Polar and Geostationary Satellite Fusion Soundings – Product User's Guide

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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 polar satellite ATMS and AMSU Microwave (MW) and Geostationary Satellite (GS) multispectral Advanced Baseline Imager (ABI) radiances to produce 2-km horizontal resolution temperature and humidity profiles, called 'PHSnMWnABI'. Experimental forecasts results indicate that the high-spatial and temporal (30 to 60 min) resolution 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 moisture profiles are continuously assimilated at hourly intervals into a 4-km High Resolution Rapid Refresh (RAP-like) Weather Research and Forecasting (WRF) model, 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 four years to experimentally demonstrate improvements in numerical forecasts of convective weather expected to result from using the satellite high-resolution sounding data in National Weather Service (NWS) operations. The User's Guide presented here 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 during the NOAA Hazardous Weather Testbed (HWT) experiments, as well as being continuously made available from University of Wisconsin, NASA/LaRC, and Hampton University websites.

2. Atmospheric Sounding Retrieval

The key elements of the 'PHSnMWnABI' retrieval process are: (1) 30 Principal Components (PC) scores are used as linear regression predictors for the PHS and MW all-sky Dual-Regression (DR) retrievals [1, 2]; (2) GS ABI IR infrared radiances are used as predictors for linear regression ABI retrievals; (3) MW soundings [5] are used to compute pseudo infrared radiances for the companion hyperspectral IR instruments (CrIS and IASI) and then used to perform DR retrievals in the exact same manner that the real CrIS and IASI radiances are used; (4) the IR and MW profiles are de-aliased to provide a vertical resolution comparable to the forecast model vertical resolution [6], the vertical alias removal being performed by computing the radiance spectrum from using ultra-fast PCRTM spectrum-based radiative transfer model [7], to define the vertical alias as the difference between the 2-hr forecast Rapid Refresh (RAP) model profile valid at the time and location of the satellite observation and the DR retrieval, obtained using the radiance spectrum calculated from the RAP forecast profile. All spatial samples, at the full spectral resolution of the PHS, MW, and ABI channels, are used to optimize the horizontal and vertical resolution of the PHSnMWnABI fusion retrieval product [2], the fusion being performed using the very fast k-dimensional search-tree method [4] and the DRDA MW retrievals being fused with the IR soundings to fill-in the IR-profile gaps below clouds.

De-Aliasing: 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 2-hour profile used for the vertical alias removal process.

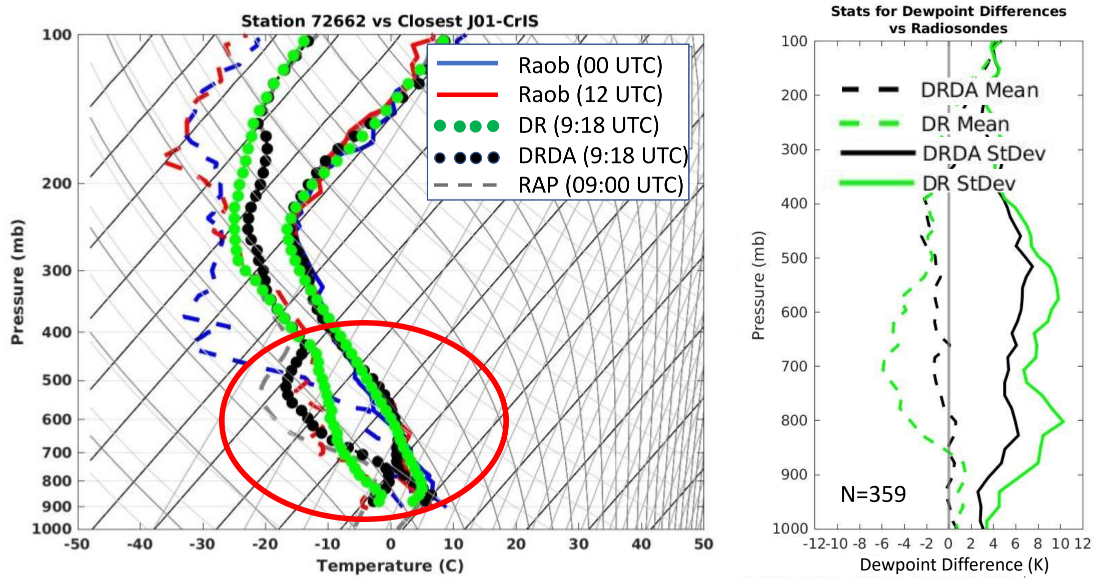


Figure 1. Comparison between Dual-Regression (DR) retrieval and De-aliased DR retrieval (DRDA), together with the model background profile (RAP 2-hour forecast) used for the alias removal, with a nearby radiosonde observation. Statistics showing the mean and standard deviation of DR and DRDA retrieval differences with one day of CONUS radiosonde observations are shown in the right-hand panel of figure 1. Much of the differences shown are due to the 3- to 6- hour differences between the polar satellite overpass and the radiosonde 00- and 12-UTC observation times.

Fusion of Polar IR and Microwave Profiles with Geostationary Satellite IR Imager Soundings: The purpose of fusing Polar Hyperspectral Sounding (PHS) InfraRed (IR), and MicroWave (MW) soundings with Geostationary Satellite (GS) soundings is to produce Fusion Soundings (FS), which possess the high-vertical resolution IR and cloud penetrating MW information provided by polar satellites with the high temporal (minutes to hourly) and spatial (2-km) resolution information provided by GS low vertical resolution water vapor profile imagery radiance data. The all-sky FS data shown on the UW website (https://www.ssec.wisc.edu/hufusion/data#plot-viewer/) are produced for assimilation into numerical models. The soundings possess an all-sky spatial resolution of 2-km and an hourly temporal resolution. The procedure for performing the fusion of these data, first described in [8], is summarized below.

(1) The first step of the fusion process is to spatially average the high horizontal resolution ABI soundings to the footprint areas observed of the CrIS and IASI polar hyperspectral sounding instruments. This provides a paired common area low-resolution ABI (i.e., LoresABI) and coincident polar hyperspectral sounding training data set to be used to predict polar hyperspectral and microwave soundings at the locations and times of the full resolution ABI data to produce the hourly interval FS data. (2) Using a K-D search tree**, the 'N'=10 LoresABI soundings in the training data set, which provide the best agreement with each of the full resolution ABI soundings (i.e., HiresABI soundings), are selected. The parameters used for the best agreement selection order are the ABI regression retrieved RH sounding and associated RAP model

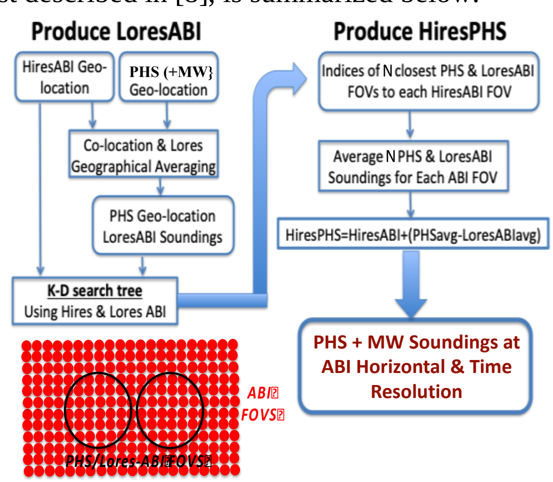


Figure 2. Schematic of the fusion process used to combine polar satellite soundings observations with geostationary satellite observations

temperature sounding as well as the latitude and longitude of the LoresABI sounding data. The value of 'N' is restricted by maximum allowable time and location differences (55-km, or 0.5 degrees, and 9-hours) between the PHS observations in the training data sample and the full resolution (Hires) ABI observation. (3) The weighted average of the PHS soundings in the training data set is ordered by best agreement between the Hires ABI soundings and the Lores ABI soundings in the training data set, as determined in (2), are then calculated for each ABI observation location and time. This weighted average PHS/LoresABI and MW/LoresABI sounding differences are then added to each ABI relative humidity and temperature sounding estimates to predict a Hires PHS and Microwave sounding at each ABI radiance measurement location and time. Polar satellite orbit overpass time to the latest ABI observation time water vapor profile fusion error is corrected using the known LoresABI data at the polar overpass time and the latest HiresABI.

Figure 3 shows a comparison of two FS profiles showing vertical regions where the dewpoint temperature agrees better with the radiosonde than does the RAP 2-hr forecast, as is used in the polar sounding retrieval and geostationary satellite fusion process.

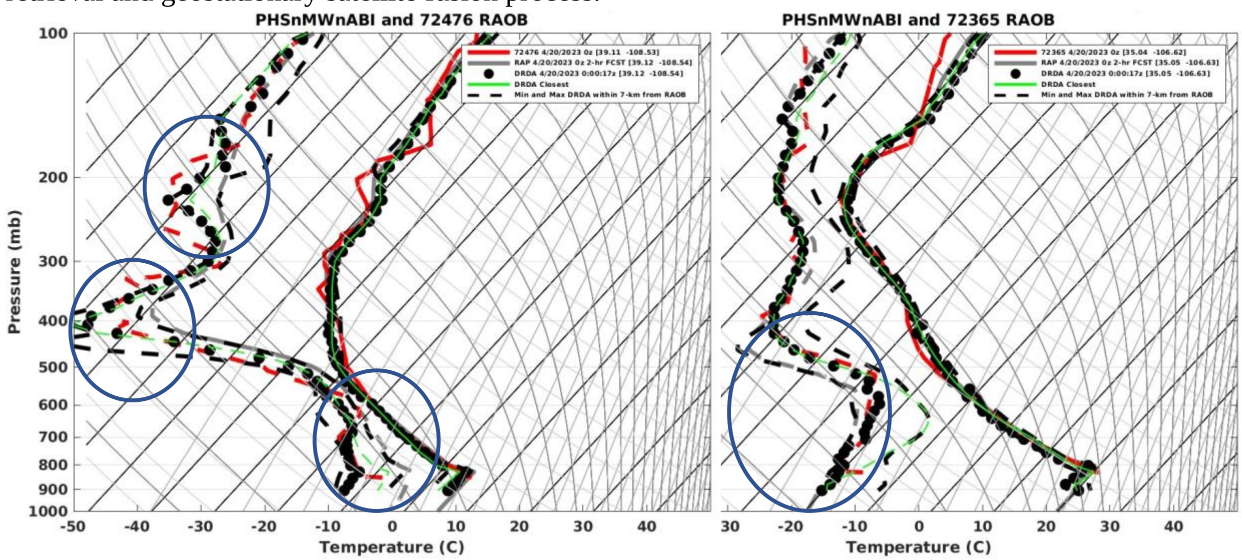


Figure 3. Comparison between FS profiles and radiosonde observations for 2 stations on April 20, 2023 (00 UTC), showing vertical regions where the dewpoint temperature agrees better with the radiosonde than does the RAP 2-hr forecast, as is used in the polar sounding retrieval and geostationary satellite fusion process.

Finally, (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 horizontal and vertical wind velocities that correspond to the spatial and time variations of the satellite observations [8, 9, 10]. The data are used by a joint University of Wisconsin, NASA/LaRC, 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 as well as to conduct weather and climate research using high-resolution satellite sounding and operational weather data.

'PHSnMWnABI' moisture soundings are assimilated into a 4-km grid spacing Weather Research and Forecasting (WRF) model to produce hourly predictions of precipitation, severe weather (high wind, extreme rainfall, hail, and tornadoes) and other forecast model output variables [7, 8, 9]. The initial condition for the forecast cycle is generated using an hourly interval assimilation of the 2-km resolution satellite soundings initialized using the operational RAP model analysis of conventional weather data. Four years of daily operation of the 'PHSnABI' and 'PHSnMWnABI' fusion 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 [8, 9, 10].

3. NWP Model Assimilation

The model forecast model and data assimilation system is a 4-km resolution (grid-point spacing) of the NOAA RAP (Rapid Refresh) /HRRR (High Resolution Rapid Refresh) versions of the Weather Research and Forecast (WRF) model as described in [11]. The data assimilation system used is the Grid-point Statistical Interpolation (GSI) analysis system [12]. As described by [14], a customized version of the WRF model [15, 16], and the GSI [17], 18], and [19] are being used. For the assimilation of the 'PHSnMWnABI' satellite soundings, no modifications are made to GSI source code. The UW-SSEC is running the version hosted by NOAA-EMC (https://github.com/NOAA-EMC/GSI). The control variable in minimization for water vapor is switched from mixing ratio to relative humidity. Only the satellite 2-km resolution retrieved relative humidity profile are being assimilated in the system (i.e., the satellite temperature profile and other retrieved cloud and surface parameters are not yet being assimilated). The observation relative humidity error covariance is updated on daily basis from the standard deviation between PHSnMWnABI profile retrievals and radiosonde observations (θ). The standard deviation (θ) of the differences between the retrievals and the radiosonde observations is also used for quality control. The embedded quality control in GSI is turned off. Instead, all water vapor profiles with 'OmB' (observation minus background) standard deviation smaller than 2θ are assimilated. Only one outer loop with 75 inner loops is used for cost function minimization.

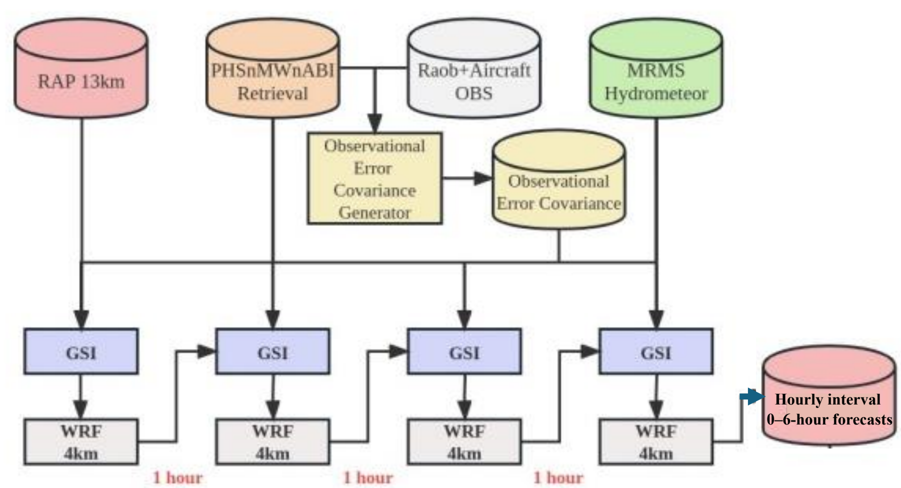


Figure 4. The Workflow for the 4-km resolution WRF Model PHSnMWnABI data assimilation system

A diagram showing the workflow of the PHSnMWnABI data assimilation and forecast system is shown in figure 4. As can be seen, an analysis cycle of the satellite profile data is initiated every hour using the RAP 13-km analysis as the background for the assimilation of the first of four sets of the satellite humidity profile retrievals using the GSI. The analysis resulting from the first hour assimilation is used to produce a 4-km resolution WRF forecast which is then used to provide the background for a 2nd hour assimilation of satellite humidity profile retrievals from which a second 1-hr WRF forecast is made. This process continues for two more hours so that a total of all satellite humidity profiles observed during a 4-hour period are assimilated to produce the final analysis, which is used to initiate a six-hour forecast cycle. The continuous assimilation of the water vapor profile data enables the wind velocity profiles, associated with the satellite derived atmospheric moisture profiles, to be derived for the initialization of the model forecast cycle [8, 9, 13]. The quasi-continuous assimilation of these satellite moisture profile data enables the model dynamics (i.e., winds) to adjust to conform to the time and spatial variations of the satellite thermodynamic observations through the time integration of the model's equations of motion. Multi-Radar Multi-Sensor (MRMS) observations are also used to initialize a 6-hour WRF model forecast cycle. It is noted that the RAP background used during the 3-hour long continuous data assimilation cycle has already assimilated the available operational conventional upper air information (e.g., radiosonde and aircraft data), as well as radar and other operational satellite remote sensing observations that are assimilated into NOAA's operational RAP/HRRR forecast systems. Therefore, the 4-km WRF model forecasts benefit from all the operational meteorological data, as well as from the high spatial/temporal resolution polar/geostationary satellite fusion humidity soundings assimilated to improve numerical forecasts of convective weather.

4. Observation Retrieval and Data Fusion Technique Overview

A simplified view of the satellite observation retrieval and data fusion technique is shown by Amy Leibrand (https://www.noaa.gov/education/resource-collections/weather-atmosphere/tornadoes). This reference provides an excellent layman's description of the rationale, objectives, and forecast improvements that can be obtained using the polar/geostationary satellite data fusion approach for improving severe weather/tornado warnings to the public.

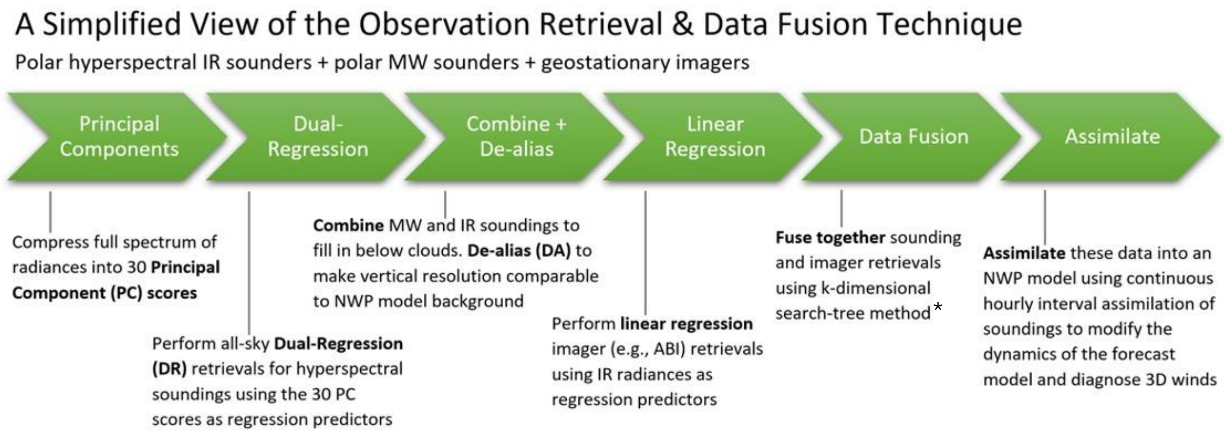


Figure 5. A simplified view of the satellite observation retrieval and data fusion technique.

5. Website Displays

Currently the PHSnMWnABI sounding retrieval product plots are available every hour at https://www.ssec.wisc.edu/hufusion/data#plot-viewer/ for a domain extending from 20 N to 50 N latitude and 70W to 160 W longitude. The website for accessing displays of the PHSnMWnABI sounding data can be viewed at: https://www.ssec.wisc.edu/hufusion/ .Plots are shown for the temperature and relative humidity at three pressure levels (i.e., 850-hPa, 700-hPa, and 500-hPa) and for relative humidity at three upper tropospheric levels (400-hPa, 300-hPa, and 200-hPa). Also shown are the Lifted Index stability parameter, cloud top pressure, and surface skin temperature.

Plot viewer: An example of displays shown in: https://www.ssec.wisc.edu/hufusion/data#plot-viewer/ are provided in figure 6 for January 27, 2024 (12 UTC). Shown are the satellite derived relative humidity and their deviation from the RAP 2-hour forecast relative humidity used to vertically de-alias the retrieval. The differences are presumed to be spatial resolution induced forecast errors in the RAP 2-hour forecast. These differences are shown relative to the cloud-top pressure and satellite radiance type (i.e., Infrared or Microwave) used for the relative humidity retrieval.

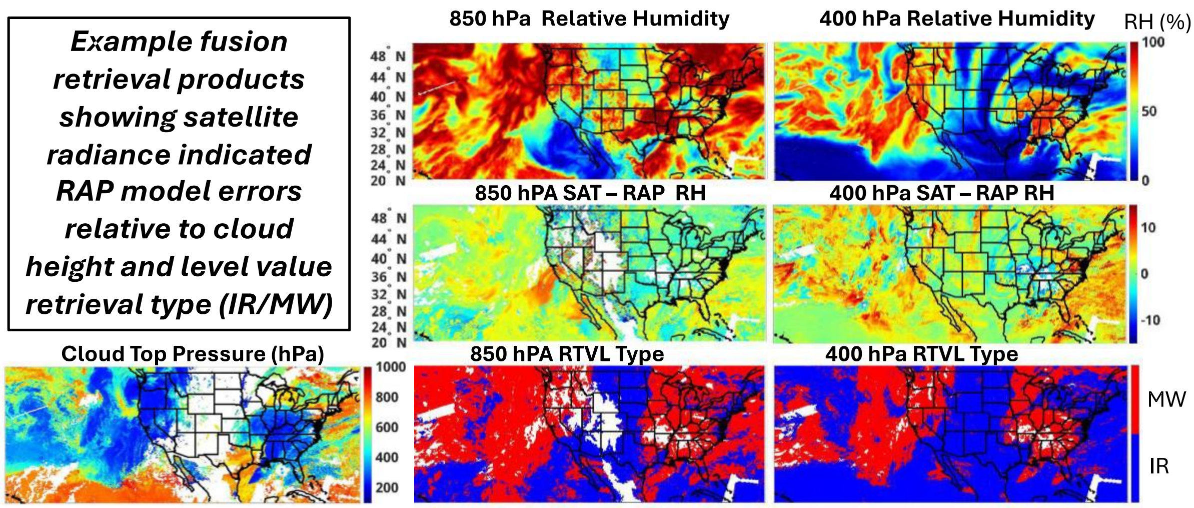


Figure 6. Satellite derived relative humidity (upper row) and their deviation from the RAP 2-hour forecast relative humidity (middle row). The cloud-top pressure and satellite radiance type (i.e., Infrared or Microwave) used for the relative humidity retrieval are shown in the bottom row of panels.

In the 'Plot Viewer' displays, the SAT+RAP color analyses are obtained by plotting the satellite retrieval data where it exists and the RAP 2-hr forecast data where the retrievals are missing. The satellite soundings may be missing due to the lack of polar satellite coverage or where the infrared or microwave retrieval data are missing due to clouds, precipitation, or high terrain. The satellite sounding coverage west of 130 W may be excluded to minimize the data processing time required to produce severe convective weather forecasts/warnings for the continental USA.

Radiosonde Comparisons: PHSnMWnABI fusion profile retrievals are compared to direct readout NOAA and Metop satellite NUCAPS, Radiosonde, and the RAP 2-hr forecast profiles used for the de-aliasing of the IR and MW fusion retrievals (https://www.ssec.wisc.edu/hufusion/data#radiosonde/). For the direct readout NUCAPS comparisons, the 2-km spatial resolution 'PHSnMWnABI' (DRDA) retrievals are averaged over the 50-km Field-Of-Regard (FOR) of the NUCAPS soundings. For the comparison of the full 2-km resolution PHSnMWnABI fusion retrievals with radiosonde comparisons, the retrieved profile within 7-km (i.e., one-half the RAP model grid point spacing) of the radiosonde location, whose 150-hPa layer average relative humidity best matches that of the radiosonde, is selected for the comparisons to account for the local airmass variations of humidity (e.g., produced by clouds) within the RAP resolution element caused by radiosonde balloon drift away from the launch location. Also shown are the retrieved sounding minimum and maximum radiosonde difference values of all the sounding retrieval values within the 7-km radius centered on the radiosonde location computed using the radiosonde wind profile to account for the balloon drift location uncertainty as it rises through the atmosphere. Figure 7 shows two example radiosonde comparisons for January 28, 2024, at 00-UTC.

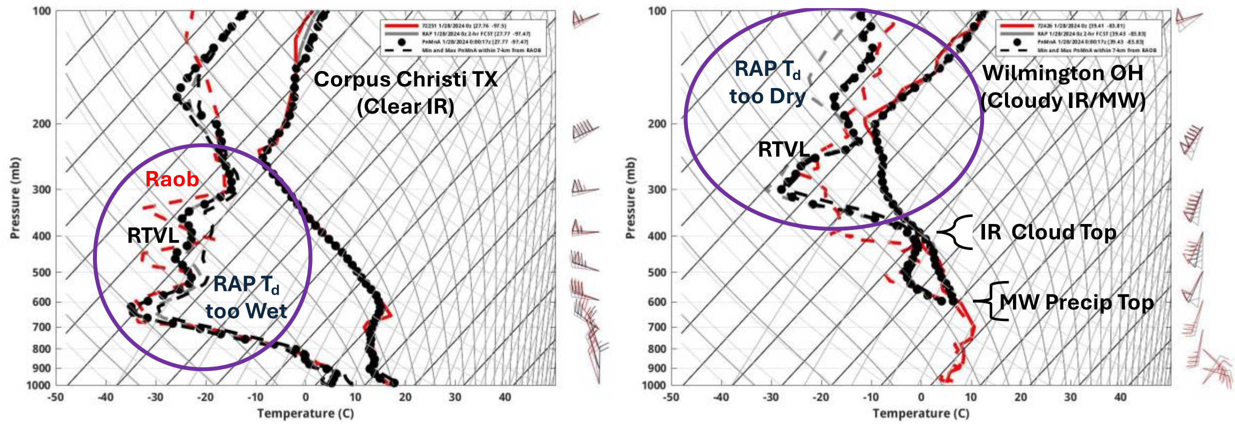
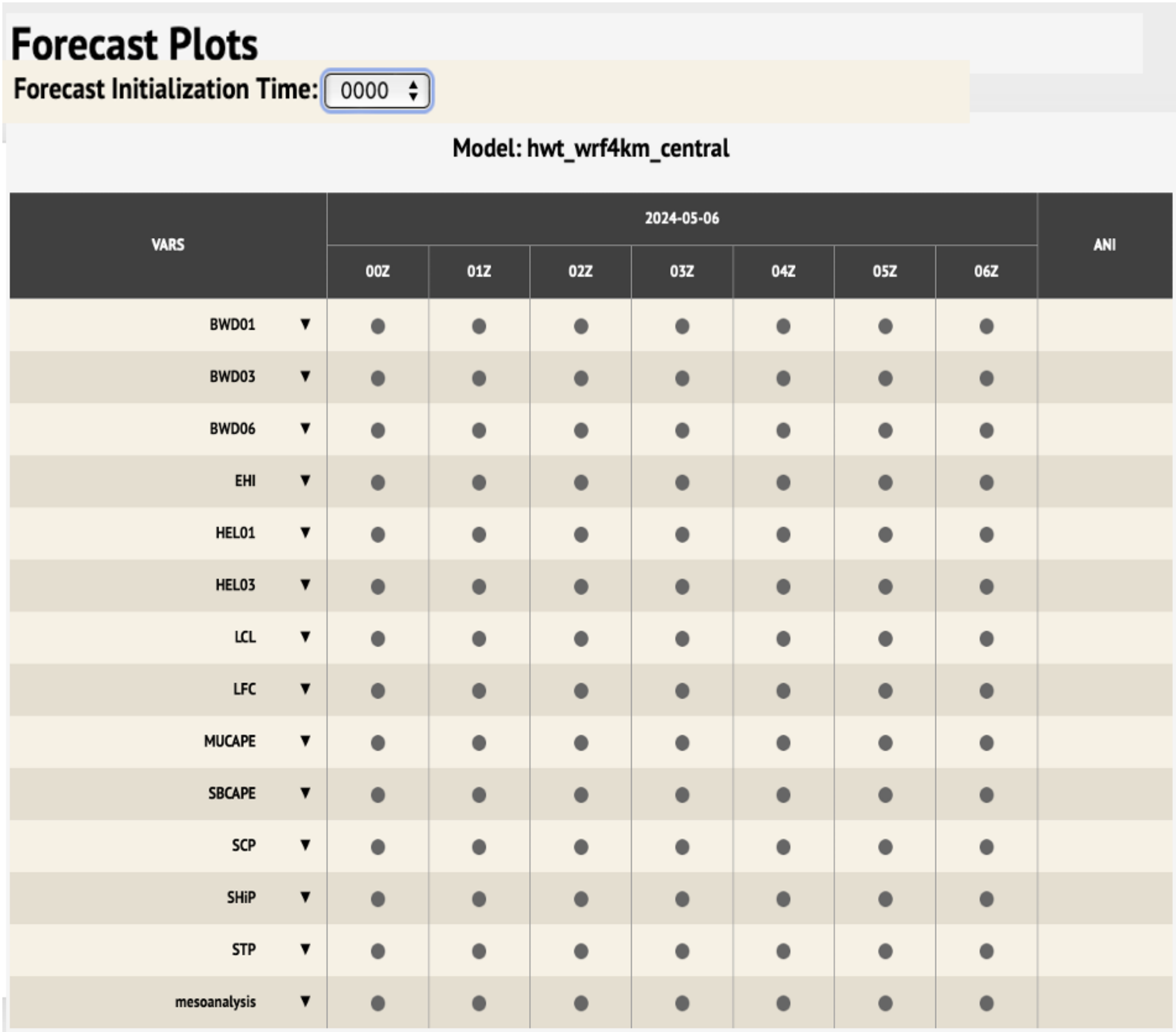


Figure 7: Example Radiosonde comparisons with fusion retrievals for January 28, 2024, at 00 UTC. The left panel shows the result for a clear-sky (Infrared-only) retrieval. The right pane shows a cloudy-sky (combined Infrared and Microwave) retrieval illustrating the cloud-top height and the precipitation-top height (i.e., profile retrieval terminated at the precipitation-top altitude) determined by the retrieval process.

Forecast Plots: The forecast model output plots can be found at: https://www.ssec.wisc.edu/hufusion/forecast-plots/ The use of the display tool is self-explanatory. Basically, the URL takes you to a calendar for the user to select the day of the month for which the forecast parameters are desired. After clicking on the day, another menu will be presented where the user can choose, using the pull-down menu, the Forecast Initialization Time for which the 0-to 6-hour forecasts that were made using that initialization time. The 0-hour forecast is the final analysis used to initialize the forecast cycle. After clicking on the initialization time desired, six panels of forecast parameters, each panel containing 14 different forecast parameters: BWD01, BWD03, and BWD06 (Bulk Wind Shear for the Surface to 1000 m, Surface to 3000m, and surface to 6000m layers, respectively), EHI (Energy Helicity Index), HEL01, HEL03 (Storm Relative Helicity for the Surface to 1000m, and Surface to 3000m layers, respectively), LCL (Lifted Condensation Level), LFC (Level of Free Convection), MUCAPE (Most Unstable CAPE), SBCAPE (Surface-based CAPE), SCP (Supercell Composite Parameter), SHIP (Significant Hail Parameter), and STP (Significant Tornado Parameter). These parameters are defined from the forecast atmospheric state parameters produced by two models, (1) the experimental satellite sounding data assimilation WRF model (section 3) and (2) NOAA's Operational High Resolution Rapid Refresh (HRRR) model These parameters defined from the model forecasts are shown for the NWS Central, Eastern, Southern, and Western CONUS regions.



Forecast Plots

Forecast Initialization Time: 0000

Model: hwt_wrf4km_central

VARS	2024-05-06							ANI
	00Z	01Z	02Z	03Z	04Z	05Z	06Z	
BWD01 ▼	●	●	●	●	●	●	●	
BWD03 ▼	●	●	●	●	●	●	●	
BWD06 ▼	●	●	●	●	●	●	●	
EHI ▼	●	●	●	●	●	●	●	
HEL01 ▼	●	●	●	●	●	●	●	
HEL03 ▼	●	●	●	●	●	●	●	
LCL ▼	●	●	●	●	●	●	●	
LFC ▼	●	●	●	●	●	●	●	
MUCAPE ▼	●	●	●	●	●	●	●	
SBCAPE ▼	●	●	●	●	●	●	●	
SCP ▼	●	●	●	●	●	●	●	
SHiP ▼	●	●	●	●	●	●	●	
STP ▼	●	●	●	●	●	●	●	
mesoanalysis ▼	●	●	●	●	●	●	●	

Figure 8: Menu for displaying all the satellite data assimilated WRF and the NOAA operational HRRR model forecast variables defined in the text. The model initialization times range from 0000 UTC to 2300 UTC for each day selected, the latest time available shown as the last time in the pull-down menu. The forecast areas are the NWS ‘Central’, ‘Eastern’, ‘Southern’, and ‘Western’ forecast regions. The NOAA operational HRRR (oper_hrr3km) forecast menus follow the WRF model (hwt_wrf4-km) menus which can be compared to illustrate the forecast modifications produced by the assimilation of the high-resolution satellite humidity profile data. Animations of the six our duration hourly interval forecasts can be shown by clicking on the ‘play’ option in the pull-down menus.

The last option in the ‘Forecast Plots’ menus for each day and initialization time is the ‘diagnostic plot’ shown in 9. The diagnostic plot shows for each of three layers: surface to 700-hPa, 700-400-hPa, and 400-100hPa , the number of humidity profile values not used in the GSI (Grid-point Statistical Interpolations) data assimilation system (1st panel), the Observation minus the Model Background (OmB)difference for those values not used (2nd panel), the total number of humidity profile values used in the data assimilation process (3rd panel) and the ‘OmB’ for those humidity values used in the WRF model satellite humidity profile data assimilation process. This is done for just the last hour of the assimilation, also known as the analysis time.

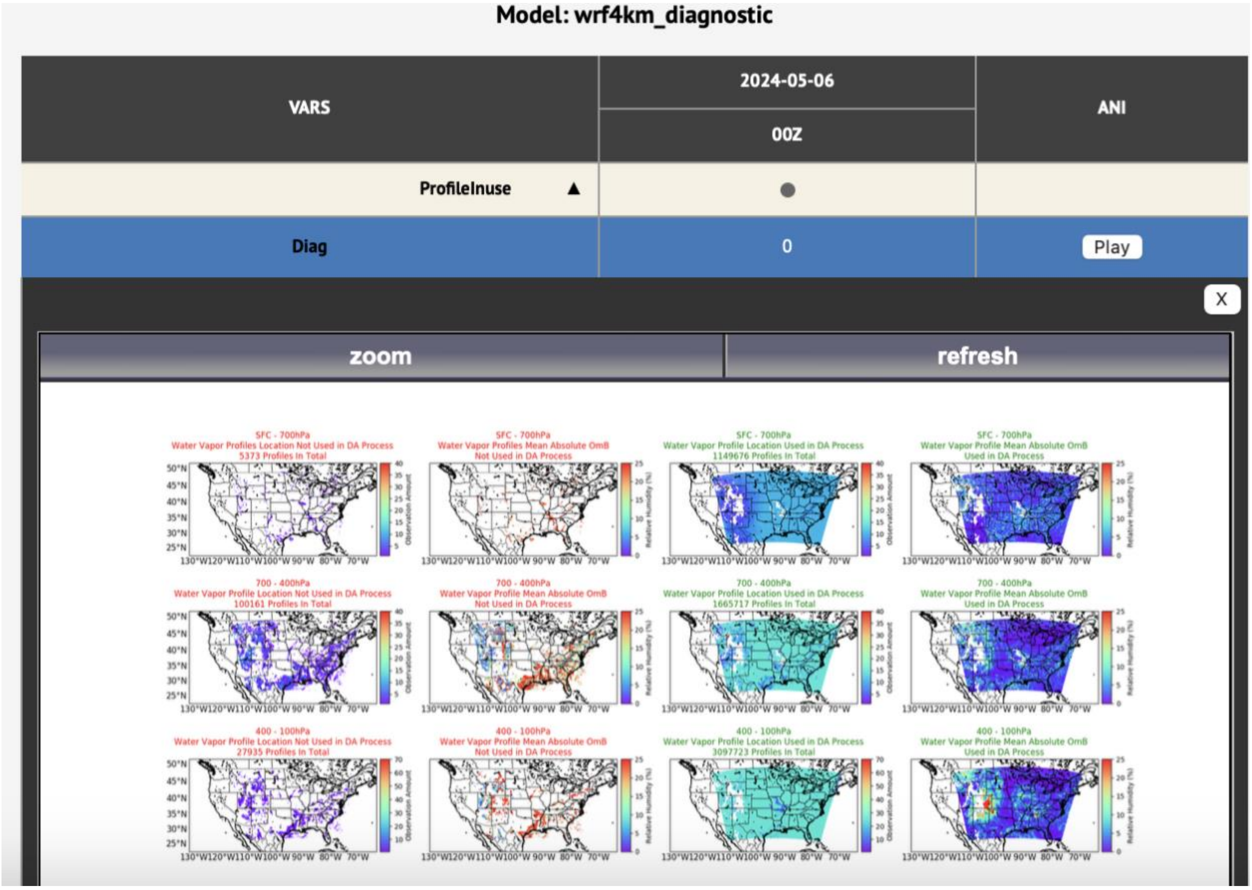


Figure 9. Diagnostic plot of initial time GSI assimilation of satellite fusion retrieval sounding data.

Fusion Sounding Map: The website also contains an application for the user to see the difference between the PHSnMWnABI (called PMnABI) profile retrieval and the RAP 2-hr forecast profile that was used as the background for the retrieval. The fusion sounding map, accessed from: http://cas.hamptonu.edu/~adinorscia/InteractiveMap/FusionMap.html. An example displaying the Fusion Map tool is shown here (figure 10). There are 3 pull down menus: one to select the day (today or yesterday), another to select the hour (00 UTC to 23 UTC), and the third to select the background image (Lifted Index, Cloud Top Pressure, surface skin temperature, and the Relative Humidity difference (Sat-RAP) for either the 850-hPa, 700-hPa, or 500-hPa levels). Clear regions can be seen by selecting the ‘Cloud Pressure’ option, where the clear pixels are shown by the white missing data pixels and the clouded regions can be seen by selecting the ‘Surface Skin Temperature’ map where the cloudy pixels are shown by the white missing data pixels. It must be remembered to always click on the ‘Load Map and Sounding’ bar when any selection is changed. After loading the background map, the user can use the cursor to select a geographical position to display a Skew-T plots of the average of all ‘PHSnMWnABI’ temperature and dewpoint profiles, and associated 2-hour RAP forecast profiles, within a 40-km radius of the geographical point selected. The Lifted Index and MUCAPE values are also shown on the Skew-T plots.

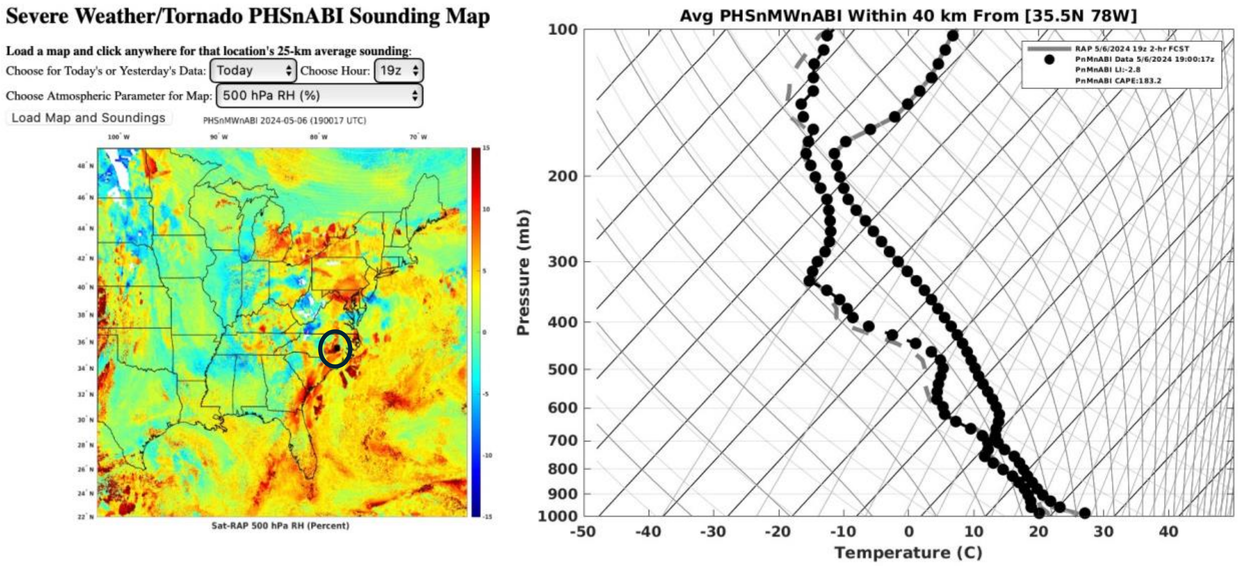


Figure 10: An example 'Fusion Plot' for May 6, 2024 at 19 UTC. The very high-resolution horizontal differences between the the 500-hPa humidity satellite retrievals and the RAP 2-hr forecast for 19 UTC are shown in the left-hand panel of figure 8. The vertical structure differences between the final satellite fusion radiance retrieved profile and the RAP 2-hr forecast is shown by the SKEW-T chart profile comparison shown for the encirled region, shown on the left-hand panel, by the right-hand panel of figure 10.

WRF Domain Plots: A Sat-WRF model forecast validation site can be reached at: https://cas.hamptonu.edu/~adinorscia/RaobDomain/NewWindPlots/Domains/. This site shows comparisons between he sounding retrieval data, radiosonde profile data, WRF anlyses/forecasts, and HRRR analyses/forecasts to enable the user to assess the accuracy of these products as shown using the 'Plot View' and 'Forecast Plot' menus discussed above. At the site one can see comparisons, using the pull down menus: (1) between radiosonde and retrieval soundings Vs. WRF and HRRR 00, and 12 UTC analyses ('12/0 UTC Analysis, (2) RTVL/Raob/WRF data minus WRF and HRRR 4-hour forecasts ('RTVL/WRF - 4hr HRRR'), (3) RTVL/Raob/WRF data minus WRF and HRRR initial analyses ('RTVL/WRF – 0hr HRRR'), (4) Radisonde and Retrieval differences with the WRF and HRRR 4-hr forecast change (SAT Diff'), (5) 4-hr Observation and WRF forecast 4-hour change from HRRR initial condition ('Change'), and (6) satellite observation and WRF analysis difference with the HRRR initial analysis for the forecast cycle ('Analysis Diff').

WRF Mesovortex Locations: This site shows where the WRF high-resolution horizontal wind shear within an convectively unstable region (i.e., where the Significant Tornado Paraneter (STP) > 2) indicates a mesovortex circulation for a 20-km radius area, surrounding a given WRF grid point (https://cas.hamptonu.edu/~adinorscia/RaobDomain/NewWindPlots/UnstableRegions/index_UnstableRegions.php . These locations are plotted for every 2-hr, 3-hr, 4-hr, 5-hr, and 6-hr forecast for a given validation time. A standard deviation wind velocity directions greater than 20 degrees identify the existance of a mesovortex circulation centered on the model grid-point location. The wind velocity shear indicated mesovortex circulation supports the development of convective storm severe winds, hail, and tornadoes near thet mesovortex grid-point location. The forecast location of severe-weather/tornado indications are plotted for both the WRF and the operational HRRR forecasts. The blakened diamond on these charts indicate the most likely location for a tornado development for each forecast validation time.

Additional information: Contact W. L. Smith Sr. (bill.l.smithsr@gmail.com or w.smith@ssec.wisc.edu) or A.DiNorscia (anthony.c.dinorscia@nasa.gov) if you have any questions or need additional information regarding these web-site products.

6. References

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