PAPER

Impact of Assimilating CYGNSS Data on Tropical Cyclone Analyses and Forecasts in a Regional OSSE Framework

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ABSTRACT

The impact of assimilating ocean surface wind observations from the Cyclone Global Navigation Satellite System (CYGNSS) is examined in a high-resolution Observing System Simulation Experiment (OSSE) framework for tropical cyclones (TCs). CYGNSS is a planned National Aeronautics and Space Administration constellation of microsatellites that utilizes existing GNSS satellites to retrieve surface wind speed. In the OSSE, CYGNSS wind speed data are simulated using output from a "nature run" as truth. In a case study using the regional Hurricane Weather Research and Forecasting modeling system and the Gridpoint Statistical Interpolation data assimilation scheme, analyses of TC position, structure, and intensity, together with large-scale variables, are improved due to the assimilation of the additional surface wind data. These results indicate the potential importance of CYGNSS ocean surface wind speed data and furthermore that the assimilation of directional information would add further value to TC analyses and forecasts.

Keywords: Observing System Simulation Experiment (OSSE), Cyclone Global Navigation Satellite System (CYGNSS), tropical cyclone

Introduction

Prior to the design and launch of a new satellite platform, a quantitative assessment of the potential of the satellite to improve numerical analyses and forecasts is potentially valuable to help agencies make informed decisions in a cost-effective manner. First, priorities for forecast improvement can be set; for example, data from the new platform may be expected to improve predictions of tropical cyclone (TC) track, structure, and intensity. Then, the Observing System Simulation Experiment (OSSE) framework can be used to prepare such a quantitative assessment. The foundation of any OSSE is a "nature run," which is treated as a proxy for the "real world" providing the "truth" for the simulation of observational datasets and for the verification for analyses and forecasts. An important step is to rigorously evaluate the physical realism of the nature run. A data assimilation scheme and numerical model are then used to evaluate the impact of assimilating the data in question. OSSEs offer the flexibility to test different configurations of existing and proposed observing systems, including their error characteristics, and also of the forecast and data assimilation systems. Traditionally, OSSEs have been conducted in global modeling frameworks of relatively coarse resolution (Atlas, 1997). This study presents a prototype effort using a high-resolution, regional modeling framework that mimics the operational regional hurricane forecasting system at National Oceanic and Atmospheric Administration (NOAA). For further perspectives on modern OSSEs, the interested reader is referred to Hoffman and Atlas (2016).

This paper uses the OSSE approach to demonstrate the potential impact of assimilating retrieved ocean surface wind speed observations from the Cyclone Global Navigation Satellite System (CYGNSS), which was the first

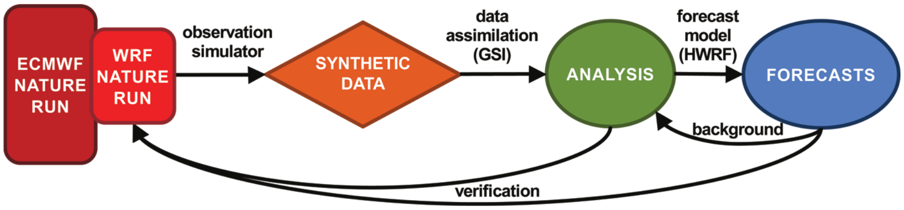
Earth Venture mission selected by the National Aeronautics and Space Administration (NASA) (Ruf et al., 2016). Previously, OSSEs quantified the impact of assimilating ocean surface vector winds from scatterometers on global model analyses and forecasts (Atlas et al., 2001). Here the focus is on CYGNSS and state-of-the-art high-resolution TC analysis and prediction. CYGNSS, a spaceborne mission launched in December 2016, has a primary motivation of sampling winds in TCs at high resolution, while largely avoiding the rain contamination problems of higher-frequency satellite scatterometers and microwave radiometers. CYGNSS consists of a constellation of eight microsatellites in a nominal 35° inclination orbit at 500-km altitude. It combines the all-weather performance of GPS-based bistatic reflectometry with the spatial and temporal sampling properties of a constellation of observatories to provide the ability to retrieve ocean surface wind speeds in all precipitating conditions and with frequent revisit times. This paper represents the first attempt to quantify the potential influence of CYGNSS on numerical TC analyses and predictions, providing a baseline for future studies.

OSSE Framework

The regional OSSE framework, developed jointly between the NOAA Atlantic Oceanographic and Meteorological Laboratory and the University of Miami, is illustrated in Figure 1. It is based on a high-resolution regional nature run embedded within a lower-resolution global nature run (Atlas et al., 2015a, 2015b). The regional nature run was created using Version 3.2.1 of the Advanced Research Weather Research and Forecasting model (WRF-ARW) with an outer fixed domain of 27 km grid spacing spanning the tropical Atlantic basin and three telescoping storm-following nested grids of 9, 3, and 1 km (Nolan et al., 2013). The global nature run is the European Centre for Medium-Range Weather Forecasts (ECMWF) T511 simulation described in Reale et al. (2007).

FIGURE 1

Flow chart of the regional OSSE framework.



Simulated conventional observations are generated for a variety of platforms from the ECMWF nature run, including radiosondes, surface stations, and numerous satellite-based instruments (e.g., GOES-Imager, GOES-Sounder, VIIRS, SEVERI, HIRS, CrIS, IASI, SSMI/S, AMSU-A, AMSU-B, MHS, ATMS, and GPS). In a fashion similar to that described in Zhang and Pu (2010) for a Doppler wind Lidar study, simulated CYGNSS observations are derived from the regional WRF nature run and include random errors as well as realistic measurement uncertainty, which is a function of the strength of the reflected GPS signal at the specular point.

The full suite of synthetic observations is then assimilated into the Gridpoint Statistical Interpolation (GSI) 3-D Variational scheme used by the National Centers for Environmental Prediction (NCEP), with 9-km grid spacing (Shao et al., 2016, and references therein). The GSI analysis is used to initialize the Hurricane Weather Research and Forecasting (HWRF) regional forecast model (v3.5) (Bernardet et al., 2015; Tallapragada et al., 2014; Atlas et al., 2015c), which is configured in this study with a fixed 9-km parent domain and a 3-km nested storm-following domain. The HWRF model parameterizations include the Global Forecast System (GFS) planetary boundary layer scheme, the new Simplified Arakawa-Schubert cumulus scheme (only for the parent domain since convection is explicit in the nested domain), the Ferrier microphysics scheme, and the Geophysical Fluid Dynamics Laboratory (GFDL) scheme for shortwave and longwave radiation. The WRF nature run domain as well as the embedded parent and nested HWRF domains are illustrated in Figure 2.

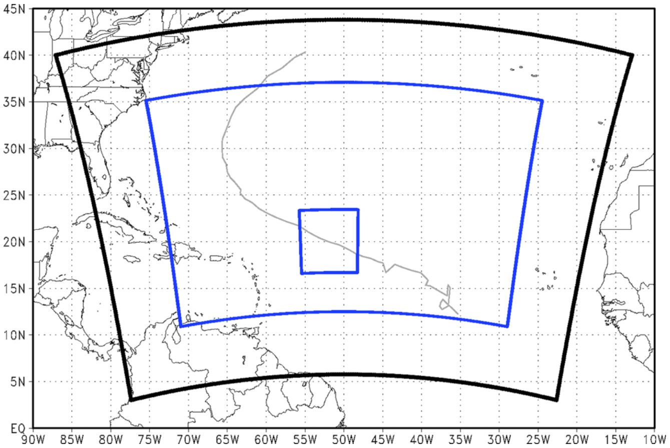
In this study, the GSI analyses and HWRF forecasts are both verified against the regional hurricane nature run. A similar framework was used by Atlas et al. (2015b) to investigate the potential impact of an Optical Autocovariance Wind Lidar (OAWL) on TC prediction.

Synthetic Observational Data

In addition to the conventional data described in the previous section, CYGNSS data are simulated and utilized in the form of retrieved values of ocean surface wind speed (Ruf et al., 2016, and references therein). Each

FIGURE 2

The WRF nature run outer domain is outlined by the thick black line, and the HWRF forecast model's parent and nested domains are outlined by the blue lines (the nested domain moves with the TC). The thin gray line traces the TC center through its evolution in the nature run. (Color version of figures are available online at: http://www.ingentaconnect.com/content/mts/mtsj/2017/00000051/00000001.)

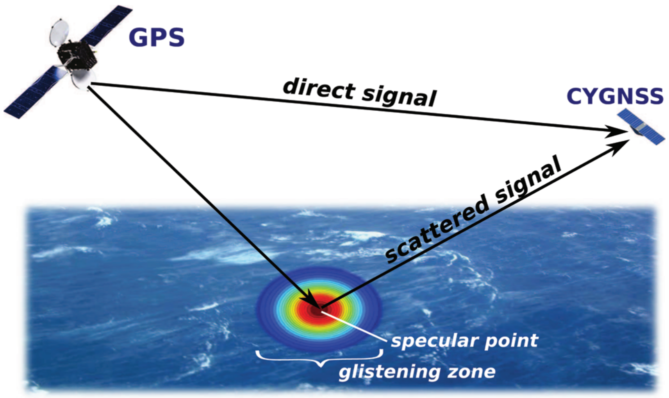


microsatellite receives useful signals reflected off the ocean from the larger, higher-orbiting, and more expensive GPS satellites whenever a "specular point" exists on the ocean and a direct line-of-sight is achieved (Figure 3). Since the roughness of water has a physical relationship to the strength of the wind blowing across it (Atlas et al., 1996) and the reflected/scattered signal contains information on ocean surface roughness, a surface wind speed can be derived (Garrison & Katzberg, 1998). The direct line-of-sight signal contains timing, location, and frequency information.

For this work, the CYGNSS Science Team created two distinct datasets based on the same orbital data of the eight CYGNSS satellites: a nominal resolution product and an enhanced high-resolution product. In the nominal resolution product, the effective averaging area (footprint) is 25 km across, whereas in the high-resolution product, the effective footprint is roughly 12.5 km across. Each data point has a quality flag and an assigned error estimate that scales inversely with the antenna gain on the CYGNSS satellite. Hence, retrievals derived from a weak signal will have higher errors. Retrievals with an antenna gain below a certain threshold are flagged and are not assimilated. Although the high-resolution dataset contains roughly twice the number of observations as compared to the nominal dataset, the observations are noisier and, after removing the observations flagged as bad, actually contain fewer usable data points.

FIGURE 3

Geometry of GPS-based, quasispecular surface scattering. The GPS direct signal provides the location, timing, and frequency references, whereas the forward scattered signal contains information on ocean surface properties. Components and distances in the schematic drawing are not to scale. Background photograph of the ocean surface in Hurricane Isabel (2003) is courtesy of Will Drennan.



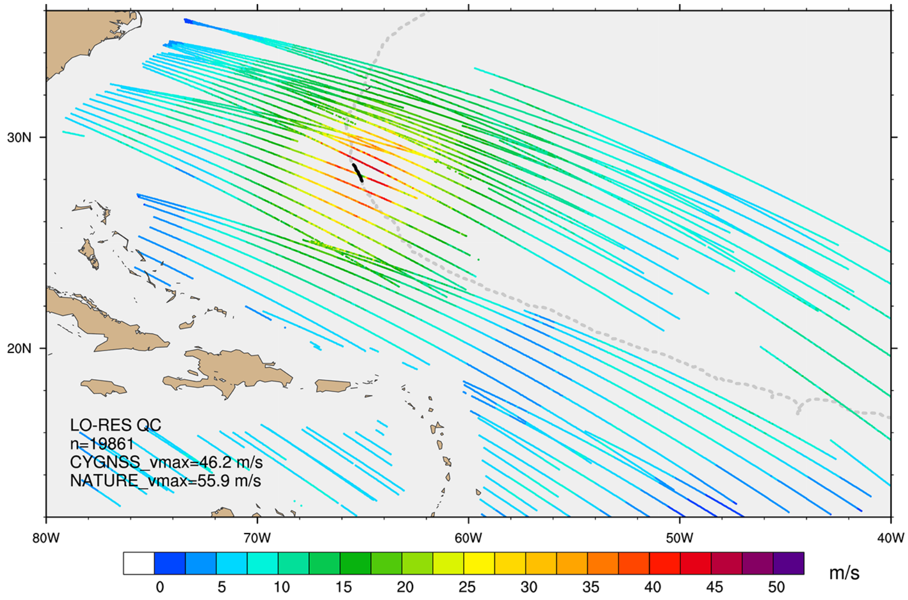
Over the subtropical and tropical latitudes, the temporal coverage from CYGNSS will generally be superior to that from existing platforms that sample ocean surface winds, with a higher frequency of revisits at any given point in the CYGNSS latitude band. An example of excellent spatial coverage over the western North Atlantic Ocean during a 6-h window is shown in Figure 4, with nearly 20,000 data points within the plotted domain (at the nominal resolution) and with complete coverage of the TC during this period.

Assimilation-Forecast Experiments

To evaluate the potential impact of assimilating different configurations of CYGNSS data, several HWRF analysis-forecast cycles are run within the OSSE system. First, as a benchmark, a "control run" is prepared using many of the conventional data that are routinely assimilated now, including radiosondes, atmospheric motion

FIGURE 4

An example of excellent TC coverage by CYGNSS wind speed retrievals over a 6-h window centered on the 0000 UTC 8 August synoptic time in the nature run. These wind speed data are selected from the nominal resolution data product with flagged observations removed. The dashed gray line traces the center of the TC throughout the duration of the nature run, whereas the solid black segment highlights the TC's position during this 6-h period.



vectors, infrared and microwave radiances, but not scatterometers. Next, the question of the impact of assimilating CYGNSS data in the nominal resolution and high-resolution datasets, in which observations are discarded if the antenna gain is too low and realistic errors are assigned to the remaining data points, is addressed. Finally, the question of the maximum potential benefit that could be derived from CYGNSS data is addressed by assimilating "perfect" CYGNSS observations of wind speed or of wind speed and direction, this latter case to assess the added benefit of directional information. This dataset is generated by simply interpolating the nature run to each latitude-longitude location in the high-resolution CYGNSS dataset and assigning zero error. Although the planned CYGNSS data product will not include wind direction, there are two reasons to study this configuration: (1) there is some directional information in the reflected signal, which might be extracted with more capable hardware or software (e.g., Komjathy et al., 2004), and (2) a variational analysis method discussed in Concluding Remarks could be applied to the wind speed retrievals to create dynamically realistic wind vectors.

Thus, the following experiments were conducted:

1. *CONTROL*: Conventional data only, listed in OSSE Framework No CYGNSS data.
2. *REAL_SPD*: CONTROL plus quality-controlled nominal resolution CYGNSS data, with realistic error assignments.
3. *REAL_SPD_HI*: Similar to REAL_SPD, but using the quality-controlled high-resolution CYGNSS dataset.
4. *PERFECT_SPD*: CONTROL plus all available high-resolution CYGNSS data points, where the wind speed is interpolated from the nature run and assumed to have zero observational error.
5. *PERFECT_VEC*: Similar to PERFECT_SPD, but wind speed and direction are interpolated.

Each of these five listed experiments is initiated with a "cold start" at 0000 UTC on 1 August in which global analyses are used as initial and boundary conditions, and then cycling is performed every 6 h through to 0000 UTC on 5 August, for a total of 16 analyses. Note that the dates and times in this study only correspond to a TC in the nature run and not an actual TC. A 5-day HWRF forecast is integrated from each analysis. Each experiment is then verified against the nature run. The cold start and the first four cycles are discarded to avoid the artificial effects of vortex spin-up and model adjustment (as described by Atlas et al., 2015a), which leaves 12 reliable cycles for calculating the error statistics.

Results

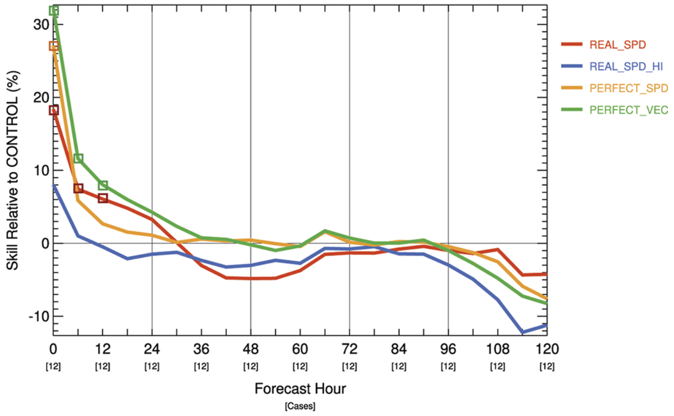
The impact of assimilating the different configurations of CYGNSS data listed in the previous section is evaluated on both the basin scale and vortex scale. Overall, the addition of CYGNSS observations improves upon CONTROL, bringing the analyses closer to the nature run on average.

For the basin scale verification, values are averaged over the HWRF parent domain and the identical area in the nature run. Although CYGNSS only introduces surface wind data over water, the improvements to CONTROL appear to extend beyond the surface wind field. Smaller, short-term improvements are also found in

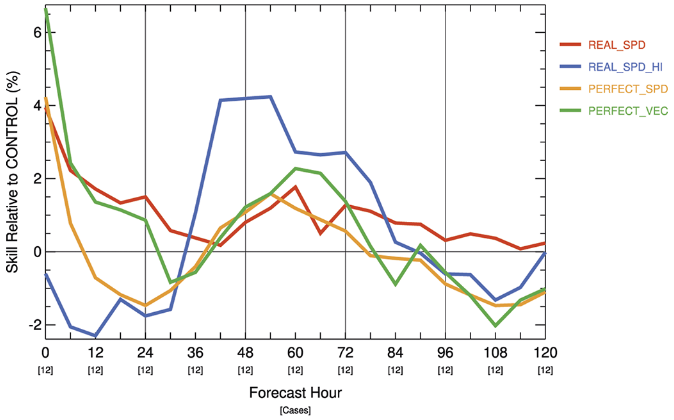
FIGURE 5

Average skill score of 5-day HWRF forecasts of (a) 10 m wind speed and (b) 200 hPa wind speed over the HWRF parent domain, averaged over the 12 forecast cases. Skill is calculated relative to CONTROL, and squares mark where the values are statistically significant at the 80% level.

(a) 10 m WIND SPEED



(b) 200 hPa WIND SPEED



the domain-averaged winds up to 200 hPa as well as the corresponding geopotential height, pressure, and temperature (not shown).

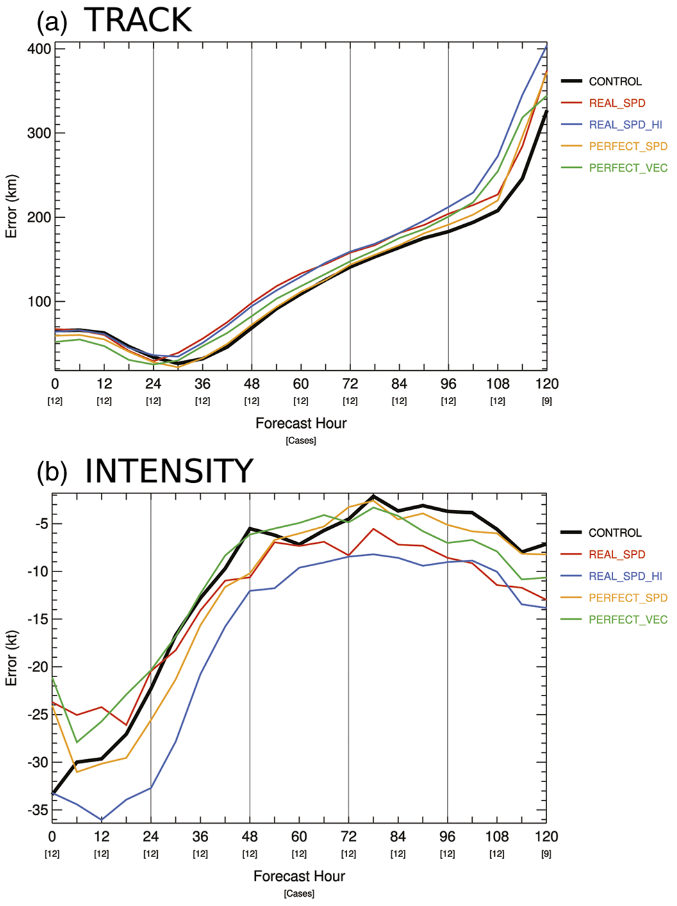
Figure 5 shows an example of the improvements in the basin scale 10 m wind field (top) and 200 hPa wind field (bottom). The errors are presented as skill scores relative to the CONTROL run. The noisy high-resolution CYGNSS wind experiment (REAL_SPD_HI) had the least skill of the experiments, and as expected, the lowest errors were found for the wind vectors interpolated directly from the nature run at the CYGNSS coordinates (PERFECT_VEC), with an improvement of approximately 32% (5%) over CONTROL at 0 h (24 h) at 10 m, and then at 200 hPa, the improvement was approximately 7% (1%) at 0 h (24 h). In general, little impact is seen in the forecasts beyond 24 h, and statistically significant differences do not extend beyond 12 h.

For the verification of TC track and intensity, the impact of assimilating CYGNSS data is generally positive though small. Slight improvements to the track are found in the two experiments using "perfect" wind vectors and speeds at the analysis time and in forecasts out to approximately 18 h (Figure 6a). It should be noted that vortex relocation is not used in this study. It is also important to note that the average 12- to 48-h track forecast errors in CONTROL are considerably smaller than the corresponding average track forecast errors of the 2014 version of the operational HWRF for real TCs, leaving little room for improvement from the assimilation of extra data. The intensity errors, as represented by the error of the maximum 10-m wind speed, are improved at the analysis time for all datasets except for the high-resolution dataset. For PERFECT_VEC (REAL_SPD), the average improvement is around 35% (25%) (Figure 6b). The corresponding intensity forecasts out to 24 h are slightly improved in PERFECT_VEC and REAL_SPD by the addition of CYGNSS data by around 15% at 12 h and decreasing to 10% at 24 h. In general, the improvements in intensity and track errors are not significant at the 80% level, with the exception of the PERFECT_VEC intensity analysis. However, many of the increased errors in intensity and track from the REAL_SPD_HI experiment are statistically significant. It should be noted that there is more room for improvement in the intensity analyses and very short range forecasts than for forecasts beyond 1 day. The corresponding results for minimum central pressure are similar to those of Figure 6b (not shown). Due to the small sample size common in OSSE studies of TCs and to the relatively small contribution that CYGNSS data make to the overall data volume, we would not expect to find statistically significant differences among all of the experiments and across all forecast lead times. It is likely for these reasons that the "perfect" experiments do not always show lower errors than the "real" experiments.

An examination of maps of the surface wind analyses provides additional

FIGURE 6

Errors of TC (a) track and (b) maximum 10 m wind speed averaged over the twelve 5-day HWRF forecasts. Note that negative wind speed errors imply that the TC is stronger in the nature run.



insights and reveals the inherent strengths and limitations of the data assimilation system. In a typical example shown in Figure 7, at 1200 UTC 3 August 2005, the nature run features a symmetric hurricane with a peak wind of 89 knots (Figure 7a), whereas the CONTROL analysis, at the 10th data assimilation cycle at this time, shows a much weaker and more asymmetric vortex (Figure 7b). A comparison of the quality-controlled data reveals the locations of the data that are flagged as bad in the realistic configuration and renders the distribution of assimilated data more asymmetric over the TC in REAL_SPD compared to PERFECT_VEC (Figures 7c and 7d). In contrast, after assimilation of the perfect wind speed and directional data, the vortex in the PERFECT_VEC analysis has a lower central pressure and is more symmetric than in CONTROL and overall closer to the nature run (Figure 7e). Finally, poorer CYGNSS data coverage in the REAL_SPD assimilation results in a lopsided vortex, although it is still an improvement upon CONTROL (Figure 7f). Since the covariance structure in the 3-D Variational GSI is quasi-isotropic and not flow-dependent, the corrections to the surface wind analysis are strongest locally where the CYGNSS data exist, to the north of the TC, with no equivalent correction on the southern flank, which is devoid of data; this is general characteristic of 3D-VAR and is not specific to this study, surface wind speed observations, or CYGNSS.

Concluding Remarks

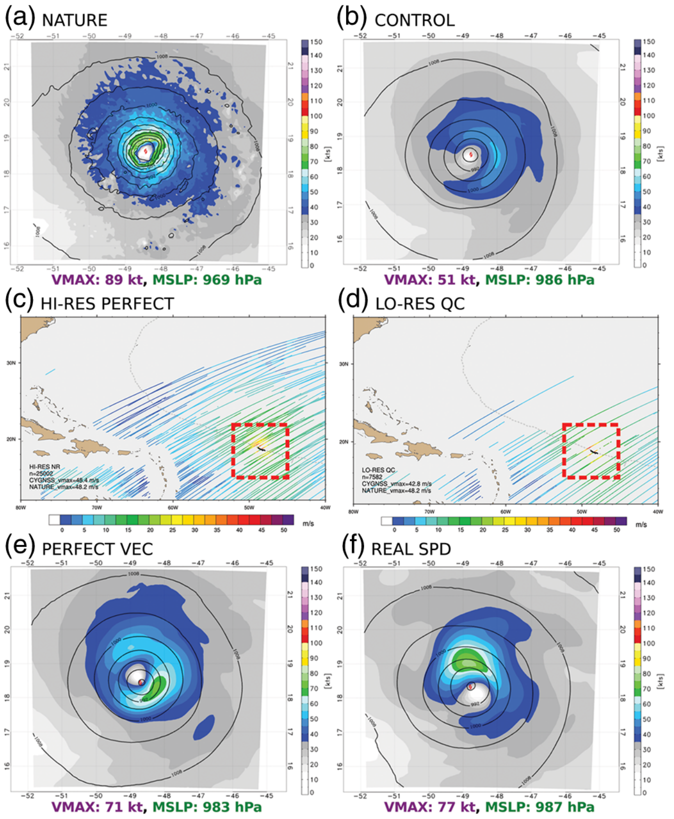
The potential for surface wind data sampled from the constellation of CYGNSS satellites to improve numerical analyses and forecasts of TCs has been examined using a novel, high-resolution regional OSSE framework. Both "perfect" and realistic configurations of wind data at CYGNSS locations over the ocean surface were examined, at nominal and high resolution.

Most promisingly, the assimilation of CYGNSS data almost always improved the HWRF/GSI analyses of TC track, intensity, and structure. The corresponding forecasts were improved out to 1 day on average, when wind speed and direction sampled at CYGNSS locations were assumed to be perfect. In reality, the observations will of course be imperfect, and wind direction data are unlikely to be available initially. However, the REAL_SPD experiments suggested that the assimilation of realistic wind speed data do have the potential to improve the vortex scale analyses and short-range forecasts. Additionally, the basin scale analyses and short-term forecasts of wind speed through the troposphere were improved, with the largest improvements in the surface wind field analysis. Impacts become smaller and less statistically significant at levels higher in the atmosphere and at longer forecast lead times.

The added directional information was found to produce better analyses and forecasts than if wind speed only were assimilated. This suggests that additional efforts to incorporate wind

FIGURE 7

Top row: 10 m wind speed and surface pressure analyses from (a) NATURE and (b) CONTROL. Middle row: CYGNSS data coverage maps spanning the 6-h period centered on 3 August 2005 1200 UTC for the (c) PERFECT_VEC and (d) REAL_SPD experiments. The red dashed boxes highlight the area shown in the panels on the top and bottom rows. Bottom row: 10 m wind speed and surface pressure analyses from (e) PERFECT_VEC and (f) REAL_SPD.



direction would be important, via exploiting the oversampling of the ocean surface and/or using a method such as the Variational Analysis Method (Atlas et al., 2011, and references therein) as a preprocessing step to the assimilation. Finally, although the enhanced high-resolution CYGNSS dataset contained more data points than the nominal product, the retrievals were very noisy, and many of them had to be discarded, resulting in degraded analyses and forecasts.

In summarizing these results, it is important to recognize that the sample size from a single TC is small, so the error statistics are not always robust. A significantly larger number and variety of cases is required to draw statistically significant conclusions, and the findings in this paper are presented primarily to suggest that CYGNSS should be a beneficial addition to the suite of TC monitoring platforms already in existence. Even if a few additional nature runs with TCs in them were available, the verification sample size would still be relatively small, a common limitation of TC OSSE studies.

Although the regional OSSE configuration used here is novel for TCs and closely mimics NOAA's operational system, it possesses limitations. One well-known problem in all models of TCs is that intense vortices in the analysis suffer from an unrealistic spin-down as the model attempts to adjust and balance the wind and mass fields (Hendricks et al., 2013; Gopalakrishnan et al., 2012). Typically, the stronger a vortex is in the analysis, the worse the spin-down problem is at the beginning of the model forecast. Additionally, a significant shortcoming of the GSI 3-D variational assimilation scheme is that it is extremely sensitive to the locations of available observations. Even for a symmetric hurricane, observations only on one side of the vortex will degrade the analysis and cause the analyzed vortex to be asymmetric. The influence from the surface wind observations may not translate through the depth of the troposphere in the subsequent analysis. To remedy these issues, a Hybrid 3D-Variational/Ensemble Kalman Filter assimilation scheme (Wang et al., 2013) is being implemented in the OSSE system. In parallel, a study underway seeks to determine the optimal assimilation frequency, which for rapidly changing weather systems such as TCs and for data available at continuous times such as CYGNSS may be shorter than the 6 h used in this study and in NOAA's operational system. Another OSSE challenge is to provide control simulations whose errors as evaluated against the nature run are comparable in magnitude and structure to errors in operational forecasts. Motivated by the REAL_SPD_HI and PERFECT_VEC results, the OSSE framework presented here could also be used to evaluate future CYGNSS-like platforms with more sensitive receivers capable of producing reliable higher-resolution retrievals or of providing wind direction information. Ongoing efforts in these areas will be reported in the near future.

The OSSE framework offers the flexibility to examine the impact of assimilating different configurations of existing and future datasets. For example, it is straightforward to build on this study and examine the impact of launching another eight CYGNSS satellites, to place the satellites in different orbital configurations, or other trade-offs. The benefits of activating a high-resolution sampling mode on CYGNSS, localized over TCs, can also be examined. Furthermore, the synergies between CYGNSS, special high temporal resolution atmospheric motion vectors, and wind data from future spaceborne Lidars (Baker et al., 2014) can be examined. Thus, realistic and validated OSSE systems offer a promising pathway forward in optimizing the use of new and future instruments to improve forecasts of high-impact weather events.

Acknowledgments

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