Assessment of global wave models on unstructured domains

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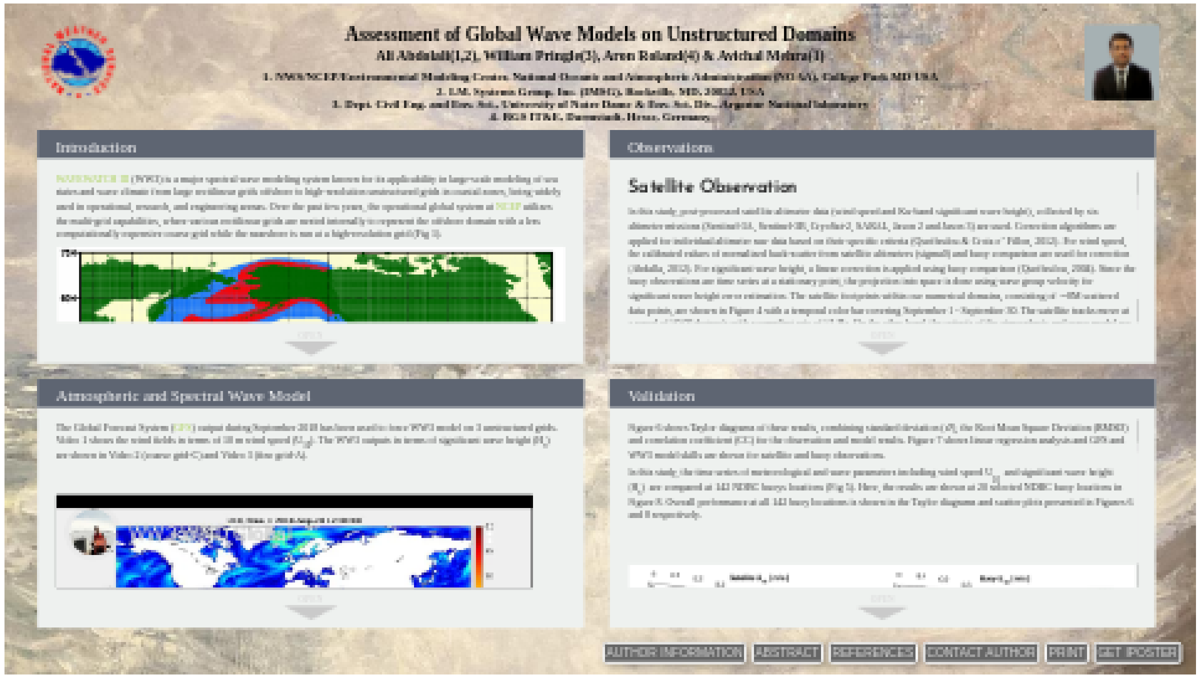
Abstract

WW3 is a major spectral wave modeling system known for its applicability in large-scale modeling of sea states and wave climate from large rectilinear grids offshore to high-resolution unstructured grids in coastal zones, being widely used in operational, research and engineering arenas. Over the past few years, the operational global system at NCEP utilizes the multi-grid capabilities, where various rectilinear grids are nested internally to represent the offshore domain with a less computationally expensive coarse grid while the nearshore is run at a high-resolution grids. Alternatively, a single unstructured grid can be used for such applications. Recent advances in the performance of the model on unstructured grids provide the opportunity to run the model on large unstructured grids efficnetly. Here, an assessment of the operational global setup and unstructured wave models on various resolutions are given. The sensitivity to global unstructured mesh design was investigated using triangular meshes with a global minimum element size that ranged from 1.5 km to 6 km with local mesh refinement in storm landfall location. The validation is performed against satellite altimeter data and offshore NDBC network during normal and stormy conditions. We demonstrate that an optimized unstructured WW3 can be used for global applications, with superior performance relative to the complicated multi-grid system.

Assessment of Global Wave Models on Unstructured Domains



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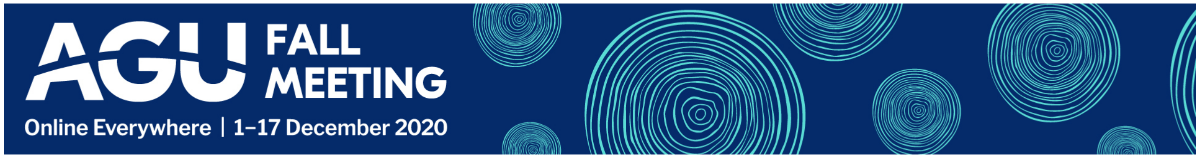

INTRODUCTION

WAVEWATCH III (https://github.com/NOAA-emc/ww3) (WW3) is a major spectral wave modeling system known for its applicability in large-scale modeling of sea states and wave climate from large rectilinear grids offshore to high-resolution unstructured grids in coastal zones, being widely used in operational, research, and engineering arenas. Over the past few years, the operational global system at NCEP (https://www.ncep.noaa.gov/) utilizes the multi-grid capabilities, where various rectilinear grids are nested internally to represent the offshore domain with a less computationally expensive coarse grid while the nearshore is run at a high-resolution grid (Fig 1).

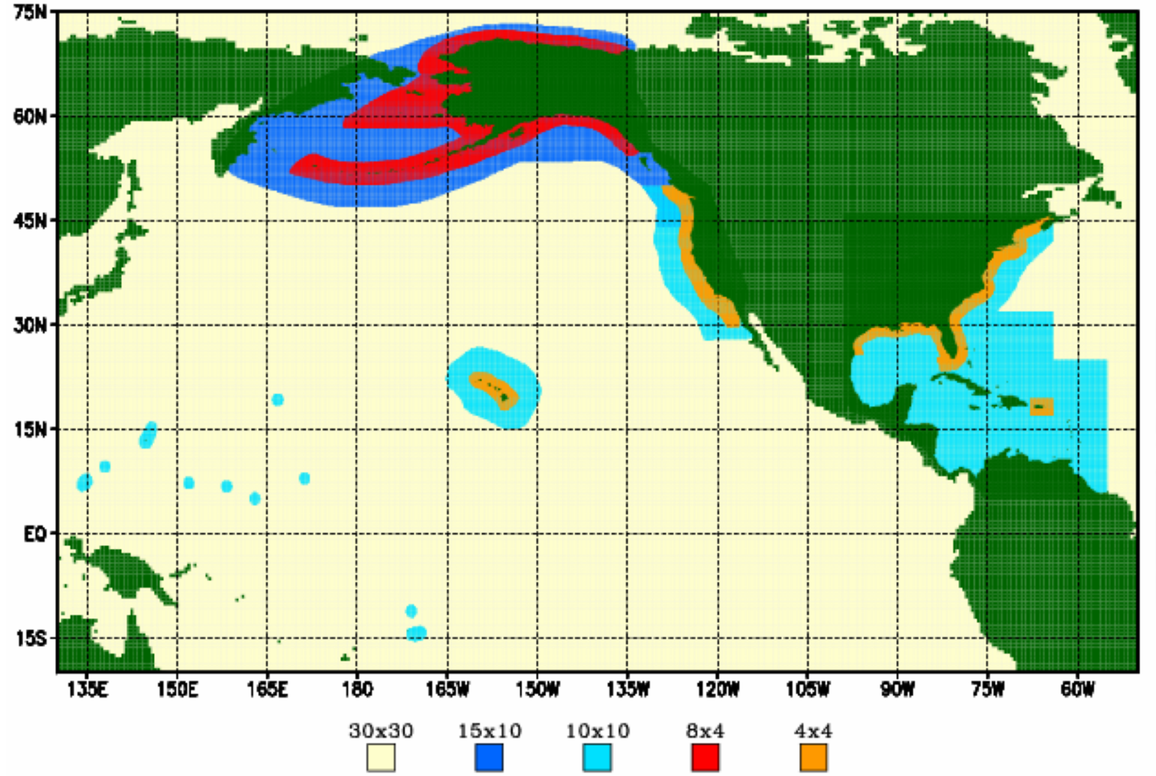

Figure 1) Operational Multi-grid setup with 5 resolutions.

Alternatively, a single unstructured grid can be used for such applications. It is known that spectral wave models (i.e. WAVEWATCH III) are relatively expensive especially on large unstructured grids with very high-resolution grid cells, in which the smallest cell size governs the model time step (due to CFL constraints in the explicit solver). In these regards, substantial improvements in the WW3 model are required. Recent developments in WAVEWATCH III on unstructured grids have pushed the limits of the model in terms of minimum grid size and computational efficiency. These developments include a new parallelization based on a domain decomposition algorithm and a robust implicit solver.

Here, an assessment of the operational global setup and unstructured wave models on various resolutions is given. In this study, the WW3 model (V6.07 (https://github.com/NOAA-EMC/WW3/wiki/files/manual.pdf)) with the implicit scheme and domain decomposition parallelization is utilized (Abdolali et al., 2020a (https://www.sciencedirect.com/science/article/pii/S0378383919305757)) where a unified time step for global, spatial propagation, intra-spectral propagation, and source term is used.

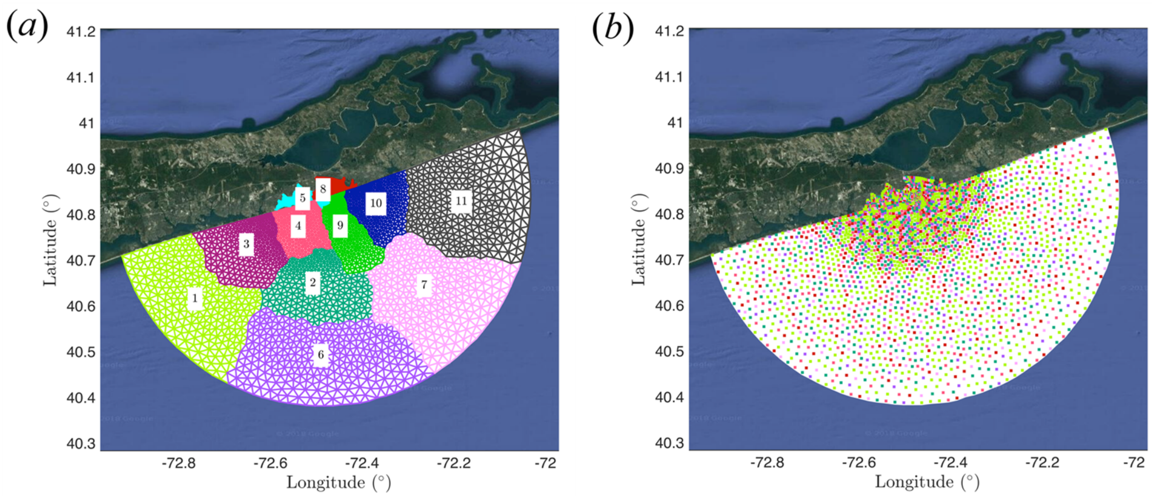

Figure 2) The schematic difference between Domain Decomposition (a) and Card Deck approach (b) on 11 computational cores represented by colors. The grid has ~3k nodes and is build for Shinnecock Inlet, NY taken from an ADCIRC example problem.

In all simulations, the model resolves the source spectrum with frequencies between 0.05 and 0.9597 Hz, divided into 32 spectral bands and 36 directions with 10˚ increments. In addition, Ardhuin et al. (2010) source term parameterizations (ST4), nonlinear wave-wave interaction using the discrete interaction approximation, DIA (Hasselmann et al.,1985), moving bottom friction (SHOWEX-BT4) (Ardhuin et al., 2003), depth-limited breaking based on Battjes-Janssen formulation (DB1) (Battjes & Janssen, 1978) have been used for the computations.

We test the sensitivity of WW3 to the spatial distribution of resolution on unstructured triangular meshes that were originally developed for testing hydrodynamic storm tide models (Pringle et al., 2020 (https://doi.org/10.5194/gmd-2020-123)). We use three grids that each have a maximum element size of 25 km but different minimum element sizes: 1.5 km (Grid A - fine), 3 km (Grid B - medium), and 6 km (Grid C - coarse) as shown in Figure 3. The validation is performed against satellite altimeter data and offshore NDBC network during normal and stormy conditions during August 2018. We demonstrate that an optimized unstructured WW3 can be used for global applications, with superior performance relative to the complicated multi-grid system.

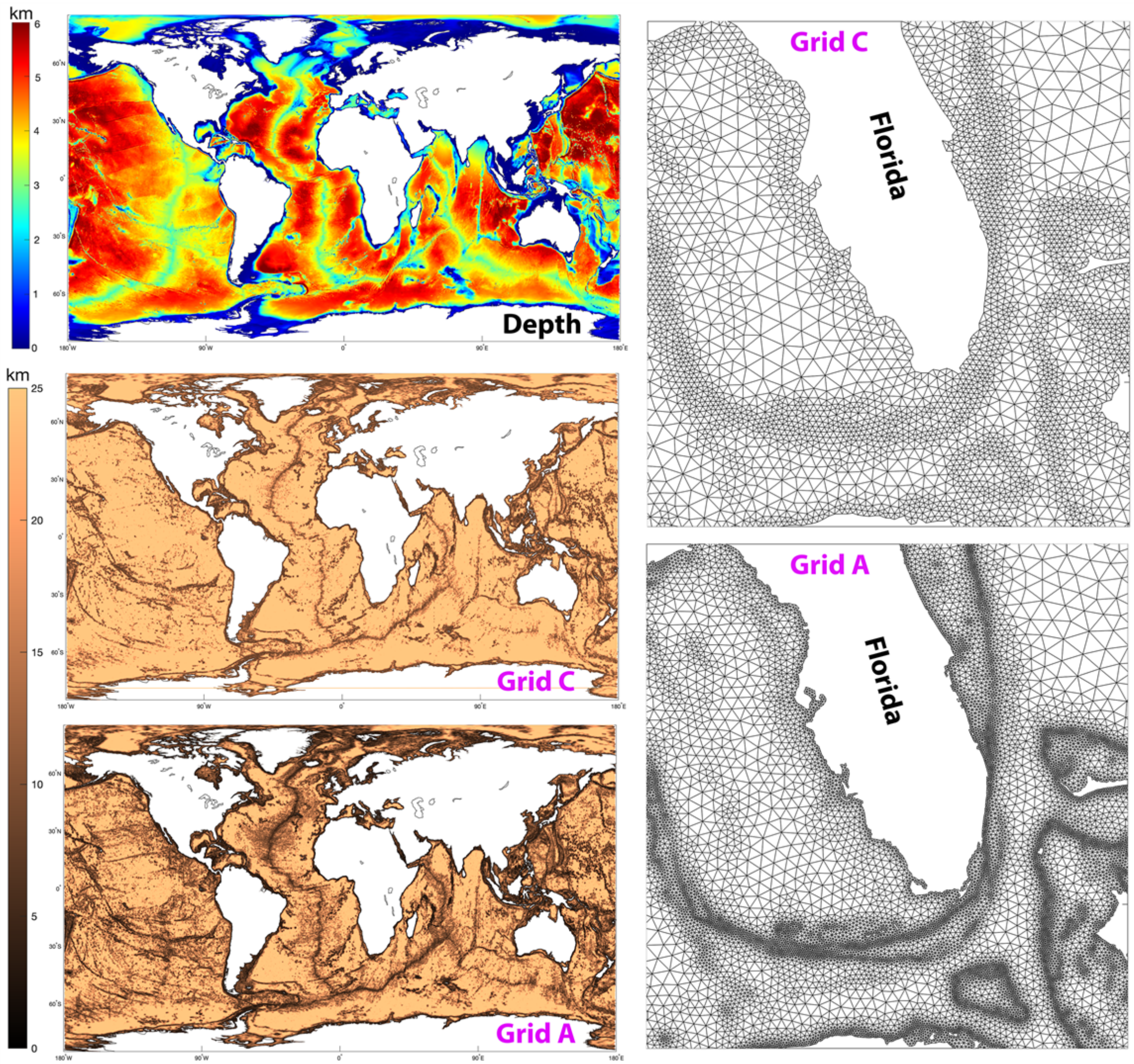

Figure 3) ocean Depth (Top left); Mesh resolution distribution (defined as the minimum connected element edge length for a mesh vertex) for two global mesh designs. Grid C and Grid A (bottom left); The zoom-in windows in the right show element sizes for Grids C and A near Florida Peninsula.

ATMOSPHERIC AND SPECTRAL WAVE MODEL

The Global Forecast System (GFS (https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs)) output during September 2018 has been used to force WW3 model on 3 unstructured grids. Video 1 shows the wind fields in terms of 10 m wind speed (U_{10}). The WW3 outputs in terms of significant wave height (H_s) are shown in Video 2 (coarse grid-C) and Video 3 (fine grid-A).

[VIDEO] https://www.youtube.com/embed/DBDE5HXdgmY?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 1) The animations of wind speed (U_{10}) field (m/s), extracted from GFS model.

[VIDEO] https://www.youtube.com/embed/Bt2-auwn1z0?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 2) The animations of significant wave height (H_s) field (meter), extracted from WW3 model on the unstructured Grid C.

[VIDEO] https://www.youtube.com/embed/wb0GFn42VFA?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Video 3) The animations of significant wave height (H_s) field (meter), extracted from WW3 model on the unstructured Grid A.

OBSERVATIONS

Satellite Observation

In this study, post-processed satellite altimeter data (wind speed and Ku-band significant wave height), collected by six altimeter missions (Sentinel-3A, Sentinel-3B, CryoSat-2, SARAL, Jason 2 and Jason 3) are used. Correction algorithms are applied for individual altimeter raw data based on their specific criteria (Queffeulou & Croiz é Fillon, 2012). For wind speed, the calibrated values of normalized back-scatter from satellite altimeters (sigma0) and buoy comparison are used for correction (Abdalla, 2012). For significant wave height, a linear correction is applied using buoy comparison (Queffeulou, 2004). Since the buoy observations are time series at a stationary point, the projection into space is done using wave group velocity for significant wave height error estimation. The satellite footprints within our numerical domains, consisting of ~8M scattered data points, are shown in Figure 4 with a temporal color bar covering September 1 - September 30. The satellite tracks move at a speed of ~0.05 degree/s with a sampling rate of ~1 Hz. On the other hand, the outputs of the atmospheric and wave model are hourly on variable grid resolutions (GFS on a static domain with resolutions of 0.5° and WW3 with variable resolutions of the unstructured grids from 25 km offshore to 1.5/3/6 km in nearshore regions). Therefore, proper projection and averaging are required for the validation and statistical analysis (Abdolali et al 2020b). In this regard, the model outputs are interpolated to the satellite data, where linear interpolation for time and Inverse Distance Weighting (IDW) are used to average between the three and four nearest points for unstructured and structured grids, respectively. Then model and satellite data are sorted in time for each altimeter separately. Finally, the data are averaged every $\Delta x = 0.5$ degrees in space.

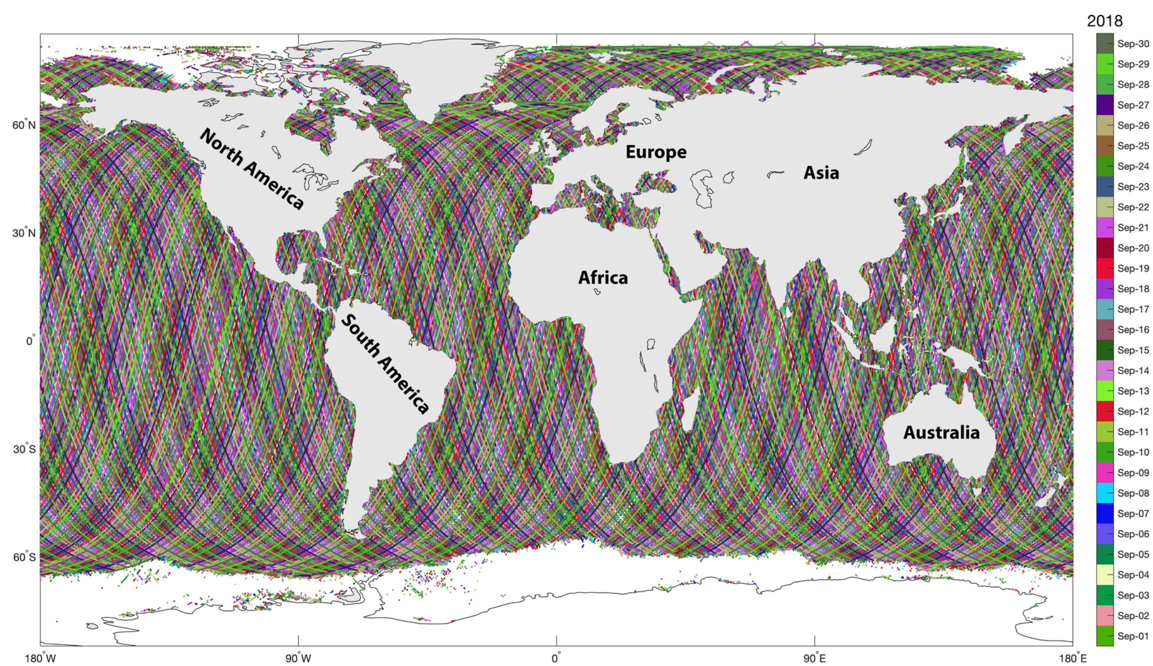

Figure 4) Satellite altimeters with track dates during the month of September 2018 collected by six altimeter missions (Sentinel-3A, Sentinel-3B, CryoSat-2, SARAL, Jason 2 and Jason 3).

Point Source Observations

In this study, the time series of meteorological and wave parameters including wind speed U_{10} and significant wave height (H_s) are compared at NDBC buoys locations. NDBC wind measurements are six 10-minute average values of wind speed and direction reported each hour. Wave measurements are 20-minute average value (Gilhousen, 1987; Steele & Mettlach, 1993). The NDBC data for this study are provided either every 10 min or hourly while the GFS/WW3 models' outputs are hourly. For the sake of a fair comparison, we averaged the NDBC data every hour. The distribution of these gauges is shown in Figure 5.

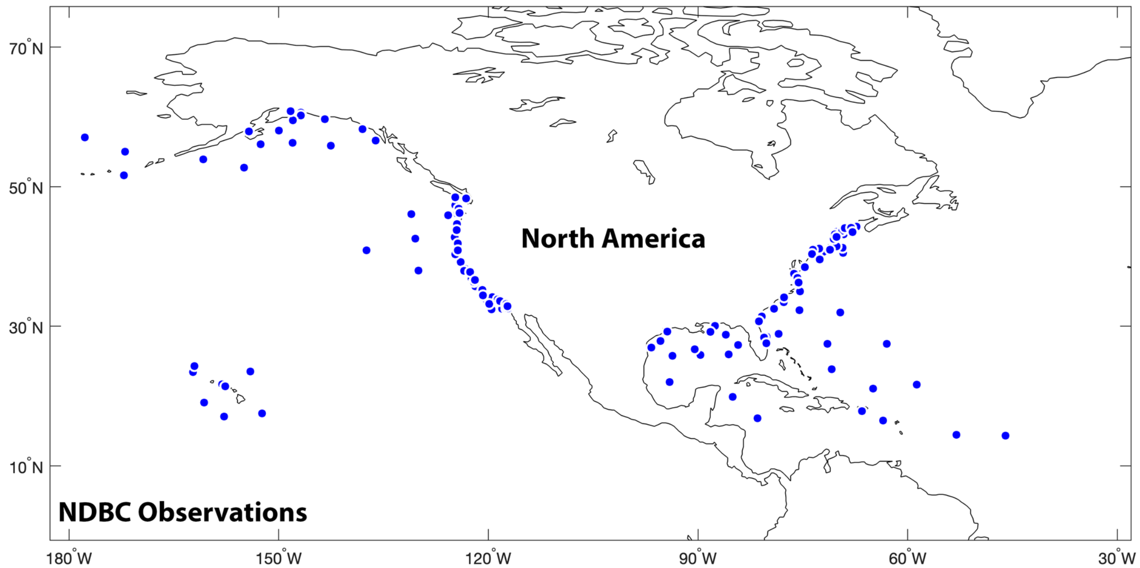

Figure 5) NDBC observations with meteorological and directional wave data during September 2018 (142 observations).

VALIDATION

Figure 6 shows Taylor diagrams of these results, combining standard deviation (σ), the Root Mean Square Deviation (RMSD) and correlation coefficient (CC) for the observation and model results. Figure 7 shows linear regression analysis and GFS and WW3 model skills are shown for satellite and buoy observations.

In this study, the time series of meteorological and wave parameters including wind speed U_{10} and significant wave height (H_s) are compared at 142 NDBC buoys locations (Fig 5). Here, the results are shown at 20 selected NDBC buoy locations in Figure 8. Overall performance at all 142 buoy locations is shown in the Taylor diagrams and scatter plots presented in Figures 6 and 8 respectively.

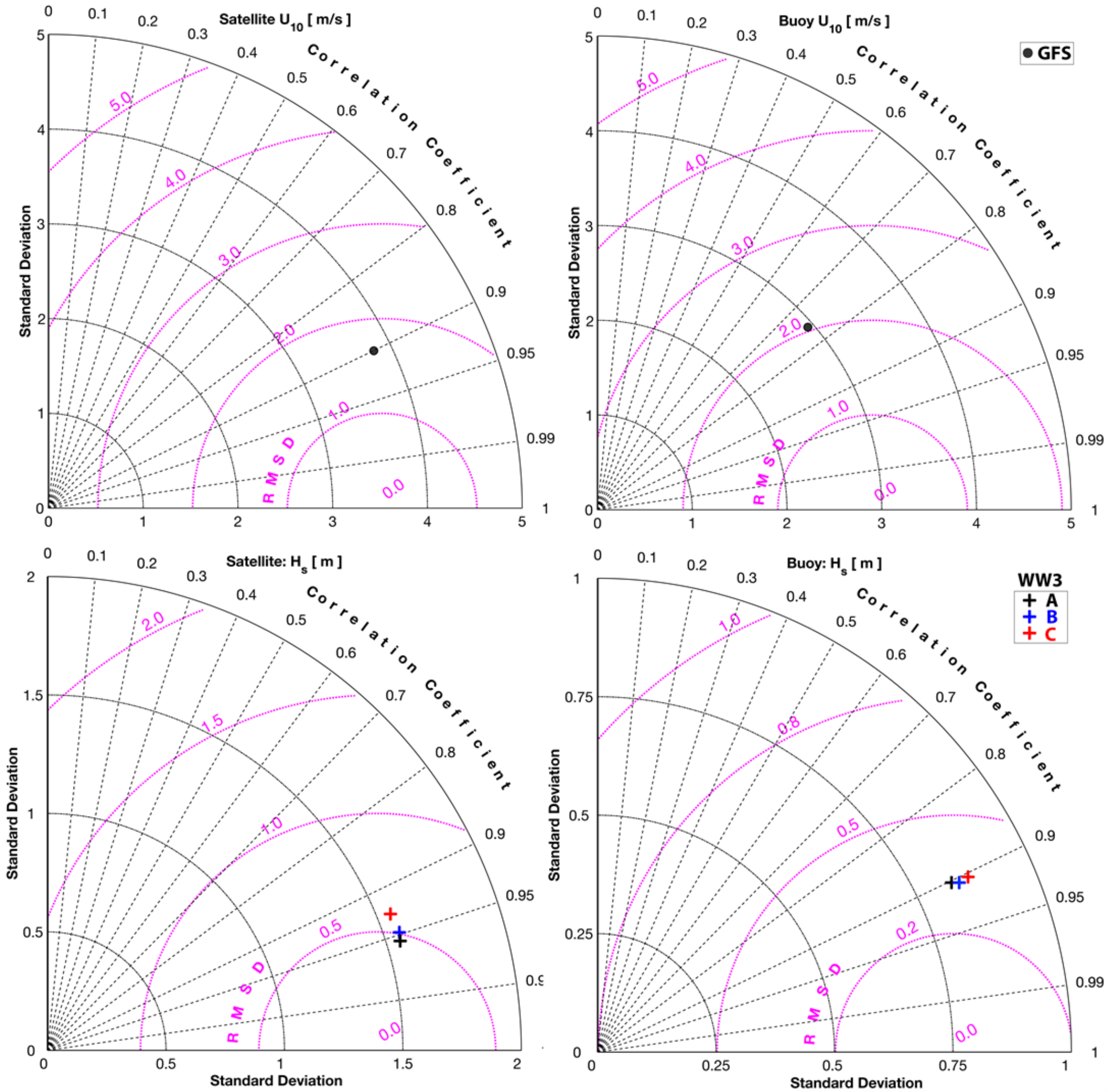

Figure 6) Taylor diagram for wind speed (U_{10}: top) and significant wave height (H_s: bottom), representing modeled and collected data along satellite track (left) and at buoy locations (right) in terms of the Pearson correlation coefficient, the Root Mean Square Deviation (RMSD) and the standard deviation σ

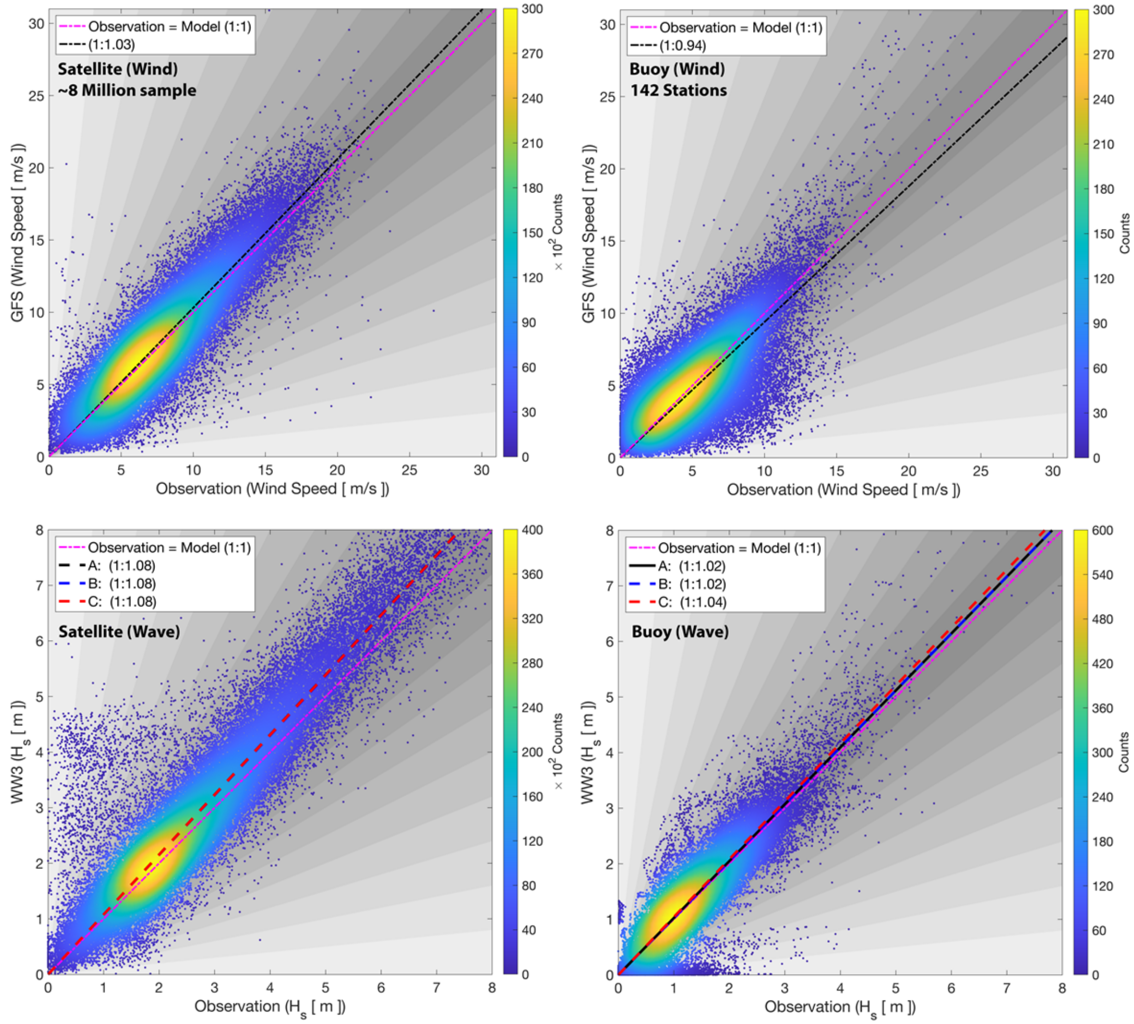

Figure 7) Linear regression comparison between satellite altimeter data (left) and at buoy observations (right) versus GFS and WW3 models, for wind speed (U_{10}: top) and significant wave height (H_s: bottom). The linear regression for different grids are shown in each subplot.

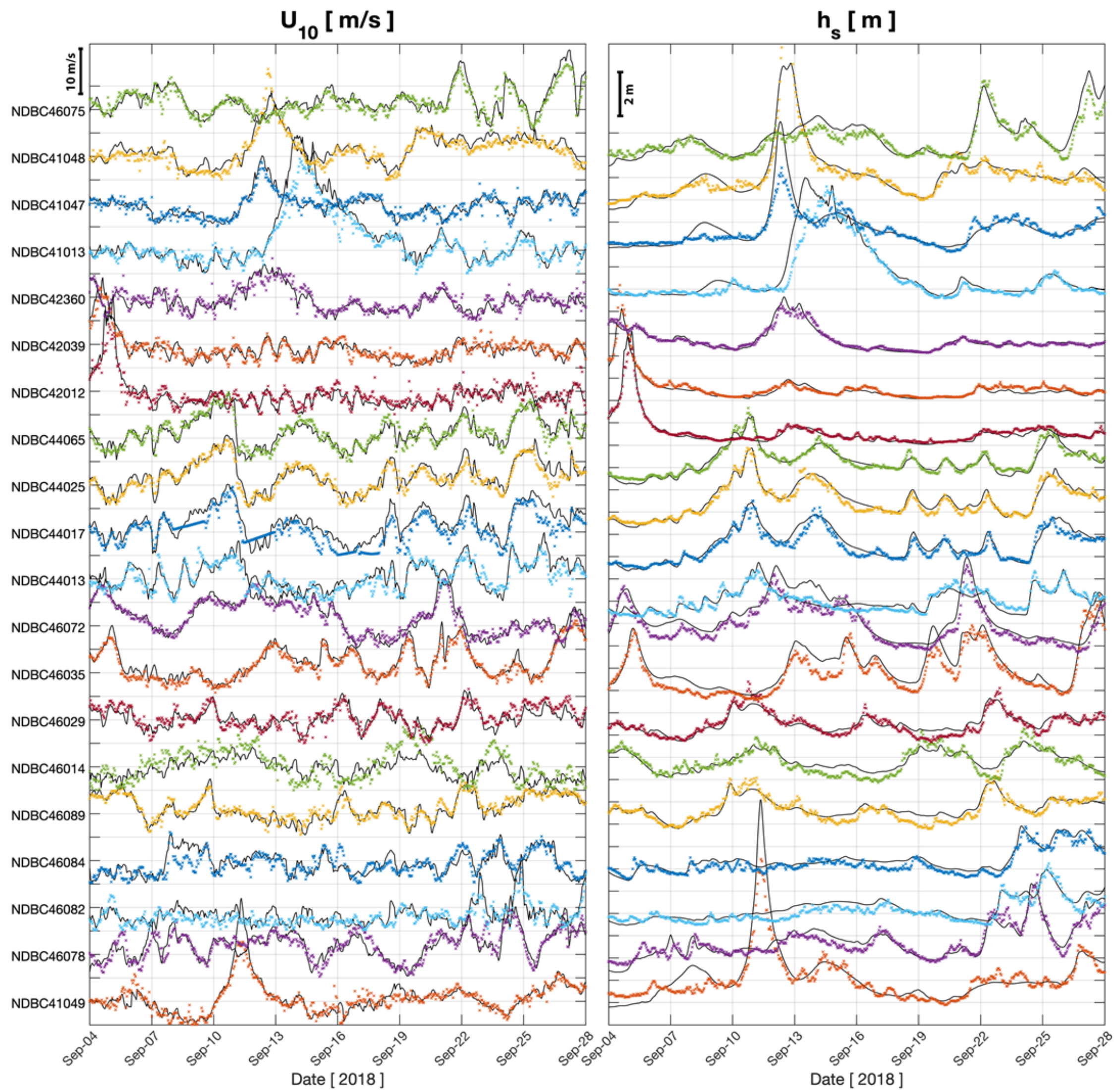

Figure 8) Atmospheric and wave Model validation at the NDBC buoy locations, GFS model (left) and WW3 model (right) shown by black lines versus observations (colored dots).

Future Work

- Conducting a long-term analysis of the model performance (multi-years) and comparing the model output with those extracted from the operational structured setups (i.e. multi-1).
- Model performance evaluation during extreme events (i.e. hurricane).
- Optimization of unstructured grid and model calibration (i.e. grid resolution refinement in coastal areas; tuning of drag and swell parameters in the model definition).

- Coupling global WW3 with an ocean circulation model via ESMF infrastructure (Moghimi et al. 2020 (http://www.mdpi.com/2077-1312/8/5/308) and Bakhtyar et al 2020 (http://https://doi.org/10.1029/2019JC015822)).

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ABSTRACT

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