STORM SURGE PREDICTION WITH CYGNSS WINDS

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ABSTRACT

The NASA Earth Venture Cyclone Global Navigation Satellite System (CYGNSS) is a constellation of eight observatories in a 35° inclination, ~530 km altitude Earth orbit. Each observatory carries a 4-channel bistatic wind scatterometer receiver. Measurements of the ocean surface scattering cross section are converted to 10 meter-referenced wind speed. The mission improves the temporal sampling of winds in tropical cyclones (TCs) with a revisit time of 2.8 hours (median) and 7.2 hours (mean) at all locations between 38 deg North and 38 deg South latitude. Operation at the 1575 MHz GPS L1 frequency permits wind measurements in the TC inner core that are often obscured from other spaceborne remote sensing instruments by intense precipitation in the eye wall and inner rain bands. The potential for improved storm surge forecast skill is examined using simulated CYGNSS science data products for Hurricane Irene. We present and compare ADCIRC 2DDI storm surge hindcasting results of Hurricane Irene using four meteorological forcing scenarios: 1) "True" meteorological data obtained from HWRF reanalysis runs; 2) "Worst-case forecast" using low-resolution NOGAPS forecast wind and pressures; 3) "Best-case forecast" using high-resolution HWRF forecast winds and pressures; and 4) a simulated "CYGNSS forecast" with wind field given by a parameterized model trained using CYGNSS-derived values for the maximum wind speed and radius of maximum winds. The results suggest that the improved temporal resolution of the CYGNSS-derived winds has a positive impact on storm surge modeling predictions.

***Index Terms*—**Storm Surge, Ocean winds, satellites

1. INTRODUCTION

Hurricane storm surge is a problem of growing importance due to increasing population density along the coasts, rising sea levels, and the possibility of greater frequency and severity of storm occurrence [1-3]. Storm surge modeling can provide guidance for warning and evacuation systems. However, modeling accuracy, particularly with respect to the intensity forecast (as opposed to storm track) is limited by a lack of high resolution meteorological data. Currently, methods of data collection within a tropical cyclone's eyewall are limited to 'hurricane hunter' type aircraft and dropsondes. Neither of these methods can provide the needed temporal and spatial data sampling necessary for accurate storm surge forecasting. The objective of this work is to examine and assess the potential for CYGNSS data products to assist with storm surge forecasts. To this end, we utilize simulated CYGNSS data for Hurricane Irene to hindcast storm surge and compare the results to alternate cases that use currently available meteorological data products; specifically, HWRF forecast winds, with imposed forecast errors.

2. CYGNSS MISSION OVERVIEW

CYGNSS employs a constellation of eight microsatellite observatories in LEO. Each observatory consists of a microsatellite platform hosting a GPS receiver modified to measure surface reflected signals. Similar GPS-based instruments have been demonstrated on both airborne and spaceborne platforms to retrieve wind speeds as high as 60 meters per second (a Category 4 hurricane) through all levels of precipitation, including the intense levels experienced in a TC eyewall [4]. Each observatory simultaneously tracks scattered signals from up to four independent transmitters in the operational GPS network. The number of observatories and orbit inclination are chosen to optimize the TC sampling properties [5].

3. CYGNSS WIND SPEED DATA PRODUCTS

CYGNSS wind speed data products are provided to the NASA PO.DAAC for public distribution and are generated as follows. L1A processing decompresses the DDMs and converts DDM pixel values from instrument counts to received power in Watts. L1B processing converts DDM pixel values in Watts to Bistatic Radar Cross Section (BRCS), in meters2. The L1B processing algorithm is described in [6]. Level 2A processing converts each DDM to a single specular point wind speed value. The L2A processing algorithm is described in [7]. Level 2B processing converts each DDM to a single specular point mean square slope value. The mean square slope is a measure of ocean surface roughness. The L2B processing algorithm is described in [8]. L3A processing uses the geolocated winds speeds in the L2A product to produce wind speeds gridded in space and time (0.2° latitude and longitude, one hour). The L3A processing algorithm is specified in the CYGNSS Level 3A Algorithm Theoretical Basis Document.

4. HURRICANE IRENE CASE STUDY

Hurricane Irene (lifecycle 21-30 Aug 2011) is used for this case study. Irene developed from a tropical wave off the coast of western Africa in mid-August, 2011. By 21 Aug, the wave had organized into a tropical storm traveling northeast from the Lesser Antilles. Over the next several days the storm strengthened, reaching category 3 windspeeds on the Saffir-Simpson Hurricane Wind Scale by the time it reached the Bahamas on 24 Aug. The cyclone then weakened to category 1 hurricane status prior to making landfall on the eastern U.S. coast during 27-29 Aug, affecting North Carolina, New Jersey and New York. Storm surge measured up to 2.2m in North Carolina, with typical values of 1.2-1.8m throughout the affected regions of the eastern coast, causing significant flooding and damage before being absorbed by a Canadian weather system on 30 Aug. The official storm track released by the National Hurricane Center is shown in Fig. 1.

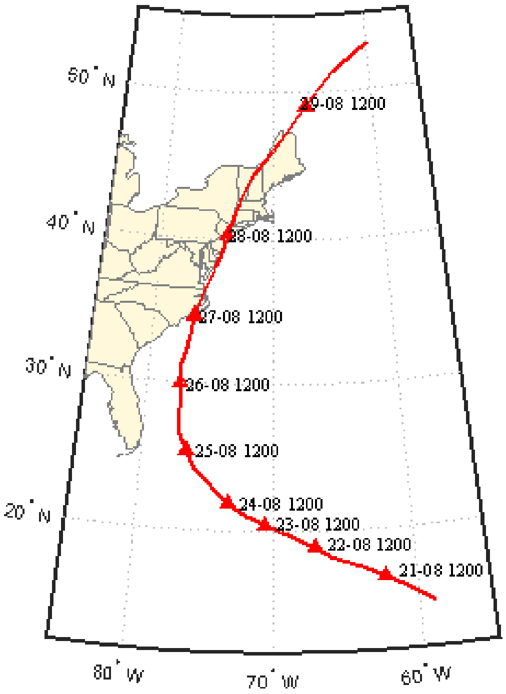

Figure 1. Official storm track for Hurricane Irene from the National Hurricane Center.

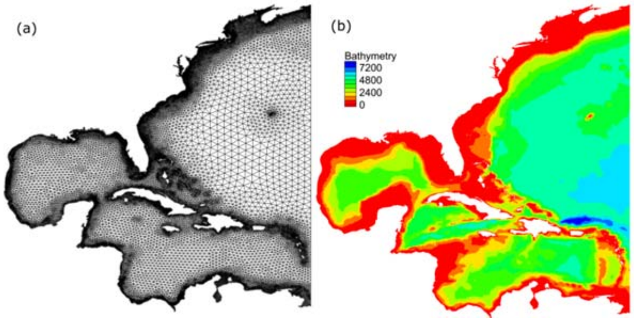

Figure 2. ADCIRC finite element mesh (a) and bathymetry (b)

5. STORM SURGE HINDCASTING MODEL

ADCIRC model description and setting

The ADvanced CIRCulation 2-Dimensional Depth Integrated (ADCIRC-2DDI) model was chosen for the storm surge modeling in this work due to its flexibility and efficient handling of meteorological input data, grid specification, wetting and drying, and tide representation, in addition to its extensive record of storm surge modeling validation [9-10]. The ADCIRC model operates on an unstructured, finite element mesh, allowing for highly detailed coastal resolution. The finite element mesh used for the present investigation encompasses the Western North Atlantic Ocean, the Gulf of Mexico, and the Caribbean Sea and contains 58,369 triangular elements on the order of up to 100 km in the open ocean portion of the domain (Fig.2). Resolution is significantly finer along the coasts, but the mesh does not contain enough detail to capture coastal floodplains.

The hydrodynamic solver in ADCIRC is based on a combined form of the depth-averaged momentum and continuity equations, the generalized wave-continuity equation (GWCE). “Primitive weighting” is applied to control the degree to which the GWCE is dominated by the wave equation or the primitive continuity equation. For the results herein, the primitive weighting used is a function of the bathymetry: in deep water, $\tau 0=0.005$, in shallow water, $\tau 0=0.02$, and in portions of the shallow southern Louisiana bays, $\tau 0=0.03$. A ramp function was implemented over the first two days of the simulation in all cases in order to transition from the zero circulation initial conditions to using the full tidal amplitude values. A spin-up time of 4 days is used in the ADCIRC simulations, giving a start time of 17 Aug 2011 00:00:00. The simulation is run for a total of 12 days; until 29 Aug 2011 00:00:00 (all times are UTC).

Meteorological forcing

Four sources of meteorological forecast data are used: Hurricane Weather Research and Forecast (HWRF) reanalysis winds, Navy Operational Global Atmospheric Prediction System (NOGAPS) forecast winds and pressures, HWRF forecast winds, and parameterized storm winds utilizing CYGNSS simulated data. For all scenarios, the

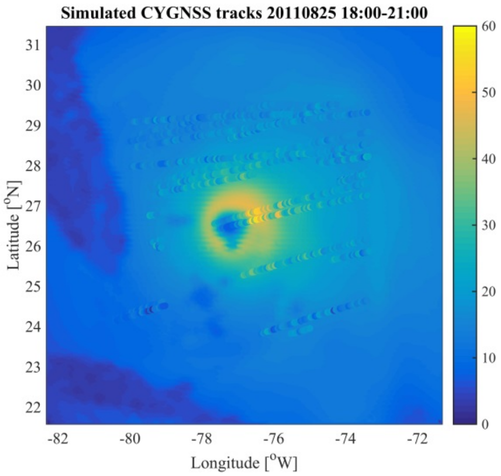

Figure 3. Three hours of CYGNSS simulated wind magnitude data passing through Hurricane Irene between 18:00-21:00 UTC on 25 Aug 2011, overlaid on the reanalysis HWRF wind field from which they are derived..

meteorological forcing in ADCIRC is implemented as full-field values of the two horizontal wind velocity components and pressure over a regularly spaced rectangular grid that spans the ADCIRC computational mesh. The wind velocities are referenced to a height of 10 m, and the pressures are referenced to the surface. For consistency, values for the NOGAPS, HWRF forecast and HWRF reanalysis fields are gridded to a 0.2 degree grid before merging into a single meteorological input file for ADCIRC.

For the reference "reanalysis" case, the background NOGAPS wind values are replaced with the higher-resolution HWRF reanalysis winds where available. HWRF uses dynamic grids to follow the trajectory of the hurricane, and thus the region of the meteorological grid that is replaced with the HWRF data varies throughout the simulation. The HWRF forecast winds are available every 3 hours and initialized every 6 hours. The forecast times are chosen to match the availability of the reanalysis winds. The HWRF winds are given on a moving 0.02 degree grid, and are first interpolated to the reanalysis wind grid for consistency.

The simulated CYGNSS data are estimated using an end-to-end simulator (E2ES) in which the HWRF reanalysis winds are sampled at simulated CYGNSS track locations and times and with a realistic representation of the expected measurement uncertainty. The results of this pre-processing give estimates of 10-m velocity magnitudes along the CYGNSS tracks. An example of the simulated CYGNSS wind sample tracks is shown in Fig. 3. Since ADCIRC requires full-field U and V components of the wind field, further pre-processing is necessary. First, in order to construct a realistic representation of the entire storm, a parameterized model is used to calculate the velocity magnitude as a function of radial distance from the center of the storm. The parameterized model used is [11]

$$\boldsymbol{V}(r) = \frac{2r\left(R_{max}V_{max}+\frac{1}{2}fR_{max}{}^{2}\right)}{R_{max}{}^{2}+r^{2}} - \frac{fr}{2} \qquad (1)$$

where r is the distance in meters from the storm center, R_{max} and V_{max} are the estimated radius of maximum winds and maximum velocity calculated by fitting a curve to the CYGNSS data, and f is the latitude-dependent Coriolis parameter [12]. To transform the wind magnitude to U and V velocity components, the direction of the CYGNSS winds are estimated from the NOGAPS wind data, and used along with $V(r)$ to recover the separate velocity components.

6. STORM SURGE FORECASTING SIMULATION

Experiment Description

In order to demonstrate the potential impact of the CYGNSS data on the forecast storm surge skill when the forecast data are less reliable, three experiments were conducted using hypothetical scenarios.

Experiment 1: The HWRF forecast data are replaced within a distance of 3 times the radius of maximum winds by wind magnitudes that are reduced by 20%.

Experiment 2: Similar to experiment 1 but HWRF forecast data are increased by 20%.

Experiment 3: Use simulated CYGNSS data in place of HWRF for the entire 8-day simulation.

Experiment Results

Storm surge predictions and coincident tide gauge measurements are examined during 26 Aug 18:00 to 28 Aug 18:00, the period of maximum storm surge, using available NOAA CO-OPS tide gauge stations. The locations of fifteen stations along the eastern seaboard are shown in Fig. 4.

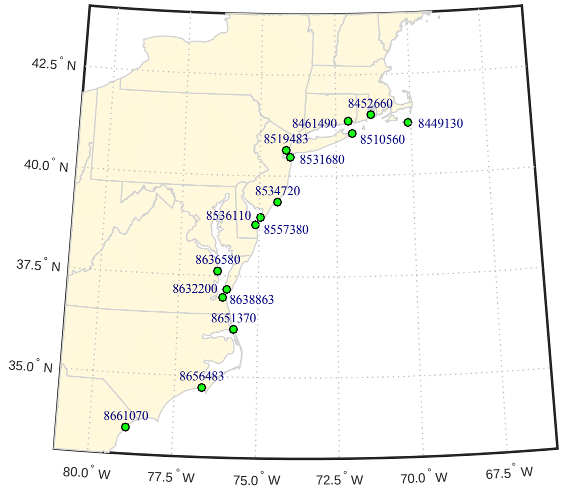

Figure 4. NOAA CO-OPS tide gauge stations affected by Hurricane Irene.

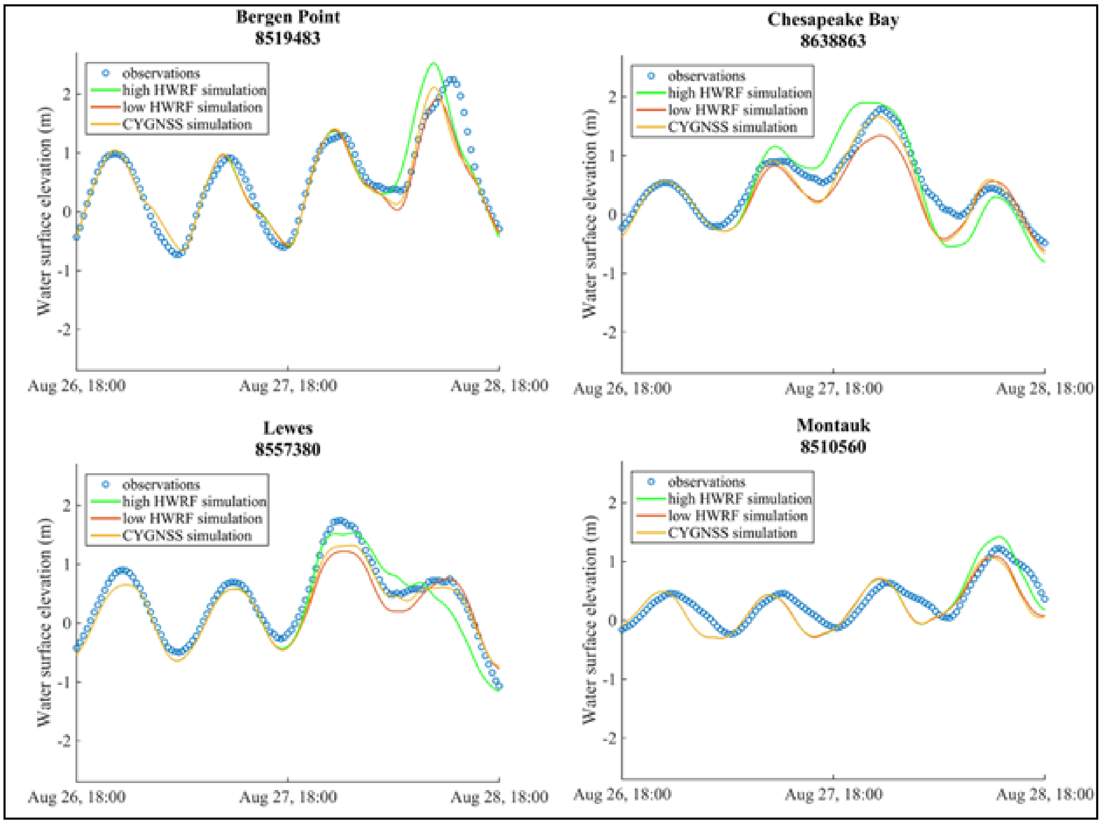

Figure 5. Observed and predicted storm surge levels during 26-28 Aug 2011 for three prediction experiments using ADCIRC with: 1) 20% low forecast winds; 2) 20% high forecast winds; and 3) CYGNSS observed winds.

Time series plots of observed storm surge, together with the values predicted by ADCIRC for each of the three experiments, are shown in Fig. 5. The RMS difference between observed and predicted peak values of storm surge during the 2 day period, averaging over all fifteen locations, is 17.7 cm, 19.3 cm and 14.4 cm for experiment 1, 2 and 3, respectively. These results suggest that CYGNSS observations, with the lowest (14.4 cm) RMS error, have a positive impact on storm surge forecast, relative to using forecast wind speed that are in error by 20%.

7. REFERENCES

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