Improving Hurricane Analyses and Predictions with TCI, IFEX Field Campaign Observations, and CIMSS AMVs Using the Advanced Hybrid Data Assimilation System for HWRF. Part II: Observation Impacts on the Analysis and Prediction of Patricia (2015)

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ABSTRACT

Diverse observations, such as the High Definition Sounding System (HDSS) dropsonde observations from the Tropical Cyclone Intensity (TCI) program, the Tail Doppler Radar (TDR), Stepped Frequency Microwave Radiometer (SFMR), and flight-level observations from the Intensity Forecasting Experiment (IFEX) program, and the atmospheric motion vectors (AMVs) from the Cooperative Institute for Meteorological Satellite Studies (CIMSS) simultaneously depicted the three-dimensional (3D) structure of Hurricane Patricia (2015). Experiments are conducted to understand the relative impacts of each of these observation types on Patricia's analysis and prediction using the Gridpoint Statistical Interpolation (GSI)-based ensemble-variational data assimilation system for the Hurricane Weather Research and Forecasting (HWRF) Model. In comparing the impacts of assimilating each dataset individually, results suggest that 1) the assimilation of 3D observations produces better TC structure analysis than the assimilation of two-dimensional (2D) observations; 2) the analysis from assimilating observations collected from platforms that only sample momentum fields produces a less improved forecast with either short-lived impacts or slower intensity spinup as compared to the forecast produced after assimilating observations collected from platforms that sample both momentum and thermal fields; and 3) the structure forecast tends to benefit more from the assimilation of inner-core observations than the corresponding intensity forecast, which implies better verification metrics are needed for future TC forecast evaluation.

1. Introduction

Hurricanes are difficult to observe over the open ocean, especially their inner-core regions. Due to heavy cloud and precipitation, utilization of all-sky satellite radiances is still a challenge and the corresponding research for tropical cyclone (TC) predictions are just beginning (Bauer et al. 2010, 2011; Yang et al. 2016; Zhang et al. 2016; Zhu et al. 2016; Geer et al. 2017). Therefore, data collected by the manned or unmanned aircraft penetrating hurricanes becomes one of the few options for hurricane inner-core studies (Marks and Houze 1984, 1987; Gamache et al. 1993; Reasor et al. 2000; Xiao et al. 2009; Zhang et al. 2009, 2011; Weng and Zhang 2012; Aksoy et al. 2013; Lu et al. 2017a,b). These aircraft are usually supported by different field campaign programs.

Starting from 2005, an Intensity Forecasting Experiment (IFEX) program was conducted by the National Oceanic

and Atmospheric Administration (NOAA). In this multiyear experiment, observations such as Stepped Frequency Microwave Radiometer (SFMR), flight-level (FL), and tail Doppler radar (TDR) observations were collected through the NOAA WP-3D aircraft (Rogers et al. 2006, 2013). The different observations primarily focus on the inner-core structures of hurricanes at various levels. For example, the SFMR samples only the surface, the FL observations are usually centered around 700–800 hPa, and the TDR scans three-dimensional (3D) structures with the number of observations peaked around 900 hPa (e.g., Fig. 1c).

These observations collected from the IFEX field campaign have been widely used in hurricane research for decades. For instance, the SFMR wind observations are commonly used to validate or estimate the maximum surface wind speed (V_{max}) for hurricanes (e.g., Uhlhorn and Black 2003; Uhlhorn et al. 2007; Powell et al. 2009; Weng and Zhang 2012). The FL observations are often used for the estimation of TC center and the

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FIG. 1. An example of the (a) temporal, (b) horizontal, and (c) vertical distribution of the observations. (b),(c) Wind observations assimilated in the innermost domain valid at 1800 UTC 22 Oct 2015 during Patricia. Best is short for the best track data form NHC. Note, the x axis in Fig. 1c is in log space.

validation of simulated TC inner-core structure (Aksoy et al. 2013; Rogers and Uhlhorn 2008; Willoughby and Chelmon 1982; Willoughby and Rahn 2004; Chen et al. 2011). The TDR radial velocity observations are extensively used for hurricane inner-core data assimilation (DA), and extensive studies have demonstrated the potential of high-resolution inner-core observations in improving high-resolution hurricane predictions using advanced DA methods (e.g., Zhang et al. 2009, 2011; Weng and Zhang 2012; Poterjoy et al. 2014; Zhang and Weng 2015; Pu et al. 2016; Lu et al. 2017a,b).

In 2015, a Tropical Cyclone Intensity (TCI) program supported by the Office of Naval Research (ONR) was conducted to collect dropsonde observations aiming at sampling the TC outflow as well as the inner-core regions (Doyle et al. 2017). These dropsondes were released by WB-57 from about the 18-km altitude and sampled all the way down to sea surface (Feng and Wang 2019). The high altitude of the aircraft provided valuable opportunities to sample upper-tropospheric information, especially for the TC outflow region. Thanks to the high definition sounding system (HDSS) and expendable digital dropsonde (XDD) technology (Black et al. 2017), these dropsonde observations have unprecedentedly high vertical spacing (~ 0.1 -hPa) (Bell et al. 2016). Given tens of dropsondes were deployed within a small time window, the finest horizontal transection spacing of the dropsondes near the inner-core regions of the TCs can be around 4.4-km (Doyle et al. 2017). Dropsondes with such a high resolution provide a great sampling of both the inner-core and the outflow structures. But due to the novelty of the dataset, there are only a few studies exploring their applications in the hurricane analysis and prediction (e.g., Feng and Wang 2019; Zhang and Pu 2019).

Other than those field campaign observations, in recent years, the “enhanced” atmospheric motion vector (AMV) observations have been produced by the Cooperative Institute for Meteorological Satellite Studies (CIMSS) (Wu et al. 2014, 2015; Velden et al. 2017). The CIMSS AMVs are designed to have higher density, larger coverage, and better quality as compared to the operationally produced AMVs provided by the National Environmental Satellite, Data, and Information Service (NESDIS) (Velden et al. 2017). These CIMSS AMVs can provide upper-level environmental information of the TCs (e.g., Fig. 1). Previous studies suggested that assimilating the CIMSS AMVs can modestly improve hurricane track and intensity predictions (Wu et al. 2014, 2015; Velden et al. 2017).

The aforementioned observations each provides sampling of certain aspects of the TC structure including the inner core, the outflow layer, the surface inflow and the environment flow. Coexistence of all these types of observations for the same hurricane and at the same time is rare. Therefore, most early studies only revealed impacts of one type of observations or only simultaneously compared the impacts of a limited subsets of these observations (Weng and Zhang 2012; Aksoy et al. 2012, 2013; Poterjoy et al. 2014; Wu et al. 2014, 2015; Lu et al. 2017a). Fortunately, through coordination between the IFEX and TCI field campaigns, Hurricane Patricia (2015) became the sole hurricane that was intensively and simultaneously sampled by all the abovementioned instruments. This provides an unprecedented opportunity to reveal and intercompare the impacts of all these types of observations. To the authors’ best knowledge, this work is the first data assimilation study that reveals the relative impacts of all these types of observations on the analysis and prediction in the same hurricane.

In addition, the simultaneous availability of these observations also provides a good opportunity to cross validate the analysis after assimilating each type of observations.

To make a good use of the observations, an efficient and advanced DA system is required. A GSI-based, continuously cycled, dual-resolution, hybrid ensemble-variational (EnVar) DA system for Hurricane Weather Research and Forecasting (HWRF) Model was recently developed (Lu et al. 2017a,b) expanded from the same hybrid DA system for the operational global forecast system (Wang et al. 2013). It was shown that the new system can improve both the track and intensity predictions upon the operational HWRF. In Lu and Wang (2019, hereafter Part I), experiments were conducted to investigate the impact of model physics and model resolution on the spindown issue during Hurricane Patricia (2015). Results indicated that assimilating the aforementioned observations altogether using the new system and modified model physics, the 3D structures of Patricia were realistically captured in the analysis. In addition, the realistic TC structure from the DA analysis was well maintained during the forecast, evidenced by the improved subsequent forecast of rapid intensification (RI) of Patricia (2015). Therefore, in this second part of the two-part study, the same system and model configurations will be used to investigate the relative impacts of these diverse observation types on the analysis and prediction of Patricia (2015). Since this is only a case study with limited sample size, the primary goal of this study is to improve the physical understanding of the relative importance of each observation type, and to suggest future directions for additional studies.

As the second part of the two-part study, we first briefly describe the model, the observations and experiment designs in section 2. Section 3 discusses the results of the impacts of various observations on the analysis and prediction of Patricia. Section 4 concludes and further discusses the results.

2. Model, data, and experiment design

a. Model description

The GSI-based, continuously cycled, dual-resolution, hybrid EnVar DA system for HWRF (Lu et al. 2017b) is used in this study as a tool to investigate the observation impacts on the analysis and prediction of Patricia. As stated in Part I, this upgraded DA system is based on the 2015 operational HWRF (H215). One major difference between the new DA system and the DA system in the H215 is the source of ensemble covariances. Specifically, a continuously cycled HWRF ensemble consistent with the intermediate domain

resolution of the control (e.g., 6-km grid spacing in this study) is used to provide ensemble background covariances in the 3DEnVar DA replacing the coarser resolution GFS ensemble. Further details about the new DA system and workflow can be found in Part I.

The horizontal grid spacing of the model is approximately 2 km (0.015°), 6 km (0.045°), and 18 km (0.135°) for the innermost (265×472 grid points), intermediate (304×604 grid points), and outermost (288×576 grid points) domains, respectively. The model is configured with 61 vertical levels and the model top is at 2 hPa. The initial and boundary conditions for the outermost domain are obtained from the Global Forecast System (GFS) analyses and forecasts. The choice of model physics parameterization schemes follows the H215 (Tallapragada et al. 2015) with modifications in the vertical and horizontal diffusion parameterizations (Table 1). Briefly, the in-cloud turbulent mixing parameterization in the planetary boundary layer (PBL) scheme proposed by Zhu et al. (2019) is adopted to enable the in-cloud mixing for the eyewall and rainband regions. The horizontal diffusion is reduced to be more consistent with the 2-km model grid spacing as suggested by Zhang et al. (2018). As discussed in Part I, the modified suite of model physics was able to better maintain the realistically analyzed TC structure and largely alleviate the Vmax spindown issue. The spindown is a short term but significant Vmax drop due to the incompatibility between the realistic DA analysis and inaccurate model physics (Lu and Wang 2019). Additional experiments (not shown) without the model physics modifications did not change the relative data impacts, although most of those experiments suffered from the spindown issue.

b. Observations and preprocessing

As introduced in section 1, there are five special types of observations that are assimilated in this study: CIMSS AMV wind; SFMR surface wind speed; FL temperature, moisture and wind; TDR radial velocity; and HDSS dropsonde temperature, moisture, and wind. Further information, descriptions and preprocessing applied for each type of observations are described below.

The CIMSS AMV observations used in this study are derived from the Geostationary Operational Environmental Satellite (GOES) by CIMSS. Following Wu et al. (2014), the CIMSS AMVs are quality controlled and superobbed before being assimilated by the DA system. Specifically, only the CIMSS AMVs with quality indices no less than 0.6 and expected error lower than 4.5 m s^{-1} , or the observations greater than 25 m s^{-1} with quality indices no less than 0.7 are assimilated. The superob prisms are configured to be $0.1^\circ \times 0.1^\circ \times 15 \text{ hPa}$, and the

TABLE 1. List of experiments and their descriptions.

Experiment name	Common features	Description
NoDA	Background: 6-h control forecast initialized from 1200 UTC 22 Oct 2015 using the GSI-based, continuously cycled, dual-resolution hybrid ensemble–variational (EnVar) DA system for HWRF (Lu et al. 2017b) valid at 1800 UTC 22 Oct 2015. Physics: Ferrier–Aligo microphysics scheme; simplified Arakawa–Schubert (SAS) cumulus scheme; HWRF modified surface layer scheme; Noah land surface model; HWRF PBL scheme; RRTMG longwave and shortwave radiation schemes; Reduced “Coac” (horizontal diffusion weight) from 0.75/3.0/4.0 to 0.75/1.0/1.2; Modified turbulent mixing parameterization.	No DA is performed
OperH		Conventional in situ data in prepbufr (radiosondes; dropwindsondes; aircraft reports; surface, ship, and buoy Observations; surface observations over land; Pibal winds; wind profilers; radar-derived velocity–azimuth display wind; WindSat scatterometer winds; integrated precipitable water derived from the global positioning system), tcvital, EMC AMVs, and satellite radiances (from HIRS, AIRS, IASI, GOES, AMSU-A, MHS, and ATMS). Note, the satellite radiances are only assimilated in the intermediate domain following the operational configuration.
CIMSS_Only		Only CIMSS AMVs are assimilated
SFMR_Only		Only SFMR observations are assimilated
FL_Only		Only flight-level observations are assimilated
TDR_Only		Only TDR are assimilated
HDSS_Only		Only HDSS dropsondes from TCI are assimilated
All		Conventional in situ data in prepbufr, tcvital, TDR, SFMR, and flight-level observations, HDSS dropsondes from TCI, CIMSS AMVs, and satellite radiances

CIMSS AMVs are averaged with equal weight within each prism. The observation errors for the CIMSS AMVs range from 2.5 to 7 m s^{-1} depending on the pressure level at which the observations are located.

The SFMR, FL, and TDR observations assimilated in this study are collected by the NOAA WP-3D aircraft during the IFEX field campaign. The SFMR equipment has been onboard NOAA WP-3D aircraft since 1984 (Uhlhorn and Black 2003) and redesigned since 2004 (Uhlhorn et al. 2007). In this study, the SFMR wind observations are obtained from Hurricane Research Division (HRD 2015) and are superobbed before the assimilation. The horizontal dimension of the superob prism is configured to be $0.03^\circ \times 0.03^\circ$, and the observation error is set to be 5 m s^{-1} . The FL observations, including wind, temperature and moisture observations, have been synthetically sampled by multiple instruments onboard the NOAA WP-3D aircraft for decades (Friedman 1982, 1984). In this study, the FL observations are directly obtained from the National Weather Service (NWS) data pool. The horizontal data resolution is about 3–5 km and therefore no further thinning or superobbing is performed. The observation errors are about 5.5 m s^{-1} , 2.5 K, and 2.5 kg kg^{-1} for the wind, temperature and specific humidity, respectively. Due to data transfer issue, the TDR data was not available in the operational HWRF before 23 October 2015 during

the real time forecast of Hurricane Patricia. The TDR data used in this study was obtained from HRD (2015). The preprocessing for the TDR radial velocity follows Gamache (2005) and Lu et al. (2017a,b), and the observation error is assigned to be 5 m s^{-1} .

The HDSS dropsondes are provided by the TCI field campaign as stated in section 1. During Hurricane Patricia, there are in total 257 dropsondes deployed during the four WB-57 missions between 20 and 23 October 2015 to sample the moisture, temperature and wind profiles in the inner-core and outflow regions of Patricia. This study only focuses on the 83 dropsondes released on 22 October 2015. These HDSS dropsondes were initially quality controlled through both software and manual inspections by the TCI scientists (Bell et al. 2016). Due to the high vertical resolution of the observations, superobbing is applied to reduce the data density. After some initial trials (not shown), the superobbed prisms are roughly chosen to be about 2 times the model grid spacing, specifically, about $0.04^\circ \times 0.04^\circ$ (roughly $4 \times 4 \text{ km}^2$) in the horizontal and every other model level (e.g., about 10 hPa near 1-km height) in the vertical in this study. The observations within each prism are averaged with equal weights. The observation errors used for the HDSS dropsondes range from 2.5 to 5.1 m s^{-1} , and from 0.5 to 2 K for the wind and temperature, respectively, and 2 kg kg^{-1} for the specific

humidity. In this study, the diagnostics and verifications are based on these superobbed dropsonde observations. Further sensitivity experiments on the optimal data preprocessing approach in the HDSS dropsondes will be presented in a forthcoming study.

c. Experiment design

For Patricia, there are only 3 DA cycles that all the IFEX, TCI, and CIMSS AMV observations are simultaneously available (Fig. 1a). This study only focuses on the cycle on 22 October 2015 for the following reasons. First, 23 October is not considered because we are mostly interested in the analysis and prediction of the RI phase of Patricia. 21 October was not selected because the actual TCI WB57 flights deviated from the original plan. The deviation makes the actual WB57 flight tracks have undesirably little overlap with the IFEX P3 flight track in the horizontal direction when both sample the inner core region. For example, on 21 October, the flight pattern from WB-57 missed the southern portions of the storm while the WP-3D captured it (not shown). Such a difference complicates the interpretation of the impact of the data on the inner core analysis. In comparison, the 22 October cycle has similar flight patterns in the inner-core region between the IFEX and TCI field campaigns. This cycle was then selected to aid in addressing the scientific objectives of the study.

To understand the relative impact of each individual observation type on the TC analysis and prediction, eight experiments denoted as “NoDA,” “OperH,” “HDSS_Only,” “TDR_Only,” “FL_Only,” “SFMR_Only,” “CIMSS_Only,” and “All” are conducted (see descriptions in Table 1). Details for each experiment are described as below.

Experiment NoDA is initialized from a relocated control background forecast valid at 1800 UTC 22 October 2015 from the newly upgraded hybrid DA system with modified model physics. The model physics are modified from the previous cycle starting from 1200 UTC 22 October 2015. There were seven DA and forecast cycles performed ahead every 6 h starting from 1800 UTC 20 October 2015 using the cycled DA system with only the operational HWRF observations assimilated and the physics configurations comparable to the 2015 operational HWRF. The configuration and design of NoDA in this study are identical to experiment “NoDA” in Part I, except the modified model physics. No vortex modification (VM) is performed but the vortex relocation (VR) is kept at the TDR-available cycle prior to DA following Lu et al. (2017b). Note that some preliminary diagnostics of this study were included in the Fig. 15 of Doyle et al. (2017). However, those preliminary diagnostics were conducted without the physics parameterization improvement and were shown

at different levels, and therefore differ from Figs. 2 and 3 in this study.

To provide a reference to reveal the impact of other specially collected observations, experiment OperH is conducted to assimilate observations from the operational HWRF data stream based on NoDA. The details about the observations assimilated in OperH are described in Table 1. Note, as indicated in section 2b, no TDR data are assimilated in the operational HWRF at 1800 UTC 22 October 2015 during Hurricane Patricia, and the clear-air satellite radiance observations are only assimilated in the intermediate domain. Therefore, the inner-core information in OperH is only provided by a few dropsondes in the lower troposphere launched from WP-3D aircraft and TCVital MSLP. Note that the analysis by this OperH experiment is different from that generated by the operational HWRF. In addition to the system differences mentioned in section 2a, the operational HWRF performs VM before the assimilation whereas this study does not.

Compared to NoDA, CIMSS_Only, SFMR_Only, FL_Only, TDR_Only, and HDSS_Only are experiments where the corresponding individual type of observations is assimilated, respectively. Intercomparison among these experiments, NoDA and OperH reveals the data impact of each individual observation type.

Experiment All assimilates all types of observations listed above based on NoDA. This experiment is conducted to reveal the impact of combining all types of observations. Note that experiment All is identical to experiment “DA-HDVD” in Part I.

3. Results

a. Evolution of Patricia observed from various platforms

As shown in Fig. 1a, Patricia became a tropical storm around 0000 UTC 21 October 2015 and started its RI on 22 October. After reaching the peak intensity around 1200 UTC 23 October, Patricia rapidly weakened and made landfall around 2300 UTC 23 October. This study primarily focuses on the RI evolution of Patricia between 1800 UTC 22 October and 1800 UTC 23 October. The structural evolution of Patricia observed from various platforms during this period is first briefly discussed in this section.

At 1800 UTC 22 October 2015, Patricia was a small-sized, category 4 hurricane. The V_{max} was 59 m s^{-1} and the radius of maximum wind (RMW) was about 18 km. Such a strong V_{max} in the northeast (NE) quadrant of Patricia and the small RMW were well captured by the SFMR observations (Fig. 2a). The small storm size and the wind speed maximum located in the NE quadrant

FIG. 2. Wind (shading and vectors, m s^{-1}) and pressure (contours, hPa) at 10-m height for (a) SFMR observations onboard NOAA P-3 aircraft centered around 1739 UTC 22 Oct 2015, (b) NoDA analysis, (c) OperH analysis, (d) CIMSS_Only analysis, (e) SFMR_Only analysis, (f) FL_Only analysis, (g) TDR_Only analysis, (h) HDSS_Only analysis, and (i) All analysis valid at 1800 UTC 22 Oct 2015 during Patricia. The black dots denote the best track position valid at 1800 UTC 22 Oct 2015.

were also consistently found in the FL and TDR observations (e.g., Fig. 3a). A southeast–northwest (SE–NW) cross section of the radial wind patterns derived from the HDSS dropsondes shows that Patricia was dominated by inflow (blue colors) in the SE section of the low-level and was dominated by outflow (red colors) in the NW section (Fig. 4a). Other than the cross sections, the environmental wind (outside the

150-km radius of the storm) sampled by the CIMSS AMVs was also available. Given the peak number of observations (Fig. 1c),¹ the corresponding radial flow

¹ The AMV observations at the lower troposphere were only distributed in the intermediate domain but outside the innermost domain at this time in this study.

FIG. 3. As in Fig. 2, but for the 3-km horizontal wind (shading and vectors, m s^{-1}) in verification with (a) the HRD radar composite. The blue lines in (a) denote the flight track of WB-57 and the blue lines in (b)–(i) denote corresponding southeast–northwest cross section to be plotted in Figs. 4 and 6.

patterns derived from the CIMSS AMVs at 150 hPa are shown in Fig. 5a. The environmental wind at this level was featured with outflow except the east (E) to SE portion. Besides the dynamic structures, the thermodynamic structures were also sampled from the HDSS dropsondes. For instance, the corresponding temperature

anomaly in the SE–NW cross section is shown in Fig. 6a. The Jordan annual mean profile (Jordan 1958) is used as the environmental sounding during the anomaly calculation. At this time, there were two warm anomaly maxima in the eye region for this cross section: one stronger upper-level warm core (UWC)

FIG. 4. As in Fig. 2, but for the radial wind (shading, m s^{-1}) analysis of the southeast to northwest vertical section in verification with (a) the HDSS dropsonde observations centered around 1820 UTC 22 Oct 2015. Positive (warm color) indicates outflow and negative (cold color) indicates inflow.

centered between 200 and 250 hPa, and one weaker midlevel warm core (MWC) centered between 550 and 600 hPa.

The above observations will then be used to verify the analyses at 1800 UTC 22 October 2015 produced by the various DA experiments. Since the next aircraft observations were only available at 1800 UTC 23 October, the subsequent 24-h forecast is verified using the *GOES-13* brightness temperature (BT), which is available every

15 min (CLASS 2015). Forecast verification is based on band 4 ($10.7 \mu\text{m}$ central wavelength), because this longwave band retrieved the cloud-top temperature and precipitation evolution of Patricia. The BT series show that Patricia featured with a well-maintained, small and symmetric eye during the 24-h period. According to the hurricane report from National Hurricane Center (NHC) (Kimberlain et al. 2016), the eye size of Patricia ranged from 13 to 18 km during this time period.

FIG. 5. As in Fig. 2, but for 150-hPa radial wind (shading, m s^{-1}) and horizontal wind (vectors, m s^{-1}) in verification with (a) the CIMSS AMV observations. The red star in (a) and the black dots in (b)–(i) denote the best track position and the blue dots in (b)–(i) denote the analyzed storm center at the surface. Note, the black and blue dots are very close to each other for each experiment due to the vortex relocation.

Not only the size of the eye remained small, the size of the central dense overcast (CDO) region in Patricia also remained small (diameter ranging from about 250 to 300 km, e.g., Figs. 7a–8a).

At 1800 UTC 23 October 2015, Patricia already entered a rapid weakening (RW) stage. But the storm was still well organized, and the $V_{\max}$ was as strong as 92.6 m s^{-1} (180 kt; $1 \text{ kt} \approx 0.5144 \text{ m s}^{-1}$). The strong $V_{\max}$ and the small size (RMW about 9 km) of Patricia can be consistently found in the Hurricane Imaging

Radiometer (HIRAD) observations at 10-m altitude (Cecil et al. 2016) and the corresponding HRD radar composite at 3-km height (Figs. 9 and 10).

b. Analysis and forecast from NoDA

This section shows model-predicted Patricia in the NoDA experiments during the 24 h between 1800 UTC 22 October and 1800 UTC 23 October 2015.

At the initial time (1800 UTC 22 October), the vortex from NoDA is spuriously large in size, weak in intensity.

FIG. 6. As in Fig. 4, but for the warm-core anomaly analysis of the southeast to northwest vertical section in verification with (a) the HDSS dropsonde observations centered around 1820 UTC 22 Oct 2015. The Jordan annual mean profile is used as the environmental sounding for all experiments for consistency.

For example, Fig. 2b shows that NoDA produces a RMW about 39-km with the $V_{\max}$ weaker than 45 m s^{-1} . Although the value of the wind speed maximum at 3 km is almost comparable with the observations (Fig. 3b), the storm is still significantly larger and more symmetric. This weak $V_{\max}$ but comparable 3-km wind maximum structure in NoDA could be attributed to the HWRF Model bias in the vertical wind profile (Tong

et al. 2018). Additionally, NoDA produces incorrect radial inflow/outflow patterns. For example, the NW low-level outflow is incorrectly represented as an inflow (Fig. 4b), and the westward upper-level outflow in the W to NW side of the storm are overestimated (Figs. 5a,b).

Aside from those inconsistencies in the model-predicted dynamical fields, NoDA also suffers from biases in the

FIG. 7. As in Fig. 2, but for the 4-h forecasted brightness temperature (K) in verification with (a) *GOES-13* band 4 valid at 2200 UTC 22 Oct 2015 during Patricia. The red dots denote the satellite-derived storm position at this time.

thermodynamic fields of the TC. Specifically, Fig. 6b shows that the center of the UWC in NoDA is about 50 hPa lower than that captured by the HDSS dropsondes. Additionally, the MWC centered around 600 hPa is stronger than that in the observations. Both warm cores are about twice as wide as those in the observations. Such an erroneously large warm-core size is consistent with the abnormally large storm size shown in Figs. 2 and 3.

Those spurious dynamic and thermodynamic structures in the initial conditions therefore produces false structural forecast within the next 24 h. For example, in the model-derived BT patterns produced by NoDA, the eye size (~ 60 km on average) and the size of the CDO region (~ 400 – 500 km) are almost tripled or doubled the corresponding sizes in the observations, respectively (Figs. 7b–8b). Moreover, given the larger

FIG. 8. As in Fig. 6, but for the 8-h forecasted brightness temperature (K) valid at 0200 UTC 23 Oct 2015 during Patricia.

regions of CDO, the spiral rainbands found in the observations become less pronounced in NoDA. For instance, at 2200 UTC 22 October, there is only a few convective bands outside of the CDO (Fig. 7b). Four hours later at 0200 UTC 23 October, the convective bands started to grow around the CDO (Fig. 8b). But the strong convective bands, which developed from

the NE quadrant in the observations (Fig. 8a), are still significantly weaker and smaller in the NoDA forecast. After 24 h of model integration, the storm size in NoDA is still significantly larger than the observations at all levels (Figs. 9b and 10b). Although the wind speed at the 3-km height in NoDA seems to be greater than the observations at hour 24, the Vmax is weaker.

FIG. 9. As in Fig. 2, but for the 24-h forecasted surface wind (shading and vectors, m s^{-1}) valid at 1800 UTC 23 Oct 2015 in verification with (a) HIRAD (Hurricane Imaging Radiometer) observations centered at 2000 UTC 23 Oct 2015 during Patricia. The domain size is the same in (a)–(i). The black dots denote the best track position at 1800 UTC 23 Oct 2015.

Again, this mismatch of the vertical wind profile could be attributed to the HWRF Model bias (Tong et al. 2018).

In addition to evaluating the TC evolution in the forecasts, the traditional minimum sea level pressure (MSLP), Vmax and track forecasts produced by NoDA are also shown in Fig. 11 and compared against the best track. Figure 11 shows that although

the initial MSLP in NoDA is almost comparable with the best track, the initial Vmax is weaker. Figure 11b also indicates that the RI rate in NoDA is roughly comparable to the best track, which is likely a result of the modified model physics as discussed in Part I. The peak intensity is, however, weaker than the best track, and the time of peak Vmax is about 6 h earlier. Overall, without any DA, NoDA produces a large

FIG. 10. As in Fig. 2, but for the 24-h forecasted 3-km wind (shading and vectors, m s^{-1}) in verification with (a) HRD radar composite valid at 1733 UTC 23 Oct 2015 during Patricia. The black dots denote the best track position valid at 1800 UTC 23 Oct 2015.

and weak storm in both the analysis and the subsequent forecast.

c. Analysis and forecast from OperH—Impact of the operational HWRF observations

Assimilating observations from the operational HWRF data stream, experiment OperH shows slight corrections in the vortex structure upon NoDA. For example, the west side of the vortex is weakened in

OperH at both the surface and 3-km height as compared to NoDA (Figs. 2c and 3c). As indicated in section 2c, these low-level inner-core modifications in OperH primarily come from the assimilation of limited dropsondes and TCVital information. But Fig. 4c shows that OperH does not significantly modify the spurious low-level inflow in the NW section from NoDA. In the upper levels, OperH reduces the strong outflow bias in the NW region of the storm as compared to NoDA (Figs. 4c and 5c).

FIG. 11. (a),(e),(i) MSLP forecast, (b),(f),(j) Vmax forecast, (c),(g),(k) track forecast, and (d),(h),(l) track forecast errors for NoDA (blue), OperH (green), CIMSS_Only (yellow), SFMR_Only (purple), FL_Only (red), TDR_Only (orange), HDSS_Only (gold), All (cyan), and best track (black) initialized from 1800 UTC 22 Oct 2015 during Patricia.

Such corrections are primarily due to the operational AMVs assimilated in OperH. To help better visualize the improvements, collocated radial wind increments from the DA analyses relative to NoDA are shown in Fig. 12. Figure 12a clearly shows the outflow reduction in the W to NW side of the storm upon NoDA. However, OperH also spuriously enhances the near-core inflow in the NW side of Patricia (around 16°N, 104.5°W). Additionally, an erroneous correction happens in the due south of TC, which resulted in the weakening of the southward outflow (e.g., between 12°–13°N and 104°–105.5°W). In the thermodynamic field, OperH slightly reduces the MWC in both size and strength upon NoDA (Fig. 6c), which is more consistent with the observations.

To further quantitatively evaluate the analysis, the root-mean-square-fit (RMSF) of the analysis against the SFMR, FL, TDR, HDSS dropsondes, and CIMSS AMV

observations is calculated (Fig. 13). The corresponding RMSF from the NoDA analysis is also given as a reference. For example, the RMSF to the SFMR, TDR, and FL observations can measure the impact of assimilating the operational observations over NoDA in the inner-core region. The corresponding RMSFs in Fig. 13 show that OperH improves the inner-core dynamic structures upon NoDA. Similarly, the RMSF calculated against the HDSS dropsonde observations can measure the 3D improvements of the DA analysis over NoDA in the inner-core and outflow regions, and the RMSF calculated against the CIMSS AMV observations can indicate that the corresponding improvements in the upper-level environment wind field. Figure 13 shows that OperH overall slightly improves both the dynamic and thermodynamic fields relative to NoDA in almost all aspects.

FIG. 12. The collocated 150-hPa radial wind increment (shading, ms^{-1}) by subtracting NoDA from (a) OperH analysis, (b) CIMSS_Only analysis, (c) SFMR_Only analysis, (d) FL_Only analysis, (e) TDR_Only analysis, (f) HDSS_Only analysis, and (g) All analysis valid at 1800 UTC 22 Oct 2015 during Patricia. The vectors are the 150-hPa horizontal wind from NoDA as a reference.

Due to these improvements in the OperH analysis upon NoDA, the structural forecasts produced by OperH are also moderately better than NoDA. For example, both Figs. 7c and 8c show that the forecasted CDO region in OperH is always smaller than NoDA. However, these slightly reduced CDO regions are still much larger than the observations. Additionally, the eye in OperH is not well organized after 5 h of model integration (e.g., Fig. 7c) and the simulated eye size is about

twice the observed size (e.g., Fig. 8c). Moreover, OperH overpredicts the storm speed, which pushes the predicted storm much closer to the Mexican coast than NoDA (e.g., Figs. 9c, 10c, and 11c). The overpredicted storm movement is likely to be associated with the weaker but still large size of the storm, which is pushed by the northward steering environmental flow more than NoDA. The overprediction of the storm speed therefore results in an early RW in the BT evolution

Experiment Verification Data Type	OperH	CIMSS_Only	SFMR_Only	FL_Only	TDR_Only	HDSS_Only	All	NoDA
OperH-q (g/kg)		2.50	3.49	2.20	2.48	2.42	2.00	2.50
OperH-t (K)		5.10	4.87	4.95	4.82	4.89	2.53	5.13
OperH-uv (m/s)		4.01	5.84	5.81	5.69	4.54	3.45	5.84
CIMSS-uv (m/s)	4.14		5.01	5.02	4.91	4.28	3.99	5.01
SFMR-spd (m/s)	6.10	6.73		6.06	6.21	6.04	4.65	6.73
FL-q (g/kg)	1.19	1.17	1.49		1.30	1.40	1.16	1.17
FL-t (K)	1.16	1.02	1.14		1.22	0.97	0.93	1.02
FL-uv (m/s)	4.49	4.98	5.43		3.42	3.75	3.12	4.98
TDR-rw (m/s)	6.17	7.03	6.19	4.87		4.42	3.58	7.09
HDSS-q (g/kg)	1.75	1.91	1.96	1.48	1.56		1.37	1.91
HDSS-t (K)	2.18	2.31	2.29	1.98	1.93		1.07	2.32
HDSS-uv (m/s)	9.62	10.77	9.74	8.21	7.98		7.37	10.89

FIG. 13. Root-mean-square fit (RMSF) of different types of observation verifications for each experiment. The colors denote the percentage of RMSF changes relative to NoDA for the independent verifications. The warmer the colors, the larger the relative RMSF.

after 1400 UTC 23 October (not shown). Such an early RW is also reflected by the Vmax and MSLP predictions (Figs. 11a,b). As a result of the early RW and the influence by land, the storm size produced by OperH becomes smaller than NoDA after 24 h at 1800 UTC 23 October (Figs. 9c and 10c). Although such a contracted storm size in OperH seems to be more consistent with the observations, the 3D correlation coefficient calculated against the collocated HRD radar composite indicates that the wind patterns produced by OperH is actually worse than NoDA due to the early RW (Table 2).²

Overall, with rather limited inner-core observations, OperH is only able to slightly improve the structural analysis and prediction of Patricia at early lead times. Such benefits cannot be well maintained during the model integration, and storm movement becomes biased and degrades the predictions at later lead times.

d. Analysis and forecast of CIMSS_Only—Impacts of CIMSS AMV observations

Since the number of CIMSS AMVs peaks around 150 hPa in the innermost domain (Fig. 1c), the surface and low-level wind patterns in CIMSS_Only are almost identical to NoDA through subjective evaluation (Figs. 2b,d and 3b,d). This similarity is also reflected by the RMSF calculated against the SFMR and FL observations (Fig. 13). Because the thermodynamic observations in OperH are only available at the lower troposphere below 700 hPa from several WP-3D dropsondes, the RMSF against OperH thermodynamic observations indicates that there is almost

no improvement in CIMSS_Only in those low levels. Likely due to that the CIMSS AMVs primarily sampled the environment wind outside 150-km radius (Fig. 1b), CIMSS_Only also does not show significant corrections in the near-core inflow and outflow wind patterns in the SE–NW cross section as compared to NoDA (Fig. 4d). The inner-core thermodynamic structures like the warm core in CIMSS_Only are also almost identical with NoDA (Fig. 6d). But the RMSFs against the 3D TDR radial velocity observations and the HDSS wind observations show that CIMSS_Only still improves the mid-to upper-level inner-core dynamic structure to some extent. Additionally, the RMSF against the OperH wind observations (primarily the operational AMVs, not shown) suggests that the CIMSS_Only produces more realistic upper-level environmental wind field than NoDA (Fig. 13). The major adjustment by CIMSS_Only is in the NW quadrant where the overly strong outflow is corrected (e.g., Fig. 12b).

The forecasted BT structures in CIMSS_Only are not significantly improved upon NoDA during the next 24 h. CIMSS_Only is almost comparable with NoDA with only slight size contraction in the BT evolution (e.g., Figs. 7d and 8d). At 1800 UTC 23 October, the storm size predicted by CIMSS_Only is only slightly smaller than that produced by NoDA (e.g., Figs. 9d and 10d). The 3D correlation coefficient against the collocated HRD radar composite also suggests only a slight improvement in the 3D inner-core structure in CIMSS_Only over NoDA (Table 2). This lack of improvements in the predicted structures in CIMSS_Only suggests that purely modifying the upper-level environment wind has limited impact on the prediction of short-term TC inner-core structure evolution. As a result, the Vmax, MSLP, and track forecasts of CIMSS_Only are almost comparable with NoDA except that the peak Vmax time and

² Table 2 is not to draw a statistically significant conclusion but to aid subjective interpretation of the difference between the predicted structure and the observations.

TABLE 2. Correlation coefficients calculated against the 3D HRD radar composite for the 24-h forecasted storm structure from each experiment.

Experiment	NoDA	OperH	CIMSS_Only	SFMR_Only	FL_Only	TDR_Only	HDSS_Only	All
Correlation coefficient	0.792 248	0.790 339	0.807 257	0.788 751	0.817 344	0.805 085	0.825 169	0.834 651

the RI rate are now slightly more consistent with the best track (Figs. 11a–d).

e. Analysis and forecast of SFMR_Only—Impact of SFMR observations

Assimilating the surface wind observations in the inner-core region, SFMR_Only shows more significant modifications in the surface vortex structure upon NoDA as compared to OperH and CIMSS_Only (Fig. 2e). For example, the surface RMW is now reduced to about 31 km, and the Vmax is significantly increased as compared to NoDA. However, the wind speed at 3-km height is also spuriously strengthened (Fig. 3e). This spurious correction is reflected by the increased RMSF against FL observations (Fig. 13), and it can be attributed to the biased vertical wind profile in the HWRF Model (Tong et al. 2018). But the RMSFs against the TDR and HDSS wind observations show that the overall 3D inner-core structure produced by SFMR is still improved upon NoDA (e.g., contracted TC size). The improvement is reflected by the radial wind pattern in the mid- to low levels (Fig. 4e). For example, SFMR_Only reduces the inaccurate midlevel inflow (between 250 and 800 hPa) in the SE of NoDA. Also, the inflow between 600 and 800 hPa in the NW of NoDA is enhanced in SFMR_Only, although this feature is only partially found and is much weaker in the observations. In the upper level, SFMR_Only shows little corrections upon NoDA in the radial wind pattern (Figs. 5e, 12c, and 13).

In contrast to the aforementioned modifications in the kinematic fields, the RMSFs against the FL, HDSS, and OperH thermodynamic observations suggest that the overall thermodynamic structures analyzed in SFMR_Only are degraded, especially in the moisture field (Fig. 13). But the size of the MWC is slightly reduced (Fig. 6e), somewhat more consistent with the observed as reflected by the RMSF against the HDSS temperature observations.

The forecasted eye and CDO sizes in SFMR_Only are reduced in comparison with NoDA at the early lead times (Figs. 7e and 8e). Nevertheless, the convections within and around the CDO are weaker than both NoDA and the observations. Moreover, the size improvement in the BT evolution is gradually lost as the model integrates (not shown). Consistently, the 24-h vortex predicted by SFMR_Only is almost comparable

with NoDA in both size and wind pattern, except the stronger wind maxima at both surface and 3-km height (Figs. 9e and 10e). Although the Vmax is closer to the best track (Fig. 11f), the 3-km height wind maximum is stronger than the observations. This can still be attributed to the HWRF Model bias and it leads to a slightly degraded 3D structural forecast (Table 2).

Altogether, these results suggest that the assimilation of purely 2D surface wind observations in SFMR_Only is primarily helpful for the short-term inner-core structural prediction for Patricia. When verified against the best track, SFMR_Only produces the best Vmax forecasts among all the experiments (Fig. 11f). This result is as expected since the assimilation of SFMR observations should primarily modify the surface wind. With the strongest initial Vmax, SFMR_Only produces the highest peak intensity forecast among all the experiments although its RI rate is slightly reduced as compared to NoDA. Finally, the track forecast seems to be almost comparable with the NoDA experiment (Figs. 11g,h).

f. Analysis and forecast from FL_Only—Impact of FL observations

Like SFMR_Only, assimilating the 2D inner-core observations in FL_Only also produces significant modifications in the wind patterns from the surface to the midlevels. For example, the surface RMW is now contracted to about 33 km and the Vmax is increased about 5 m s^{-1} , in more agreement with the observations than NoDA (Figs. 2f and 11f). Additionally, FL_Only reduces the 3-km height wind speed in the SW region of the storm (Fig. 3f). Figure 4f shows that FL_Only also produces corrections to the midlevel outflow and inflow in the SE and NW sections, respectively. These improvements in the inner-core dynamics are also reflected by the RMSF against the SFMR, TDR, and HDSS wind observations (Fig. 13). However, like SFMR_Only, FL_Only barely changes the upper-level wind patterns when verified against the AMVs (Figs. 5f, 12d, and 13). Likely due to the assimilation of additional thermodynamic observations, the RMSFs against the OperH and HDSS temperature and moisture observations suggest that the inner-core thermodynamic structure produced by FL_Only is improved relative to NoDA. Such an improvement can be consistently found in Fig. 6f where FL_Only

slightly reduces the MWC, and slightly elevates the UWC upon NoDA.

Overall, although both SFMR and FL data sample the TC's inner core in the horizontal direction, the additional thermodynamic information in the FL observations produces a better analysis of the TC structure in FL_Only compared to SFMR_Only. Consequently, while the improvements from SFMR_Only over NoDA gradually diminish over time, the improvements from FL_Only last for the next 24 h of model integration. For example, FL_Only continuously produces small eye (about 45 km in average) and small CDO regions after hours of spinup (e.g., Figs. 7f and 8f). The contracted storm produces a better fit to the observations than any NoDA, OperH, CIMSS_Only, or SFMR_Only experiments. At 1800 UTC 23 October, the 24-h forecasted vortex in FL_Only is still smaller and fits the observations better than the aforementioned experiments (Figs. 9f and 10f, and Table 2). However, the size contraction is still not sufficient when compared to the observations. Moreover, since the corrections from FL_Only are primarily in the inner-core region, the convections away from the core region evolve freely as the CDO region contracts. For instance, there are stronger and larger convective bands between the TC and the coast of Mexico generated around 0200 UTC 23 October (Fig. 8f), which lasts several hours longer than the observations (not shown).

Verification against the best track indicates that the intensity forecast in FL_Only is only improved relative to NoDA within the first 6 h of model integration, in addition to the better timing of the Vmax peak (Fig. 11f). The track forecast at early lead times in FL_Only is slightly improved upon NoDA. However, such an improvement is lost at later lead times due to the slower movement after landfall (Fig. 11g). Overall, the improvements in the TC structural forecast produced by FL_Only upon NoDA do not lead to apparent improvement in Vmax, MSLP or track forecast. Although sampled at different levels, the results between FL_Only and SFMR_Only suggest the benefits of additional thermal observations upon the pure wind observations in maintaining the structural improvements from the DA analysis during forecast.

g. Analysis and forecast of TDR_Only—Impacts of TDR observations

As compared to FL_Only and SFMR_Only, assimilating 3D wind observations in TDR_Only leads to more contraction in the storm inner-core structures (Figs. 2g and 3g). The RMW in TDR_Only (28 km) is even smaller than SFMR_Only (31 km). In addition to the vortex size corrections, TDR_Only also modifies radial

wind flow in the SE–NW cross section upon NoDA (Fig. 4g). For example, the midlevel inflow in the SE cross section is corrected to be an outflow, and the low-level inflow in the NW cross section (outside the 30-km radius) is corrected to be an outflow. These midlevel to surface improvements are reflected by the RMSFs against the SFMR and FL wind observations (Fig. 13). But in the upper level, compared to NoDA, the NW outflow in TDR_Only is even more unrealistically strong (Figs. 4g and 12e). Even with these degradations in the upper-level outflow, the RMSF against the HDSS wind observations still indicates better analysis of the 3D inner-core dynamic structures than any other aforementioned DA experiment.

Other than improvements in the TC dynamics, positive data impacts are also apparent in the thermodynamic fields. For example, the two warm cores in TDR_Only are reduced in both size and strength, and the center of the UWC is elevated to be between 200 and 250 hPa, in better agreement with the observations than NoDA. The only exception concerns the smaller depth of the UWC (Fig. 6g). Subsequently, the RMSF against the corresponding HDSS thermodynamic observations is smaller in Fig. 13. However, although the RMSFs against the OperH and HDSS thermodynamic observations indicate improvements, the RMSFs against the FL moisture and temperature observations still suggest some degradations in the TC thermodynamic structure as compared to NoDA. Note that the thermodynamic modifications in TDR_Only are purely from the cross-variable covariances due to the absence of thermodynamic observations. Such cross-variable corrections may not be accurate in the regions with highly nonlinear processes like the eyewall and rainbands.

Consequently, the early lead time BT forecasts produced by TDR_Only are worse than NoDA. For example, there is no clear eye formed, and the convective bands are less organized as compared to either the observations or NoDA during the 4-h BT forecast evolution (Fig. 7g). Such a BT evolution reflects the imbalances between the dynamic and the thermodynamic fields in the early lead times. However, once the balance is reestablished 6 or 7 h later, TDR_Only produces a storm structure more consistent with the observations than NoDA. For example, the eye size of TDR_Only is almost comparable with the observations at hour 8 although the CDO size is slightly smaller (Fig. 8g). The modification in the storm size in TDR_Only can be consistently found in the next 24 h (Figs. 9g and 10g). But outside the CDO, when TDR_Only “cuts off” the connection between the CDO and those convective bands due to size contraction, the convections inherited from the spuriously large background in the data void

regions become freely developed. For instance, the spiral rainbands in the SW section are incorrectly larger (Fig. 8g) and the NE convective bands exist much longer (not shown) than the observations.

Verification against the best track data suggests that the intensity forecast in TDR_Only is not improved compared to NoDA. For example, the intensification in Vmax forecast is lagged and the peak intensity is lowered in TDR_Only in Fig. 11j. The track forecast at the early times is improved in TDR_Only as compared to NoDA but is slightly degraded after hour 15 (Figs. 11k,l). Overall, the improved structural analysis and forecast produced by TDR_Only upon NoDA do not lead to apparent improvements in the Vmax, MSLP or track forecast. In comparison to the 2D wind observations sampled by CIMSS AMV and SFMR, TDR has a 3D sampling of the TC inner-core structure with a broader spatial coverage. Therefore, the results between CIMSS_Only, SFMR_Only, and TDR_Only suggest the benefits of 3D over 2D observations in maintaining the TC structural analysis improvements during the forecasts.

h. Analysis and forecast from HDSS_Only—Impact of HDSS dropsonde observations

Similar to TDR_Only, assimilating the 3D HDSS dropsonde observations produces a significantly contracted storm that is more consistent with the observations than NoDA (Figs. 2h and 3h). For example, the initial Vmax is stronger (Fig. 11j), and the storm size in HDSS_Only is even smaller than TDR_Only (RMW 24 vs 28 km). Additionally, HDSS_Only better captures the wind speed reduction in the SW quadrant of the storm than both NoDA and TDR_Only at 3-km height, although the wind maximum is stronger (Fig. 3h). As expected, the inner-core dynamic and thermodynamic structures produced by HDSS_Only fits the HDSS dropsondes the best among all the single-type observation DA experiments (Figs. 4h and 6h). For example, the size and the height of both warm cores are simulated better than all the aforementioned DA experiments. Moreover, the unique sampling of the near-storm outflow in HDSS dropsondes ameliorates the upper-level outflow of the HDSS_Only analysis. For instance, the overly strong upper-level outflow in NoDA is now reduced to be comparable with CIMSS AMVs (Figs. 5h and 12f). Such corrections made by HDSS_Only are even better than CIMSS_Only and OperH in the NW regions. These corrections are reflected by the corresponding RMSFs against the CIMSS and OperH wind observations (Fig. 13). Also, the RMSFs against the SFMR, FL, and TDR observations show that the HDSS_Only analysis produces the largest improvement

in the inner-core structure among all single-type observation DA experiments, except the degradation in the RMSF against the FL moisture observations. The RMSF against OperH thermodynamic observations indicates that HDSS_Only improves the overall analyzed thermodynamic structure over NoDA.

As a result of simultaneous improvements in the TC thermodynamics and dynamics, HDSS_Only produces better BT forecasts than NoDA. For example, both the eye and CDO region sizes are consistently smaller during the 24 h of model integration (Figs. 7h and 8h). Unlike TDR_Only, the contracted CDO region and a clear eye can be quickly found in HDSS_Only within 4 h of model integration (Fig. 7h). Furthermore, the spurious convective bands found in the NW of TDR_Only dissipated in HDSS_Only at hour 4 due to the distribution of HDSS observations at the analysis time. The remaining spurious convective bands primarily originated from the HDSS data sparse regions such as the SE quadrant of the storm. After 8 h of model integration, the BT forecasts produced by HDSS_Only can capture the major features from observations (Fig. 8h). In addition to the comparably small eye and CDO sizes, a line of spotted convective bands in the SW quadrant and the relatively large NE convective bands can be consistently found in both HDSS_Only and GOES-13 observations. Although these convective bands are generally larger in size, stronger in strength and have longer lifetime as compared to the observations, the overall BT evolution in HDSS_Only outperforms all the other single-type observation DA experiments in the next 16 h (not shown). At forecast hour 24, HDSS_Only continues to produce small storm size that is comparable with TDR_Only (Figs. 9h and 10h). The 3D inner-core structure forecasted by HDSS_Only fits the TDR observations even better than TDR_Only (Table 2). This result suggests that HDSS_Only produces not only the best structural analysis but also the best structural prediction up to 24 h among all the single-type observation DA experiments. However, like TDR_Only and FL_Only, such an improvement in the structural prediction does not lead to apparently improved Vmax, MSLP, or track forecast. For example, although the RI of HDSS_Only is not delayed, the overall Vmax forecast improvement in HDSS_Only compared to NoDA is reflected primarily at the early lead time and by the corrected timing of peak Vmax (Figs. 11i,j). Similar to the differences between CIMSS_Only, SFMR_Only, and TDR_Only, the difference between FL_Only and HDSS_Only also suggests the benefits of 3D over 2D observations in maintaining the TC structure improvements during the forecasts. Additionally, comparison between TDR_Only and HDSS_Only also suggests the

benefits of additional thermal observations upon the wind observations in efficiently spinning up a storm from the DA analysis.

i. Analysis and forecast of All—Impacts of all observations

Assimilating all observations together produces the most optimal dynamic structures among all experiments. For example, the surface wind pattern in All is comparable with HDSS_Only (Fig. 2i). They are both more consistent with the observations than other experiments. But All outperforms HDSS_Only in several aspects. For instance, the wind field like the maximum at 3-km height in All is more comparable with the observations than HDSS_Only (Fig. 3i). Additionally, below 400 hPa and within 30-km radius, All produces slightly weaker inflow in the NW cross section that fits the HDSS dropsondes even better than HDSS_Only (Fig. 4i). Such improvements are likely come from the assimilation of additional FL and TDR observations in All (Figs. 4f and 4g). The upper-level radial wind fields produced by All also fit the observations better than any other experiment (Fig. 5i). This better upper-level wind analysis in All can be attributed to the complementary sampling from the HDSS dropsondes and the CIMSS AMVs, where HDSS dropsondes sample more in the inner-core and outflow region, and CIMSS AMVs sample more over the near-storm environment (Figs. 5i and 11g). The analyzed thermodynamic field in All seems to be dominated by the assimilation of the HDSS dropsonde observations, where both warm cores are more consistent with the observations in size, height and strength than any other experiment except HDSS_Only (Fig. 6i). These results suggest that assimilating all observations produce the most realistic analysis among all experiments. Such benefits are reflected in Fig. 13, where All shows the smallest RMSF to all observation types although this RMSF verification is no longer using independent observations.

Consistent with the superior analysis, the corresponding forecasts produced by All outperform all other experiments in several aspects as well. For example, like HDSS_Only, both the eye size and storm size in All are more comparable with the observations than other experiments (Figs. 7i and 8i). With the near-storm environmental information from the CIMSS AMVs, All also produces further improved BT fields as compared to HDSS_Only in addition to the size contraction. Such an improvement is reflected in the less spurious convection in the E and NE portions of storm in the early hours (e.g., Fig. 7i), although the well-organized eye is formed about one hour later in All than HDSS_Only. Consistently, after hour 8, the spiral rainbands in the NE and SW side

of the storm in All are weaker and more realistic than HDSS_Only (Fig. 8i). Overall, All produces the best BT evolution during the first 24 h among all experiments. At 1800 UTC 23 October, the 3-km wind maxima in All is now reduced to be in agreement with the HRD radar composite (Fig. 10i) and the storm size is the smallest among all the experiments (Figs. 9i and 10i). Consistently, the All forecast produces the highest 3D correlation coefficients (Table 2). In general, assimilating all the observations leads to analysis and forecast of the TC structure that are superior to the individual data addition experiments.

Verification against the best track data suggests the improvement on intensity forecast are more limited than the structural forecast improvement. For example, the Vmax forecasts are improved for the first several hours and the timing of the peak Vmax is also corrected (Fig. 11). These results suggest that commonly used intensity verification metrics like surface Vmax and MSLP may not be sufficient for a TC forecast evaluation. The size, the 3D structure and the near-surface wind speed are important variables that need to be considered for future TC forecast evaluation.

4. Summary and discussion

Using the upgraded GSI-based, continuously cycled, dual-resolution hybrid EnKF-Var DA system for HWRF, this second part of a two-part study investigates the data impacts of various types of observations including those collected from the recent field campaigns from NOAA IFEX and ONR TCI programs and CIMSS AMVs on the analysis and prediction for Hurricane Patricia (2015). Since this is a single-case study with one DA cycle, generalization of the impact results requires some cautions. This study does not aim to draw any statistically robust conclusion for the data impacts. Instead, the primary goal is to improve the physical understanding of the relative importance of these various types of observations on the analysis and prediction of different aspects of the storm.

While the background produced through the continuously cycled hybrid DA system produces a weak and large hurricane in NoDA, assimilating different types of observations impacts different aspects of the TC analysis and prediction: 1) OperH primarily improves the upper-level environment wind upon NoDA in the analysis, but produces early RW and early landfall. 2) CIMSS_Only shows further improved upper-level environmental analysis upon OperH, however, these improvements are short lived. 3) SFMR_Only significantly modifies the surface wind structure in the analysis. Although these surface structure improvements cannot be maintained during the forecast, SFMR_Only produces the best Vmax

forecast among all experiments; 4) FL_Only considerably modifies the inner-core structures in the lower troposphere, and these inner-core structure modifications can be consistently found in the model forecasts up to hour 24. 5) TDR_Only has more significant corrections in the 3D TC inner-core dynamic structures than SFMR_Only and FL_Only. But given the lack of adequate thermodynamic corrections, TDR_Only degrades the early lead-time thermodynamic structure prediction and delays the RI. 6) HDSS_Only produces comparable 3D dynamic structures as TDR_Only in the inner-core region. In addition, HDSS_Only further modifies the inner-core thermodynamic structures as well as the upper-level outflow. Consequently, HDSS_Only produces the best structure analysis and forecast among all the single-type observation experiments. 7) All further outperforms HDSS_Only in both structure analysis and forecast due to the complementary effects from combining all observations in consideration. 8) Although lots of these aforementioned experiments show apparent improvements of the structure in both the analysis and forecast, such structural improvements are not necessarily directly translated into the Vmax and MSLP forecast improvements. In fact, most of the experiments do not show much of improvement on the peak intensity value although some experiments demonstrate intensity improvements for the first several hours and some demonstrate corrections in the timing of peak intensity.

Overall, this study hints that 1) assimilating observations that only sample the 2D structures of the storm can improve the TC structure analysis, but the improvement is not as large as that produced by assimilating 3D observations (e.g., CIMSS_Only and SFMR_Only v.s. TDR_Only, FL_Only v.s. HDSS_Only); 2) assimilating observations that purely samples the momentum field can correct the inner-core thermodynamic structure to some extent through the cross-variable covariance. However, compared to assimilating observations that sample both the momentum and thermodynamic fields, such corrections can be shorter lived (e.g., SFMR_Only v.s. FL_Only) or be associated with slow spinup (e.g., TDR_Only v.s. HDSS_Only); and 3) the inconsistency of the data impact on the intensity and structural forecast implies that future TC forecast evaluation would need to consider multiple verification metrics at once.

Additionally, Part I of this two-part study suggests that the model resolution can be a critical factor to influence the predicted peak intensity for small hurricanes like Patricia. Therefore, additional experiments are also conducted in this study and the results show that increasing model resolution significantly improves the intensity forecasts for all experiments (not shown). But the relative data impacts remain nearly the same except

for TDR_Only, HDSS_Only and All. Further extensive experiments regarding the impact of high-resolution configurations are still needed. In addition, a further study on how different combinations of each type of observations can help improve the TC analysis and prediction are planned in future papers.

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REFERENCES

- Aksoy, A., S. Lorsolo, T. Vukicevic, K. J. Sellwood, S. D. Aberson, and F. Zhang, 2012: The HWRF Hurricane Ensemble Data Assimilation System (HEDAS) for high-resolution data: The impact of airborne Doppler radar observations in an OSSE. *Mon. Wea. Rev.*, **140**, 1843–1862, <https://doi.org/10.1175/MWR-D-11-00212.1>.
- , S. D. Aberson, T. Vukicevic, K. J. Sellwood, S. Lorsolo, and X. J. Zhang, 2013: Assimilation of high-resolution tropical cyclone observations with an ensemble Kalman filter using NOAA/AOML/HRD's HEDAS: Evaluation of the 2008–11 vortex-scale Analyses. *Mon. Wea. Rev.*, **141**, 1842–1865, <https://doi.org/10.1175/MWR-D-12-00194.1>.
- Bauer, P., A. J. Geer, P. Lopez, and D. Salmond, 2010: Direct 4D-Var assimilation of all-sky radiances. Part I: Implementation. *Quart. J. Roy. Meteor. Soc.*, **136**, 1868–1885, <https://doi.org/10.1002/qj.659>.
- , and Coauthors, 2011: Satellite cloud and precipitation assimilation at operational NWP centres. *Quart. J. Roy. Meteor. Soc.*, **137**, 1934–1951, <https://doi.org/10.1002/qj.905>.
- Bell, M. M., and Coauthors, 2016: ONR tropical cyclone intensity 2015 NASA WB-57 HDSS dropsonde data, version 1.0. UCAR/NCAR–Earth Observing Laboratory, accessed 3 September 2019, <https://doi.org/10.5065/D6KW5D8M>.
- Black, P., L. Harrison, M. Beaubien, R. Bluth, R. Woods, A. Penny, R. W. Smith, and J. D. Doyle, 2017: High-Definition Sounding System (HDSS) for atmospheric profiling. *J. Atmos. Oceanic Technol.*, **34**, 777–796, <https://doi.org/10.1175/JTECH-D-14-00210.1>.
- Cecil, D., S. Biswas, W. L. Jones, and F. Alquaied, 2016: Hurricane Imaging Radiometer (HIRAD) data, version 2.1. UCAR/NCAR–Earth Observing Laboratory, accessed 13 September 2018, <https://doi.org/10.5065/D6CF9NGC>.

- Chen, H., D.-L. Zhang, J. Carton, and R. Atlas, 2011: On the rapid intensification of Hurricane Wilma (2005). Part I: Model prediction and structural changes. *Wea. Forecasting*, **26**, 885–901, <https://doi.org/10.1175/WAF-D-11-00001.1>.
- CLASS, 2015: Comprehensive Large Array-data Stewardship System dataset. NOAA, accessed 21 March 2017, <https://www.class.ngdc.noaa.gov/saa/products/welcome>.
- Doyle, J. D., and Coauthors, 2017: A view of tropical cyclones from above: The Tropical Cyclone Intensity (TCI) experiment. *Bull. Amer. Meteor. Soc.*, **98**, 2113–2134, <https://doi.org/10.1175/BAMS-D-16-0055.1>.
- Feng, J., and X. Wang, 2019: Impact of assimilating outflow layer dropsonde observations collected during the TCI field campaign on the prediction of intensity and structure of Hurricane Patricia (2015). *Mon. Wea. Rev.*, **147**, 3069–3089, <https://doi.org/10.1175/MWR-D-18-0305.1>.
- Friedman, H. A., 1982: Airborne research meteorological data collected by the National Hurricane Research Laboratory during the NOAA/RFC WP-3D era: Inventory and availability. NOAA Data Rep. ERL AOML-2, 376 pp.
- , 1984: Airborne research meteorological data collected by the National Hurricane Research Laboratory (Hurricane Research Division/AOML) during the 1982–1983 hurricane seasons: Inventory and availability. NOAA Data Rep. ERL AOML-3, 158 pp.
- Gamache, J. F., 2005: Real-time dissemination of hurricane wind fields determined from airborne Doppler radar data real-time dissemination of hurricane wind fields determined. NOAA, 38 pp., https://www.nhc.noaa.gov/jht/2003-2005reports/DOPLRGamache_JHTfinalreport.pdf.
- , R. A. Houze Jr., J. Frank, and D. Marks, 1993: Dual-aircraft investigation of the inner core of Hurricane Norbert. Part III: Water budget. *J. Atmos. Sci.*, **50**, 3221–3243, [https://doi.org/10.1175/1520-0469\(1993\)050<3221:DAIOTI>2.0.CO;2](https://doi.org/10.1175/1520-0469(1993)050<3221:DAIOTI>2.0.CO;2).
- Geer, A. J., and Coauthors, 2017: All-sky satellite data assimilation at operational weather forecasting centres. *Quart. J. Roy. Meteor. Soc.*, **144**, 1191–1217, <https://doi.org/10.1002/QJ.3202>.
- HRD, 2015: Hurricane Research Division dataset during Hurricane Patricia. NOAA, accessed 19 November 2017, http://www.aoml.noaa.gov/hrd/Storm_pages/patricia2015/.
- Jordan, C. L., 1958: Mean soundings for the West Indies area. *J. Meteor.*, **15**, 91–97, [https://doi.org/10.1175/1520-0469\(1958\)015<0091:MSFTWI>2.0.CO;2](https://doi.org/10.1175/1520-0469(1958)015<0091:MSFTWI>2.0.CO;2).
- Kimberlain, T. B., E. S. Blake, and J. P. Cangialosi, 2016: National Hurricane Center tropical cyclone report: Hurricane Patricia (20–24 October 2015). NOAA Tech. Rep. EP202015, 32 pp., https://www.nhc.noaa.gov/data/tcr/EP202015_Patricia.pdf.
- Lu, X., and X. Wang, 2019: Improving hurricane analyses and predictions with TCI, IFEX field campaign observations, and CIMSS AMVs using the advanced hybrid data assimilation system for HWRF. Part I: What is missing to capture the rapid intensification of Hurricane Patricia (2015) when HWRF is already initialized with a more realistic analysis? *Mon. Wea. Rev.*, **147**, 1351–1373, <https://doi.org/10.1175/MWR-D-18-0202.1>.
- , —, Y. Li, M. Tong, and X. Ma, 2017a: GSI-based ensemble-variational hybrid data assimilation for HWRF for hurricane initialization and prediction: Impact of various error covariances for airborne radar observation assimilation. *Quart. J. Roy. Meteor. Soc.*, **143**, 223–239, <https://doi.org/10.1002/qj.2914>.
- , —, M. Tong, and V. Tallapragada, 2017b: GSI-based, continuously cycled, dual-resolution hybrid ensemble-variational data assimilation system for HWRF: System description and experiments with Edouard (2014). *Mon. Wea. Rev.*, **145**, 4877–4898, <https://doi.org/10.1175/MWR-D-17-0068.1>.
- Marks, F. D., and R. A. Houze, 1984: Airborne Doppler radar observations in Hurricane Debby. *Bull. Amer. Meteor. Soc.*, **65**, 569–582, [https://doi.org/10.1175/1520-0477\(1984\)065<0569:ADROIH>2.0.CO;2](https://doi.org/10.1175/1520-0477(1984)065<0569:ADROIH>2.0.CO;2).
- , and —, 1987: Inner core structure of Hurricane Alicia from airborne Doppler radar observations. *J. Atmos. Sci.*, **44**, 1296–1317, [https://doi.org/10.1175/1520-0469\(1987\)044<1296:ICSOHA>2.0.CO;2](https://doi.org/10.1175/1520-0469(1987)044<1296:ICSOHA>2.0.CO;2).
- Poterjoy, J., F. Zhang, and Y. Weng, 2014: The effects of sampling errors on the EnKF assimilation of inner-core hurricane observations. *Mon. Wea. Rev.*, **142**, 1609–1630, <https://doi.org/10.1175/MWR-D-13-00305.1>.
- Powell, M. D., E. W. Uhlhorn, and J. D. Kepert, 2009: Estimating maximum surface winds from hurricane reconnaissance measurements. *Wea. Forecasting*, **24**, 868–883, <https://doi.org/10.1175/2008WAF2007087.1>.
- Pu, Z., S. Zhang, M. Tong, and V. Tallapragada, 2016: Influence of the self-consistent regional ensemble background error covariance on hurricane inner-core data assimilation with the GSI-based hybrid system for HWRF. *J. Atmos. Sci.*, **73**, 4911–4925, <https://doi.org/10.1175/JAS-D-16-0017.1>.
- Reasor, P. D., M. T. Montgomery, F. D. Marks, and J. F. Gamache, 2000: Low-wavenumber structure and evolution of the hurricane inner core observed by airborne dual-Doppler radar. *Mon. Wea. Rev.*, **128**, 1653–1680, [https://doi.org/10.1175/1520-0493\(2000\)128<1653:LWSAEO>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<1653:LWSAEO>2.0.CO;2).
- Rogers, R., and E. Uhlhorn, 2008: Observations of the structure and evolution of surface and flight-level wind asymmetries in Hurricane Rita (2005). *Geophys. Res. Lett.*, **35**, L22811, <https://doi.org/10.1029/2008GL034774>.
- , and Coauthors, 2006: The Intensity Forecasting Experiment: A NOAA multiyear field program for improving tropical cyclone intensity forecasts. *Bull. Amer. Meteor. Soc.*, **87**, 1523–1538, <https://doi.org/10.1175/BAMS-87-11-1523>.
- , and Coauthors, 2013: NOAA'S hurricane Intensity Forecasting Experiment: A progress report. *Bull. Amer. Meteor. Soc.*, **94**, 859–882, <https://doi.org/10.1175/BAMS-D-12-00089.1>.
- Tallapragada, V., and Coauthors, 2015: Hurricane Weather Research and Forecasting (HWRF) model: 2015 scientific documentation. Developmental Testbed Center, 113 pp., http://www.dtcenter.org/HurrWRF/users/docs/scientific_documents/HWRF_v3.7a_SD.pdf.
- Tong, M., and Coauthors, 2018: Impact of assimilating aircraft reconnaissance observations on tropical cyclone initialization and prediction using operational HWRF and GSI ensemble-variational hybrid data assimilation. *Mon. Wea. Rev.*, **146**, 4155–4177, <https://doi.org/10.1175/MWR-D-17-0380.1>.
- Uhlhorn, E. W., and P. G. Black, 2003: Verification of remotely sensed sea surface winds in hurricanes. *J. Atmos. Oceanic Technol.*, **20**, 99–116, [https://doi.org/10.1175/1520-0426\(2003\)020<0099:VORSSS>2.0.CO;2](https://doi.org/10.1175/1520-0426(2003)020<0099:VORSSS>2.0.CO;2).
- , —, J. L. Franklin, M. Goodberlet, J. Carswell, and A. S. Goldstein, 2007: Hurricane surface wind measurements from an operational stepped frequency microwave radiometer. *Mon. Wea. Rev.*, **135**, 3070–3085, <https://doi.org/10.1175/MWR3454.1>.
- Velden, C., W. E. Lewis, W. Bresky, D. Stettner, J. Daniels, and S. Wanzong, 2017: Assimilation of high-resolution satellite-derived atmospheric motion vectors: Impact on HWRF

- forecasts of tropical cyclone track and intensity. *Mon. Wea. Rev.*, **145**, 1107–1125, <https://doi.org/10.1175/MWR-D-16-0229.1>.
- Wang, X., D. Parrish, D. Kleist, and J. Whitaker, 2013: GSI 3DVar-based ensemble–variational hybrid data assimilation for NCEP global forecast system: Single-resolution experiments. *Mon. Wea. Rev.*, **141**, 4098–4117, <https://doi.org/10.1175/MWR-D-12-00141.1>.
- Weng, Y., and F. Zhang, 2012: Assimilating airborne Doppler radar observations with an ensemble Kalman filter for convection-permitting hurricane initialization and prediction: Katrina (2005). *Mon. Wea. Rev.*, **140**, 841–859, <https://doi.org/10.1175/2011MWR3602.1>.
- Willoughby, H. E., and M. B. Chelmon, 1982: Objective determination of hurricane tracks from aircraft observations. *Mon. Wea. Rev.*, **110**, 1298–1305, [https://doi.org/10.1175/1520-0493\(1982\)110<1298:ODOHTF>2.0.CO;2](https://doi.org/10.1175/1520-0493(1982)110<1298:ODOHTF>2.0.CO;2).
- , and M. E. Rahn, 2004: Parametric representation of the primary Hurricane Vortex. Part I: Observations and evaluation of the Holland (1980) model. *Mon. Wea. Rev.*, **132**, 3033–3048, <https://doi.org/10.1175/MWR2831.1>.
- Wu, T.-C., H. Liu, S. J. Majumdar, C. S. Velden, and J. L. Anderson, 2014: Influence of assimilating satellite-derived atmospheric motion vector observations on numerical analyses and forecasts of tropical cyclone track and intensity. *Mon. Wea. Rev.*, **142**, 49–71, <https://doi.org/10.1175/MWR-D-13-00023.1>.
- , C. S. Velden, S. J. Majumdar, H. Liu, and J. L. Anderson, 2015: Understanding the influence of assimilating subsets of enhanced atmospheric motion vectors on numerical analyses and forecasts of tropical cyclone track and intensity with an ensemble Kalman filter. *Mon. Wea. Rev.*, **143**, 2506–2531, <https://doi.org/10.1175/MWR-D-14-00220.1>.
- Xiao, Q., X. Zhang, C. Davis, J. Tuttle, G. Holland, and P. J. Fitzpatrick, 2009: Experiments of hurricane initialization with airborne Doppler radar data for the Advanced Research Hurricane WRF (AHW) Model. *Mon. Wea. Rev.*, **137**, 2758–2777, <https://doi.org/10.1175/2009MWR2828.1>.
- Yang, C., Z. Liu, J. Bresch, S. R. H. Rizvi, X.-Y. Huang, and J. Min, 2016: AMSR2 all-sky radiance assimilation and its impact on the analysis and forecast of Hurricane Sandy with a limited-area data assimilation system. *Tellus*, **68A**, 30917, <https://doi.org/10.3402/tellusa.v68.30917>.
- Zhang, F., and Y. Weng, 2015: Predicting hurricane intensity and associated hazards: A five-year real-time forecast experiment with assimilation of airborne Doppler radar observations. *Bull. Amer. Meteor. Soc.*, **96**, 25–33, <https://doi.org/10.1175/BAMS-D-13-00231.1>.
- , —, J. A. Sippel, Z. Meng, and C. H. Bishop, 2009: Cloud-resolving hurricane initialization and prediction through assimilation of Doppler radar observations with an ensemble Kalman filter. *Mon. Wea. Rev.*, **137**, 2105–2125, <https://doi.org/10.1175/2009MWR2645.1>.
- , —, J. F. Gamache, and F. D. Marks, 2011: Performance of convection-permitting hurricane initialization and prediction during 2008–2010 with ensemble data assimilation of inner-core airborne Doppler radar observations. *Geophys. Res. Lett.*, **38**, L15810, <https://doi.org/10.1029/2011GL048469>.
- , M. Minamide, and E. E. Clothiaux, 2016: Potential impacts of assimilating all-sky infrared satellite radiances from GOES-R on convection-permitting analysis and prediction of tropical cyclones. *Geophys. Res. Lett.*, **43**, 2954–2963, <https://doi.org/10.1002/2016GL068468>.
- Zhang, J. A., F. D. Marks, J. A. Sippel, R. F. Rogers, X. Zhang, S. G. Gopalakrishnan, Z. Zhang, and V. Tallapragada, 2018: Evaluating the impact of improvement in the horizontal diffusion parameterization on hurricane prediction in the operational Hurricane Weather Research and Forecast (HWRF) Model. *Wea. Forecasting*, **33**, 317–329, <https://doi.org/10.1175/WAF-D-17-0097.1>.
- Zhang, S., and Z. Pu, 2019: Numerical simulation of rapid weakening of Hurricane Joaquin with assimilation of high-Definition sounding system dropsondes during the tropical cyclone intensity experiment: Comparison of three- and four-dimensional ensemble–variational data assimilation. *Wea. Forecasting*, **34**, 521–538, <https://doi.org/10.1175/WAF-D-18-0151.1>.
- Zhu, P., B. Tyner, J. A. Zhang, E. Aligo, S. Gopalakrishnan, F. D. Marks, A. Mehra, and V. Tallapragada, 2019: Role of eyewall and rainband eddy forcing in tropical cyclone intensification. *Atmos. Chem. Phys.*, **19**, 14 289–14 310, <https://doi.org/10.5194/ACP-19-14289-2019>.
- Zhu, Y., and Coauthors, 2016: All-sky microwave radiance assimilation in NCEP’s GSI analysis system. *Mon. Wea. Rev.*, **144**, 4709–4735, <https://doi.org/10.1175/MWR-D-15-0445.1>.