A SEVEN-MEMBER ENSEMBLE, COASTAL HYDRODYNAMIC FORECAST TOOL AND ITS APPLICATION TO THE INDIAN RIVER LAGOON SYSTEM

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Abstract: An operational coastal-circulation-wave forecast system was developed for the express purpose of hydrodynamic predictions. To better represent the uncertainties in the atmospheric forcing, winds and pressure are obtained from a deterministic high-resolution regional weather forecast model (NAM), and six statistical analyses -- three from an ensemble high-resolution regional weather forecast model, SREF, and three from a global ensemble lower-resolution weather forecast models, GEFS. The ensemble system, which is currently running operationally for the east coast of Central Florida, resolves the IRL estuarine system in fine scale. The forecast skill of the ensemble predictions is assessed for a forecast cycle in January 2019. With respect to the ensembles, it is found that predicted water levels in the open-ocean have less variability, while wave height forecasts are more sensitive to variations in the individual members. Inside the estuary, the predicted water level is relatively sensitive to the different forcing.

Introduction

Coastal and ocean circulation models are widely used in conjunction with atmospheric, and wave models to study hydrodynamic processes and responses such as storm surge characteristics (e.g., Heerden *et al.*, 2007; Hope *et al.*, 2013). Additionally, these (individual or coupled) models provide input forcing to pollutant dispersion models for simulating oil spill trajectories, search and rescue (Jordi *et al.*, 2006; Dietrich *et al.*, 2012), to sediment transport and morphology models for studying bathymetric changes (Tang, Keen and Khanbilvardi, 2009; Lindemer *et al.*, 2010), and to fisheries-related consulting and research projects (Hobday *et al.*, 2011; Haase *et al.*, 2012). The atmospheric forcing plays a key role in forecast accuracy with respect to both ocean circulation and wave simulating models. Although numerical weather predictions have improved over the past few decades, weather predictions are still sensitive to the uncertainties introduced by model initial conditions and model physics (Stensrud *et al.*, 1999a). Even small uncertainties in wind forcing, when applied to circulation and wave models, can result in degraded predictions. Therefore, predictions made by a single deterministic forecast of these models cannot quantify the uncertainty in the forecasts. On the other hand, ensemble forecasting has better forecast skill than single deterministic predictions (Stensrud *et al.*, 1999b; Grimit and Mass, 2002; Ramakrishnan *et al.*, 2007). Probabilistic ensemble-based forecasting can provide client models an envelope of input variables containing the unknown "true" state of the predicted parameter(s) (Stensrud *et al.*, 1999b). For this purpose, we developed a daily ensemble-based module to address the uncertainties in input wind forcing and their impact on hydrodynamic prediction uncertainties.

Background

An operational, high-resolution regional coastal ocean model system was developed by Taeb and Weaver (2019) in an effort to reduce the computational cost of high-resolution finite-element (FE) based model as well as to provide support for ensemble modeling. The system employs a nesting approach and is built around the ADvanced CIRCulation (ADCIRC) model (Luettich *et al.*, 1992; Luettich and Westerink, 2015). The modeling processes and communication are scripted into a software program referred to as "Multistage". The system obtains and processes atmospheric data, manages model control input parameters and output data, delivers results, and processes the results for visualization and dissemination. The output of the current Multistage tool includes water level (and inundation), current velocity and wave predictions. The system has been operational since summer 2018 for the east coast of Central Florida.

The objective of the Multistage system is similar to the ADCIRC Surge Guidance System (ASGS, Fleming *et al.*, 2008). However, while the ASGS employs a single domain, the Multistage integrates a high-resolution computational mesh with a large-scale coarse mesh via conventional one-way nesting. The nesting results in significant reductions in wall-clock time. Similar to ASGS, the Multistage system has a tropical cyclone-based module that includes both ensemble and deterministic forecasting components. The deterministic forecasts are run four times daily and, when the conditions warrant, provide initial conditions for the tropical cyclone module. The tropical cyclone component, activated when a hurricane approaches, downloads the latest advisory and storm parameters (i.e., track, intensity) from the National Hurricane Center (NHC). The daily forecasts are forced by gridded wind and pressure fields from the National Centers for Environmental Prediction (NCEP)'s North American Mesoscale (NAM) model.

An additional goal of developing Multistage is to address the lack of an operational forecast system for the east coast of Central Florida. The National Operational Coastal Modeling Program (NOCMP) has developed an operational, integrated coastal forecast system based on numerical hydrodynamic models that are driven by real-time data (https://tidesandcurrents.noaa.gov/models.html). The system consists of five coastal regions in the Atlantic, two nested northeast and Northwest Gulf of Mexico Operational Forecast Systems (NEGOFS/NWGOFS), Tampa Bay in west Florida, Great Lakes and the two coastal regions along the Pacific West Coast. While the NOCMP model network includes most of the critical coastal waters, it does not capture estuaries such as the Indian River Lagoon (IRL).

Coastal Emergency Risk Assessment (CERA) (http://nc-cera.renci.org) has implemented ASGS in an operational mode, employing a basin-scale domain covering the entire north Atlantic, Caribbean Sea, the Gulf of Mexico and most critical estuarine systems, rivers, bays, and other coastal regions along the US coast. However, as with NOCMP, the computational mesh does not resolve the IRL, especially in geometrically complex regions such as causeways where accurate model predictions are required for detailed studies such as bridge abutment design. Moreover, it does not resolve some regions such as the Haulover Canal which connects the Mosquito Lagoon to the Indian River, nor the Barge Canal that connects Banana River and Indian River. Such deficiencies could result in unrealistic predictions of circulation patterns.

Description of the system

Figure 1 illustrates the Multistage workflow of the daily forecasts. The system is comprised of a core model, ADCIRC or ADCIRC+SWAN, and several utilities and modules, each of which is tasked to perform specific functions. In our previous work (Taeb and Weaver, 2018), we illustrated the workflow of these modules and briefly described their applications and functions. For ensemble forecasting, additional modules have been developed and incorporated in the system that manage the downloading, processing, and creation of ensemble atmospheric forcing files.

Selection of atmospheric ensemble models

The atmospheric ensemble members, which provide wind forcing to the hydrodynamic model, consist of a medium-range coarse resolution (0.5 degrees) global and short-range, higher resolution (16 km) regional model. The former is the Global Ensemble Forecast System (GEFS) and latter, is the Short-Range Ensemble Forecasting (SREF) system. Regional models are forced at their lateral boundaries using boundary conditions obtained from global models, which can be problematic with respect to accuracy. However, higher spatial resolution is important with respect to capturing circulation patterns in confined water bodies such as estuaries (Weaver *et al.*, 2016). The goals of this preliminary study are to lay the groundwork to determine whether or not forecast skill can be improved by applying an ensemble approach and to determine the sensitivities with respect to its individual members.

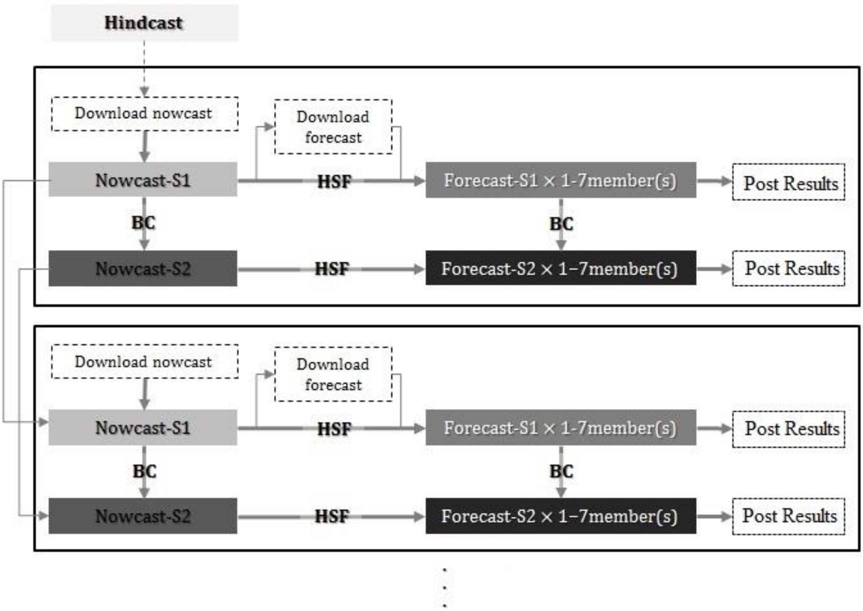

Fig. 1. Ensemble-Multistage workflow. S1 indicates stage one (large-scale coarse mesh run) and S2 indicates stage two (small-scale fine mesh run). BC and HSF are Boundary Conditions and Hot-Start File, respectively. The sequence in which the simulations are performed are delineated by the gray shading with the lighter (darker) shades indicating an earlier (later) process.

Global Ensemble Forecast Model (GEFS)

The Global Ensemble Forecast System (GEFS) is a global weather forecast model run by the National Center for Environmental Prediction (NCEP). GEFS is comprised of one analysis and 20 perturbations and its products are available by the NOAA National Operational Model Archive and Distribution System (NOMADS) four times daily at 00Z, 06Z, 12Z and 18Z. GEFS products are provided in longitude and latitude grids on 2.5°, 1°, and 0.5° resolution and files are formatted in GRIB2.

Short-Range Ensemble Forecast (SREF)

The Short-Range Ensemble Forecast (SREF) is a regional weather forecast, multi-model multi-initial condition-based system, originally developed in 1995 (Stensrud *et al.*, 1999b). The current version of the SREF is run using the Weather Research and Forecasting (WRF) Model. The SREF-WRF system contains two dynamical solvers, the Advanced Research WRF (ARW) (Schwartz *et al.*, 2015), and a Non-hydrostatic Mesoscale Model (NMM) core SREF cycles are issued four times daily at 03Z, 09Z, 15Z, and 21Z on different grids. For the North American Grid, SREF products consist of outputs from one control run of ARW and a control run of NMM on a B grid (NMMB) with 6 negative and 6 positive perturbations from each for a total of 26 members. The files are formatted in GRIB2 and data are presented in Lambert Conformal projection with a spatial resolution of approximately 16 km. For this study, we use the NMM control run and its 12 perturbations. The NAM model is also run with an NMM version of WRF.

Workflow

For each forecast cycle, a six-hour nowcast is performed using the NAM analysis. The purpose of the nowcast simulation is to update the hydrodynamic model state from the start of the previous forecast cycle to the beginning of the current cycle. Prior to the launch of the coarse mesh nowcast simulation, data files are downloaded to generate the six-hour wind forcing. These nowcast simulations are forced only by NAM analyses. Since these short simulations are forced by analyses, it eliminates the need for multiple runs under different atmospheric conditions (i.e., ensembles are not run during this portion of Multistage). The NAM is preferred over that of GEFS as it features higher spatial resolution (12 km vs 0.5°) as well as the SREF whose products are available but the model has a cycle offset of 3 hours.

The 6-hour nowcast is then used to initialize a 3.5-day forecast. The first nowcast is hot started from a tidal spin-up simulation. Subsequent forecast cycles are initiated from the previous nowcast cycle (model hot-starting, e.g., Ramakrishnan *et al.*, 2007). The downloading and processing is comprised of 29 NAM forecast files (F00 to F84) at 3-hourly intervals as well as 21 GEFS ensemble members and 13 SREF members (also 29 files at a 3-hourly interval). Because the download process is time intensive, in order to maximize the efficiency, forecast data files are retrieved simultaneously using all available CPUs. The user has the option to determine the number of ensemble runs via the command line. NAM files are retrieved and processed using sub-programs of the ASGS system that are embedded in Multistage. SREF and GEFS files are downloaded and processed by modular software programs developed in this work. The workflows of these modules are initiated by downloading GRIB2 files and extracting U and V components of forecast winds at 10 m above mean sea level as well as forecast sea surface pressure. For each ensemble model (SREF and GEFS), the mean and standard deviation of U and V wind components are separately calculated. The mean and standard deviation of the sea surface pressure is also calculated. Three distinct wind and atmospheric pressure forcing grids at 3 hourly resolution are generated from 13 members of SREF, and three forcing grids are created from 21 members of GEFS. Calculating the mean and standard deviation of the U and V components separately creates variations of wind directions within the generated wind forcings.

Application to the East Coast of Central Florida

The system began operations in 2018 as a 4-member ensemble, one NAM and three statistical GEFS's, along the east coast of Central Florida. Three additional members (SREF) were added in 2019. Of particular interest is the Indian River Lagoon (IRL), which is a long narrow estuarine system consisting of three main sub-basins (Mosquito Lagoon, Indian River, and Banana River). The estuarine system stretches 250 km along the east coast of Florida between 26.89°N and 29.10°N. It is connected to the Atlantic Ocean through, from north to south, Ponce, Sebastian, Fort Pierce, Saint Lucie, and Jupiter inlets (Weaver *et al.*, 2016).

Model setup

In Multistage, the predictions are made by physics-based numerical models. The coastal circulation characteristics are calculated by the ADCIRC model while the wave is forecast by the **S**imulating **WA**ve **N**earshore (SWAN) model which is tightly coupled to the ADCIRC model (for details regarding ADCIRC see Luettich and Westerink, 2004, 2015 and for SWAN see Booij, Ris and Holthuijsen, 1999; Booij *et al.*, 2004). The east-central Florida model set-up (model domains, the coarse and nested fine meshes) is described in previous work (Taeb and Weaver, 2019). The FE-based unstructured coarse mesh consists of approximately 40,350 nodes encompassing the western North Atlantic Ocean, the Caribbean Sea, and the Gulf of Mexico, Fig. 2(A). An open boundary is located at 60°W in the deep Atlantic Ocean. The domain size is necessary for accurately representing circulation patterns on the continental shelf and coastal regions, including energy transformation from deep to shallow water, wave evolution and dissipation, and interactions between basins (Blain, Westerink and Luettich, 1994; Dietrich *et al.*, 2011). The coarse mesh has a maximum grid spacing of roughly 9 km in the deep Atlantic Ocean and a minimum of 900 m at IRL inlets and around the Caribbean and Bahamas Islands. A nested unstructured fine-scale high-resolution mesh consisting of 126,770 nodes represents the entire IRL and the proximity low-lying land, Fig. 2(B). The fine-scale mesh resolves most of the complex geometry inside the lagoon with a minimum grid spacing of 15-30 m near the causeways and relief conveyances, creeks, as well as the channels that pass through residential communities. Larger grid spacing on the order of 100-600 m is used for inland regions.

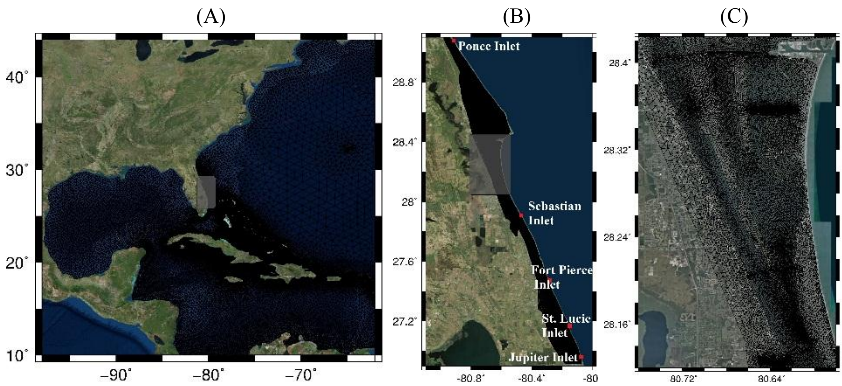

Fig. 2. (A) Large-scale coarse mesh domain. (B) Nested fine-scale high-resolution mesh representing the IRL system. (C) A subset of the fine mesh illustrating the complex geometry resolved by the high-resolution unstructured mesh. The open boundaries of the nested mesh (Inlets) are marked by red dots in B.

Hydrodynamic responses

Validation graphics are presented at locations where real-time observations are available. The forecast cycle chosen for this study starts on January 24, 2019, at 00Z. The model performance is validated using an old cycle starting on January 22, 2019, at 00Z, ending at the beginning of the forecast cycle. Validation points are illustrated in Fig. 3. The model-predicted water level is validated at Trident Pier station operated by National Oceanic and Atmospheric Administration (NOAA) and at a nearshore gauge in Sebastian Inlet operated by Coastal Process Research Group (CPRG) at Florida Institute of Technology (Zarillo and Watts, 2018). The water level instrument, which is located at the north jetty of the inlet allows us to validate the boundary condition forcing at this location. Significant wave height, H_s, is also validated by CPRG using real-time data collected form oceanographic instrumentation located approximately 530 m northeast of the Inlet mouth at depth of 10 m. Significant wave height is also validated at the Cape Canaveral nearshore station (NDBC) 41113 run by NOAA – which is located less than 6 km east of Port Canaveral at a depth of 9.8 m. Within the estuary, validation is limited to two locations, one in the northern and a second in the southern portions of the IRL, and is limited to surface elevation only. These are the only hydrodynamic observations made available in near real-time inside the IRL. Both stations are operated by the US Geological Survey (USGS). For quantifying the model predictions, forecast skill is computed at validation points as defined by Warner *et al.* (2005), i.e.,

$$Skill = 1 - \frac{\sum_{i=1}^{N} |q_m - q_{Obs}|^2}{\sum_{i=1}^{N} (|q_{Obs} - \bar{q}_{Obs}| + |q_m - \bar{q}_{Obs}|)^2} \quad (1)$$

Where q_m is the hydrodynamic model time series, q_{obs} is the observation time series, and the overbar denotes the observation mean. A skill of 1 indicates strong agreement while a skill of 0 shows complete disagreement.

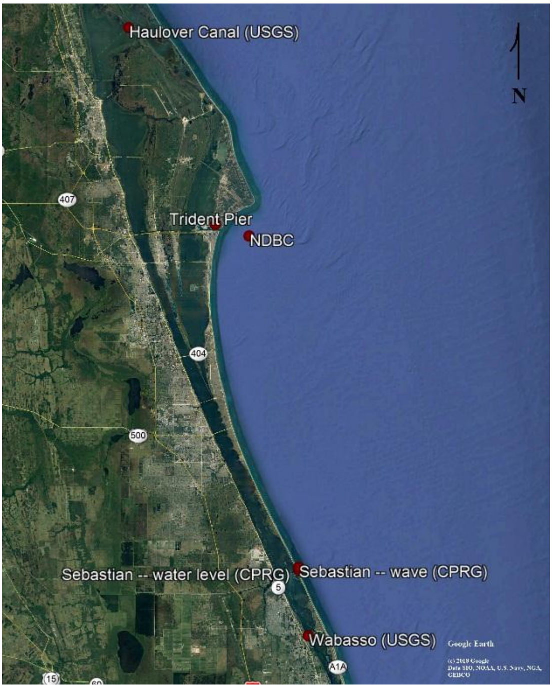

Fig. 3. Validation points.

Water Level

Figure 4 depicts a time series plot of predicted water level at Sebastian Inlet and Trident Pier. Both of these locations are within the coarse mesh. The model predicted water level is in good agreement with the observed (Fig. 4a) with an average forecast skill of 0.992±0.0032. Of the five open boundaries within the IRL domain, the Sebastian Inlet CPRG station is the only location for validating the boundary forcing. The model prediction and observations are also in good agreement at the Trident Pier station (Fig. 4b). The best forecast skill, 0.992, is calculated from both the NAM and “SREF mean – std” simulations while the other members yield forecast skills of roughly 0.98. At these two stations, the uncertainty in predicted water level during validation cycle is larger for the GEFS-forced simulations. During the forecast cycle, the spread is similar between GEFS and SREF (titled as “current cycle” in plots). The combined forecast spread (total of GEFS, SREF, and NAM) is relatively small early in the forecast cycle. It increases 10 hours after the beginning of the forecast cycle and reaches a maximum around 10 cm at Sebastian and 20 cm at Trident Pier around 15 UTC January 24, it decreases thereafter. The “GEFS mean” and “GEFS mean – std” runs are similar throughout the forecast cycle while the “GEFS mean + std” deviates from these simulations in the early part of the cycle, but then become more similar to the other GEFS members. Water level time series predicted by NAM most often lies in the middle of the SREF runs.

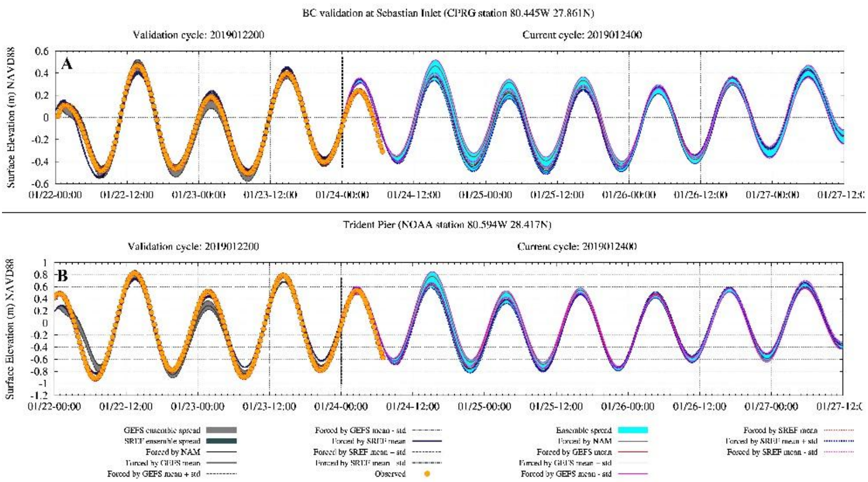

Fig. 4. Ensemble of predicted water level and validation at (A) Sebastian Inlet and (B) Trident Pier.

Time series plots of water level at the Haulover canal and Wabasso stations are shown in Figs. 5a and 5b. These validation points are located inside the estuary i.e. inside the fine scale high-resolution mesh. The hydrodynamic model appears to struggle somewhat at both locations, especially during the beginning of the validation cycle. At Haulover Canal, during the latter portion of the validation cycle, the SREF members appear to better match the observations while at

Wabasso, it is the GEFS members that capture the observations within their ensemble spread. The highest forecast skill scores are obtained from the "GEFS mean" and "GEFS mean + std", 0.85 and 0.82, respectively. The NAM run, which falls within the GEFS ensemble spread, has lower forecast skill (0.67) while the SREF members have forecast skill scores below 0.72. Similar to the validation at the Sebastian and Trident Pier stations, the GEFS has wider spread compared to the SREF during the validation cycle. At Wabasso, the spread in the GEFS simulations encompass the SREF members during the first 2.5 days of the forecast cycle. The maximum spread peaks around 20 cm on January 25. At Haulover Canal, the maximum ensemble spread occurs on January 24, which is similar to Sebastian CPRG and Trident Pier stations. While Haulover Canal is 40 km away from the nearest open boundary (i.e., Ponce Inlet), the Wabasso station is located 9 km south of the Sebastian Inlet. Similar to the open ocean validation locations, the NAM forced simulation is close to that of the SREF ensemble mean during the forecast cycle. The forecast skill of the NAM and the SREF mean are both 0.8 while that of the GEFS are quite low (0.158±0.05).

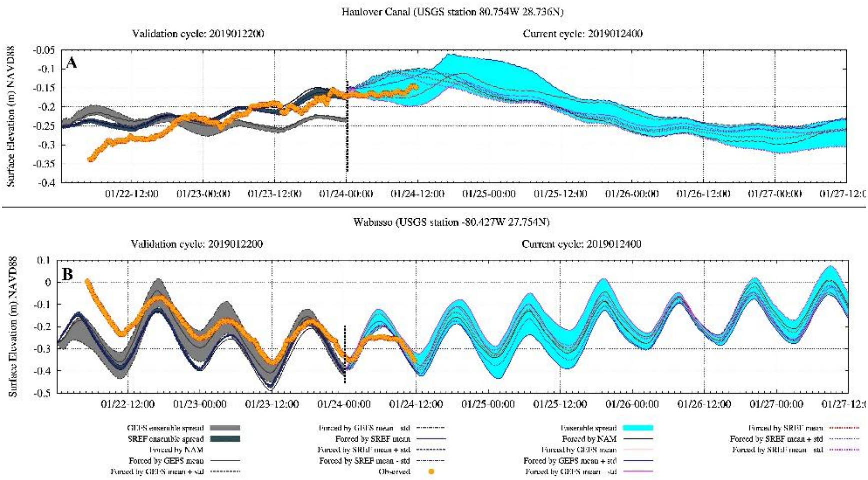

Fig. 5. Ensemble of predicted water level and validation at (A) Haulover Canal and (B) Wabasso.

Wave Height

Nearshore wave validation is provided at both the Sebastian CPRG station and at Cape Canaveral nearshore (Figs. 6a and 6b, respectively). The hydrodynamic predictions forced by NAM, "GEFS mean + std", and "SREF mean – std" yield the largest forecast skill scores (0.841, 0.8, and 0.84 respectively). During the forecast cycle, the GEFS ensemble spread begin to grow after 12 hours of the beginning of the forecast cycle while the SREF spread evolves after the first day of the forecast cycle. Towards the end of the forecast cycle, the SREF ensemble spread is much larger than the GEFS's. The NAM forecast is in better agreement with the "SREF mean" throughout the forecast cycle. During the validation period at Cape Canaveral, the "SREF mean" ensemble member had a skill score of 0.94 while the NAM's performance was similar (i.e., a skill of 0.95). Among GEFS members, the "GEFS mean – std" had the best forecast skill (0.85). The "SREF mean" shows better performance from January 22 through 12 UTC January 23 while the NAM appears to perform best during the latter portion of the forecast cycle. During the forecast cycle, the NAM run is close to the "SREF mean" run beginning the second day of the forecast cycle. Similar to the Sebastian CPRG station, the GEFS ensemble spread grows quickly over the first couple of days and reaches the maximum of 70 cm at 15 UTC January 24. The GEFS spread then shrinks towards the end of the forecast cycle (to approximately 40 cm).

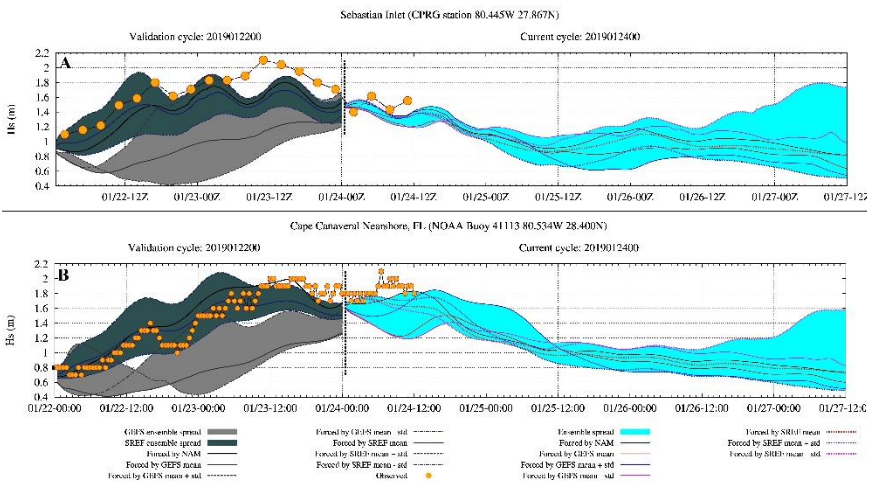

Fig. 6. Ensemble of significant wave height and validations at (A) Sebastian Inlet and (B) Cape Canaveral nearshore.

Conclusion

A high resolution operational ensemble-based coastal forecast system has been developed for the east coast of Central Florida with the main focus on the IRL estuarine system. We use the spread of the hydrodynamic predictions, generated from the various wind forcings, as a proxy measure of uncertainty. The atmospheric model members include the deterministic NAM, three members from both the SREF GEFS. The outputs from the seven-member hydrodynamic ensemble are compared to one another as well as to observations within both the IRL and coastal zone. Preliminary results indicate that, in the nearshore, each of the members perform reasonably well compared to observations and the spread amongst the members is not significant i.e. no remarkable difference is seen within predictions made by seven ensemble members. However, the relative uncertainty could be considerable inside the estuary. The performance of the SREF and GEFS varied with respect to the two consecutive forecast cycles presented here and also depends on the validation locations. The largest spread was observed in the nearshore wave predictions (i.e., at buoy 41113). For the selected forecast cycles in this study, the SREF and NAM had better forecast skill than the GEFS. This finding is not entirely surprising given that these two weather forecast models have higher spatial resolution than the GEFS. Resolving the nuanced land water geometry has been shown to be critical in capturing hydrodynamic variations within a coastal estuary (Weaver *et al.*, 2016).

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