Forecaster Users Guide
Combined Polar and Geostationary Satellite Atmospheric Sounding Products

1. Introduction

Atmospheric radiance data from polar and geostationary orbiting satellites instruments can provide near-continuous high spatial and temporal resolution atmospheric temperature and humidity soundings on both global and regional scales. Direct Broadcast Satellite (DBS) Polar Hyperspectral Sounder (PHS), Cross-track Infrared Sounder (**CrIS**) and the Infrared Atmospheric Sounding Interferometer (**IASI**) atmospheric radiances are combined with Geostationary Satellite (GS) multispectral Advanced Baseline Imager (ABI) radiances to produce 2-km horizontal resolution temperature and humidity profiles, called 'PHSnABI'. Also, polar satellite MW (i.e., ATMS and AMSU) soundings, derived using the same PHS retrieval methodology, have been fused with the 'PHSnBI' to produce PHSnMWnABI' profiles. Experimental forecast system results indicate that the high-spatial and temporal (30 to 60 min) resolution temperature and moisture measurements resolve the thermodynamic (i.e., atmospheric stability) and dynamic (i.e., horizontal, and vertical motions) processes responsible for localized severe weather. The satellite profiles are continuously assimilated at hourly intervals into 8-km resolution Rapid Refresh (RAP-like) and 3-km resolution High Resolution Rapid Refresh (HRRR-like) Weather Research and Forecasting (WRF) models, to improve the skill of forecasting atmospheric state parameters, including 3-D winds, precipitation, and severe convective weather. The high-resolution satellite sounding/Numerical Weather Prediction (NWP) system has been operated in near real-time (24/7) for the past three years to experimentally demonstrate improvements in the weather analysis/forecast operation expected to result from using the satellite high-resolution sounding data in National Weather Service (NWS) operations. This Forecasters User's Guide is intended to provide the basis for the high-resolution atmospheric profiles and the nowcasting and numerical forecasting products derived from them. Products are available through the NOAA AWIPS system, as well as being made available from University of Wisconsin and Hampton University websites.

2. Atmospheric Sounding Retrieval

The key elements of the 'PHSnABI' retrieval process are: (1) 30 Principal Components (PC) scores are used as regression predictors for the PHS all-sky Dual-Regression (DR) retrievals [1] and GS IR radiances are used as regression predictors for the linear regression ABI retrievals; (2) all spatial samples, at the full spectral resolution of the PHS and ABI channels, are used to optimize the horizontal and vertical resolution of the PHSnABI fusion retrieval product [2], the fusion being performed using the very fast k-dimensional search-tree method [3]; (3) MW soundings [4] are fused with the IR soundings to fill-in the IR-profile gaps below clouds; (4) the IR and MW profiles are de-aliased to provide a vertical resolution comparable to the forecast model vertical resolution [5], the vertical alias removal being performed by computing the radiance spectrum from the forecast model background profile using the ultra-fast PCRTM spectrum-based radiative transfer model [6], the vertical alias being defined as the difference between the model background radiance retrieval and the model background profile used to calculate the radiances; (5) continuous NWP model assimilation of the satellite thermodynamic profile data is used to diagnose, through the numerical integration of the primitive equations of motion, 3-D winds that correspond to the spatial and time variations of the satellite observations [7, 8]. The data are used by a joint University of Wisconsin and Hampton University research team to produce high-resolution (i.e., 2-km spatial resolution and 30-minute temporal resolution) temperature and moisture profiles in near real-time for nowcasting and short-term numerical weather forecasts to provide warnings of localized intense storms.

3. NWP Model Assimilation

'PHSnABI' and 'PHSnMWnABI', and corresponding wind, soundings are assimilated into NOAA operational Rapid Refresh model (RAP)-like and High-Resolution Rapid Refresh model (HRRR)-like Weather Research and Forecasting (WRF) models to produce hourly predictions of precipitation, severe weather (wind, hail, and tornadoes) and other forecast model output variables [6]. Three years of daily operation of the 'PHSnABI' data production and assimilation system have shown significant, and consistent, improvements in the numerical prediction of CONUS region hazardous weather, particularly flood producing rainfall and tornados [6,7].

4. Sounding and Forecast Characteristics

DeAliasing: Figure 1 shows the importance of enhancing regression retrieval vertical resolution to that of the model into which they are being assimilated. The vertical de-aliasing improves the agreement between the satellite derived profile and the radiosonde for both temperature and dewpoint temperature, reducing the dewpoint temperature differences by as much as a factor of 2. Most important is that the DRDA retrieval generally agrees better with the radiosonde than does the RAP model background profile used for the vertical alias removal process.

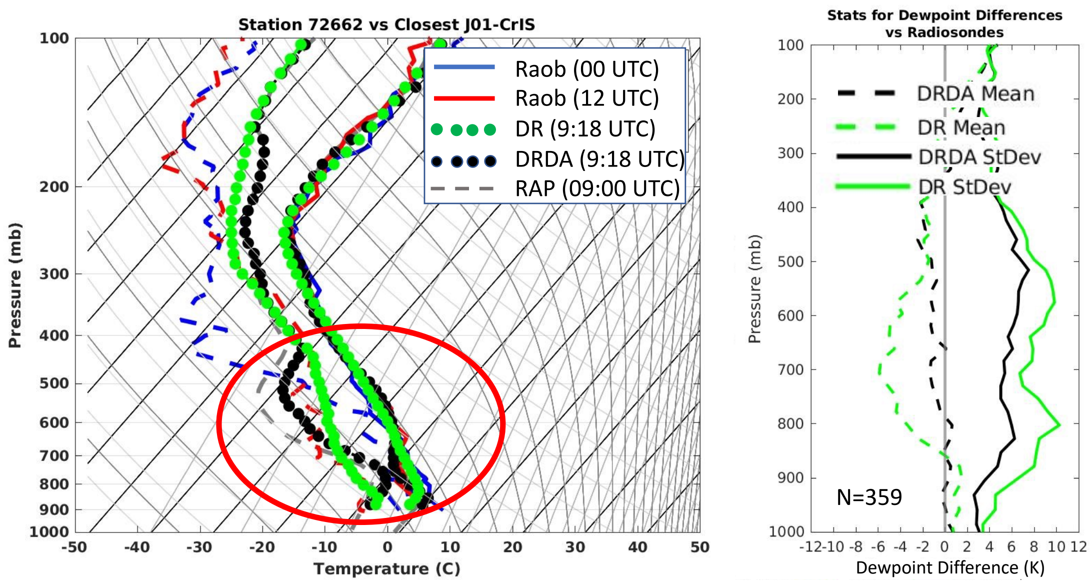

Figure 1. Comparison between Dual-Regression (DR) retrieval and De-aliased DR retrieval (DRDA), together with the model background profile (RAP 2-hour forecast) used for the alias removal, with a nearby radiosonde observation on November 11, 2021.

Humidity Example: Figure 2 shows a comparison between 700-hPa relative humidity profiles derived from PHS, PHSnABI, and PHSnMWnABI radiance observations. The top row of panels shows analyses of combined RAP and satellite retrieval data (i.e., missing satellite retrieval data are filled with RAP data) while the bottom row of panels shows the difference between the

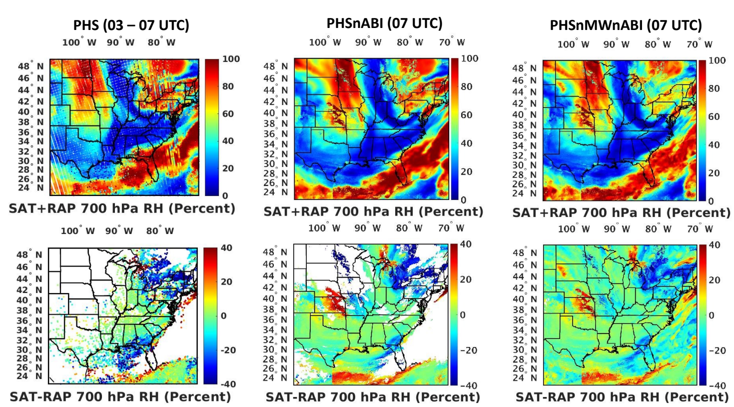

Figure 2. Comparison between three satellite retrieval products ('PHS, 'PHSnABI', and 'PHSnMWnABI'') and RAP model 700-hPa relative humidity data.

satellite retrieval data and the RAP profile data. As can be seen from the top row of panels, the various types of profile data are in good large-scale agreement, but the bottom row of panels show that there are significant small-scale differences between the RAP 2-hour forecast and the various satellite profile retrievals. It is also apparent from the 'RAP – SAT' differences that the ABI data plays a key role in providing temporal and horizontal consistency to the satellite product and the MW data enables nearly complete horizontal coverage.

3-D Wind: Figure 3a and 3b shows the 8-km horizontal resolution model workflow and example results of using 3-hr continuous thermodynamic profile assimilation used to diagnose 3-D winds associated with the spatial and temporal variations of the profiles being assimilated. As depicted in figure 3a, the process is initiated using the NOAA operational RAP analysis as the initial background for the assimilation of the satellite profile data. The assimilation is performed at hourly intervals over a 3-hr period. The 3-D winds result from the numerical integration of the equations of motion, which force the model dynamics to be consistent with the spatial and temporal variations of the thermodynamic profiles being assimilated. The resultant model diagnosed winds and associated temperature and moisture profiles are then used to initialize a model forecast cycle in which the forecast model variables are output at hourly intervals over an eighteen-hour period. Figure 3b shows the 3-hour assimilated PHSnABI model diagnosed winds at 00 UTC and 12 UTC compared with independent CONUS radiosonde observations and cloud and water vapor track winds obtained throughout June and October 2020. Shown are the standard deviations of the differences between model-diagnosed 3-hr Retrieval Data Assimilated (RDA) winds and CONUS radiosonde observations (red curves), together with statistics for differences between to the 'Control' model forecast winds (CTL), generated over the 3-hr assimilation period without the assimilation of the satellite retrieval data and differences of operational cloud and water vapor Derived Motion Wind (DMW) vectors and radiosonde observations (cyan and green curves, respectively). As can be seen, the model diagnosed retrieval assimilated winds are in much better agreement with the radiosonde observations, than is the control forecast winds (i.e., satellite soundings excluded) and the operational feature tracked (DMW) winds. These results are consistent with findings by ECMWF [9] that the assimilation of satellite sounding radiances with high temporal resolution leads to improved analyses and forecasts of global 3-D winds.

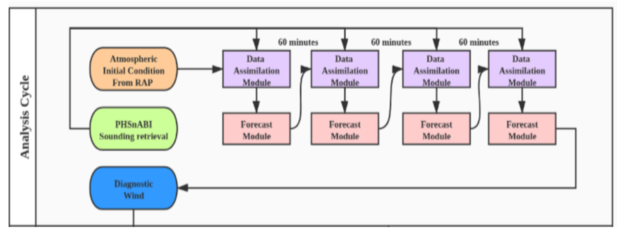

Figure 3a. Workflow process used for the assimilation of satellite profiles.

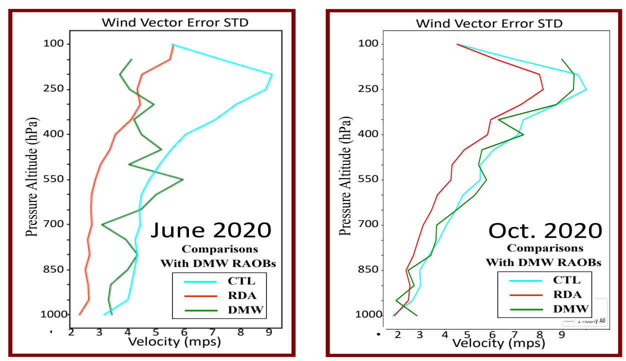

Figure 3b. Standard deviation of the differences between 3-hr satellite Retrieval Data Assimilated (RDA) model winds, Control (CTL) forecast model winds, and GOES-16 cloud and water vapor Derived Motion Winds (DMW) with radiosonde winds for the months of June and October 2020.

Figure 4 shows the standard deviations between north American radiosonde observations of temperature, humidity, and wind velocity and 6-hr/8-km resolution model forecasts. initialized 'with' and 'without' satellite sounding data (i.e., Satellite Vs Control forecasts). As can be seen, the assimilation of the high-resolution sounding data makes a significant improvement in forecasts because of the improvement in the forecast model initial conditions. As to be shown through examples below, the improvement of the atmospheric state parameters (temperature, humidity, and wind velocity) results in improvements of the forecast of precipitation and, severe convective weather parameters, such as the Significant Tornado Parameter (STP).

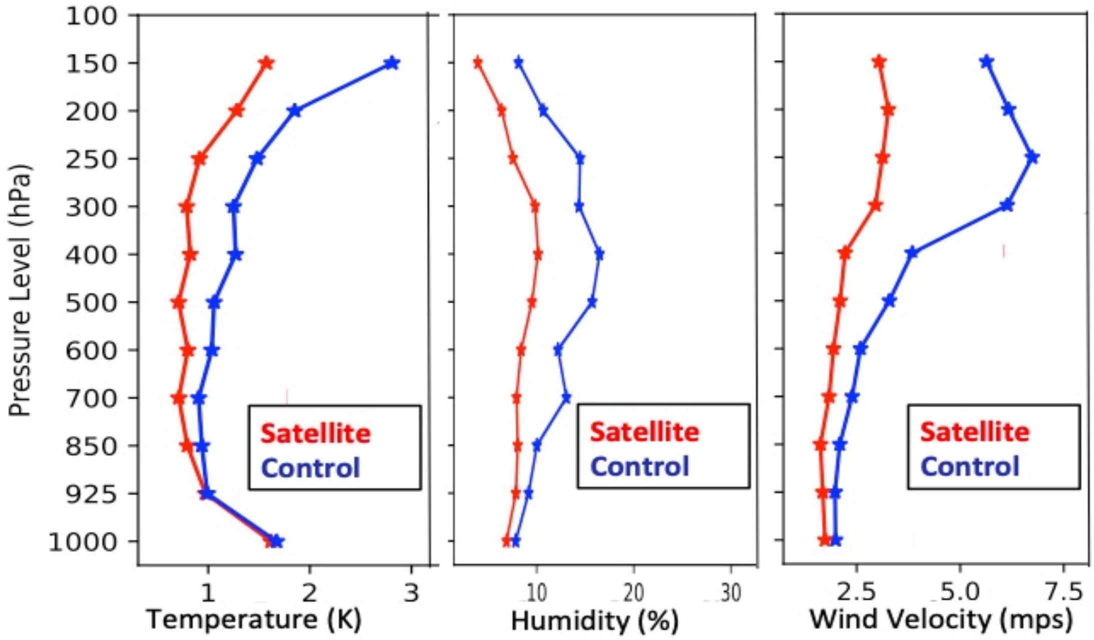

Figure 4. Standard deviations between radiosonde observations and 6-hour 8-km resolution forecasts initialized 'with' and 'without' (Control) satellite profile retrieval observations during February and March 2021.

Continental Severe Storms: Severe convective storms and Tornadoes are forecast using the Significant Tornado Parameter (STP) [7], calculated from the forecast temperature, moisture, and wind profiles, which indicate where severe convective cells spawning tornados will form. For example, on March 3, 2020, a tornado occurred at 06:50 UTC near Nashville Tennessee killing 23 people. Figure 5 illustrates the SWRC STP forecasts provided for this case, showing that the forecast that included the satellite sounding data (upper left panel) pinpointed the highest STP to tornado location (red dot), as indicated by the NOAA Storm Prediction Center (SPC). Conversely, the RAP forecast placed the highest STP at a considerable distance to the west of the tornado location (upper right). On the bottom of Figure 5, the 2 to 6-hour satellite data assimilated forecasts indicated that the maximum STP would occur at Nashville TN at a time within 1-hr of the actual time of

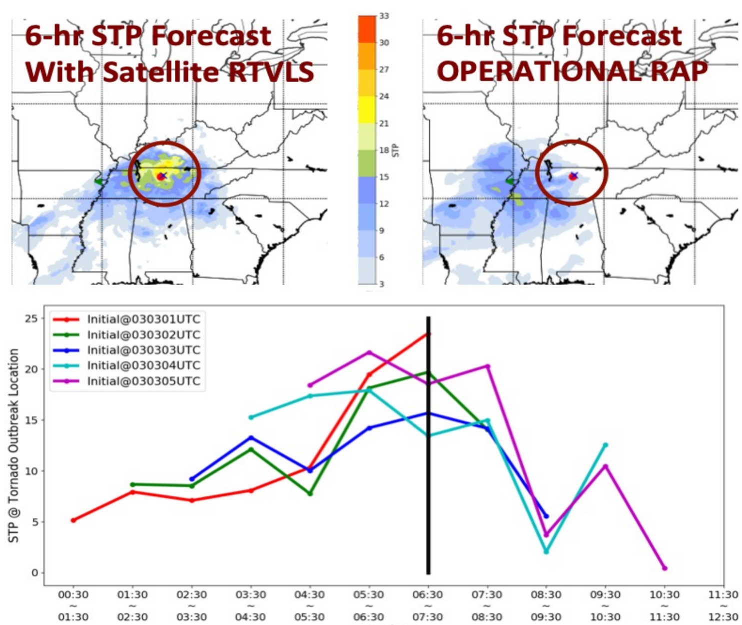

Figure 5. March 3, 2020. Upper panels show 6-hr STP forecasts 'with' satellite assimilated data Vs. 'RAP' forecast. The lower panel shows the 'with' satellite data forecast STP Vs time at Nashville TN.

the tornado development. In summary, this case is a good example of how both the location and time of the maximum STP associated with tornado occurrence could be predicted with considerable skill by assimilating satellite profiles into the NWP model.

Flash Flood Precipitation: Heavy localized precipitation can cause deadly flash flooding. During 2021, there were two major flash flood events causing the loss of life: (1) a flash flood on August 21 near Waverly TN, which killed 18 people and (2) A flash flood on September 1 caused by the remnants of Hurricane Ida, which killed more than 20 people in the New York City (NYC) area. In both cases, dramatic improvements in the forecast location and time of heaviest precipitation were made by assimilating the high-resolution satellite data [8]. As an example, figure 6 shows the comparison between 3-km and 8-km model satellite profile data assimilated 8-hr forecasts of hourly precipitation (mm/hour) for the time of heaviest rainfall nearest NYC compared to NOAA's operation HRRR and RAP forecasts. The 3-km/8-hr satellite sounding data assimilated forecast maximum hourly accumulated rainfall forecast maximum, which occurred during the 10 to 11 PM EST period, was in excellent agreement with the surface-based rain gauge and radar observations (NOAA Stage IV analysis) used to validate these forecasts. Long-term precipitation forecasts validated using Stage IV show consistent improvement of satellite profile data assimilated precipitation forecasts relative to Control and Operational forecasts, which do not benefit from the assimilation of the high-resolution satellite profile data [7,8].

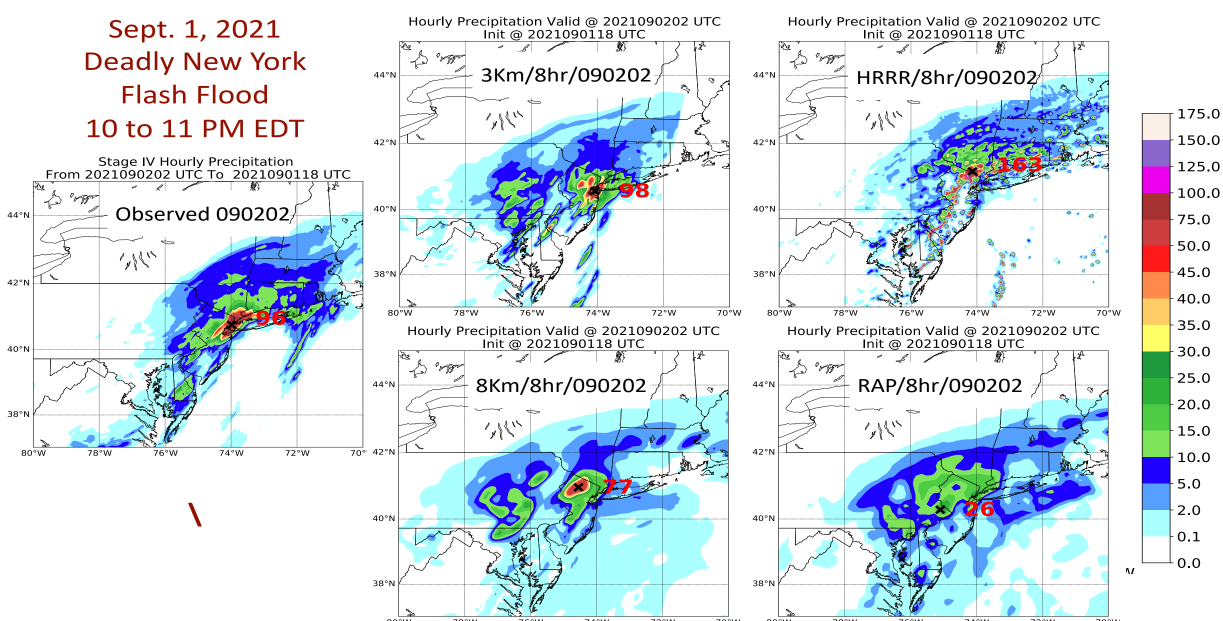

Figure 6. 3-km and 8-km high-resolution satellite data assimilated forecasts of extreme hourly precipitation compared to Stage IV rain gage and radar observations and operational HRRR and RAP model forecasts.

5. Website Displays

Currently the products are available for two large domains shown in figure 7: (1) a "West Domain" and (2) an East Domain. PHSnMWnABI soundings are assimilated on a continuous hourly basis to initialize 3-km and 8-km resolution WRF models to provide 1– to 9- hour predictions of precipitation and convective initiation of severe storms and tornadoes across the US mainland [7].

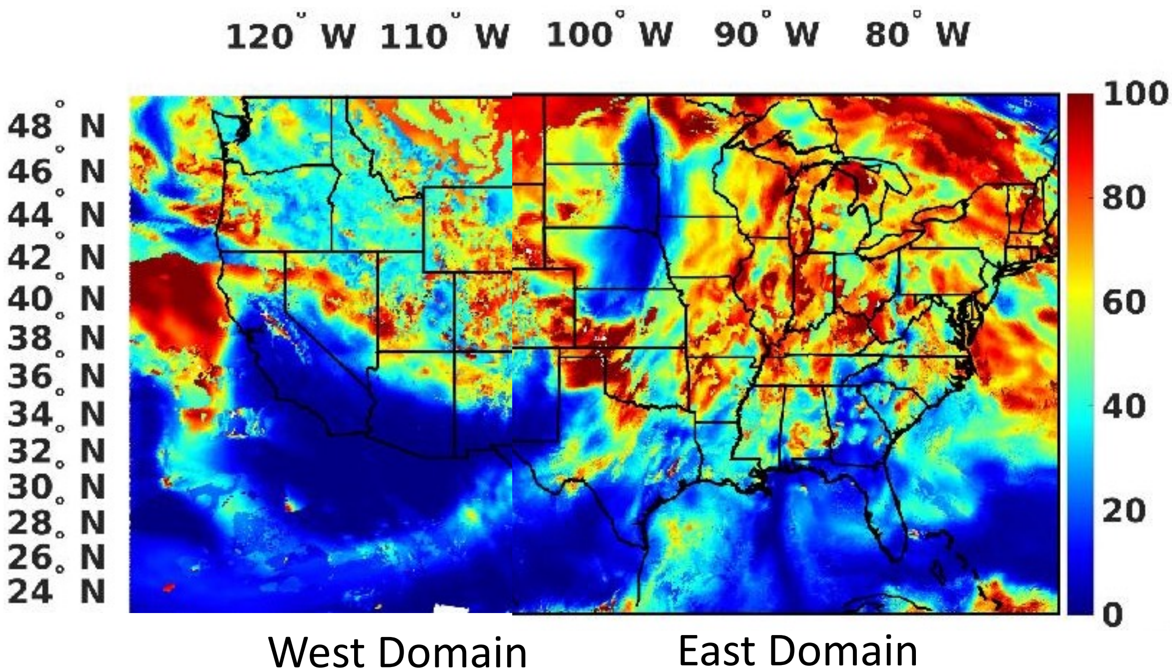

Figure 7. Image of 700-hPa Relative Humidity obtained at 16 UTC on April 13, 2022, obtained from the PHSnMWnABI soundings at the NASA LaRC for the West Domain and at the UW and the HU for the East Domain (right).

Atmospheric Profile Analyses: The PHSnMWmABI atmospheric profiles are plotted over the horizontal domain for several standard pressure levels at: https://www.ssec.wisc.edu/hufusion/plot-viewer/#thumbnails/20220414_t210020 and http://cas.hamptonu.edu/~adinorscia/ABInPHS_plots/TotalDomain-PnM/. Shown are false color analyses of the satellite temperature and humidity sounding data for the 850-hPa, 700-hPa, and 500-hPa levels, the top row being the sounding values with missing data being filled with the model background RAP 2-hour forecast profile data used for the satellite sounding de-aliasing discussed in section 4. The bottom row is the difference between the satellite sounding data and the RAP 2-hour forecast profile data, with missing satellite data regions being shown as white. Besides the temperature and humidity values, panels are shown for the 'Lifted Index' and 'Total-Totals' stability parameters, and the cloud height and underlying surface skin-temperature derived during the satellite vertical profile retrieval process. Analyses of upper tropospheric (i.e., 150-hPa to 400-hPa, at 50-hPa intervals) relative humidity are also shown. Note that the images can be animated to show the motions of the temperature, water vapor, stability, and surface skin-temperature parameters. Examples for an assortment of the retrieved atmospheric parameters, provided by the UW and HU atmospheric product websites, are shown in figure 8. The blank areas in the SAT-RAP analyses reveal where satellite profile data is missing and in its place RAP 2-hour forecast data valid at the time of the satellite observation is plotted in its place for the atmospheric temperature and humidity constant pressure level displays.

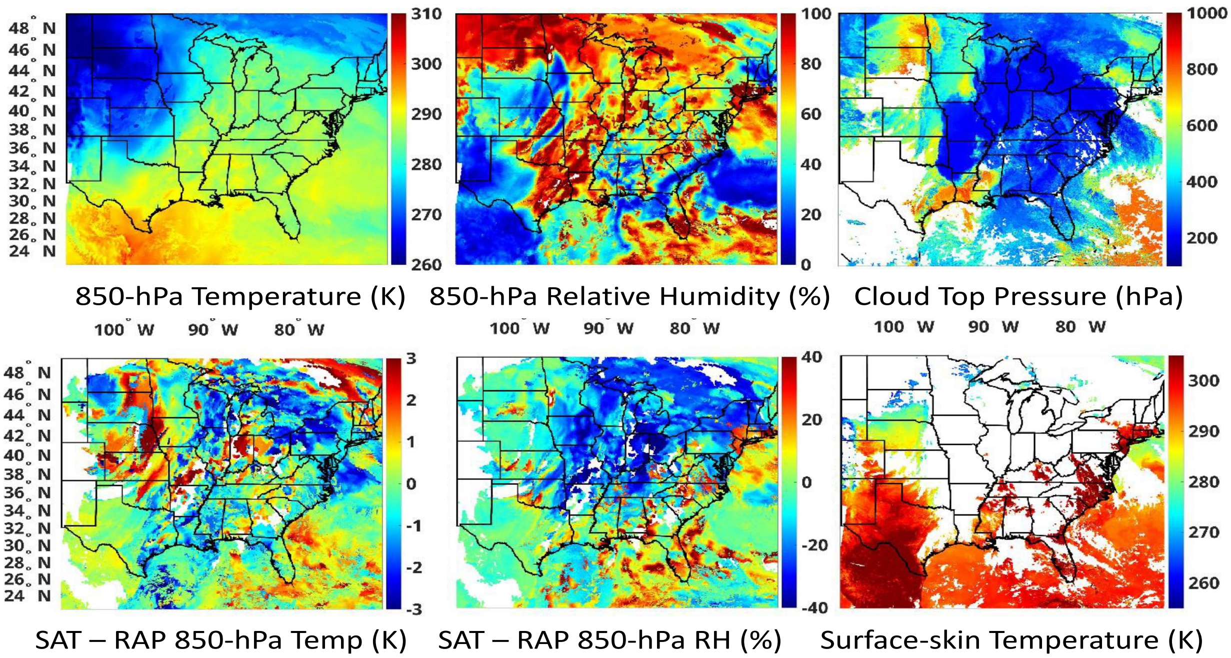

Figure 8. Examples of variable plots shown on the on the Atmospheric Variable Plot website for April 13, 2022, 16:00 UTC.

Radiosonde Profile Comparisons: The atmospheric profile websites also include comparisons between the satellite profile retrievals and radiosonde observations. See: https://www.ssec.wisc.edu/hufusion/data#radiosonde/ and http://cas.hamptonu.edu/~adinorscia/InteractiveMap/interactive-map.html .

The viewer needs to use the pull- down menus to select either 'PHSnMWnABI RTVL' or 'NUCAPS 'comparisons on the UW/SSEC website or 'Instrument' (i.e., CrIS J01, CrIS NPP, IASI M01, IASI M03, NUCAPS J01, PHSnMWnABI RTVL) on the HU website. On the HU website be sure to click on 'available radiosondes' to refresh the radiosonde comparison availability map.

Forecast Model Products: The forecast model product display website is obtained at: http://cas.hamptonu.edu/~qi.zhang/home_2.0/S4Show_New.html .

The workflow schematic at the top of this website display shows how the forecast cycle is initialized for the 8-km and 3-km resolution models. To diagnose the water vapor and wind velocity grid point values used as the background for initializing the forecast cycle, PHSnMWnABI sounding data are assimilated at hourly intervals over a 3-hour period for the 8-km model and at 30-minute intervals over a two-hour period for the 3-km model. The analysis used as the initial condition for the forecast cycle is then defined from a background analysis consisting of the 13-km RAP analysis grid point values interpolated to the 8-km or 3-km model grid points with the water vapor humidity and wind velocity grid point values being the 'analysis' grid point values resulting from the continuous satellite sounding data assimilation process shown in the workflow schematic. The final initial condition for the forecast initialization time is produced by assimilating all the conventional surface and upper air conventional and PHSnMWnABI moisture profile observations available at the forecast model initialization time. Since the density of the 2-km resolution satellite data is much larger than that of the conventional data, the forecast cycle initial condition atmospheric moisture features reflect those of the PHSnMWnABI satellite moisture retrievals. As stated earlier, the RAP-configured WRF is used for the 8-km resolution forecasts and the HRRR-configured WRF model for the 3-km resolution forecasts. The NOAA operational Grid-point Statistical Interpolation (GSI) system is used to perform the data assimilations, with the satellite sounding data being treated as if they were radiosonde upper air observations. It is important to note that the analysis and forecast domain for 3-km resolution model is positioned using the NWS day-one severe weather outlook. The analysis/forecast domain center is specified as the geometrical center of the highest risk region. If there are multiple highest risk regions, the geometrical center for the region with largest high-risk area is selected. The domain center is restricted to be south of 35N and east of 92W, so that the analysis and forecast domain is covered by the PHSnMWnABI data obtained over the observation domain shown in figure 8 above.

6. References

[1] Smith, W. L., E. Weisz, S. V. Kireev, D. K. Zhou, Z. Li, and E. E. Borbas, 2012: Dual-Regression Retrieval Algorithm for Real-Time Processing of Satellite Ultraspectral Radiances. J. Appl. Meteor. Climatol., 51, 1455–1476, https://doi.org/10.1175/JAMC-D-11-0173.1

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[9] McNally, Tony, “Data Assimilation considerations for future infrared sounder deployment”, NOAA Sounder Workshop, 6 December 2021, presentation available at https://www.jpss.noaa.gov/science_events/20211206-noaa-virtual-infrared-sounder-workshop/TonyMcNally_20211206-noaa-virtual-infrared-sounder-workshop.pdf

[10] Smith, W. L., Sr., and E. Weisz, 2017: Dual-regression approach for high-spatial-resolution infrared soundings. *Comprehensive Remote Sensing*, M. Goldberg, Ed., Elsevier, 297–311.

7. Summary of Website Display URLs

University of Wisconsin Website: https://www.ssec.wisc.edu/hufusion/

Sounding Displays: https://www.ssec.wisc.edu/hufusion/data#plot-viewer/
Radiosonde Comparison: https://www.ssec.wisc.edu/hufusion/data#radiosonde/
Forecast Plots: http://cas.hamptonu.edu/~qi.zhang/home_2.0/S4Show_New.html

Hampton University: http://dbps.cas.hamptonu.edu/development/

HU Received Polar Sounding Orbits:
http://dbps.cas.hamptonu.edu/development/polar_sounding/
UW Received Polar Sounding Orbits:
http://cas.hamptonu.edu/~adinorscia/UWPolar/
Polar + GEO Sounding:
http://cas.hamptonu.edu/~adinorscia/ABInPHS_plots/TotalDomain-PnM/
Radiosonde Comparison:
http://cas.hamptonu.edu/~adinorscia/InteractiveMap/interactive-map.html
Forecast Plots: http://cas.hamptonu.edu/~qi.zhang/home_2.0/S4Show_New.html