Impact of CYGNSS Ocean Surface Wind Speeds on Numerical Simulations of a Hurricane in Observing System Simulation Experiments

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ABSTRACT

The NASA Cyclone Global Navigation Satellite System (CYGNSS) was launched in late 2016. It will make available frequent ocean surface wind speed observations throughout the life cycle of tropical storms and hurricanes. In this study, the impact of CYGNSS ocean surface winds on numerical simulations of a hurricane case is assessed with a research version of the Hurricane Weather Research and Forecasting Model and a Gridpoint Statistical Interpolation analysis system in a regional observing system simulation experiment framework. Two different methods for reducing the CYGNSS data volume were tested: one in which the winds were thinned and one in which the winds were superobbed.

The results suggest that assimilation of the CYGNSS winds has great potential to improve hurricane track and intensity simulations through improved representations of the surface wind fields, hurricane inner-core structures, and surface fluxes. The assimilation of the superobbed CYGNSS data seems to be more effective in improving hurricane track forecasts than thinning the data.

1. Introduction

During the last two decades, tropical cyclone (TC) track forecasting has improved significantly, but despite recent improvements in hurricane modeling (Atlas et al. 2015a; Gall et al. 2013; Gopalakrishnan et al. 2012; Zhang et al. 2015), intensity forecasting remains a challenging problem (Cangialosi and Franklin 2016). One of the most cited reasons for the slower improvements in the TC intensity forecasting is *a lack of frequent and accurate observations of winds* in the inner core of TCs (Rogers et al. 2006, 2013). Specifically, current satellite observing systems are unable to penetrate heavy rainfall, and in situ measurements by aircraft and dropwindsondes are limited in space and time. The NASA Cyclone Global Navigation Satellite System (CYGNSS; Ruf et al. 2013, 2016a), launched in late 2016, is specifically designed to address this observation deficiency by collecting ocean surface wind speeds in the tropics, including those in hurricane inner-core regions.

CYGNSS is a constellation of eight microsatellites that utilizes the Global Navigation Satellite System (GNSS) reflection technique (Katzberg et al. 2001, 2006) and combines the all-weather performance of GNSS bistatic ocean surface reflectometry with frequent sampling properties. The bistatic radar cross section of the ocean surface at the specular reflection point between a GPS transmitter and a CYGNSS receiver is measured in the form of a delay-Doppler map (DDM). The ocean surface wind speeds (SWSs) can be estimated from the DDMs using a minimum variance estimator (Clarizia et al. 2014). Compared with previous ocean surface wind measurements, it is anticipated that three improvements will result from the CYGNSS SWSs, including 1) better

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spatial and temporal resolution of the SWSs over the tropical oceans and particularly within the precipitating core of hurricanes; 2) better understanding of the momentum and energy fluxes at the air–sea interface within the core of hurricanes, and the role of these fluxes in the maintenance and intensification of these storms; and 3) better ability to forecast hurricane intensity.

Before CYGNSS, previous studies demonstrated that ocean surface vector winds, such as those from NASA QuikSCAT, are useful for improving hurricane track, intensity, and structure forecasts (Atlas et al. 2001, 2005; Chen 2007; Pu et al. 2008; Brennan et al. 2009; Zhang and Pu 2014). In contrast to QuikSCAT ocean surface vectors, CYGNSS provides only SWSs. However, while QuikSCAT provides few usable data near a hurricane's inner-core region due to precipitation contamination, CYGNSS can sample winds in the hurricane's inner core (Ruf et al. 2016a). To examine the value of this unique feature of CYGNSS data prior to launch, this study assesses the impact of CYGNSS winds on hurricane forecasting, especially hurricane intensity forecasting through numerical simulations in a series of observing system simulation experiments (OSSEs) for a hurricane case. Two different methods of reducing the CYGNSS data volume in data assimilation (DA) are also tested.

2. Data and methods

An OSSE is commonly used to assess the data impact of hypothetical or future instruments or satellite sensors on numerical weather prediction (NWP) and to develop and test new DA methods for the new data source. As described in previous studies (Atlas 1997; Zhang and Pu 2010; Atlas et al. 2015b; Hoffman and Atlas 2016; Pu et al. 2017), an OSSE should include the following components: 1) a nature run (NR) that represents the characteristics or nature of real atmospheric conditions or phenomena; 2) simulated observations generated from this NR; 3) an NWP model and DA system; and 4) a verification process that evaluates the data impacts against the NR.

The hurricane NR (Nolan et al. 2013) here was produced by the Advanced Research version of the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008) embedded in the ECMWF T511 global NR (Andersson and Masutani 2010). It represented the life cycle of an Atlantic hurricane during the period of 0000 UTC 1 August 2005 to 0000 UTC 11 August 2005.

An end-to-end simulator (Ruf et al. 2016b) was developed by the CYGNSS project to produce simulated CYGNSS measurements. It uses sensor-based inputs, such as GPS satellite locations, CYGNSS satellite locations, transmitter and receiver positions and orientations, and antenna patterns, together with high-resolution wind fields (from the NR), to produce simulated DDMs. These DDMs are then used within retrieval algorithms developed at the University of Michigan (Clarizia et al. 2014) to produce retrieved SWSs and estimated errors.

Figures 1a,b illustrate the error characteristics of the CYGNSS-retrieved wind data as revealed by comparing them with the hurricane NR ("truth") at 3-km grid spacing. They show that the correlation between the CYGNSS wind retrievals and the NR (true) wind speeds is nearly 84% (Fig. 1a). The wind speed error standard deviation is $2.56\,\mathrm{m\,s^{-1}}$, while the wind speed standard deviation is $\pm 4.59\,\mathrm{m\,s^{-1}}$. A preliminary quality control removes CYGNSS observations from the DA if the estimated standard deviation of the retrieved wind speed errors is greater than $13\,\mathrm{m\,s^{-1}}$. For the sample data shown in Fig. 1a, this removes approximately 37% of the CYGNSS winds, increases the correlation with the NR to 99%, reduces wind speed error standard deviation to $0.54\,\mathrm{m\,s^{-1}}$, while reducing the wind speed standard deviation to $\pm 4.1\,\mathrm{m\,s^{-1}}$ (Fig. 1b).

Figures 1c–e show maps of CYGNSS wind speeds after the quality control at 1200, 1500, and 1800 UTC 1 August 2005. In general, CYGNSS observes both the hurricane environment and inner-core region well. More importantly, the wind speed gradients from the inner-core region to the storm environment are clearly depicted.

OSSEs are conducted using a research version of the NCEP Hurricane Weather Research and Forecasting (HWRF) Model, version 3.7 (Tallapragada et al. 2015), released by the Development Testbed Center at NCAR. The model configuration was set to be as close as possible to the NCEP operational HWRF in spring 2016 (i.e., as used during the 2015 hurricane season) but with a horizontal resolution of 27/9/3 km in three HWRF nested domains without ocean model coupling. The DA system uses the NCEP Gridpoint Statistical Interpolation (GSI)-based hybrid ensemble three-dimensional variational DA (3DVAR) system (Wu et al. 2002). Because of the absence of ensemble forecasts for the simulation case, DA is performed using the operational GSI-based ensemble 3DVAR system for all three HWRF nested domains, but with static background error covariances (Parrish and Derber 1992), while setting the weight for the ensemble component of the background covariance to zero. Note that the background error covariances vary and are consistent with each model domain resolution.

The initial and boundary conditions for HWRF are provided by the ECMWF T511 NR. All other

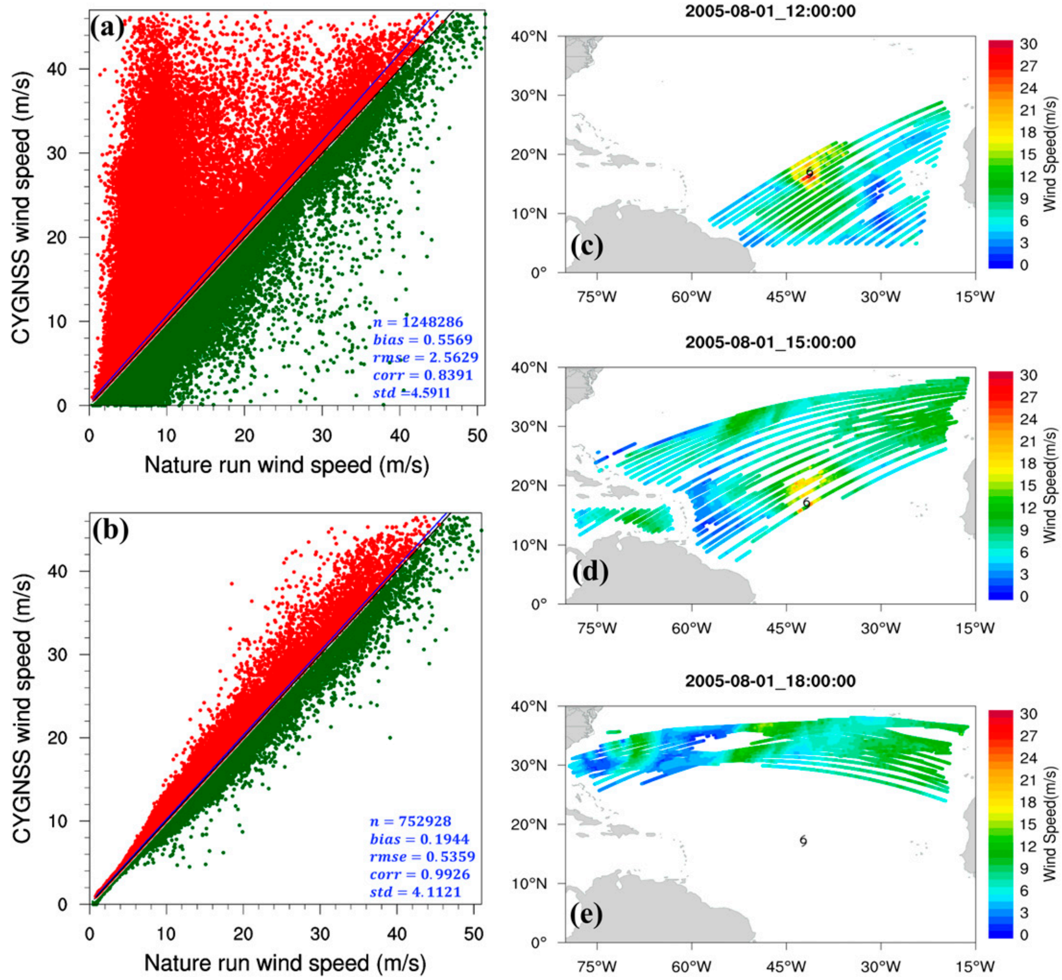

FIG. 1. (a),(b) Scatterplots of CYGNSS wind speed vs hurricane NR wind speed (a) before and (b) after quality control; red (green) dots indicate that CYGNSS wind speed has a positive (negative) observational error. All the data available during 0000 UTC 1 to 0000 UTC 11 Aug 2005 are counted. (c)–(e) CYGNSS data distribution and corresponding wind speeds at (c) 1200, (d) 1500, and (e) 1800 UTC 1 Aug 2005; the small black tropical cyclone symbols denote the storm center location.

observations, including conventional and satellite observations but excepting the CYGNSS observations, are simulated with realistic random errors from the ECMWF T511 NR by the Joint OSSE effort (Masutani et al. 2010; Andersson and Masutani 2010). This is reasonable since Nolan et al. (2013) nudged the hurricane NR to close to T511 NR. For the regional OSSE with HWRF, DA and simulation results are validated by the regional hurricane NR.

3. OSSEs and results

Since this study focuses on evaluating the impact of CYGNSS wind observations on hurricane intensity forecasting, the OSSEs are conducted during the intensification stage of the hurricane in the regional hurricane NR (Nolan et al. 2013) from 1200 UTC 1 to 1800 UTC 6 August 2005. Within this period there was extreme rapid intensification during 3 August 2005 with the decrease in minimum central pressure about 30 hPa.

Two sets of OSSEs are presented. The first OSSE includes only two consecutive 3-h DA cycles, followed by a 72-h forecast to mimic the common setup for numerical simulations in the research community for case studies. The second OSSE assimilates CYGNSS winds in 22 continuous 3-h DA cycles (a total of 66 h), followed by a 48-h forecast to simulate an operational scenario.

Three experiments are conducted—CTRL, CYGNSS-THIN, and CYGNSS-SUPO. CTRL assimilates simulated observations that match the types, locations, and times of all observations that were assimilated in reality in 2005, including conventional observations from ships,

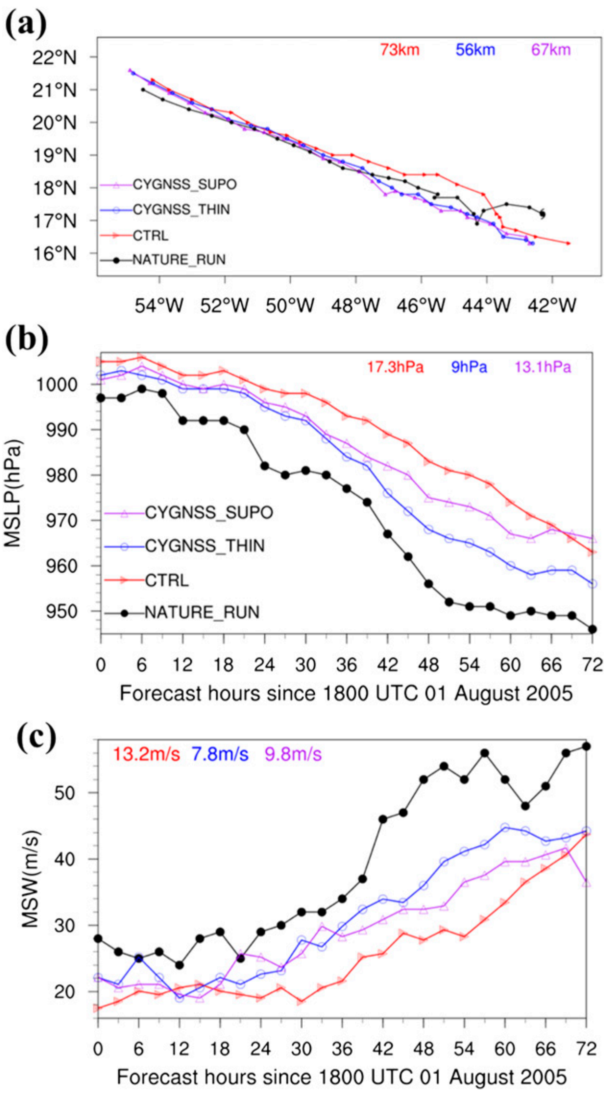

FIG. 2. Time series of (a) track, (b) MSLP, and (c) maximum surface wind between 1800 UTC 1 Aug 2005 and 1800 UTC 4 Aug 2005 from CTRL (red) and CYGNSS (SUPO in pink and THIN in blue) data assimilation experiments compared against the hurricane NR (black). The colored numbers at the top of (a) denote the averaged track errors during the first 36-h forecast and those in (b), (c) represent the averaged absolute intensity errors during the whole simulation period (72 h) for the experiments corresponding to the same colored lines.

buoys, aircraft, and radiosondes, and satellite radiances. The other two experiments assimilate the simulated CYGNSS winds in addition to those used in CTRL. Note that the effective resolution of CYGNSS is 25 km, but observations may be oversampled and closer together than this resolution. Both the CYGNSS-THIN and CYGNSS-SUPO reduce the observation density to one per grid box. CYGNSS-THIN keeps the CYGNSS SWS closest to each grid point, and CYGNSS-SUPO averages ("superobs") the CYGNSS SWSs in the grid volume around each grid point. Since the analysis is done separately for each HWRF domain (27/9/3 km), different selections or averages are used in each domain.

Two sets of analyses and forecasts of the three OSSEs are presented. In each set, three OSSEs are compared to each other and the NR. The first case is after a 6-h DA window (with three 3-hourly DA cycles) at the start of the rapid intensification (RI) phase, and the second phase is after 22 DA cycles, each 3 h (in the total 66-h window), at the start of the mature phase of the hurricane. The starting point for all experiments is a 12-h forecast valid at 1200 UTC 1 August 2005 from initial conditions interpolated from the T511 to the HWRF domains at 0000 UTC 1 August. The RI phase forecasts starts from analyses valid at 1800 UTC 1 August and ends 72 h later at 1800 UTC 4 August, and the mature phase forecasts start from analyses valid at 0600 UTC 4 August and end 42 h later at 0000 UTC 6 August.

a. *Analysis and forecast impacts during the RI phase*

1) IMPACT ON TRACK AND INTENSITY FORECASTS

Figure 2 shows the time series of track and intensity [represented by the minimum sea level pressure (MSLP) and surface maximum wind (MSW)] during the 72-h forecast. The track errors are similar in all experiments. Positive impacts in the first 36-h track forecast are notable in both DA experiments, with 23% and 8% averaged error reductions in CYGNSS_THIN and CYGNSS_SUPO, respectively. All three experiments capture the intensification of the hurricane during the 72-h simulations, although the overall intensity forecasts are weaker than that in the NR (Figs. 2b,c). Experiments with the assimilation of CYGNSS SWSs improve the intensity forecast during the whole 72-h simulation period (Figs. 2b,c). Specifically, the MSLP and MSW errors are reduced by about 23% and 40% from CTRL in CYGNSS_THIN and CYGNSS_SUPO, respectively. Compared with the assimilation of the superobs SWSs, assimilating the thinned SWSs seems to provide greater benefits to intensity forecasts.

2) IMPACT ON HURRICANE INNER-CORE STRUCTURE

To examine the impact of CYGNSS DA on the hurricane inner-core structure in analyses and forecasts, the horizontal and vertical vortex structure obtained at the end of DA (1800 UTC 1 August 2005) and the 24-h forecast (1800 UTC 2 August 2005) from CYGNSS_THIN and CYGNSS_SUPO are compared with the NR and CTRL (Fig. 3). Figures 3a,d show that, compared to

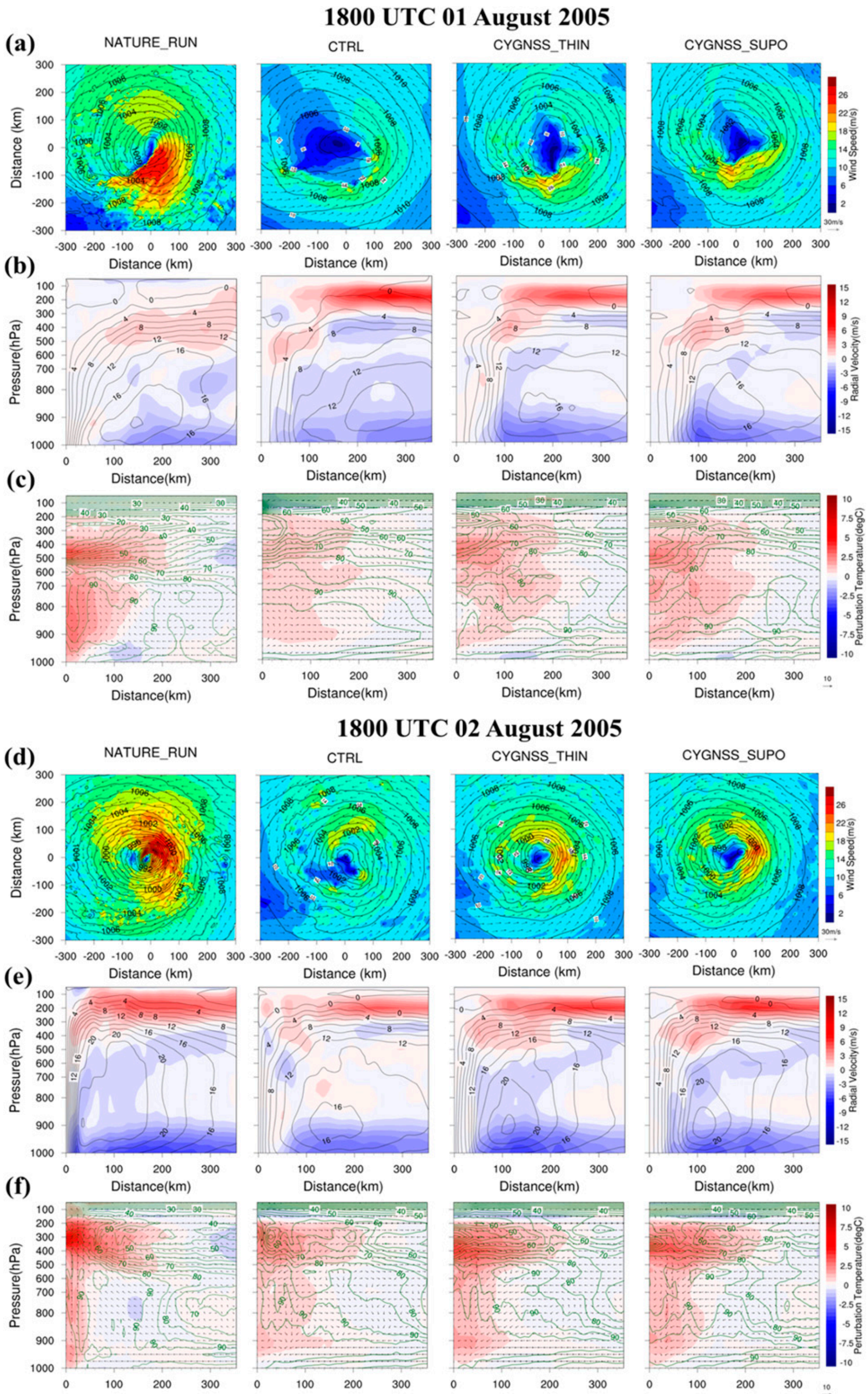

FIG. 3. Comparison of the structure of the hurricane vortices from (left to right) the hurricane NR vs the CTRL, CYGNSS_THIN, and CYGNSS_SUPO at (a)–(c) 1800 UTC 1 Aug 2005 and (d)–(f) 1800 UTC 2 Aug 2005. (a),(d) Sea level pressure (hPa, black contour), 10-m wind field (m s^{-1}, black vectors with reference vector below color bar), and wind speed (m s^{-1}, color shaded contours). (b),(e) Vertical cross section of azimuthally averaged tangential wind (m s^{-1}, black contours) and radial wind (m s^{-1}, color shaded contours). (c),(f) Vertical cross section of azimuthally averaged temperature perturbations (°C, color shading), relative humidity (%, green contours with 5% interval), and secondary circulations [represented by u–w vectors, where u is the radial velocity (m s^{-1}) and w is the vertical velocity (cm s^{-1})] with the vector magnitude legend below the color bar.

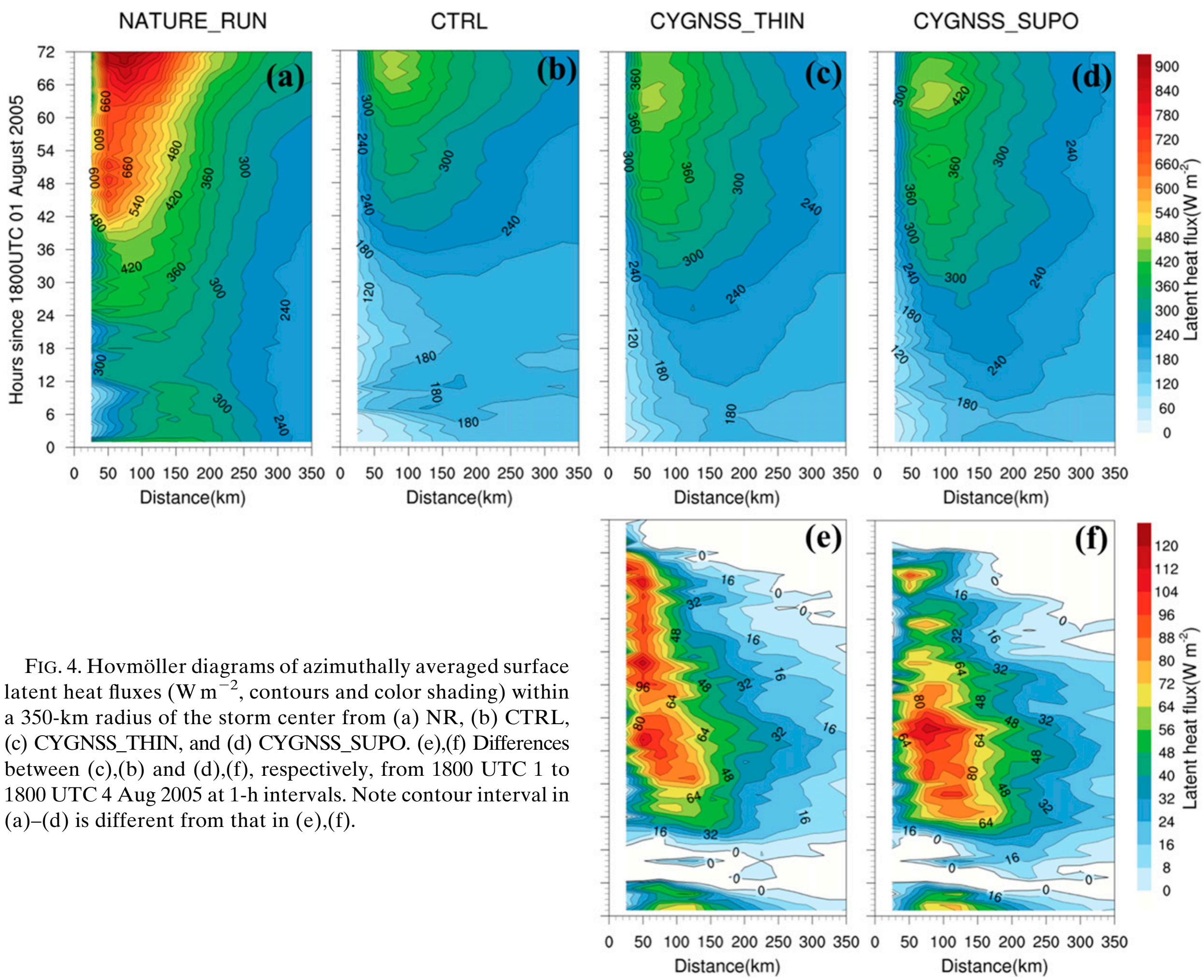

FIG. 4. Hovmöller diagrams of azimuthally averaged surface latent heat fluxes (W m^{-2}, contours and color shading) within a 350-km radius of the storm center from (a) NR, (b) CTRL, (c) CYGNSS_THIN, and (d) CYGNSS_SUPO. (e),(f) Differences between (c),(b) and (d),(f), respectively, from 1800 UTC 1 to 1800 UTC 4 Aug 2005 at 1-h intervals. Note contour interval in (a)–(d) is different from that in (e),(f).

CTRL, CYGNSS_SUPO and CYGNSS_THIN better capture the sea level pressure and wind distribution, and in particular the asymmetry of the vortex and the location of maximum wind speed, in both the analysis and forecast. Figures 3b,e indicate that assimilation of CYGNSS winds leads to an improved depiction of the tangential wind and radial winds. In addition, assimilation of CYGNSS winds has resulted in significant improvements in the low- to the midlevel vertical structure of the motion and warm core at 1800 UTC 1 August (Fig. 3c). At 24 h (1800 UTC 2 August; Fig. 3f), a moderate low- to midlevel upward motion located within around a 50–100-km radius of the storm center is better stimulated in the CYGNSS_THIN and CYGNSS_SUPO forecasts. The low- and upper-level warming are enhanced and more comparable to the NR.

Overall, assimilation of CYGNSS ocean SWSs directly improves the low-level inflow, which increases moisture transport to the inner-core region in the low level and enhances the low-level warm core. The maintenance of strong low-level inflow stimulates a moderate upward motion around the storm center, which leads to the enhancement of vertical moisture transport from the low level to the midlevel around the storm center, thus increasing the latent heat release in the eyewall region. As both the low- and upper-level warm cores are enhanced, the secondary circulation and warm-core structure of the hurricanes forecast by CYGNSS_THIN and CYGNSS_SUPO become more similar to the NR. Also, the stronger upper-level warming in CYGNSS_THIN and CYGNSS_SUPO result in a greater surface pressure drop (Fig. 3d; Zhang and Zhu 2012; Li and Pu, 2014), leading to a better intensity forecast. Therefore, it is reasonable to attribute improvements in intensity forecasts in both CYGNSS_THIN and CYGNXX_SUPO to the enhanced low-level inflow due to the assimilation of CYGNSS SWSs.

Figure 4 shows Hovmöller diagrams of azimuthally averaged surface momentum and latent heat flux around a 350-km radius of the storm center from the NR, and the CTRL, CYGNSS_THIN, and CYGNSS_SUPO

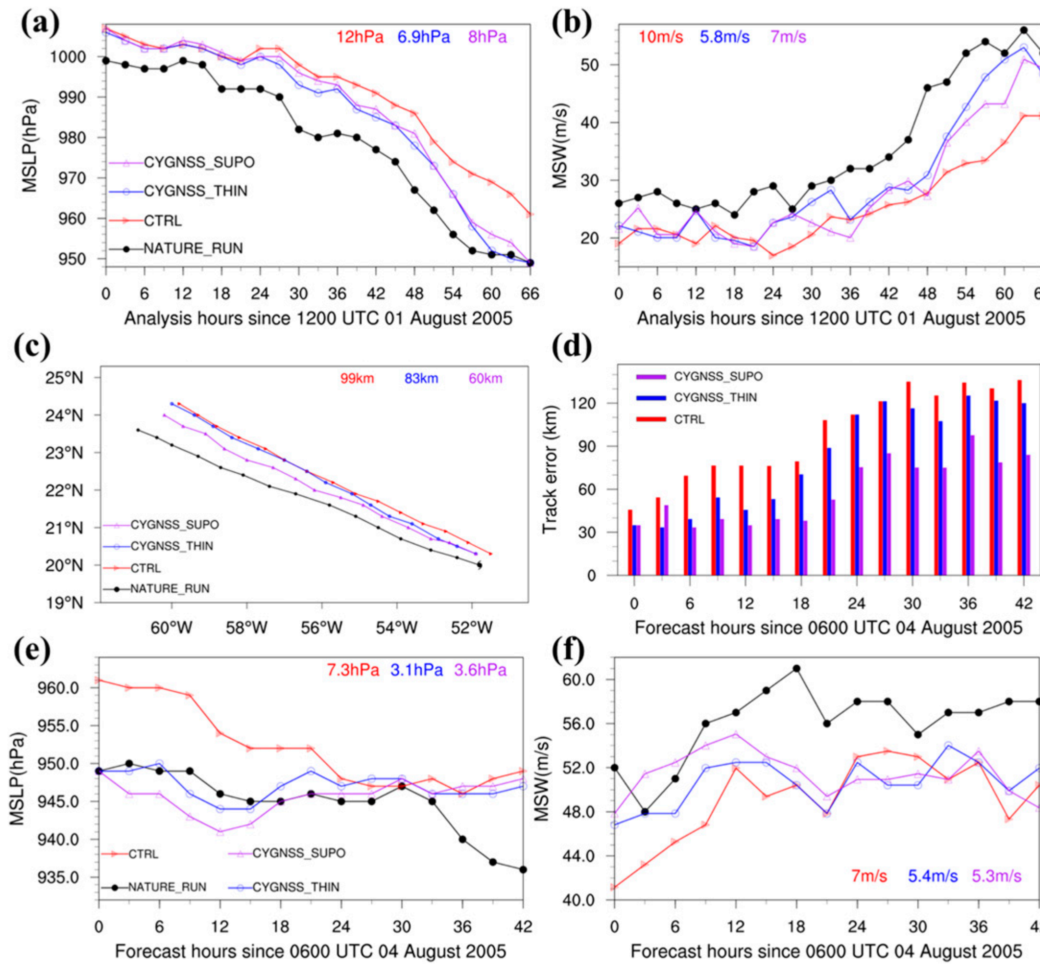

FIG. 5. Time series of (a) MSLP and (b) maximum surface wind between 1200 UTC 1 and 0600 UTC 4 Aug 2005 for the analysis during the cycled DA period: CTRL (red) and CYGNSS (SUPO pink and THIN blue) DA experiments vs the hurricane NR (black). (c)–(f) As in (a),(b), but for track, track errors, MSLP, and maximum surface wind, respectively, for the forecasts between 0600 UTC 4 and 0000 UTC 6 Aug 2005. The colored numbers in each panel denote the averaged absolute errors for track or intensity over the whole period of analysis or simulation for the experiments corresponding to the line colors.

simulations. Although the wind speeds (Fig. 3c) and fluxes are still much too weak in both CYGNSS_THIN and CYGNSS_SUPO forecasts compared with the NR, the assimilation of CYGNSS winds significantly enhances the latent heat fluxes around the storm center throughout the analysis and forecast periods relative to CTRL. Similar results are also found for surface sensible heat and moisture fluxes (figures not shown).

b. *Analysis and forecast impacts during the mature phase*

In an operational environment, DA is performed in a continuous forecast–analysis cycle. For regional models, a 3-h DA cycle is usually used. The 3-h forecast provides the prior or background for the subsequent analysis. Longer forecasts (here out to 48 or 72 h) are made at regular intervals from the analyses. The second OSSE we present here performs continuous DA during 1200 UTC 1 August to 0600 UTC 4 August 2005, for a total of 66 h, and then makes a 48-h forecast from the last analysis. Figures 5a,b show the time series of the MSLP and MSW within the DA cycles. It is clearly seen that after 24 h of continuous DA, the data assimilation begins to show obvious positive impacts as the quality of the analysis improves continuously with time. The improved analysis quality due to the assimilation of CYGNSS winds results in a significant positive impact on the short-range intensity and track forecasts. Figures 5c,d show the impacts on track forecasts for the sample forecast from 0600 UTC 4 August 2005 (at the end of the DA experiment). Compared with thinned CYGNSS winds, the superobs SWSs have notable positive impacts on the hurricane track forecasts. Specifically, on average the assimilation of thinned (superobs) CYGNSS winds improves the track errors by 16% (~40%). Both DA experiments improve the intensity forecast (Figs. 5e,f).

4. Conclusions and remarks

The results from the OSSEs in this paper suggest that the assimilation of CYGNSS ocean surface winds not only has the potential to improve hurricane track and intensity forecasts but also to help provide a better representation of the dynamic and thermodynamic structure and surface fluxes in the hurricane inner-core region. Compared with the assimilation of thinned CYGNSS winds, assimilation of the superobs CYGNSS winds seems to be more effective in improving hurricane track forecasts, implying that it is necessary to test various configurations of DA to maximize the impact of CYGNSS winds. In addition, because of the limitations imposed by the available data sources, the OSSEs conducted in this study used the 3DVAR DA method with the static background error covariance for a single hurricane case. Research aircraft observations that are commonly available during the hurricane season were not included in the OSSEs. Furthermore, the use of a global NR might provide boundary conditions that were less erroneous than the global analysis–forecast in the real world. Future work should emphasize more advanced DA methods, such as the hybrid ensemble–variational (En3DVAR, En4DVAR etc.) and EnKF methods, which include the flow-dependent background error covariance term, and should be performed for multiple hurricane cases and also use the operational models and all available observational data sources when CYGNSS data are available after its launch.

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