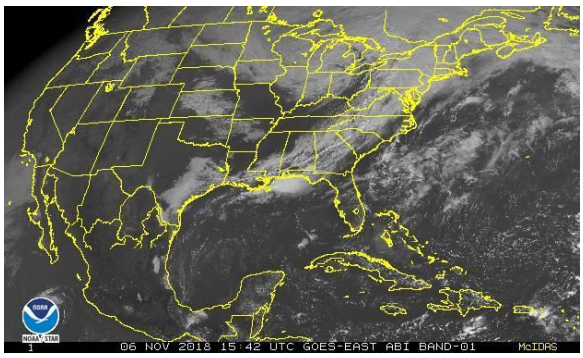

Figure 1a. Raw image from channel 1 of the GOES-16

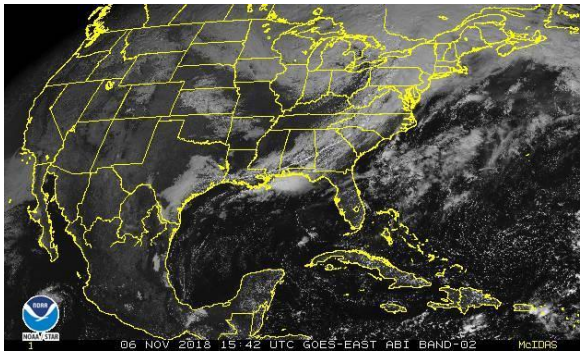

Figure 1b. Raw image of channel 2 of the GOES-16.

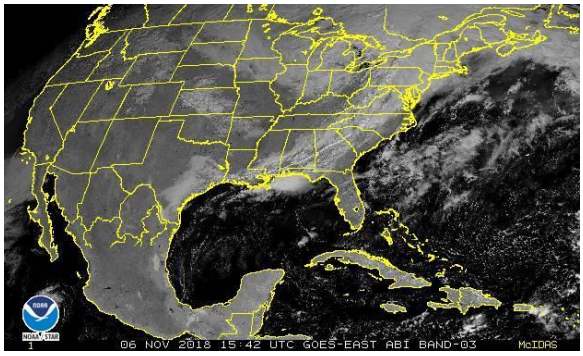

Figure 1c. Raw image of channel 3 of the GOES-16.

Figure 1d. Derived GeoColor image made from the three channels in the figures 1a, 1b, and 1c. This illustrates the power of making derived products available rather than just having the raw images.

NOAA has a variety of derived products available, but has chosen not to make these products available to the American public. Perhaps NOAA could learn from NASA's experience with the Hubble Space Telescope.

2.0 HUBBLE DERIVED IMAGES

The Hubble Space Telescope was launched in 1990, but on checkout it was found that there was a mechanical problem with the optics system which prevented the Hubble from achieving the full design performance goals. A servicing mission in 1993 installed a fix to correct the Hubble telescope to its full intended quality. In early 1994, NASA released before and after photos showing the improved sharpness of the telescope. The Hubble telescope then went into service providing images for astronomers, with little public attention. That changed after April 1995 when Jeff Hester and Paul Scowen of Arizona State University released the image of the "Pillars of Creation". This image forever changed how astronomers present images to the public.

The image is a false color RGB image with the 502 nanometer oxygen band image with going to the blue gun, the 675 nanometer hydrogen band image going to the green gun, and the 763 nanometer sulfur going to the red gun. The study of evaporating gaseous globules (EGG) lead to the creation of the image for

astronomical purposes, but the beauty of the image caused NASA and astronomers to consider how to make beautiful images of stars for release to the public.

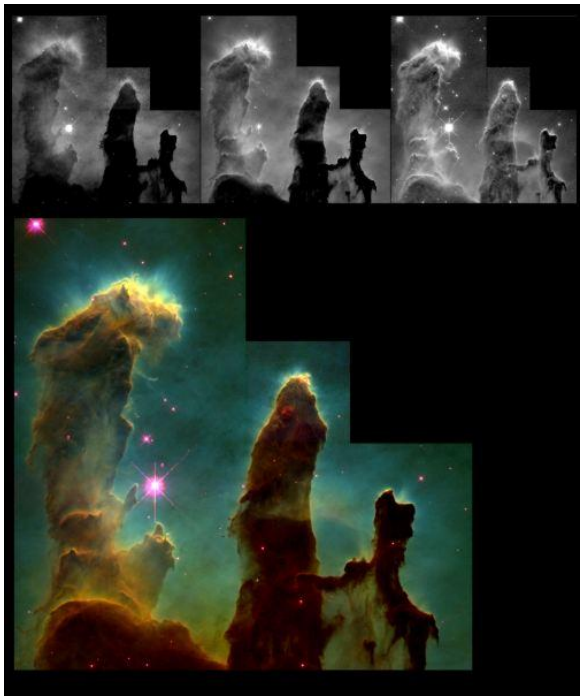

Figure 2. False color RGB image titled "Pillars of Creation" generated from three bands of the Hubble Space Telescope. The oxygen band went to the blue gun, the hydrogen band went to the green gun, and the sulfur band went to the red gun.

NASA has recognized the importance of public enthusiasm for the space program, and has established a NASA art program as one means of bring the scientific results of NASA to the public. NASA has funded graphic artists to assist astronomers in making beautiful images for release to the public. Astronomy images are routinely used as screen savers on PCs. Books of the Hubble images have been published, and posters of the images are available for purchase. NASA has contests for space art. Having public enthusiasm for the NASA astronomy program has resulted in continued generous funding by the American public for the Hubble and other NASA stellar imaging programs.

3.0 Derived Images from GOES-17/18

The 16 specific image channels on the GOES-16/17 satellites were selected with potential products in mind. The following table lists the imager baseline products which were to be ready at the first satellite launch.

Aerosol Detection (Including Smoke and Dust)
Aerosol Optical Depth (AOD)
Clear Sky Masks
Cloud and Moisture Imagery
Cloud Optical Depth
Cloud Particle Size Distribution
Cloud Top Height
Cloud Top Phase
Cloud Top Pressure
Cloud Top Temperature
Derived Motion Winds
Derived Stability Indices
Downward Shortwave Radiation: Surface
Fire/Hot Spot Characterization
Hurricane Intensity Estimation
Land Surface Temperature (Skin)
Legacy Vertical Moisture Profile
Legacy Vertical Temperature Profile
Radiances
Rainfall Rate / QPE
Reflected Shortwave Radiation: TOA
Sea Surface Temperature (Skin)
Snow Cover
Total Precipitable Water
Volcanic Ash: Detection and Height

Table 1. Imager baseline products to be ready in time for the launch of GOES-R (16).

These products are being generated and sent to the National Weather Service forecasters via the NOAAport communications system. In addition to the baseline products, NOAA has plans for additional products to be implemented after the first launch of GOES-16. Table 2 lists these additional future products. Some of these have been completed and are routinely being generated and sent to the meteorologists at the NWS. None of the baseline or future products have been made available to public users via the NOAA web sites.

Absorbed Shortwave Radiation: Surface
Aerosol Particle Size
Aircraft Icing Threat
Cloud Ice Water Path
Cloud Layers/Heights
Cloud Liquid Water
Cloud Type
Convective Initiation
Currents
Currents: Offshore
Downward Longwave Radiation: Surface
Enhanced "V" / Overshooting Top Detection
Flood/Standing Water
Ice Cover
Low Cloud and Fog
Ozone Total
Probability of Rainfall
Rainfall Potential
Sea and Lake Ice: Age
Sea and Lake Ice: Concentration
Sea and Lake Ice: Motion
Snow Depth (Over Plains)
SO_2 Detection
Surface Albedo
Surface Emissivity
Tropopause Folding Turbulence Prediction
Upward Longwave Radiation: Surface
Upward Longwave Radiation: TOA
Vegetation Fraction: Green
Vegetation Index
Visibility

Table 2. NOAA planned future derived products to be implemented after the initial launch of GOES-16. Some of these products are currently being generated and sent to the NWS.

However, some university and other Government web sites have been putting some of these derived products on their web sites. Some of the web sites with derived GOES products include the College of DuPage at https://weather.cod.edu/satrad/exper/ and NASA Marshall Space Flight Center (MSFC) at https://weather.msfc.nasa.gov/cgi-bin/sportPublishData.pl?dataset=goeseastabiconus&product=10p35um.

While the derived products can be useful, not much thought went into the composition and color schemes of the products. They require training to use and often the object of the product show up in subtle changes in the colors, Take as examples the following images obtained from the MSFC web page.

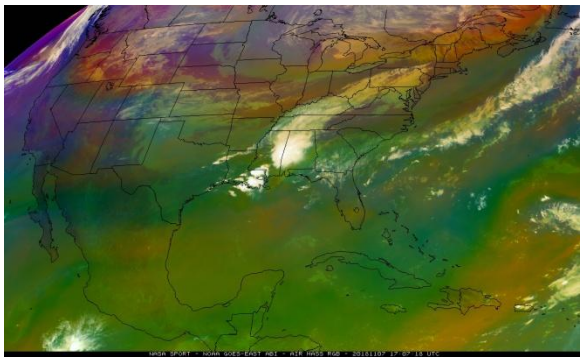

Figure 3a. Air Mass derived image for Nov. 7, 2018 at 17:07 UTC. (Obtained from MSFC SPoRT web site)

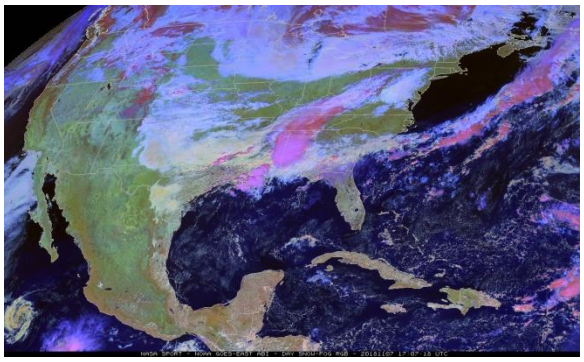

Figure 3b. Snow Fog derived image at the same time as previous figure.

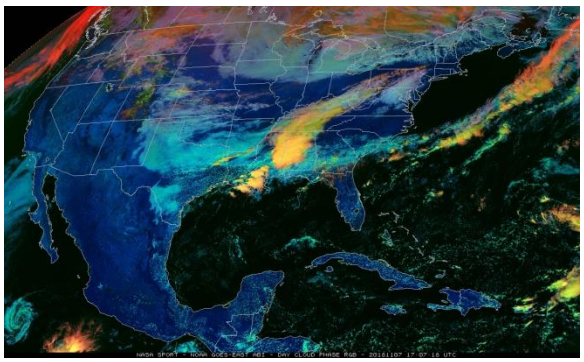

Figure 3c. Cloud Phase derived image at the same time as previous figure.

4.0 ALTERNATIVE DERIVED PRODUCTS

It may be possible to construct derived images which are easier to interpret as well as bing artistically pleasing. Most of the GOES derived products were developed prior to the actual launch of the GOES-16 using simulated data for validation. Since the launch of GOES-16, a number of new, different derived products have been developed at Embry-Riddle Aeronautical University (ERAU) and are available at wx.erau.edu. The following are some of these new derived product:

4.1 WATER VAPOR IMAGES

Water Vapor images show the distribution of water vapor in the upper part of the atmosphere. The GOES-16/17 satellites have three water vapor channels; channel 8 (6.17 microns showing highest level water vapor (around 250-400 mb)), channel 9 (6.97 microns showing mid level water vapor (around 400-550 mb)), and channel 10 (7.34 microns (around 500-850 mb)). Channel 9 is approximately the same as the water vapor channel on previous GOES satellites. The Water Vapor images traditionally are displayed with an enhancement which stretches the brightness values so as to better see the water vapor features. Sometimes color is used to show features such as the jet streaks (i.e. dry, dark features where the jet core causes substance). At the NOAA satellite web site, the three water vapor channels are displayed separately, with three different color enhancements. Figures 4a, 4b, 4c show the NOAA water vapor images.

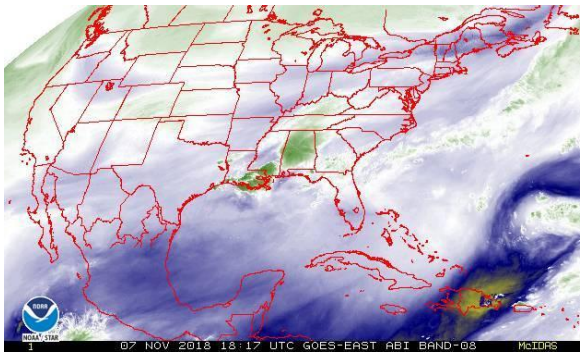

Figure 4a.Channel 8 of GOES-16 for Nov. 7, 2018 at 18:17 UTC from NOAA web site.

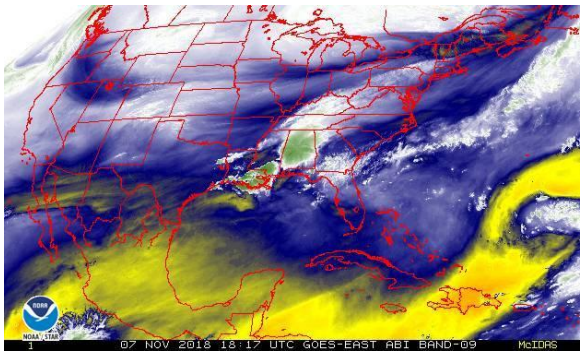

Figure 4b. Channel 9 for the same time as previous figure.

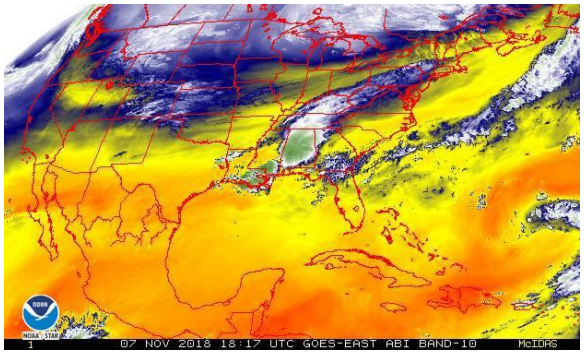

Figure 4c. Channel 10 for the same time as the previous figures.

Rather than display the water vapor images as separate images, ERAU has chosen to display them as a false color RGB image. Channel 8 (the highest level image) is shown on the blue gun, channel 9 on the green gun, and channel 10 (lowest) goes to the red gun. Where the 3 channel image is blue, only the highest level has substantial water vapor. Where the image shows cyan (blue + green) there is a thick layer of water vapor in the upper atmosphere. The lowest channel (red) rarely shows up, other than for mid to low level cloud tops. The three channel image still shows the dry areas associated with jet streams and substance, and also shows more information on the distribution of the water vapor as compared to single channel images. Also many people find the 3

channel water vapor images more pleasing to look at as compared to the single channel images. The following figure 4d shows the 3 channel water vapor image available from ERAU.

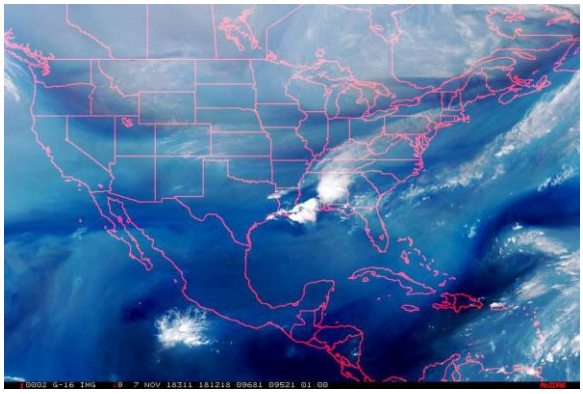

Figure 4d. 3 channel water vapor image from the ERAU web site for the same time as the previous figures.

4.2 SMOKE IMAGES

Smoke is generally composed of very small particles. The blue channel (.47 micron) will show the scattering from the smoke particles, while the longer wavelength channels (such as the .86 micron vegge" channel 3) will not detect scattering from the smoke. The longer wavelength infrared channels will not detect any smoke particles, so it is not possible to detect smoke at night. The ERAU smoke images are generated using a false color RGB technique with the channel 1 going to the blue and green guns, and the channel 3 going to the red gun. The images are brightness normalized to remove the brightness change caused by varying sun angles. In addition to the smoke information, pixels that show a surface skin temperature of hotter than 150 degree F in channel 7 are modified to show a yellow color. Figure 5 shows an image of the ERAU derived smoke display for California wild fires on Nov. 8. 2018.

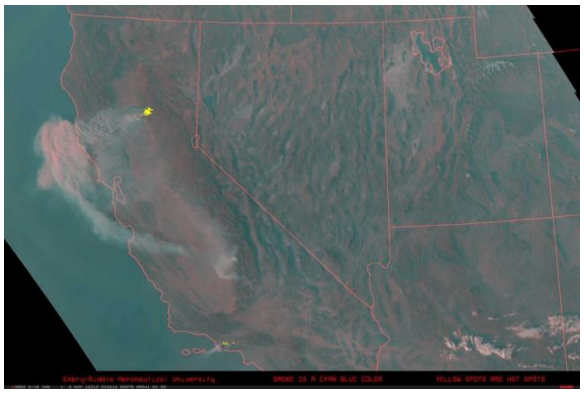

Figure 5. Smoke image for Nov. 8, 2018 at 23:42 UTC. The yellow spots have surface temperatures of greater than 150 degrees F.

4.3 AIRMASS IMAGES

Upper level potential vorticity (PV) is one factor driving cyclogenesis. The European Organization for the Exploitation of Meteorological Satellites (EUMET-SAT) has developed an RGB airmass satellite product using the mid level water vapor channel in the blue gun, the difference between the high and low level water vapor channels in the red gun, and the difference between the 9.7 micron (ozone) and the 10.8 (IR window) channels to the green gun. The intent of the images is to show the tropical air masses (with low levels of ozone) and polar air masses (with higher levels of ozone) superimposed on the water vapor images showing the location of the jet streams. Figure 6a. shows an image of the airmass image obtained from the COD web site for Nov. 10, 2018 at 14:15 UTC.

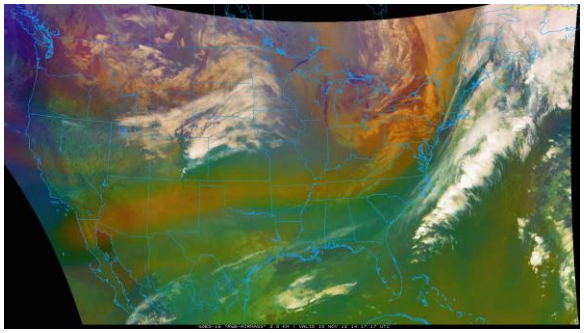

Figure 6a. Airmass image (from COD web site) for Nov. 10, 2018 at 14:15 UTC.

Many users find the traditional airmass images to be difficult to interpret. ERAU has developed a slightly different version of the product called "JETS4". In the ERAU version, the negative of the mid level water vapor image (channel 9) is sent to the red gun. The negative enhancement is used to make the clouds dark, so that your eye is drawn to the underlying jetstream information rather than the clouds. An analysis of the difference between the upper and lower water vapor channels shows most of the information in the difference comes from the upper level channel. Hence the negative of the upper level water vapor image (channel 8) is sent to the green gun. An analysis of the ozone-window IR difference showed that this was not an optimum method of showing the ozone in the upper atmosphere. A temperature difference between the ozone and CO_2 channels (channel 12-16) with the 15 to 35 degree C difference stretched into gray scale of 2 to 254 show more information about the ozone distribution, so it was sent to the blue gun. The resultant image is shown in figure 6b fir the same time as figure 6a.

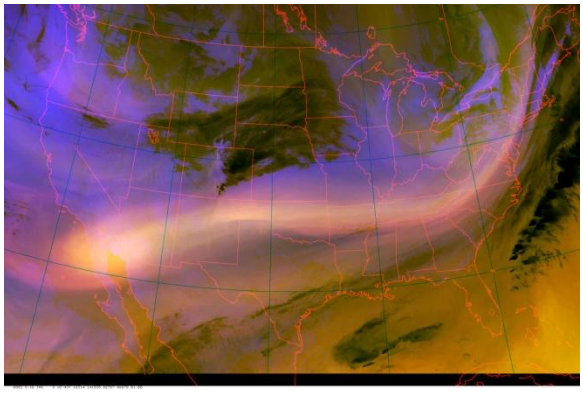

Figure 6b. ERAU version of an airmass image for the same time as figure 6a. The blue areas have high ozone concentrations (polar air masses), the yellow areas have low ozone (tropical air masses), the clouds are shown as black, and the jet streams show up as streaks. Jet streams with white have high levels of ozone showing where stratospheric intrusions have high values of potential vorticity.

4.4 OZONE IMAGES

In the processing of the airmass image, an upper level ozone image was generated from the difference of channels 12 and 16. Since the image was available, it was displayed as a single channel image with a color enhancement. Figure 7 shows the ozone image for the same time as figures 6. The color scale is arbitrary without any calibration.

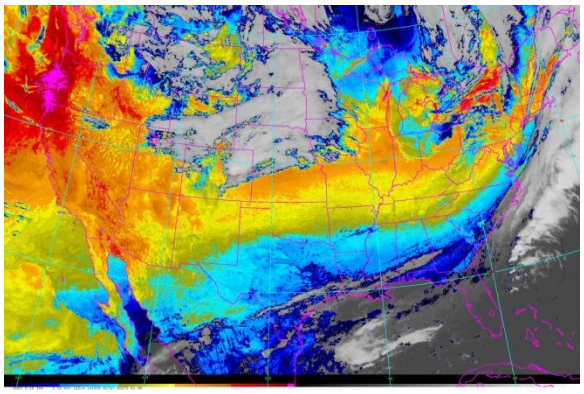

Figure 7. Ozone image generated from the difference of GOES-16 channels 12 and 16. The image is not yet calibrated and the color scale is arbitrary with the reds being higher concentrations of ozone and blues to gray being low concentrations of ozone.

4.5 DUST & ASH

Silicates from rocks have an absorption band which will impact the channel 15 (12.3 microns) and channel 11 (8.44 microns). The difference between the 12 micron (the dirty window) and the 11 micron (the clean window) has traditionally been used to detect dry volcanic ash and wind-blown dust in the atmosphere, such as the Saharan dust blowing off Africa. A volcanic ash and dust product was one of the NOAA day one initial products for the GOES-16. On April 13, 2018 there was a dust storm in west Texas which was severe enough to impact low flying aviation. The Aviation Weather Center (AWC) forecasters noticed the dust on their satellite displays and issued a SIGMET warning aircraft of the dust hazard. Figure 8a shows the derived image used by the forecasters to detect the

dust, and a graphic overlay of the SIGMET and surface observations.

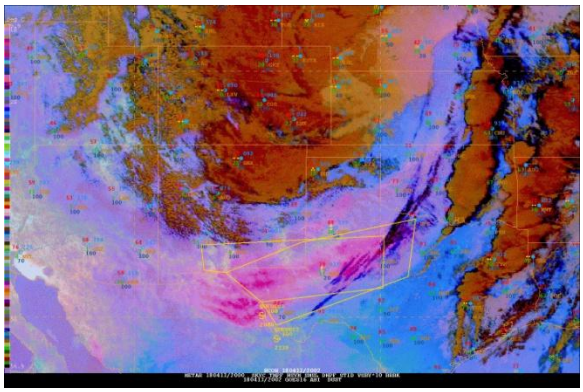

Figure 8a. NOAA derived image of dust (red-pink color) from April 13, 2018 at 20:02 UTC with the overlay of SIGMETs issued to warn aviation of the dust hazard.

ERAU has independently developed an ash & dust algorithm¸ but has used a different design for the end product. The ERAU product adds together the GOES channels 11 and 15 and then subtracts 2*channel 13, and then stretches the resultant temperatures from -5 to +10 degrees C into the gray scale range of 0 255. The image is displayed as a black and white image. The algorithm was designed to eliminate the clouds (as black) so that the only thing showing in white is the dust or ash hazard. This is in contrast to the NOAA product using red (the universal color for hazards) to show the dust. Figure 8b. shows the ERAU dust product for the same time as the figure 8a.

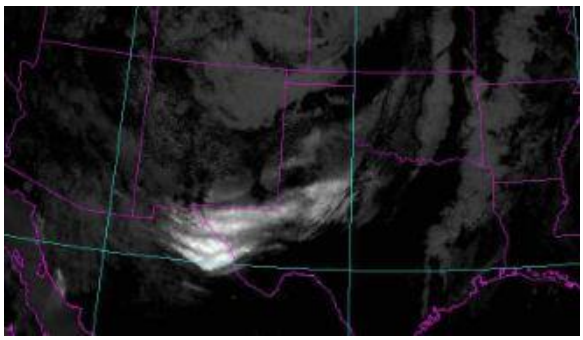

Figure 8b. ERAU ash & dust product for the same time and location as figure 8a.

4.6 PRECIPITABLE WATER (PW) IMAGES

While GOES channels 8, 9, and 10 have strong water vapor absorption bands, channels 7, 14, and 15 have weak water vapor absorption bands. The strong water vapor absorption results in the satellite image of the upper level water vapor distribution. The weak absorption results in a satellite image of the low level water, since most of the water vapor is at lower levels. A precipitable water vapor (PW) image was one of NOAA's day one derived products which is delivered to the NWS, but not to the web. ERAU has independently developed a PW product for the hemispheric 15 minute sectors. The PW product is generated first taking the difference between channels 13 and 14 and stretching the temperature difference of -1 to 3 C into the 0 255 gray scale. This image is sent to the red gun. A second image is generated by taking the difference between channels 13 and 15 and stretching the temperature difference of -1 to 9 C into the 0 255 gray scale. This image is sent to the green and blue guns. The following figure shows the PW image for Nov. 11, 2018 at 16:00 UTC. The higher levels of PW are the bright cyan color, with the darker clear areas being lower level of PW. The thick clouds are a dark brown, while the thin cirrus clouds are white.

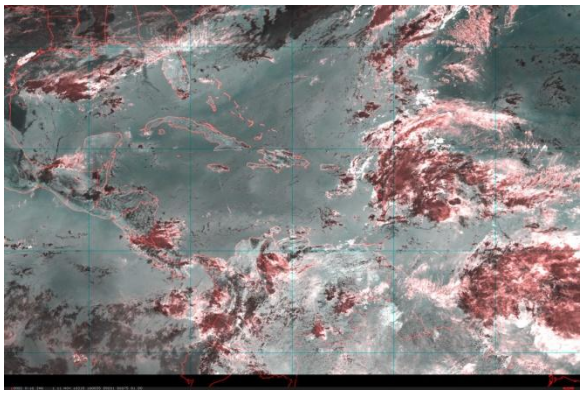

Figure 9. Precipitable Water (PW) image on Nov. 11, 2018 at 16:00 UTC. The higher levels of PW are the bright cyan color with the lower levels of PW being the dark cyan in the clear sky regions. Thick clouds are brown to black while thin cirrus is white.

4.8 COLOR VISIBLE IMAGES

A number of web sites have color visible GOES images. The GOES has a blue (channel 1) and a red (channel 2), but not a green channel. A green channel can be generated form a combination of the red, blue, and near infrared "veggie" (channel 3). The weights assigned to the various channels is arbitrary, so the amount of greenness of the different producers of color GOES visible products will vary. The ERAU product uses weights of .29, .29, and .33 for the channels 1, 2, and 3. The ERAU Day/Night color product has the land greener than the NOAA GeoColor product. The ERAU color product also generates a blue tint for clouds higher than 21,000 feet to help beginning users distinguish low clouds from high. Figure 10a shows the NOAA GeoColor image for Nov. 11, 2018 at 17:02 for the Southern Plains sector while figure 10b shows the ERAU color visible for approximate same region at the same time.

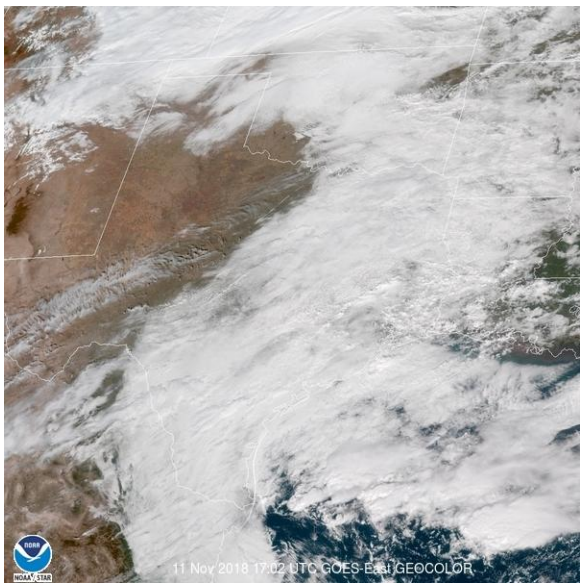

Figure 10a. NOAA GeoColor image for Nov. 11, 2018 at 17:02 UTC for the Southern Plains sector.

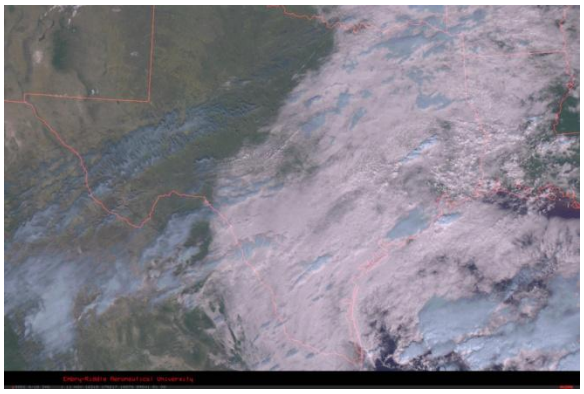

Figure 10b. The ERAU Day/Night color image at the same time as figure 10a. The blue clouds are clouds above 21,000 feet.

At night, there is no reflected sunlight, so the visible channels go dark. Many of the web sites generating color GOES images allow their displays to go to black. However, the NOAA GeoColor and the ERAU Day/Night color images generate derived products at night to allow for the user to continue monitoring the clouds and weather. The GeoColor generates low clouds from the difference in channels 13 and 7 and displays them in blue. The GeoColor generates high clouds from the IR channel 13 and displays them as white. In the clear areas the GeoColor inserts a static image of city lights at night. The ERAU nighttime image also uses the 13-7 difference to generate the low clouds and displays them as white. The high clouds are generated from the channel 13-12 difference and displayed as blue for clouds above 21,000 feet. The 13-12 difference is used to better show cloud thickness as compared to using the channel 13 alone which shows cloud temperature (height). The ERAU nighttime images give a green tint to the clear land areas with brightness values lower than 80 counts and a blue tint to the clear ocean areas. Figure 10c. shows the GeoColor image at 10:02 UTC (nighttime) for the same location as figure 10a, while figure 10b shows the ERAU image at the same time.

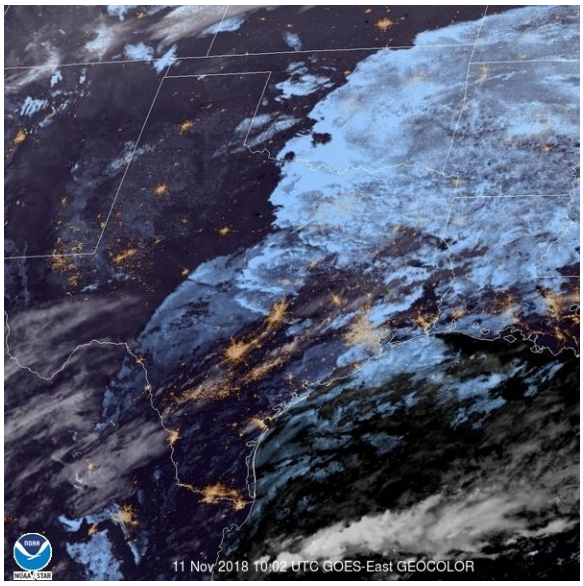

Figure 10c. The GeoColor image for 10:02 UTC (nighttime) for the same location and date as figure 10a. The blue clouds are low clouds, the white are high clouds, and the city lights static image is inserted in clear areas.

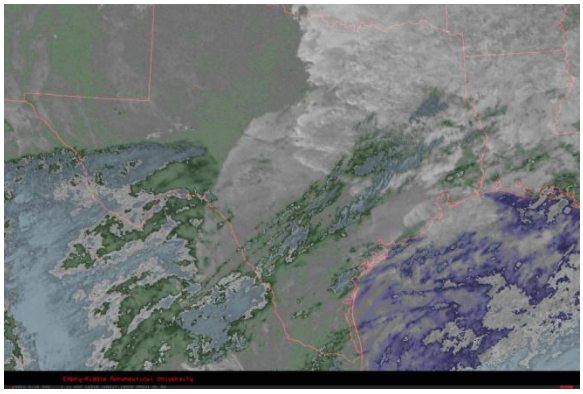

Figure 10d. ERAU Day/Night image for the same time as 10c for the approximately same location. The white clouds are low, the clouds above 21,000 feet are tinted blue, the dim land areas (below 80 counts) are tinted green, while the dim water areas are colored blue.

5.0 RECOMMENDATIONS

The following are recommendations of how to improve the GOES-16/17 products, especially for its public web site at: https://www.star.nesdis.noaa.gov/GOES/index.php

1. NOAA should put all of its operational derived GOES products on its public web page.

2. NOAA should provide graphic artists to assist its scientists in developing artistically pleasing as well as scientifically valid derived products.

3. NOAA should reopen opportunities to develop new or improved derived GOES products.

4. NOAA should monitor the number of raw channel downloads and possibly reduce the raw images on the web page to a visible, water vapor, and infrared product suite.

Currently the American public is not getting the full benefit of the GOES-16/17 satellites. Hopefully in the future they will be able to appreciate the art and beauty of the new GOES satellites.