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Key Points:

- The NASA Cyclone Global Navigation Satellite System (CYGNSS) provides an unprecedented opportunity to obtain ocean surface wind data over a hurricane inner-core region
- This study found that the assimilation of CYGNSS data results in improved track, intensity, and structure forecasts for two notable landfalling hurricanes, Harvey and Irma (2017)

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A Preliminary Impact Study of CYGNSS Ocean Surface Wind Speeds on Numerical Simulations of Hurricanes

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Abstract The NASA Cyclone Global Navigation Satellite System (CYGNSS) was launched in December 2016, providing an unprecedented opportunity to obtain ocean surface wind speeds including wind estimates over the hurricane inner-core region. This study demonstrates the influence of assimilating an early version of CYGNSS observations of ocean surface wind speeds on numerical simulations of two notable landfalling hurricanes, Harvey and Irma (2017). A research version of the National Centers for Environmental Prediction operational Hurricane Weather Research and Forecasting model and the Gridpoint Statistical Interpolation-based hybrid ensemble three-dimensional variational data assimilation system are used. It is found that the assimilation of CYGNSS data results in improved track, intensity, and structure forecasts for both hurricane cases, especially for the weak phase of a hurricane, implying potential benefits of using such data for future research and operational applications.

Plain Language Summary The NASA Cyclone Global Navigation Satellite System (CYGNSS) was launched in December 2016. It provides an unprecedented opportunity to obtain ocean surface wind speeds over a hurricane inner-core region. In this study, we combined the early version of CYGNSS data with all other observations that are currently available for operational forecasts to form initial conditions (inputs data) for a numerical weather prediction model. A research version of the National Oceanic and Atmospheric Administration operational hurricane forecast model named the Hurricane Weather Research and Forecast (HWRF) model is used. Results show that adding CYGNSS data into HWRF model results in improved track, intensity, and structure forecasts for two notable landfalling hurricanes, Harvey and Irma (2017), demonstrating the potential benefits of using CYGNSS data for future research and operational applications.

1. Introduction

Modern high-resolution numerical models for hurricane prediction that include a suite of sophisticated physical parameterizations have paved the way for obtaining improved tropical cyclone (TC) forecasts in the past few decades, but model deficiencies in physical parameterizations and uncertainties in initial conditions still have a large impact on forecast accuracy (e.g., Atlas et al., 2015; Gall et al., 2013; Otkin et al., 2017). It has been recognized that the lack of frequent and accurate observations of winds in the inner core of TCs (Rogers et al., 2006, 2013) contributes significantly to inaccurate prediction. Previous studies have proved that assimilation of hurricane inner-core observations, such as those from airborne Doppler radar, can result in significant improvements in TC track and intensity forecasts (e.g., Gall et al., 2013; Pu et al., 2009, 2016; Zhang et al., 2011). However, airborne Doppler radar missions are limited in space and time, and many satellites are unable to penetrate the heavy rainfall in a hurricane inner-core region. A recent NASA satellite mission, the Cyclone Global Navigation Satellite System (CYGNSS; Ruf et al., 2016), was launched on 15 December 2016 and was specifically designed to overcome observational deficiencies, as it provides an unprecedented opportunity to obtain ocean surface wind data within a hurricane's inner core.

CYGNSS is a constellation of eight microsatellites that receive direct Global Positioning System (GPS) signals and scattered signals from the ocean surface. These microsatellites provide detailed ocean surface wind speeds (OSWS) in the tropics. Compared with most space-based measurements that use backscattered microwave radar pulses (e.g., QuikSCAT and ASCAT), GPS signals are in an L band frequency and are largely unaffected by precipitation. Therefore, CYGNSS-derived OSWS are available in a TC inner-core region

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and provide high temporal resolution and spatial coverage under all precipitating conditions and over the full dynamic range of wind speeds experienced in a TC (Morris & Ruf, 2017; Ruf et al., 2016). Before its launch, a variety of observing system simulation experiments (e.g., Annane et al., 2018; Leidner et al., 2018; McNoldy et al., 2017; Zhang et al., 2017) suggested that assimilation of CYGNSS OSWS would have positive impacts on short-range hurricane forecasts of both track and intensity with the Hurricane Weather Research and Forecasting (HWRF) model.

CYGNSS data became available in March 2017. The goal of this study is to demonstrate the impact of a preliminary version of CYGNSS-retrieved OSWS on numerical simulations of hurricanes. Two notable hurricane cases, Harvey and Irma (2017), are used. Considering the significant losses caused by both hurricanes after their landfall, the data impact study emphasizes the period before and near their landfall. The National Centers for Environmental Prediction (NCEP) HWRF model and the Gridpoint Statistical Interpolation (GSI)-based hybrid ensemble three-dimensional variational data assimilation system (e.g., 3DVar; Wang et al., 2013) are employed to facilitate the data assimilation experiments.

2. CYGNSS Data, HWRF Model, and Experimental Design

2.1. CYGNSS Data

With the CYGNSS science team's efforts to develop the calibration and retrieval algorithm, the first science quality CYGNSS on-orbit OSWS data product is Version 2.0 Level 2 retrieved wind speeds, which consist of time-tagged and geolocated average wind speed and corresponding uncertainty with about a 25-km resolution (Ruf et al., 2018). Considering the quality of retrieved OSWS and the current ability and limitation of the HWRF system to assimilate inner-core observations (Zhang et al., 2018), this study uses only the fully developed seas (FDS) version. An alternative, the young seas/limited fetch (YSLF) version of OSWS data, is not used here. The YSLF should be better estimates under TC conditions, but the quality of the Version 2.0 YSLF OSWS data is poor and inconsistent with that of the FDS. Figure 1a shows the sample FDS data coverage in four consecutive periods (00 UTC, 06 UTC, 12 UTC, and 18 UTC) on 6 September 2017. High-density data cover the Atlantic Ocean and vicinity in at least two periods (e.g., 00 UTC and 06 UTC). Along each data line, there is no distinct data gap. Even though there are some occasional dropouts near the storm center, these data still reliably represent low to moderate winds (Ruf & Balasubramaniam, 2018).

To obtain the characteristics of the CYGNSS-retrieved OSWS and their associated errors, we take data samples over an area of interest (the domain enclosed by the dashed line in Figure 1a) from 00 UTC 15 August to 00 UTC 16 September 2017, which covers the entire life cycle of both Harvey and Irma, for a statistical analysis. Figure 1b shows that low wind speeds are dominant, while high wind speeds are present in smaller quantities out to about 36 m/s. Figure 1c shows that there is a strong dependence of these assigned wind speed errors on wind speed. Most wind observation standard deviations are concentrated below 6 m/s, and only a small proportion of high wind speed data corresponds to the high-speed error value (around 10 m/s). Figures 1b and 1c also show that the characteristics of CYGNSS data for Hurricanes Harvey and Irma (2017) are consistent with the sample data at large.

2.2. HWRF Model and Assimilation Method

A research version of the NCEP operational HWRF model used is Version 3.9a (Biswas et al., 2017), released by the University Corporation for Atmospheric Research Developmental Testbed Center (<https://dtcenter.org>). The model is configured in a three-level nested domain, with horizontal resolutions of 18, 6, and 2 km, respectively. It carries a suite of TC-specific physics schemes with improved surface exchange coefficients in the surface layer, and it also contains a vortex initialization scheme before the data assimilation that is first used to relocate the vortex in HWRF's preliminary background (which always comes from the Global Forecast System (GFS)/Global Data Assimilation System (GDAS) or previous HWRF forecast cycle), and then to correct the size and intensity of the vortex with dynamic and thermodynamic consistency based on the National Hurricane Center TC vital statistics (see details in Tallapragada et al., 2017). The boundary conditions for HWRF are provided by the GFS global forecasts. The NCEP Automated Data Processing (ADP) conventional data include land surface, marine surface, radiosonde, pibal, and aircraft reports from the Global Telecommunications System, profiler and U.S. radar-derived winds, and satellite-derived winds that are assimilated routinely in operations (archived at <https://rda.ucar.edu/datasets/ds337.0/>). The

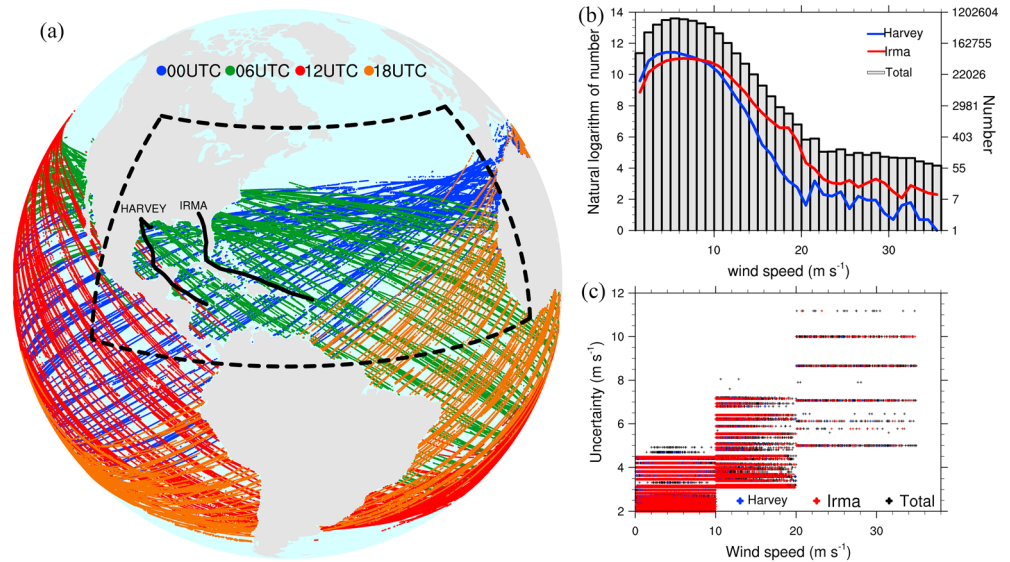


Figure 1. (a) CYGNSS sample data swath at 00 UTC (blue), 06 UTC (green), 12 UTC (red), and 18 UTC (orange) on 6 September 2017. Bold, solid curves indicate tracks of Hurricanes Harvey and Irma during the time window of this study (track spans from 0600 UTC 21 August to 1200 UTC 29 August 2017 for Harvey and from 0000 UTC 06 September to 0000 UTC 12 September 2017 for Irma, respectively). The domain enclosed by the dashed line is the region for statistical calculations for (b) and (c). (b) Data count according to wind speed ranges during 0600 UTC 21 August to 0600 UTC 24 August 2017 (for Harvey; indicated by the blue line) and 0000 UTC 6 September to 0000 UTC 9 September 2017 (for Irma; denoted by the red line). The bar chart is similar to the lines, but the total data count over the period of 0000 UTC 15 August to 0000 UTC 16 September 2017. The left vertical axis is the natural logarithm of the numbers for each wind speed range. (c) Similar to (b) except for scatterplots of CYGNSS wind speed versus standard deviation for Harvey (blue crosses), Irma (red crosses), and the total (black crosses).

CYGNSS data are available at CYGNSS official website (<https://clasp-research.engin.umich.edu/missions/cygnss/>).

The GSI-based 3D EnVar uses a variational framework with a hybrid of static and ensemble background error covariance terms. The configurations of the HWRf model and data assimilation system used in this study are similar to those of the NCEP 2017 operational HWRf system. One-way hybrid data assimilation is performed in the inner two nested domains of HWRf (e.g., at 6- and 2-km grid spacings, referred to as Ghost D02 and Ghost D03, respectively). For the hybrid background error covariance, a factor of 0.8 is used for ensemble covariance that comes from the 80-member GFS EnKF data assimilation system.

Before assimilation, the CYGNSS OSWS data were thinned at 25-km resolution. The observation error was set to 2.1429 m/s, which was statistically defined in considering the errors of the maximum probability distribution of wind speed samples. More quality control steps (e.g., a gross check) were carried out inside GSI to exclude questionable observations, including some of the high wind speed (> 20 m/s) data. Less than 2% of thinned CYGNSS data were rejected during the data assimilation process.

2.3. Assimilation Experiments

Three data assimilation experiments (DA_ADP, DA_CGS, and DA_ALL) are conducted for comparison. DA_ADP acts as a control experiment and assimilates the NCEP ADP data that are routinely assimilated into the NCEP operational analysis, and Tail Doppler Radar radial velocity when they are available from the National Oceanic and Atmospheric Administration (NOAA) Hurricane Research Division (HRD) airborne mission. DA_CGS assimilates CYGNSS OSWS only. DA_ALL assimilates both CYGNSS OSWS and all data assimilated into DA_ADP. Note that for HWRf system, a vortex initialization (e.g., a vortex relocation and an intensity correction as mentioned above) is performed before the data assimilation in each analysis cycle when necessary (e.g., when storm center location and intensity differ from the TC vital data). Before the first cycled assimilation with CYGNSS data, the HWRf system is spun up for 2 days with 6-hourly analysis-forecast cycles that are similar to DA_ADP. Two sets of 6-hourly cycled data assimilation experiments are then performed. Each contains three assimilation experiments (DA_ADP, DA_CGS, and

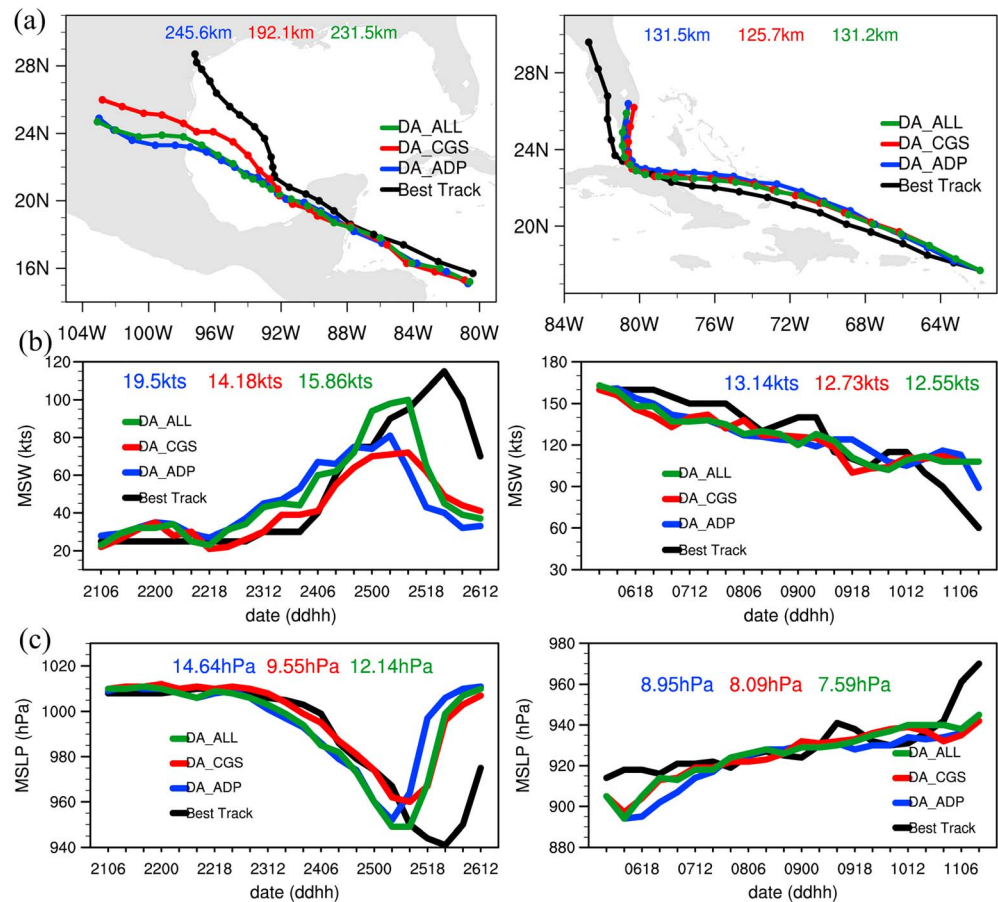


Figure 2. Time series of the track (a) and intensity (b: MSW; c: MSLP) forecasts for Harvey (left column; initiated at 0600 UTC 21 August 2017) and Irma (right column; initiated at 0600 UTC 6 September 2017). The colored number in each panel denotes the average absolute error for track and intensity over 126-hr simulation for the experiments corresponding to the line colors. MSW = maximum surface wind; MSLP = minimum sea level pressure.

DA_ALL) for comparison. The first set is for Hurricane Harvey, starting at 0600 UTC 21 August 2017, approximately 5 days ahead of landfall in Texas and ending at 0600 UTC 24 August 2017. The second set is for the mature phase of Hurricane Irma before its Florida landfall. Similarly, the 6-hourly assimilation cycle starts at 0000 UTC 6 September 2017, which is also approximately 5 days ahead of landfall in southwestern Florida. A 126-hr forecast is made after data assimilation for each analysis cycle in all cases.

3. Results

3.1. Data Impact on Track and Intensity Forecasts

Figures 2a–2c compare time evolution of the track and intensity between the best track data and forecasts for Harvey initialized at 0600 UTC 21 August 2017 (left column) and also for Irma initiated at 0600 UTC 6 September 2017 (right column) from all experiments. Generally, there is a positive impact of assimilation of CYGNSS OSWS (in both DA_CGS and DA_ALL) on track and intensity forecasts regarding both maximum surface wind (MSW) and minimum sea level pressure (MSLP). Compared with DA_ADP, the DA_CGS performs slightly better than DA_ALL, reflecting on complex combinations between vortex initialization and data assimilation during the analysis procedure. DA_ALL has a neutral impact of the track forecast of Irma, while the DA_CGS slightly improved the track forecast. Meanwhile, assimilation of CYGNSS data had positive effects on the intensity forecast (DA_CGS and DA_ALL), while DA_ALL perform better than DA_CGS in the intensity forecast for this case. All experiments capture the slowly weakening feature in the best track analysis.

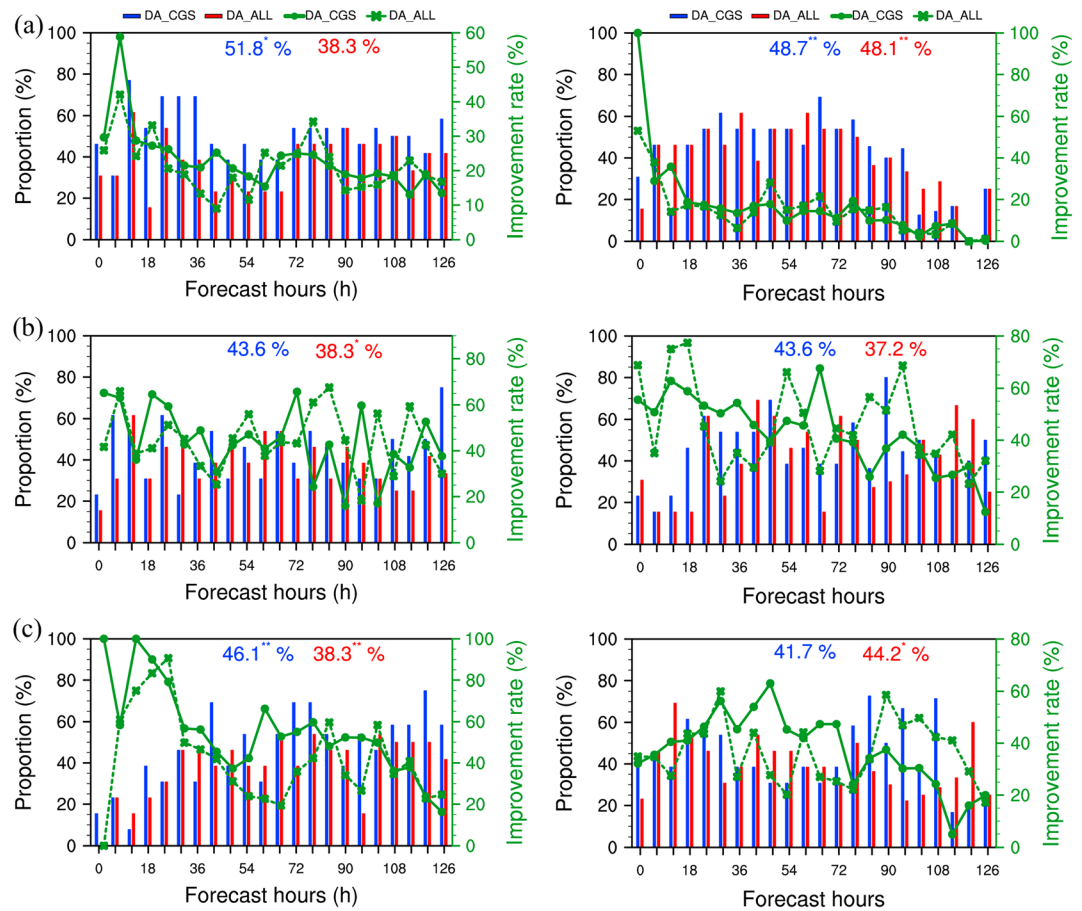


Figure 3. Proportion of the number of experiments (bar chart; left Y axis) in which the simulation errors in DA_CGS (blue) or DA_ALL (red) are less than those in DA_ADP at all forecast times for Harvey (left column) and Irma (right column) in terms of errors for track (a), MSW (b), and MSLP (c). Green solid and dashed lines with markers indicate the average improvement rate (right Y axis) of DA_CGS and DA_ALL, respectively, for all analysis cycles in each forecast hour. The numbers in blue and red denote the average proportion of ALL positive track (a), MSW (b), and MSLP (c) impacts in DA_CGS and DA_ALL, over all forecast times for Harvey, and the first 66-hr forecasts for Irma, respectively. The single and double asterisks indicate that the average proportion is significant at the 75% and 90% confidence levels, respectively, using the bootstrapping technique. MSW = maximum surface wind; MSLP = minimum sea level pressure.

To obtain overall comparison among different experiments, and also to quantitatively evaluate the impact of OSWS on track and intensity forecasts, an improvement rate is introduced to measure improvements of the track and intensity in all the cycling analysis times over all forecast periods.

$$r_{\text{track/intensity}} = (\text{err1}_{\text{track/intensity}} - \text{err2}_{\text{track/intensity}}) / \text{err1}_{\text{track/intensity}} \times 100\%$$

where r represents the improvement rate, err1 is the track or intensity error in DA_ADP, and err2 is the track or intensity error in DA_CGS or DA_ALL. The subscript denotes that the improvement rate calculation for track and intensity uses the same equation; thus, a positive value means the track or intensity error in DA_ALL or DA_CGS less than that in DA_ADP.

Figure 3 shows the proportion of the number of experiments with a positive rate of improvement and averaged improvement rates at each forecast time. Out of the total 13 assimilation cycles, over 50% exhibit a positive impact on track forecasts at all forecast times. The average improvement rate fluctuates around 20% except for the 96- to 126-hr forecasts for Irma. As indicated by the colored numbers, the track improvements in the whole simulation period of Harvey and the first 66-hr forecasts of Irma are statistically significant according to a bootstrapping confidence test (Efron & Tibshirani, 1993). Note that forecast performance differs between Harvey and Irma after 90 hr. The improved proportion in both

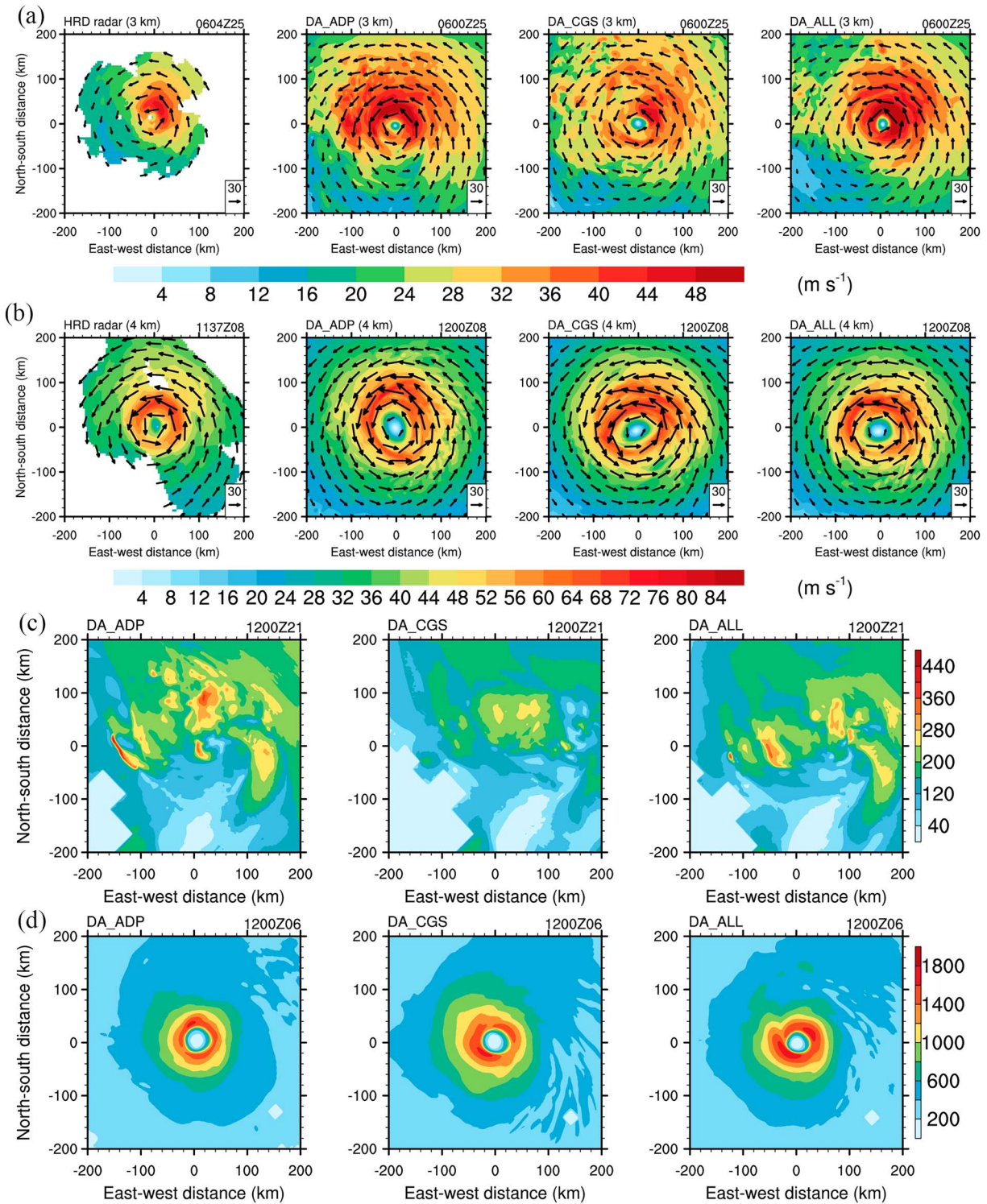


Figure 4. (a and b) Wind speeds (shaded contours) and vectors of (a) Harvey at 0600 UTC 25 August (96-hr forecasts from 0600 UTC 21 August 2017) and (b) Irma at 1200 UTC 8 September 2017 (54-hr forecast from 0600 UTC 6 September 2017) from experiments DA_ADP, DA_CGS, and DA_ALL, compared with Hurricane Research Division radar analysis at the 3- and 4-km height level, respectively. (c and d) Corresponding 6-hr forecasts of surface latent heat flux initiated at the same time from experiments DA_ADP, DA_CGS, and DA_ALL for Harvey and Irma, respectively.

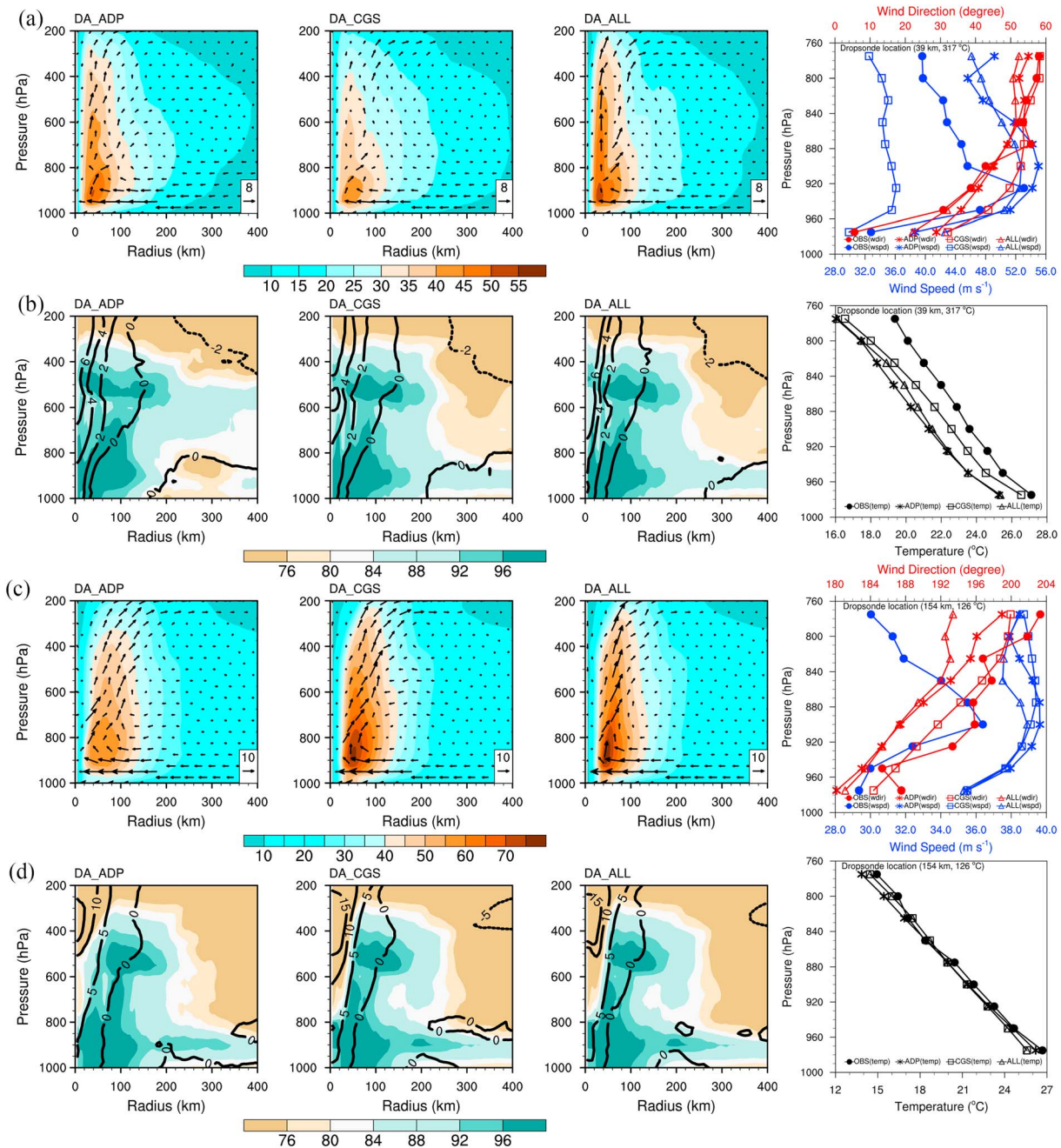


Figure 5. Comparison of the vertical cross section (first to third columns) of azimuthally averaged hurricane vortices for Harvey (a, b) and Irma (c, d) from DA_ADP, DA_CGS, and DA_ALL at the same time as in Figure 4 (a and b). (a and c) The primary circulation denoted by tangential wind (m/s; colored shading) and secondary circulation represented by radial (m/s) and vertical (0.1 m/s) velocities. (b and d) Relative humidity (%; colored shading) and potential temperature anomaly (K; contours). The fourth column shows the vertical wind (a, c) and temperature (b, d) profiles of the dropsonde data from National Oceanic and Atmospheric Administration/Hurricane Research Division, compared with Hurricane Weather Research and Forecast simulations. Red, blue, and black lines indicate the wind direction, wind speed, and temperature, respectively. For Harvey (a and b), the dropsonde is located 39 km from the storm center at an azimuth angle of 317°. For Irma (c and d), the dropsonde observation is located 154 km from the storm center at an azimuth angle of 126°.

DA_CGS and DA_ALL dramatically decreases for Irma, which implies that CYGNSS OSWS may be less capable of improving long-range track forecasts in the mature stage (e.g., Irma) of an intense hurricane, compared with one in the formation stage (e.g., Harvey). Although the proportion in DA_CGS often exceeds that in DA_ALL during the middle-range track forecast (18 to 54 hr) due to the complicated interactions between HWRf vortex initialization and data assimilation, MSW and MSLP forecasts in

the 13 assimilation cycles (Figures 3b and 3c) indicate that DA_ALL shows an almost comparable average improvement rate to DA_CGS except for a few individual forecast hours. Meanwhile, the average proportion in DA_ALL is statistically significant when ignoring the MSW forecast of Irma but not significant in DA_CGS. This statistical significance of the improvement rate from DA_ALL indicates the DA_ALL is more confident and reliable than DA_CGS for improving intensity forecast. There is some inconsistency in the Irma MSW simulation, which may be because the best track analysis data set contains subjective uncertainties in estimating MSW.

3.2. Impact on Hurricane Inner-Core Structure

Figure 4 shows the wind in the low-level troposphere and the surface latent heat flux from HWRF simulations initialized at 0600 UTC 21 August for Harvey and at 0600 UTC 06 September 2017 for Irma, respectively. HWRF simulations are compared with airborne radar wind data from the NOAA HRD) at the closest time (Figures 4a and 4b). Although the simulated wind speed is a bit stronger than that in the radar analysis, DA_ALL is the most consistent with the radar-observed patterns in wind structure. Specifically, in both the radar analysis and DA_ALL for Harvey, the maximum wind bands wrap around the northeast side of the hurricane center. In the same comparison for Irma, DA_ALL also matches the radar analysis better in terms of location and size for the inner maximum wind band. The horizontal distribution of surface latent heat flux at the early time (6 hr after analysis time; Figures 4c and 4d) and also at the corresponding time (not shown) indicate that the maximum flux location and strength differ considerably between DA_ADP and DA_ALL. The asymmetric feature adjustments for the fluxes in DA_ALL and DA_CGS compared to DA_ADP should be of great help in reproducing the realistic wind structure.

Figure 5 compares the inner-core thermodynamic and kinematic aspects of Hurricanes Harvey and Irma at the same forecast time as in Figures 4a and 4b. The dropsonde data from reconnaissance aircraft missions collected by NOAA HRD are also used to verify simulations of the vertical structure (the fourth column of Figure 5). Distinct differences among the three assimilation experiments can be found. DA_ALL shows a more reasonable secondary circulation in the vortex core region and a distinct modification in the low-level inflow layer and is more consistent with the dropsonde wind and temperature than DA_ADP, although there is a mixture impacts in some cases. At the same time, the middle to low-level warm core and moisture distribution change considerably between DA_ADP and DA_ALL. This suggests that assimilation of CYGNSS data with conventional data distinctly improves storm structure. In particular, the simulation accurately captures the asymmetrical distribution of the vortex circulation, which could be attributed to improvement in the hurricane vortex circulation and low-level heat and moisture adjustments around the inner-core region, as in Zhang et al. (2017).

Results above are also consistent with previous studies (e.g., Kepert, 2017; Leslie & Smith, 1970) that hurricane intensity forecasts highly depend on low-level circulation and the surface dynamic conditions (e.g., OSWS) in the core region. Moreover, the DA_ALL are generally more reliable than DA_CGS, especially in the long-range forecast, proving that the better representations of TC structure could improve hurricane forecasts (Chan, 2005).

4. Concluding Remarks

The Year 2017 was the first Atlantic hurricane season in which the CYGNSS mission operated in its data-taking mode. This study demonstrated the potential positive impacts of CYGNSS data on the prediction of hurricane track and intensity by examining the assimilation of CYGNSS winds for two hurricane cases. Compared with the assimilation of conventional data, assimilation of CYGNSS winds is more effective in improving track forecasts, whereas the assimilation of both CYGNSS and conventional data has great potential to provide a better representation of vortex structure and is also helpful in producing a reasonable track forecast, especially in the medium range. Results also suggest that track forecasts could be affected by latent heat flux on the ocean surface and by TC structure, while intensity forecasts are highly dependent on the accuracy of the vortex structure. Future work should emphasize understanding the relevant details of the physical processes and merge the CYGNSS data with conventional data in the operational systems to obtain better track forecasts. More work should be done to comprehensively evaluate and compare data impacts using more cases and with different versions (e.g., Version 2.1) and types (e.g., YSLF) of the retrieved wind

products and also with the different model systems to better understand the processes associated with vortex and environmental flow that could be strongly influenced by CYGNSS data assimilation.

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