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Assessing the impact of assimilating CYGNSS ocean surface winds on tropical cyclone analyses and forecasts with regional OSSEs

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1. Introduction

Tropical cyclone (TC) track forecasts by the global and regional modeling systems at NCEP and other operational numerical weather prediction centers have improved in accuracy by about 50% over the last two decades (Aberson, 2001; Franklin et al., 2003; Rogers et al., 2006; Zhang and Weng, 2015). This improvement has depended largely on enhanced mesoscale and synoptic modeling, data assimilation, better representation of hurricane vortices, and improved representation of tropical physics. However, there has been essentially no improvement or only limited improvement in the accuracy of TC intensity forecasts especially in the rapidly evolving (genesis and rapid intensification) stages of the TC life cycle (DeMaria and Gross, 2003; DeMaria et al., 2005; Gall et al., 2013; Rogers, 2013; Ruf et al., 2013a; Goldenberg et al., 2015; Zhang and Weng, 2015). One of the important factors that limits the improvement in intensity forecasting is a deficiency in the systematic collection of inner-core data that can provide real-time estimates of TC intensity and structure to forecasters and be assimilated into numerical models (Rogers et al., 2006; Goldenberg et al., 2015). This is because 1) much of the inner-core ocean surface is obscured from conventional remote sensing instruments; and 2) the genesis and rapid intensification stages of the TC life cycle are poorly sampled in time by conventional polar-orbiting, wide-swath surface wind imagers (Ruf et al., 2013a).

The Cyclone Global Navigation Satellite System (CYGNSS), scheduled for launch in October 2016, is specifically designed to address the above two deficiencies in collecting hurricane inner-core data. CYGNSS is a constellation of eight microsatellites that will measure surface winds utilizing the GPS reflection technique (Katzberg et al., 2001; Katzberg et al., 2006) in and near the inner-core of hurricanes, including the regions beneath the eye wall and intense inner rainbands that could not previously be measured from space (Ruf et al., 2012). The CYGNSS observation and data retrieval techniques are well documented in previous studies (Zavorotny and Voronovich, 2000; Schlax et al., 2001; Gleason et al., 2005; Gleason, 2007, 2012; Rose et al., 2012; Ruf et al., 2012, 2013a, 2013b, 2014, 2015; Murray et al., 2015). In brief, through combining the all-weather performance of the Global Navigation Satellite system (GNSS) bistatic ocean surface scatterometry with the sampling properties of a constellation of satellites, 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 Delay-Doppler Maps (DDMs). The sea surface wind speed can be estimated from the DDMs using a minimum variance (MV) estimator (Clarizia et al., 2014). The CYGNSS data will enable scientists to probe key air-sea interaction processes that take place near the core of the storms – processes that change rapidly and play a critical role in the genesis and intensification of hurricanes (Ruf et al., 2015, Ruf et al., 2013b). Three improvements can be induced by using CYGNSS surface wind data, including 1) the spatial and temporal resolution of the surface wind field within the precipitating core of hurricanes; 2) the 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) the ability to forecast hurricane intensification (Murray et al., 2015).

In this paper, observing system simulation experiments (OSSEs) are performed using the Hurricane Weather Research and Forecast (HWRF) model (Tallapragada et al., 2013, 2014, 2015) and the NCEP Gridpoint Statistical Interpolation (GSI) system, a three-dimensional variational data assimilation system (Parrish and Derber 1992; Wu et al. 2002). The HWRF model has been operational at the National Centers for Environmental Prediction (NCEP) since 2007. The model description and configurations are well documented (Tallapragada et al., 2013, 2014, 2015). Our goal is to explore the potential benefits of CYGNSS wind data in the operational HWRF model for hurricane track and intensity forecasts, which can provide the preliminary guidance on how to use CYGNSS data in the operational HWRF model for the National Hurricane Centers (NHC).

2. A regional OSSE framework based on the HWRF system

An OSSE is an extension of the concept of an observing system experiment (OSE). In an OSE, real observations during a single weather event (e.g., a major storm) or period of weather (e.g., a summer drought) are used to initialize numerical models that forecast the weather during the event(s) of interest (Atlas, 1997, Nolan, et al., 2013). Due to limitations in our ability to observe the atmosphere, OSSEs are extended to study the performance of the new observations by replacing real weather observations with "synthetic" observations from a high-quality numerical simulation of the weather (Arnold and Dey, 1986; Atlas, 1997, Nolan, et al.,). This simulation is so-called nature run, which replaces the actual weather events or periods that will be forecasted. Two nature runs, namely, the joint OSSE nature run (JONR) and the Hurricane Nature Run (HNR) are used in this study. JONR was generated by the European Center for Medium Range Weather Forecasts (ECMWRF) and was a free running from 01 May 2005 to 01 June 2006. HNR is a regional nature run developed by RSMAS/University of Miami and

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NOAA/AOML (Nolan, et al., 2013). This regional nature run was initialized by JONR using an advanced research version of the weather research and forecasting (WRF) model (Skamarock et al., 2008). An Atlantic hurricane during the period from 00Z July 29 2005 to 18Z August 10 2005 was simulated and used to provide the synthetic observations for the regional hurricane forecast model. Detailed descriptions of JONR and HNR are well documented (Reales et al., 2007, Masutani et al., 2009; Andersson and Masutani, 2010; Nolan, et al., 2013).

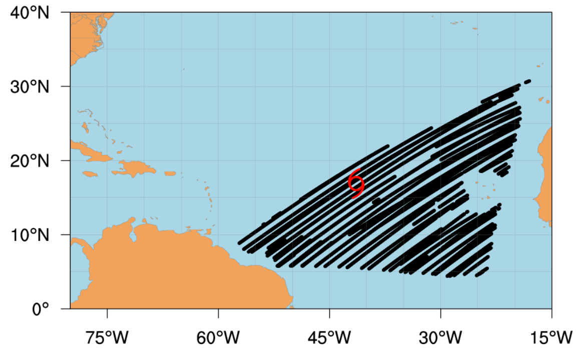

Figure 1: CYGNSS wind data distribution at 12z August 01 2005. All the observations in a 3h data assimilation window are plotted. Red sign demonstrates the storm location at current time.

JONR is used to provide the initial and boundary conditions for HWRF model. A series of CYGNSS ocean surface winds have been simulated and provided by University of Michigan (http://claspresearch.engin.umich.edu/missions/cygnss/reference-material.php) based on HNR. An example of the horizontal distribution of CYGNSS wind data enters to data assimilation system at 12z August 01 2005 is illustrated in Figure 1. It clearly shows that CYGNSS wind data has a very high resolution in horizontal. More importantly, the data has a broad coverage in the inner-core region. These data are assimilated into HWRF using the GSI-3DVAR system. Nine experiments for the data assimilation and sensitivity studies were conducted for rapid intensification phases of the Atlantic hurricane in HNR from 28 July to 11 August 2005. Detailed information on the experiments and their configurations is shown in Table 1.

Table 1: List of experiments and their configurations

Exp.	HWRF VERSION	Vortex initialization	Assimilation periods	Assimilated data	Assimilation domain
FREE_RUN_V15	2015	No	--	---	--
CYGNSS_V15	2015	No	1200 UTC 01 Aug 2005 1500 UTC 01 Aug 2005 1800 UTC 01 Aug 2005	CYGNSS sea surface wind speed	d01 d02 d03
CYGNSS_V15_G0	2015	No	1200 UTC 01 Aug 2005 1500 UTC 01 Aug 2005 1800 UTC 01 Aug 2005	CYGNSS sea surface wind speed	d01 d02
CTRL_RUN_V15_VI1	2015	Relocation only	--	--	--
CYGNSS_V15_VI1	2015	Relocation only	1200 UTC 01 Aug 2005 1500 UTC 01 Aug 2005 1800 UTC 01 Aug 2005	CYGNSS sea surface wind speed	d01 d02 d03
CTRL_RUN_V15_VI2	2015	Relocation + Intensity correction	--	--	--
CYGNSS_V15_VI2	2015	Relocation + Intensity correction	1200 UTC 01 Aug 2005 1500 UTC 01 Aug 2005 1800 UTC 01 Aug 2005	CYGNSS sea surface wind speed	d01 d02 d03
FREE_RUN_V13	2013	No	--	---	--
CYGNSS_V13	2013	No	1200 UTC 01 Aug 2005 1500 UTC 01 Aug 2005 1800 UTC 01 Aug 2005	CYGNSS sea surface wind speed	d01 d02 d03

3. Simulation results and verification

3.1 CYGNSS data impacts: 2013 HWRF vs. 2015 HWRF

HWRF has been operational at the NCEP since 2007. During about 10 years of development, the track and intensity forecasts by HWRF have been significantly improved due to improvements in the physical and dynamical parameterizations as well as in the analysis schemes such as vortex initialization and data assimilation methods. Two versions of HWRF with updates in 2013 (2013 HWRF) and in 2015 (2015 HWRF) are used to investigate the impacts of CYGNSS wind data on hurricane track and intensity forecasts in the two different HWRF systems. The configurations of 2013 HWRF and 2015 HWRF are shown in Table 2. Compared with 2013 HWRF, the microphysics, radiation, land surface parameterizations and vertical model levels are revised in 2015 HWRF. For both 2013 HWRF and 2015 HWRF, the NCEP Gridpoint Statistical Interpolation (GSI) system, a three-dimensional variational data assimilation system (Parrish and Derber 1992; Wu et al. 2002) is used for assimilating CYGNSS wind data.

Table 2: List of 2013 HWRF model configurations and 2015 HWRF upgrades

Scheme	2013 HWRF	2015 HWRF
Model horizontal resolution	27/9/3 km (E-grid)	27/9/3 km (E-grid)
Dynamic core	WRF-NMM (Version 3.4a)	WRF-NMM (Version 3.7)
Model Domain	216x432(27km domain), 88 x 170 (9 km domain), and 154 × 272 (3 km domain)	216x432(27km domain), 106 x 204 (9 km domain) and 198 × 354 (3 km domain)
Number of Vertical model levels	43	61
Model top	50hPa	2hPa
Cumulus parameterization	GFS convection parameterization	GFS convection parameterization
Microphysics	Ferrier Microphysics parameterization	Ferrier-Aligo Parameterization
Boundary layer	Modified GFS PBL scheme with variable critical Richardson number (Vickers and Mahrt 2003)	Modified GFS PBL scheme with variable critical Richardson number (Vickers and Mahrt 2003)
Surface physics	Improved GFDL surface physics	Improved GFDL surface physics
Land-surface	GFDL slab land surface model	Noah Land -Surface Model
Radiation	GFDL short/long wave schemes	RRTMG scheme

Currently, the formation of the HWRF initial conditions (i.e., analysis) includes vortex initialization (including vortex relocation and vortex size and intensity correction) and data assimilation. In order to eliminate the impacts of vortex initialization (which will be discussed in the next section) on the HWRF analysis, four experiments are performed using two versions of HWRF without the vortex initialization. Figure 2 demonstrates the 72-h forecasted track and track errors using 2013 HWRF (Fig2.a, c) and 2015 HWRF (Fig2.b, d), compared with two control experiments. FREE_RUN_V15 (Fig.2b) has fewer track forecast errors than FREE_RUN_V13 (Fig.2d), and the track forecast by FREE_RUN_V15 is closer to the track from the nature run. This means that improvements in dynamical and physical parameterizations in 2015 HWRF can benefit the track forecast. With assimilation of CYGNSS wind data, a moderate improvement can be seen in track forecast of CYGNSS_V13 during the whole 72-h simulation periods, as the track errors in CYGNSS_V13 are smaller than those in FREE_RUN_V13. However, compared with FREE-RUN_V15, the track errors are decreased only in the 24-h forecasts in CYGNSS_V15. The track errors in the 24-72h forecasts in CYGNSS_V15 are larger than those in FREE_RUN_V15.

For the intensity forecasts, as indicated by Figure 3, not much difference is shown in FREE_RUN_V13 and FREE_RUN_V15 for the minimum sea level pressure (MSLP) and maximum wind speed (MWS) forecasts, which indicates that the improvements in the dynamical and physical parameterizations by model upgrades do not necessarily improve the intensity forecast despite their beneficial effect on track forecast. However, compared to the intensity forecasts with 2013 HWRF (Fig.3a, c), the assimilation of CYGNSS wind data with 2015 HWRF has more improvements in the MSLP and MSW forecasts (Fig.3b, d).

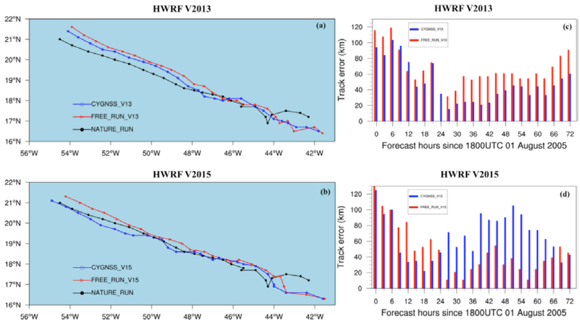

Figure 2: 72-h forecasted track (left) and track errors (right) using (a), (c) 2013 HWRF and (b), (d) 2015 HWRF.

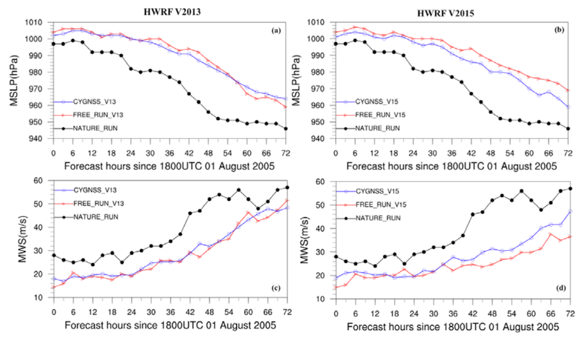

Figure 3: 72-h MSLP (top) and MWS (bottom) forecasts using (a), (c) 2013 HWRF and (b), (d) 2015 HWRF

Overall, the performances of 2015 HWRF are better than those of 2013 HWRF with respect to the track and intensity forecasts, and the impacts of CYGNSS wind data assimilation are enhanced in the 2015 HWRF especially in the first 24-h forecasts.

3.2 The influence of vortex initialization on CYGNSS data assimilation

HWRF initialization comprises of both a vortex relocation/intensity correction procedure and data assimilation (Liu et al. 2006; Tallapragada et al. 2014), which consists mainly of five major steps: 1) interpolation of the global analysis fields from the GFS/GDAS onto the HWRF operational 27–9–3-km model grids; 2) removal of the GFS/GDAS vortex from the global analysis environment; 3) modification of the vortex from the previous 6-h HWRF forecast based on observed location and strength, and incorporation into the GFS/GDAS environment field; and 4) further modification of the first guess with an improved vortex using the HWRF data assimilation system (i.e., GSI) and 5) merging the analysis field generated by 3) and 4) to the forecast domain and using it as the initial conditions. Studies have shown that vortex initialization and data assimilation counteract each other in some cases (Tallapragada et al. 2015). Two sets of experiments are conducted to test the impacts of vortex initialization on HWRF analyses and the performances of CYGNSS data assimilation. Considering 2015 HWRF is a newer version, the discussions from now on are based on the 2015 HWRF. Figures 4 and 5 show the 72-h track and intensity forecasts with vortex relocation only (Fig.4a, c; Fig5.a, c) and with both relocation and intensity correction (Fig.4b, d; Fig5b, d).

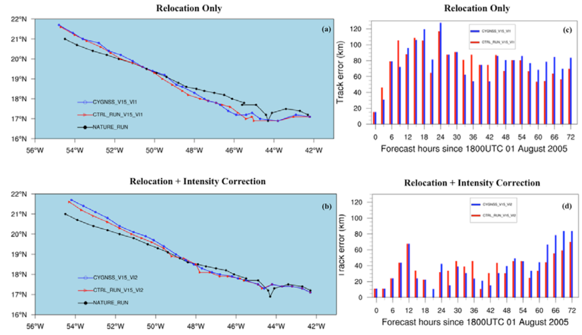

Figure 4: 72-h forecasted track (left) and track errors (right) with (a), (c) relocation only and (b), (d) relocation and intensity correction in 2015 HWRF

As shown in Fig.4a and 4b, the vortex position can be moved to the observation position (i.e. the vortex position in HNR) with the vortex relocation scheme, and the initial track error is significantly reduced (Fig.4c, d) compared to the experiments without vortex relocation (Fig.2d). However, track errors will increase quickly after the initial time if only vortex relocation is performed (Fig.4c). The track errors become even larger than those without vortex relocation after 12-h forecasts (Fig.2d). With both vortex relocation and intensity correction, the track errors are improved significantly during the whole 72-h simulation periods (Fig.4d) compared to the experiments with vortex relocation only (Fig.4c) and without vortex initialization (Fig.2d).

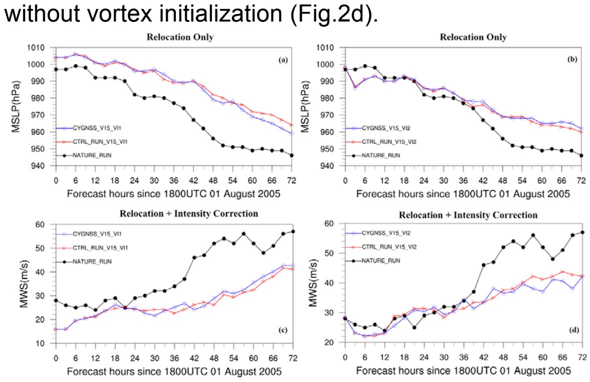

Figure 5: 72-h MSLP (top) and MWS (bottom) forecasts with (a), (c) relocation only and (b), (d) relocation and intensify correction in 2015 HWRF

The MSLP and MSW forecasts with vortex relocation only (Fig.5a, c) are similar to the experiments without vortex initialization (Fig.2b, d) except that the MSW forecasts during 12-24h are little better than those without vortex initialization. With both relocation and intensity correction, the MSLP and MSW during the first 48-h forecast can perfectly match the nature run although a weak vortex spin-down is shown in the first 6-h forecasts (Fig.5b, d).

As for the CYGNSS wind data assimilation, vortex initialization will washes out the impacts of the CYGNSS data since both track and intensity forecasts in the CYGNSS assimilation experiments (blue bars in Fig.5c, d) are nearly the same as those in the control experiments (red bars in Fig.5c, d). Combining this with the results from Fig.1d, it is apparent that the vortex initialization could prevent the HWRF forecasts to show impacts from the CYGNSS data assimilation, as the vortex intensity correction imposes very strong (and dominated) information into the initial vortex.

3.3 The impact of CYGNSS inner-core data assimilation

In the current HWRF, the satellite data are not assimilated in the inner most domain since the studies have shown that the assimilation of satellite-derived winds in the inner-core region can degraded the intensity forecast (Tallapragada et al. 2015). Since the CYGNSS wind data is also a type of satellite-derived products, testing the impacts of assimilating of CYGNSS in the inner-core region on the HWRF track and intensity forecasts is necessary. In order to do this, two experiments are performed using 2015 HWRF and without vortex initialization. The CYGNSS wind data are the only data assimilated in both experiments (CYGNSS_V15 and CYGNSS_V15_G0). Here, CYGNSS_V15 is the same as the experiment in section 3.1, the CYGNSS wind data is assimilated in all three model domains, including the innermost domain. CYGNSS_V15_G0 is the same as CYGNSS_V15 but the CYGNSS wind data are not assimilated in the innermost domain (i.e. without the inner-core data assimilation). As shown in Figure 6, the track forecasts in CYGNSS_V15 and CYGNSS_V15_G0 are similar (Fig.6a). Both experiments can capture the tracks of NR except that a large initial track error is shown (Fig.6b). However, CYGNSS_V15 has smaller track errors than CYGNSS_V15_G0 in the first 24-h forecasts (Fig.6b). For the intensity forecast, the assimilation of CYGNSS wind data in the inner-core region slightly improves the MSW forecasts during the whole 72-h simulations while the assimilation of CYGNSS wind data in the inner-core region has only a slight positive impacts on the MSLP forecasts in the first 24-h. Overall, the assimilation of the CYGNSS wind data in the inner-core region has positive impacts on both track and intensity forecasts.

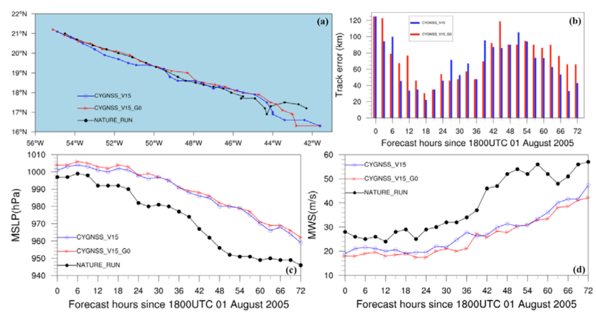

Figure 6: 72-h forecasts with/without inner core data assimilation in 2015 HWRF for (a) track, (b) track error, (c) MSLP and (d) MWS (bottom)

4. Summary and discussions

In this study, various data assimilation and sensitivity studies have been conducted within a regional OSSE framework using the HWRF model. The impacts of CYGNSS wind data assimilation on hurricane track and intensity forecasts in HWRF are studied, and the results show that:

- Overall, assimilation of CYGNSS ocean surface wind data has positive or neutral impacts on hurricane track and intensity forecasts. Specifically, the track forecasts are improved in 2015 HWRF compared to 2013 HWRF. These improvements are contributed by the enhancement of the dynamical and physical parameterizations due to the upgrades of model systems. The assimilation of CYGNSS wind data in 2013 HWRF and 2015 HWRF has different effects on track and intensity forecasts. Specifically, the assimilation of CYGNSS wind data can decrease the track errors in the 24-h forecasts for both 2013 HWRF and 2015 HWRF, while the assimilation of CYGNSS wind data in 2015 HWRF degrades the track forecasts during the 24-72h simulations. In addition, the assimilation of CYGNSS wind data with 2015 HWRF shows more improvements in the hurricane intensity (MSLP and MSW) forecasts.
- Vortex initialization washes out the impact of CYGNSS data assimilation as the vortex intensity correction imposes very strong (and dominated) information into the initial vortex.
- Assimilation of CYGNSS wind data in the inner-core region has positive impacts on both track and intensity forecasts although the impacts are not significant.

The above experiments can provide some insight into how to use the CYGNSS and to what extent we should expect CYGNSS data to improve t track and intensity forecast in the operational HWRF model. Future studies should be performed to combine the CYGNSS wind data with other conventional and satellite observations into the HWRF model with an integrated data assimilation. In addition, the impact of CYGNSS wind data assimilation on the momentum and energy flux also remains to be studied in the future.

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