Impact of Atmospheric Retrievals on Hurricane Florence/Michael Forecasts in a Regional NWP Model

Min Shao1 and William L. Smith1,2

1Atmospheric and Planetary Sciences, Hampton University, Hampton, VA, USA, 2Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, Madison, WI, USA

Abstract Atmospheric temperature and water vapor profiles from the Infrared Atmospheric Sounding Interferometer and the Cross-track Infrared Sounder with acceptable qualities under clear condition and above clouds are derived using the Dual-Regression algorithm based on the Principle Component-based Radiative Transfer Model. The application of the derived atmospheric retrievals with high temporal and spatial resolutions in a regional weather model is studied for two hurricane cases by assimilating the retrievals in an hourly update cycle. Improvements on hurricane forecast are obtained by assimilating satellite retrievals as compared to both conventional operational data and radiance assimilation. Position of the predicted hurricane center, which is especially critical for landfall position, is corrected with a maximum improvement of 45 km compared to conventional assimilation. Predictions of heavy precipitation produced by hurricanes are improved with smaller bias and standard deviation. Precipitation scores used for the validation of predictions also show great improvements in heavy precipitation forecast against conventional data and radiance assimilation. Hurricane structure representation is substantially improved. Specifically, more symmetric structures, stronger warm cores, deeper convections, and more accurate winds lead to the improvements in precipitation forecasts. Potential applications of such approaches can be applied to assimilating the retrieved information from the geostationary satellite instruments by adding higher temporal and horizontal resolutions to the polar satellite hyperspectral sounding data.

1. Introduction

Adding atmospheric information to the initial conditions of a numerical forecast model is critical for improving regional nowcasting and forecasting severe weather events such as convection storms and hurricanes. With the availability of accurate hyperspectral radiance measurements at thousands of spectral channels within the infrared (IR) band, atmospheric temperature and water vapor profiles can be retrieved with much higher vertical resolutions by applying various retrieval algorithms (Aires et al., 2002; Kwon et al., 2012; Liu et al., 2009; Smith et al., 2005). For example, the Infrared Atmospheric Sounding Interferometer (IASI) carried on the MetOp satellites provide 8,461 channels covering the spectral region from 3.7 to 15.5 μm (Blumstein et al., 2004) and the Cross-track Infrared Sounder (CrIS)—a new generation of National Oceanic and Atmospheric Administration (NOAA) hyperspectral IR instrument—onboard the Suomi National Polar-orbiting Partnership (Suomi-NPP), and the Joint Polar Satellite Systems (JPSS) provides 2211 channels over three IR wavelengths (Han et al., 2013). Much more atmospheric vertical information can be provided by using hyperspectral retrievals compared to traditional conventional observations which lead to a new era of global/regional atmospheric sounding applications.

Important satellite data applications including improving the forecast of hurricanes as well as tropical cyclones (TCs) and local severe storms in global/regional data assimilation and prediction systems have been of great interest. Satellite observed radiances from both microwave and infrared sounders have been widely used in both global and regional numerical weather prediction systems and been proven to have large impacts on forecasts of hurricanes and TCs (Garand et al., 2013; Zou et al., 2013). However, only about 10% of the satellite channels that are not affected by clouds are assimilated in most of the meteorological centers (Collard, 2007; Guidard et al., 2011). Recently, cloud-cleared radiance observations from the Atmospheric Infrared Sounder with proper data thinning technique also showed substantial improvements in TC forecasts (Reale et al., 2018). Compared to satellite radiance assimilation, satellite retrievals have the advantages: (i) retrievals use the full spectral resolution without any information loss when using proper
radiative transfer models, (ii) atmospheric profiles can also be retrieved under cloudy conditions, and (iii) assimilating retrievals can avoid the use of radiative transfer model as forward observation operators. As discussed in Migliorini (2011), two requirements are needed to obtain equivalence between radiance and retrieval assimilation. Researches have shown that the high vertical resolution soundings retrieved from the Advanced IR Sounder can improve hurricane/TC path and intensity forecasts (Li & Liu, 2009; Liu & Li, 2010; Reale et al., 2009; Zhou et al., 2010). Heavy precipitation forecasts have also been studied by assimilating layered precipitable water retrieved from the Advanced Himawari Imager, the Advanced Baseline Imager, and the Advanced Geosynchronous Radiation Imager (Wang et al., 2018).

In this study, the atmospheric temperature and water vapor retrieval products that are generated at the Hampton University Center for Atmospheric Research and Education in near-real time using IASI on MetOp-A/B and CrIS on Suomi-NPP and JPSS are used. Experiments are conducted on NOAA/National Environmental Satellite, Data, and information Service/Center for Satellite Applications and Research supercomputer for Satellite Simulations and data assimilation Studies (S4; Boukabara et al., 2016). The advanced research version of the Weather Research and Forecasting (WRF-ARW, version 3.9.1) model and the community Gridpoint Statistical Interpolation (GSI, version 3.6) three-dimensional variational (3D-Var) systems are used to study the hurricanes/TCs Florence and Michael which occurred in September and October 2018.

Section 2 provides an overview of the algorithms and quality control of the assimilated retrievals. Detailed model description, configuration, and experimental design are described in section 3. Section 4 presents the impact of assimilated retrievals on both cases. Sections 5 and 6 provide the summary and references.

2. Data

2.1. Satellite Retrievals

The atmospheric temperature and water vapor information from IASI and CrIS are derived using the Dual-Regression retrieval algorithm based on the Principle Component-based Radiative Transfer Model (Smith & Weisz, 2017; Xu et al., 2006; Xu et al., 2016). The Dual-Regression algorithm fulfill both clear-sky and cloudy-sky conditions and the Principle Component-based Radiative Transfer Model enables the use of the full information content of hyperspectral resolution measurements provided by those instruments. Under cloudy conditions, if a nonopaque cloud exists, the final outputs are combined by clear-trained retrievals above the cloud and cloud-trained retrievals at and below the cloud; otherwise, the values below the cloud are set to missing due to no radiance information below the cloud. The differences between the clear-trained and cloud-trained retrievals are used to quality control the outputs below clouds (Smith et al., 2012; Weisz et al., 2013).

Furthermore, a de-aliasing technique is used to correct the vertical resolution alias errors caused by the limited vertical resolution of radiance measurements. In this study, radiance spectrum calculated from the Rapid Refresh (RAP; Benjamin et al., 2016) 2-hr predicted atmospheric profiles are used to simulate satellite radiance measurements and to produce the simulated radiance retrievals as needed to estimate the vertical resolution alias used to correct the observed radiance sounding retrievals.

It is always a challenge to identify cloud in satellite retrievals. In this study, we first assume that it is a cloudy condition and calculate the cloudy-trained retrievals for each field of view. Then, the pressure level where a positive systematic difference in temperature is found between the cloudy-trained and the clear-trained retrievals from that level down to the surface is identified as the cloud height. A criterion that if the difference between the RAP’s near-surface temperature and the retrieved near-surface temperature is smaller than 2.5° and the RAP’s near-surface temperature is less than the retrieved surface skin temperature, the condition is set to clear. The retrieved atmospheric profiles have a horizontal resolution around 15 km and 101 levels from surface to 0.005 mb. Due to the lack of satellite information and relatively large bias in the upper atmosphere, only the tropospheric retrievals (45 levels from surface to 100 mb) are used.

The satellite radiance-derived atmospheric profiles cover the main region for Hurricane Florence (30°–45°N, 66°–82°W) and Michael (30°–45°N, 74°–86°W). Figure 1 shows the scatterplot of the satellite-retrieved temperature (top panel) and water vapor (bottom panel) in three tropospheric layers [lower troposphere (surface to 850 mb): L, middle troposphere (850 to 400 mb): M, and upper troposphere (400 to 100 mb): U] against the
2-hr predicted atmospheric profiles from RAP. The total retrieved data sample sizes of the L, M, and U layers during Hurricane Florence are 633, 31,933, and 132,301, respectively. The total retrieved data sample sizes for Michael are 504, 21,772, and 98,812 in different layers, respectively. Detailed information of satellite retrievals during Florence and Michael are shown in Table 1. As shown in Figure 1, the $R^2$ of temperature exceeds 0.9 for three layers. For case Florence, the mean difference between temperature retrievals and RAP at lower and middle troposphere are 2.5 and 2.4 K, respectively. For case Michael, the differences are 2.0 and 2.3 K, respectively. Due to the large differences between retrieved temperature profiles and RAP, bias correction based on RAP is applied to the temperature profiles (WRF interrupted when assimilating original retrieved temperature). Satellite-retrieved water vapor has more variations than temperature. Only the water vapor at middle troposphere has $R^2$ exceeds 0.85. No bias correction of water vapor is applied (water vapor with bias correction showed worse results; figures are not shown).

### 2.2. Data Used for Validation

Three sets of data are used to validate the performance of assimilating satellite retrievals:

1. The Best Track Data (BTD) including the geoposition of hurricane center and minimum sea level pressure (MSLP) from the National Hurricane Center is used to validate the predicted hurricane paths and MSLP. The geoposition of the MSLP in predictions are defined as the center of the hurricanes in this study. As shown in Figure 2,

![Figure 1](image-url)
the black lines are the paths of the BTD. Hurricane Florence made landfall at the coast of North Carolina and then turned to extratropical system three days after landing. Hurricane Michael made landfall at the Panama City Beach and moved toward the northeast at a faster speed and turned to extratropical system after entering the Atlantic Ocean from coast of Virginia. Data can be reached through http://tropicalatlantic.com/models/models.cgi?archive=al.

2. The conventional and satellite radiance observations used in the Global Data Assimilation System produced by the National Centers for Environmental Prediction (NCEP) are assimilated to conduct the CTRL experiments in this study. The conventional observations alone are also used to validate the initials produced by a series of experiments in this study. The real-time data can be reached at http://www.nco.ncep.noaa.gov/pmb/products/gfs/.

3. The NCEP Stage IV, a precipitation analysis over the continental United States based on the multisensor Stage III analyses produced by the 12 River Forecast Centers is used for the validation of precipitation produced by different WRF experiments. The Stage IV analysis is produced on a 4-km polar-stereographic grid with advantages from manual quality controls. To compare with the model predicted precipitation, both the Stage IV and model results are interpolated to a 0.05-degree grid covering the east coast of United States (30°–45°N, 72°–87°W). Data can be requested through https://data.eol.ucar.edu/dataset/21.093.

3. Model Configuration
3.1. Regional Weather Model and Data Assimilation System
The WRF-ARW version 3.9.1 model (Wang et al., 2011; William et al., 2008) is a nonhydrostatic, fully compressible, primitive equation model produced by the National Center for Atmospheric Research, the Air

Figure 2. Domain coverages for WRF and the hurricane tracks for Florence and Michael (black = best track data, colored = GFS predicted paths).
### Table 2

| Experiments          | Description                                                                 |
|----------------------|-----------------------------------------------------------------------------|
| CTRL                 | Only conventional observations are assimilated                              |
| CTRL + Rad           | Both conventional and radiance are assimilated                               |
| CTRL + RTVL\_L       | Conventional and both T and WV retrievals at lower troposphere              |
| CTRL + RTVL\_M       | Conventional and both T and WV retrievals at middle troposphere             |
| CTRL + RTVL\_U       | Conventional and both T and WV retrievals at upper troposphere              |
| CTRL + RTVL\_LM      | Conventional and both T and WV retrievals at lower + middle troposphere     |
| CTRL + RTVL\_MU      | Conventional and both T and WV retrievals at middle + upper troposphere     |
| CTRL + RTVL\_LWV     | Conventional and only WV retrievals at lower troposphere                    |
| CTRL + RTVL\_MWV     | Conventional and only WV retrievals at middle troposphere                   |
| CTRL + RTVL\_UWV     | Conventional and only WV retrievals at upper troposphere                    |
| CTRL + RTVL\_LMWV    | Conventional and only WV retrievals at lower + middle troposphere           |
| CTRL + RTVL\_MUWV    | Conventional and only WV retrievals at middle + upper troposphere           |
| CTRL + RTVLWV        | Conventional and only tropospheric WV retrievals                           |

T = temperature, WV = water vapor, RTVL = retrievals, L = lower troposphere, M = middle troposphere, U = upper troposphere, LM = lower + middle troposphere, MU = middle + upper troposphere.

Force Weather Agency, the NOAA, and other governmental agencies and universities. The 3-hr interval forecast initialized at September 13 00:00 and October 10 12:00 UTC 2018 from the Global Forecast System produced by the NCEP, which has a horizontal resolution of 0.25° × 0.25° and 32 unevenly distributed vertical levels with a top at 10 hPa, are used as the initial atmospheric and lateral boundary conditions for the WRF-ARW model. As shown in Figure 2, the WRF-ARW model domain is designed with horizontal grid spacing of 9 km × 9 km to cover the east coast of United States (20° to 47°N, 64° to 88°E). The hybrid sigma-pressure vertical coordinate system is used in this study with 51 vertical levels from surface to 10 mb. The selection of physical schemes are as follows: New Thompson et al. scheme for microphysics, the RRTMG scheme for longwave and shortwave radiation, the Mellor-Yamada Nakanishi and Niino for surface layer and planetary boundary layer, the RUC land surface model for land surface, and the Grell-Freitas scheme for cumulus parameterization.

The GSI (Hu et al., 2016; Kleist et al., 2009) system is the second-generation analysis system, based on the operational Spectral Statistical Interpolation analysis system, developed by the NOAA and NCEP. It is a model constructed in physical space, can be used for both global and regional applications, and is designed to be a flexible, state-of-art system that can be efficiently run on all available parallel computing platforms. The GSI system can use all of the observational data at the same time, including conventional observational data and satellite radiance data. The basic Three-Dimensional Variational (3D-Var) method is used. Configurations are the same for all experiments: same observation forward operators (the observation forward operator for satellite retrievals are the same as radiosondes), same quality control decisions, and two loops with 50 iteration steps each. Similar to the RAP, the data assimilation is an hourly cycled system and the digital filter technique which removes noise from the initial conditions is applied whenever observations are assimilated (Benjamin et al., 2016; Peckham et al., 2016). Satellite retrievals are vertically thinned to model levels to avoid bringing fake vertical information into the model. Satellite retrievals are also horizontally thinned to 15 km. A test of using all the satellite retrievals without horizontal thinning showed more detailed structures but also brought more precipitation in the forecast. More research about the horizontal thinning scales are needed.

### 3.2. Experimental Design

A set of experiments (Table 2) are designed to investigate the impacts of assimilated satellite retrievals on predicting hurricanes using WRF-ARW. All experiments for two hurricanes’ predictions are started at 13 September 03:00 and 10 October 12:00 UTC with hourly cycled assimilation of observations. Forty-eight-hour predictions are made in each experiment starting from 13 September 18:00 and 11 October 00:00 UTC. The CTRL experiment only assimilates the conventional observations. The CTRL + Rad assimilates both conventional and radiance observations from IASI and CrIS. The satellite retrievals are then divided into three layers as discussed in the data section. The results of assimilating bias-corrected water vapor profiles are not shown due to the overall worse performance. A total of 14 experiments are used to illustrate how satellite retrievals affect the predictions.

### 4. Case Studies

#### 4.1. Case 1: Hurricane Florence

Hurricane Florence was the first major hurricane of the 2018 Atlantic hurricane season. It touched down in North Carolina, resulting in severe flash flooding in that region. This is also the wettest hurricane North Carolina has seen. At first, Global Forecast System failed to forecast the landing position. As shown in...
Figure 2, although the two-day forecast of Global Forecast System adjusted the landing position to the south, the landing time was still 12 hr delayed. The cost for preparation in Virginia was over $10 million and the damage caused in North and South Carolina were at least $17 billion.

Figure 3 shows the 24-hr accumulated precipitation from Stage IV, CTRL, (bottom left) precipitation difference between CTRL + RTVL and CTRL, and (bottom right) precipitation difference between CTRL + RTVLWV and CTRL, from 13 September 18:00 to 14 September 18:00 UTC 2018. Black boxes are regions used for validation.

Figure 3. The 24-hr accumulated precipitation from (top left) Stage IV, (top right) CTRL, (bottom left) precipitation difference between CTRL + RTVL and CTRL, and (bottom right) precipitation difference between CTRL + RTVLWV and CTRL, from 13 September 18:00 to 14 September 18:00 UTC 2018. Black boxes are regions used for validation.

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Figure 3 shows the 24-hr accumulated precipitation from Stage IV and CTRL and the precipitation differences between CTRL + RTVL, CTRL + RTVLWV, and CTRL. In general, the WRF-predicted precipitation patterns agree with the Stage IV observations. Heavy precipitation locations can be found not only in the hurricane center region but also at the northeast side of the hurricane in CTRL. However, when satellite retrievals are assimilated, precipitation is strongly reduced at the northeast side of the hurricane. The
extreme precipitation locations are also changed in the hurricane center region (e.g., it is enhanced over the southwest of the hurricane in CTRL + RTVLWV). This indicates that the assimilated satellite retrievals have great impact on the predicted precipitation amount and its distributions. To quantitatively verify the precipitation predictions, the mean bias and standard deviation (STD) between experiments and Stage IV are concluded in Table 3. First, the assimilation of radiance observations can reduce the forecast errors in reflectance of both mean bias and STD. However, the assimilation of satellite retrievals not always reduce the forecast errors especially when temperature profiles are assimilated. By assimilating water vapor alone, the magnitude of mean bias is largely reduced compared to both CTRL and CTRL + Rad. Only CTRL + RTVL_UWV and CTRL + RTVL_MUWV show lower STD compared to CTRL. By assimilating the whole tropospheric satellite retrievals, the STD is increased about 10%, but the STD only increased a small amount by assimilating water vapor retrievals alone.

To further evaluate the impacts of satellite retrievals on hurricane forecast, the differences between the predicted hurricane center determined by MSLP and the BTD, and the equitable threat score (ETS), the probability of detection (POD), and the false alarm ratio (FAR) calculated against the Stage IV are introduced. The calculation of ETS, POD, and FAR can be found in Wang et al. (2018).

The root-mean-square error (RMSE) of the predicted MSLP from a set of selected experiments against the BTD and the distances between the predicted hurricane center and the BTD as a function of forecast time are plotted in Figure 4. In general, the radiance observations produced close MSLP results and hurricane paths within the 24-hr forecast. However, the assimilation of water vapor alone has more advantages in

### Table 3

| Unit (mm) | CTRL   | CTRL + RTVL | CTRL + RTVL_L | CTRL + RTVL_M | CTRL + RTVL_U | CTRL + RTVL_LM | CTRL + RTVL_MU |
|-----------|--------|-------------|---------------|---------------|---------------|----------------|----------------|
| Mean bias | −1.997 | −2.390      | −2.469        | −1.607        | 0.077         | −2.451         | −1.872         |
| STD       | 40.855 | 44.401      | 40.799        | 43.354        | 42.014        | 44.993         | 42.854         |

| Unit (mm) | CTRL + Rad | CTRL + RTVLWV | CTRL + RTVL_LWV | CTRL + RTVL_MWV | CTRL + RTVL_UWV | CTRL + RTVL_LMWV | CTRL + RTVL_MUWV |
|-----------|------------|---------------|-----------------|-----------------|-----------------|------------------|------------------|
| Mean bias | −1.721     | −1.580        | −1.731          | −1.457          | 0.278           | −2.732           | −1.187           |
| STD       | 40.778     | 41.149        | 41.863          | 44.468          | 38.643          | 41.247           | 38.066           |

Numbers in red mean improvements have been made upon CTRL.

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**Figure 4.** (a) Predicted MSLP RMSE (hPa) and (b) distance (km) between predicted centers of Hurricane Florence from selected experiments and the BTD as a function of forecast lead times.
predicting hurricane MSLP than assimilating both temperature and water vapor. There is an average of 15% reduction in RMSE with the assimilation of water vapor alone compared to the assimilation of both temperature and water vapor. A maximum of 21.3% reduction of RMSE can be obtained by assimilating upper tropospheric water vapor retrievals compared to the CTRL. Most of the experiments with water vapor retrievals alone also show advantages in predicting hurricane paths especially within the 36-hr forecast. For predictions longer than 36 hr, the errors grow much faster than those in the CTRL experiment. The CTRL + RTVL_L, CTRL + RTVLL, and CTRL + RTVL_LWV produced the best hurricane paths with an average of 10 km closer to the BTD hurricane center than the CTRL and CTRL + Rad. Table 4 shows the distance from the predicted hurricane center to the observed hurricane center in BTD and the differences between the predicted MSLP and the BTD around landfall. The differences of the predicted MSLP in CTRL and CTRL + Rad are around 19 hPa while most of the experiments with satellite water vapor retrievals give lower differences (e.g., 16.6 hPa in CTRL + RTVL_LWV). The MSLP error is large at the first 24-hr forecast but reduced to 1 hPa at 36-hr forecast. The distances are also largely reduced when satellite retrievals are assimilated. In the CTRL and CTRL + Rad, the distances are around 47 km. A reduction of the distance from the predicted to the observed hurricane center from 6 to 35 km can be obtained when the satellite retrievals are assimilated.

The ETS, POD, and FAR of 24-hr accumulated precipitation from different experiments against the Stage IV are plotted in Figures 5 and 6 as a function of precipitation threshold. The assimilation of radiance data shows small differences against the CTRL. However, most of the experiments that assimilate satellite retrievals show great advantages against the CTRL. The ETS of most of the experiments with satellite retrievals beat the CTRL between thresholds at 10 to 60 mm. The largest improvement of ETS (0.12) is found at 30-mm precipitation threshold in CTRL + RTVL_LMWV which assimilated the water vapor retrievals below 400 hPa. The ETS in experiments that assimilate both temperature and water vapor dropped faster than the CTRL and CTRL + Rad when precipitation is greater than 60 mm. However, when water vapor is assimilated alone, most of the experiments produced comparable ETS to the CTRL + Rad and beat the CTRL. For POD, most of the experiments are 0.1 greater than the CTRL and CTRL + Rad when precipitation threshold is larger than 20 mm. Similar to ETS, most of the experiments with satellite retrievals give lower FAR values for weaker rainfalls. Among all the experiments with satellite retrievals, those with water vapor only show better and more stable results than those with both temperature and water vapor.

As discussed in Wang et al. (2018), the assimilated precipitable water only positively affect heavy precipitation forecast in the first 48-hr period. As shown in Figure 4b, the assimilated water vapor retrievals have positive impacts on the prediction of hurricane path during the first 36-hr period. The ETS, POD, and FAR as a function of forecast lead time from the CTRL, CTRL + Rad, and selected experiment with satellite retrievals for precipitation greater than or equal to 30 mm are plotted in Figure 6. The experiments with satellite water vapor retrievals give much higher ETS than the CTRL and CTRL + Rad during the first 24-hr forecast, and then gives comparable results. For FAR, more advantages can be found during 18- to 48-hr forecast. The precipitation scores show that the assimilation of satellite water vapor retrievals can adjust the moisture field of the initial conditions and improve the precipitation forecast of Hurricane Florence more effectively than assimilating conventional and radiance observations.

Figure 7 shows the initial temperature and relative humidity (RH) at 850, 500, and 300 hPa from CTRL and CTRL + RTVLLWV at 13 September 18:00 2018 UTC. The assimilation of WV alone shows large adjustments

| Table 4 Predicted MSLP Differences and Distance Against BTD Around Landfall |
|-------------------------------|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                              | CTRL             | CTRL + RTVL     | CTRL + RTVL_L   | CTRL + RTVL_M   | CTRL + RTVL_U   | CTRL + RTVL_LM  | CTRL + RTVL_MU  | CTRL + RTVL_LMWV |
| MSLP (hPa)                   | 18.8             | 21.6            | 17.3            | 23.7            | 17.2            | 23.1            | 21.6            | 23.3            |
| Distance (km)                | 46.9             | 31.9            | 31.3            | 23.2            | 40.7            | 17.2            | 23.3            | 23.3            |
| MSLP (hPa)                   | 19.2             | 18.6            | 16.6            | 19.7            | 16.4            | 19.9            | 18.6            | 18.6            |
| Distance (km)                | 47.7             | 15.3            | 17.7            | 11.0            | 21.5            | 16.5            | 27.8            | 27.8            |
on the initial relative humidity. The range of relative humidity increments against the CTRL experiment shown in Figure 3 are $-73.4$–$45\%$, $-77.1$–$66.4\%$, and $-95.0$–$70.4\%$ at 850, 500, and 300 mb, respectively. Much dryer conditions are obtained at the east and northeast side of Hurricane Florence at 850 mb, which is related to the reduced precipitation over the northeast region shown in Figure 3. The magnitudes of temperature increment differences against the CTRL experiment are much smaller than those for relative humidity. The temperatures at each layer are generally adjusted to a warmer condition when water vapor retrievals are assimilated. At 500 mb, a warmer and dryer hurricane eye can be found in the CTRL + RTVLWV, indicating that a stronger second circulation over the eyewall is obtained. The assimilated water vapor caused a decrease of around 20% in RH and an increase of 4-degree K at the eye of the hurricane at 500 mb. At 300 mb, wetter and cooler conditions are found over the boundary of the hurricane. Thus, the improved precipitation forecast of Hurricane Florence is due to the adjusted hurricane structure and intensity via assimilation of satellite retrievals.

### 4.2. Case 2: Hurricane Michael

Hurricane Michael is the second major hurricane of the 2018 Atlantic hurricane season as well as the strongest hurricane formed in October. It was marked as the strongest hurricane in terms of its maximum sustained wind speed since hurricane Andrew in 1992. As shown in Figure 2, the moving speed of Hurricane Michael is much faster than Hurricane Florence over the continental United States. The peak winds obtained from Hurricane Michael reached 250 km/hr and caused at least $14$ billion in damages. Similar to Hurricane Florence, the predicted path and MSLP of Hurricane Michael are corrected when satellite retrievals are assimilated. The RMSE of the predicted MSLP and the distance between the predicted hurricane center determined by MSLP and the observed center in BTD are calculated. The RMSE of the predicted MSLP in the CTRL is 8.128 hPa. When satellite radiance observations are assimilated, the RMSE of predicted MSLP is slightly reduced to 8.106 hPa. However, most of the experiments with satellite retrievals assimilated give much lower RMSE values. An average reduction of 0.6 hPa in RMSE is obtained among those experiments with satellite retrievals. The lowest RMSE of predicted MSLP is given by the CTRL + RTVL_MU with a value of 7.126 hPa. The distance between the predicted hurricane center and the
The assimilation of radiance observations caused a reduction of 6.9 km at 24-hr forecast lead time. An average reduction of 12.5 km in distance can be obtained at 24-hr forecast lead time when satellite retrievals are assimilated. The largest improvement is found in the CTRL + RTVL_MU with a reduction of 45 km in distance.

The 24-hr accumulated precipitation from the Stage IV and CTRL are plotted in Figure 8 along with the precipitation differences between the CTRL + RTVL, CTRL + RTVLWV, and CTRL. As shown in Figure 8, Hurricane Michael caused extremely heavy rainfall over a large region at the east coast of United States in 24 hr. Compared to the CTRL experiment, decrease/increase of precipitation can be obtained over the northwest/southeast side of the hurricane when the satellite retrievals are assimilated. Similar to case 1, the mean bias and STD of the predicted 24-hr accumulated precipitation in the black boxes shown in Figure 8 are calculated in Table 5. The assimilation of radiance shows slightly improvement upon the CTRL. While the assimilation of satellite retrievals gives much smaller mean biases and STDs except when only the upper tropospheric retrievals are assimilated. The magnitude of mean biases of the experiments with satellite retrievals are reduced to the power of $10^{-1}$ to $10^{-2}$ instead of $10^0$ in the CTRL and CTRL + Rad experiments. A 22% reduction of STD is obtained in the CTRL + RTVL compared to the CTRL.

To explore the impact of the satellite retrievals on the prediction of precipitation, the ETS, POD, and FAR scores from different experiments against the Stage IV are calculated for Hurricane Michael. The ETS,
POD, and FAR scores at different precipitation thresholds are plotted in Figure 9. In this case, there is no big difference between the assimilation of both temperature and water vapor retrievals and assimilation of water vapor retrievals alone for the 24-hr accumulated precipitation. Similar to case 1, both sets of experiments give worse scores at small precipitation thresholds. In case 2, better scores are obtained at precipitation thresholds larger than 30 mm. The ETS at precipitation thresholds larger than 30 mm calculated from the CTRL + RTVL_LM is 0.19 larger than those in the CTRL. The FAR is also reduced about 0.2 at precipitation thresholds larger than 30 mm. The POD is largely reduced at precipitation thresholds smaller than 40 mm. Figure 10 shows the ETS, POD, and FAR scores with threshold at 50 mm as a function of forecast lead time. Unlike the case 1, which shows that the impact of assimilated satellite retrievals will mostly affect the first 24-hr forecast, in case 2, the assimilated satellite retrievals will have larger positive impact after 18-hr forecast. The close score at 6-hr forecast lead time is due to the lack of skill in predicting weak precipitations with satellite retrievals. Both cases indicate that the assimilation of satellite retrievals will have less skill in predicting weak rainfalls especially in predicting 24-hr accumulated precipitation under 20 mm.

The initial temperature and RH fields from the CTRL and the CTRL + RTVL at 11 October 00:00 UTC are plotted in Figure 11. Similar to case 1, the RH changes are as large as 90%. The RH changes are in the range of...
−55.2–38.7%, −71.8–69.2%, and −89.9–86.4% at 850, 500, and 300 mb, respectively. At 850 mb, more dry regions ahead and east side of Hurricane Michael are obtained when the satellite retrievals are assimilated. Thus, a large reduction of precipitation amount is obtained as shown in Figure 8. As Hurricane Michael has weakened to a weak tropical storm on 11 October 12:00 UTC, the second circulation is not as strong as the one in Hurricane Florence. No significant differences can be found at 500 mb. However, at 300 mb, a much dryer (40% less RH) and warmer (2-degree K higher) hurricane eye structure can be obtained when the satellite retrievals are assimilated. Thus, the improved precipitation forecast of Hurricane Michael is also due to the adjusted hurricane structure and intensity via assimilation of satellite retrievals.

Figure 8. The 24-hr accumulated precipitation from (top left) Stage IV, (top right) CTRL, (bottom left) precipitation difference between CTRL + RTVL and CTRL, and (bottom right) precipitation difference between CTRL + RTVLWV and CTRL, from 11 October 00:00 to 12 October 00:00 UTC 2018. Black boxes are regions used for validation.
4.3. Analysis of Hurricane Structures

Figure 12 shows the zonal vertical cross section including horizontal wind, temperature and temperature anomaly, and horizontal wind at 850 hPa with SLP, across the center of Hurricane Florence, in the CTRL, CTRL + RTVLWV, and CTRL + Rad analyses, at 1800 UTZ 13 September 2018. The CTRL cross section reasonably represented the storm structure with a maximum wind speed of 63.8 m/s at 850 hPa located at the southwest of the storm center. The maximum surface wind speed in CTRL is 41.7 m/s which is much weaker than the record 46 m/s in BTD. The assimilation of radiance observations in CTRL + Rad only shows slightly difference compared to the CTRL. No significant difference of the storm structure is observed. The maximum wind speed is 63.6 m/s at 850 hPa, and the maximum surface wind is 41.8 m/s. A slightly stronger warm core is obtained in CTRL + Rad. The CTRL + RTVLWV shows the impact of assimilating satellite water vapor retrievals on the storm. Similar to the results in Reale et al. (2018) by assimilating adaptively thinned Atmospheric Infrared Sounder radiance observations, a stronger storm is obtained in the CTRL + RTVLWV. The storm structure resulting from assimilating water vapor retrievals is substantially better, with a tighter eye, a stronger warm core with deeper convections, and a more symmetric structure. The maximum wind speed is also increased to 66.9 m/s at 850 hPa located at the north side of the storm center, and the maximum surface wind speed is much closer to the BTD data which is 45.2 m/s.

Table 5

| Unit (mm) | CTRL | CTRL + RTVL | CTRL + RTVL_L | CTRL + RTVL_M | CTRL + RTVL_U | CTRL + RTVL_LM | CTRL + RTVL_MU |
|-----------|------|-------------|---------------|---------------|---------------|----------------|----------------|
| Mean bias | 6.408 | −0.901 | 5.119 | −0.091 | 5.750 | −0.293 | 0.038 |
| STD | 23.940 | 18.634 | 21.312 | 17.950 | 25.953 | 17.254 | 21.229 |
| Mean bias | 6.342 | −0.027 | 5.669 | 0.730 | 5.848 | 0.406 | −0.119 |
| STD | 23.537 | 22.03 | 22.939 | 20.448 | 25.803 | 20.233 | 20.828 |

Figure 9. Same as Figure 5 but for Hurricane Michael.
Figure 13 shows the zonal vertical cross section and horizontal transects at 850 hPa, across the center of Hurricane Michael, in the CTRL, CTRL + RTVLWV, and CTRL + Rad analyses, at 0000 UTZ 11 October 2018. The CTRL and CTRL + Rad also reasonably represented the storm structure, but the cross sections and the horizontal transects at 850 hPa show an excessive asymmetry structure. The maximum wind speeds are 47.9 and 47.8 m/s and both located at 900 hPa at the east side of the storm center in CTRL and CTRL + Rad, respectively. The maximum surface wind speeds in CTRL and CTRL + Rad are both around 38 m/s, which is slightly weaker than the BTD record 41 m/s. However, a more symmetric storm structure is obtained in CTRL + RTVLWV with slightly stronger warm core and deeper convection. Moreover, the wind speed at the top of the storm is stronger especially over the west side of the storm center. The maximum wind speed is increased to 50.9 m/s and the location of maximum wind speed has been moved to a lower layer at the northwest side of the storm center. The maximum surface wind speed is increased to 40.8 m/s, which is much closer to the BTD record than those in CTRL and CTRL + Rad.

Since the forecast skill is strongly related to the quality of the initial conditions and the precipitation forecast skill is largely dependent on the degree of representation of the hurricane structures, the assimilation of satellite retrievals can lead to a better representation of TC structures in the initial conditions, and hence, a better precipitation forecast can be obtained.

5. Summary and Discussion

The impact of hyperspectral satellite instrument (IASI and CrIS) radiance-derived atmospheric temperature and water vapor profiles on regional hurricane forecasts have been evaluated through two hurricane cases.
Satellite retrievals which fulfill both clear and cloudy (above clouds) conditions using full information from hyperspectral instruments are derived using the Dual-Regression algorithm based on the Principle Component-based Radiative Transfer Model. Derived atmospheric profiles with strong quality control criteria show good quality under both clear and cloudy conditions.

Satellite retrieval assimilation experiments were conducted with the regional weather forecast model WRF-ARW using a 9-km horizontal resolution. The impacts of the assimilated satellite retrievals on the prediction of hurricanes are discussed in this study. Overall, satellite retrievals with good qualities have a positive impact on the forecast of hurricanes. Temperature retrievals have to be bias corrected before assimilating into the model. Predictions with satellite retrievals assimilated can provide better MSLP and correct the paths of hurricanes to the observed hurricane center as large as 45 km. Satellite-observed water vapor information is critical to the prediction of precipitation produced by hurricanes. Precipitation scores show that the assimilation of satellite retrievals usually have positive impact on medium to heavy rainfall forecast instead of weak rainfall forecast. The ETS score alone can be improved as large as 0.2 for the medium rainfall forecast in both cases.

Although the assimilation of satellite radiance observations shows some improvements in predicting hurricanes compared to the CTRL experiment, the assimilation of satellite retrievals is studied as another approach for assimilating atmospheric information from hyperspectral satellite instruments. The experiments show that overall satellite retrieval assimilation have more advantages than satellite radiance.
assimilation especially in the precipitation forecast. The retrievals at lower and middle troposphere, which can provide extra information for the surroundings of hurricanes, are critical to the forecast of hurricane’s intensity, track, and associated precipitation. The satellite retrievals above clouds can also provide useful information for the formation of clouds in numerical models. Better representation of hurricane structures (specifically, more symmetric structures, stronger warm cores, deeper convections, and more accurate winds are obtained in the two cases studied in this paper) which is critical to the distribution and intensity of precipitation forecast are obtained in the initial conditions. The high temporal and spatial resolution of satellite retrievals can provide a large amount of observations and benefit the models especially for regional- and storm-scale models.

The assimilation of atmospheric temperature retrievals is still a remaining challenge. The assimilation of temperature retrievals alone still faces large errors (not shown) in precipitation forecasts. The results shown in this paper are not consistent for the two cases especially when temperature retrievals are assimilated along with water vapor retrievals. The differences between case 1 and case 2 are mainly due to the data coverage. Most of the satellite retrievals in case 1 are over ocean. Satellite retrievals for case 2 then mainly cover the eastern part of U.S. continent. As we used the near-surface temperature from RAP’s 2-hr forecast for the retrievals, the quality of temperature retrievals may vary over land and ocean due to the lack of information.

Figure 12. (top) Zonal vertical cross section of wind (m/s; shaded), temperature (°C; solid black contours), and the temperature anomaly (solid red contours; contours every 2 °C, only ≥4 °C for clarity) for Hurricane Florence at 1800 UTC 13 September 2018, comparing the CTRL, CTRL + RTVLWV, and CTRL + Rad experiments. (bottom) Horizontal winds at 850 hPa (m/s; shaded) and SLP (hPa; solid black contours).
over ocean in the RAP. An important future study is the improvement of satellite retrievals’ qualities by using more accurate backgrounds and cloud information.

This paper focuses on the assimilation of hyperspectral radiance-derived atmospheric profiles from polar-orbiting satellites and demonstrating the impact of the added information on hurricane forecast especially for heavy precipitation forecast caused by hurricanes. The results shown here are considered to be preliminary. Improvements in the forecast accuracies shown here are expected to result from future improvements in the profile retrieval algorithm and the satellite data assimilation procedures. Future work will also include other information such as fusion of hyperspectral satellite retrievals and Advanced Baseline Imager to create data sets with more accurate water vapor information with even higher temporal and spatial resolutions. These combined polar and geostationary satellite sounding information will be used to investigate the impacts of very high resolution retrievals in numerical weather prediction systems.

To place this work into an operational system properly, several issues need to be addressed. First, this research is focused on IASI and CrIS only due to their ability to provide high vertical resolution retrievals via hyperspectral channels. But still, the vertical error correction has to be done through the de-aliasing technique described in this study. For other instruments with fewer spectral channels, it is a challenge to derive atmospheric profiles with considerable vertical resolutions with limited spectral channels.

Second, despite that hyperspectral instruments can provide large amount of atmospheric retrievals, experiments using all the profiles have shown nonnegligible errors due to the error correlation problem. More
specifically, data density should be treated more carefully based on model resolutions. Thus, better data thinning strategies are needed for these instruments before the data can be applied to an operational system. Third, the impacts of the derived atmospheric profiles on weather forecast systems are very sensitive to coverage. As shown in the current work, the experiments are done in a regional scale over both land and ocean with profiles available under clear conditions and partial available on cloudy conditions. The regression algorithm used to derive the atmospheric profiles are fast enough for the practical and crucial constraints of a regional real-time forecasting; the minimum latency can be reduced to about 0.5 hr. Thus, there is a potential for the application of this algorithm in a global weather forecasting system with limited latency.

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