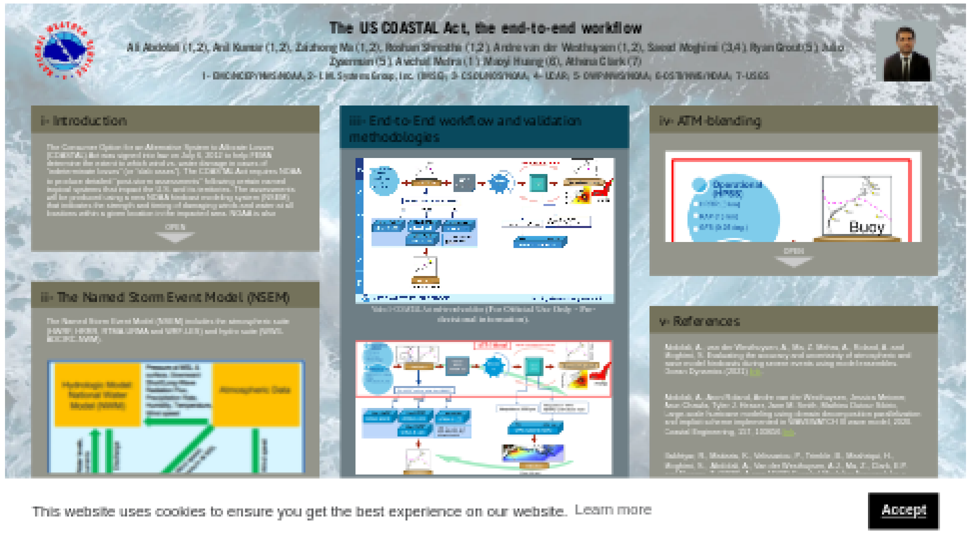
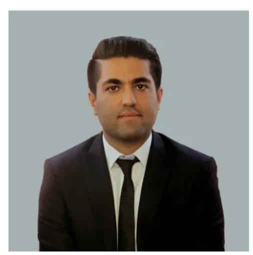
The US COASTAL Act, the end-to-end workflow



Ali Abdolali (1,2), Anil Kumar (1,2), Zaizhong Ma (1,2), Roshan Shrestha (1,2), Andre van der Westhuysen (1,2), Saeed Moghimi (3,4), Ryan Grout (5), Julio Zyserman (5), Avichal Mehra (1), Maoyi Huang (6), Athena Clark (7)

1- EMC/NCEP/NWS/NOAA; 2- I.M. Systems Group, Inc. (IMSG); 3- CSDL/NOS/NOAA; 4- UCAR; 5- OWP/NWS/NOAA; 6-OSTI/NWS/NOAA; 7- USGS



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I- INTRODUCTION

The Consumer Option for an Alternative System to Allocate Losses (COASTAL) Act was signed into law on July 6, 2012 to help FEMA determine the extent to which wind vs. water damage in cases of "indeterminate losses" (or "slab cases"). The COASTAL Act requires NOAA to produce detailed "post-storm assessments" following certain named tropical systems that impact the U.S. and its territories. The assessments will be produced using a new NOAA hindcast modeling system (NSEM) that indicates the strength and timing of damaging winds and water at all locations within a given location in the impacted area. NOAA is also required to make post-storm assessment results and observations from the storm available to the public via a new online database. To meet these requirements, the COASTAL Act team has been developing the Named Storm Event Model (NSEM), as a well-defined coupled modeling system with model components for storm surge and waves, winds, gusts and surface pressure analyses, and precipitation and hydrology, as well as the Coastal Wind and Water Event Database (CWWED) for hosting the output.

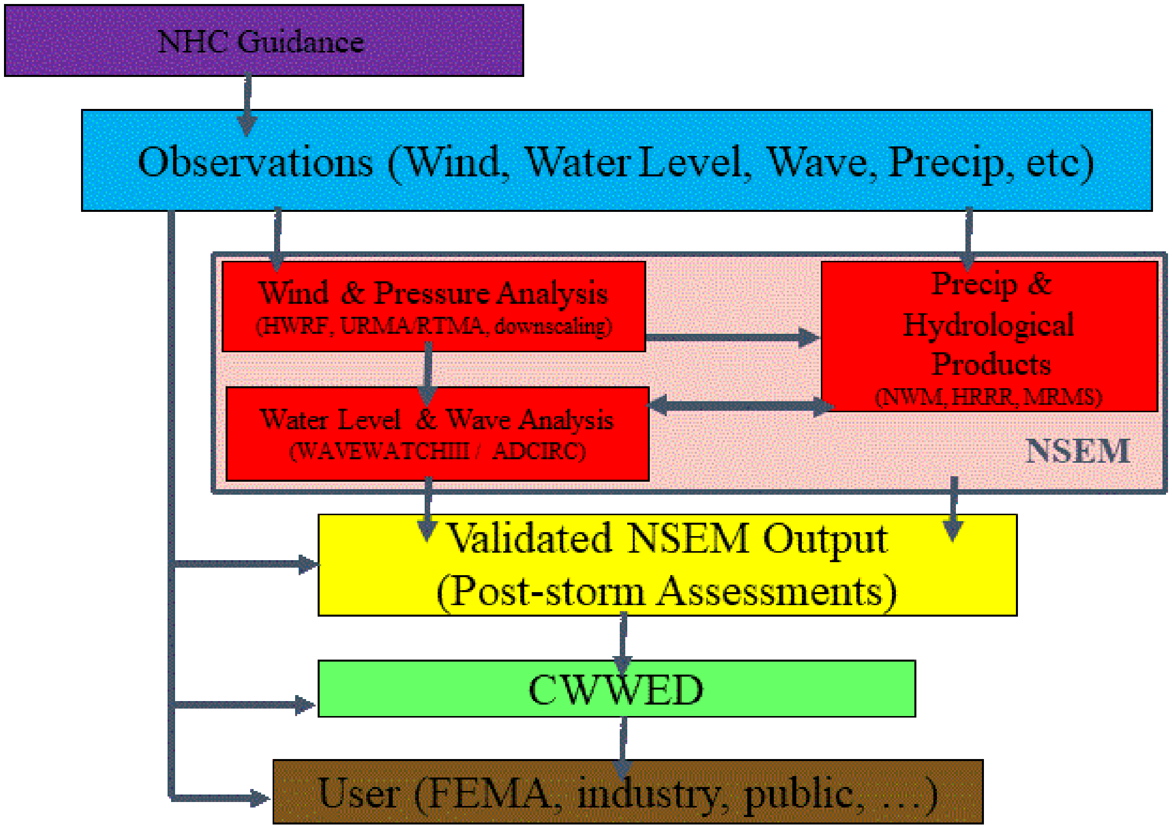


Figure 1- COASTAL Act process (For Official Use Only - Pre-decisional information).

II- THE NAMED STORM EVENT MODEL (NSEM)

The Named Storm Event Model (NSEM) includes the atmospheric suite (HWRF, HRRR, RTMA-URMA and WRF-LES) and hydro suite (WW3-ADCIRC-NWM).

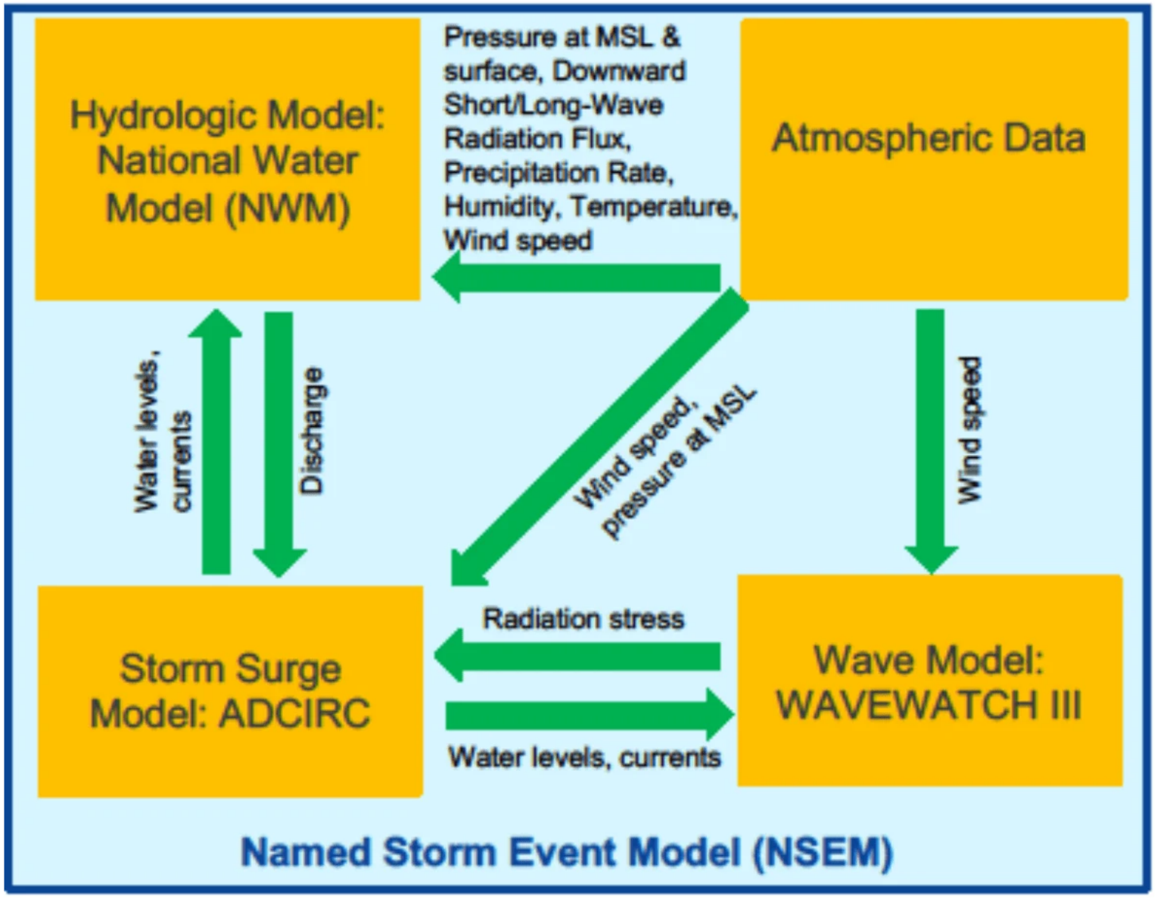


Figure 2- The Named Storm Event Model (NSEM) framework (For Official Use Only - Pre-decisional information).

ATMOSPHERIC Suite

HWRF Reanalysis and Reforecasting

For near-shore oceanic environments, in the presence of tropical storms and hurricanes, the operational Hurricane Weather Research and Forecast (HWRF (http://doi.org/10.3390/atmos11090888)) system can be used in retrospective (historical) mode to generate the URMA background field. The HWRF executes operationally at 2 km resolution near the tropical cyclone's center where the strongest winds are usually found. The URMA and HWRF systems can provide a consistent starting point for the NSEM wind analyses since they are of comparable resolution.

Wind and Surface Pressure Analyses (RTMA-URMA)

The NOAA Hurricane Weather Research and Forecast (HWRF) system and the NOAA High-Resolution Rapid Refresh (HRRR)-Rapid Refresh (RAP) provide the background and the UnRestricted Mesoscale Analysis (URMA), part of the NOAA Real-Time Mesoscale Analysis (RTMA) system. RTMA-URMA performs the mean wind, gust, surface pressure and AS analyses. The URMA will include additional available observations gathered and processed into the analysis. The URMA serves as an intermediate solution for constraining & improving the parcel-scale downscaled wind analysis by providing a reanalysis of the available surface observations.

Wind Analysis Downscaling (WRF-LES):

wind analysis and to estimate the strength and timing of damaging winds at a given, "parcel-scale" over-land location in the area impacted by the tropical cyclone and to drive surge and wave models for estimating the water damage. Since parcels are approximately 100 m in extent, and feasible wind analyses are in the 1,000-2,500 m range, some further estimate of wind at the parcel scale must be derived using a "downscaling" technique.

A very fine 30-meter- resolution land-use data along with 10-meter resolution terrain data are implemented which allows us to capture fine details (at parcel-scale) for coastal geography and water inundation characteristics. The Wind downscaling is designed to produce 5-minutes interval surface wind speed, wind gusts, wind direction time series at any given coastal location where maximum damages occur over residential or commercial structures.

Precipitation:

The Multiple-Radar Multiple-Sensor (MRMS) precipitation analysis, which combines data from radar, satellites, surface observations, upper air observations, rain gauges, and models, provides an approximation of the amount of precipitation accumulated on areas in near-real time. The High-Resolution Rapid Refresh (HRRR) model is a real-time, 3km resolution convective-allowing model (CAM), updated hourly, with 3km radar data assimilated every 15 minutes over a 1 hour period.

Hydro-suite

A significant portion of flooding due to storm-induced hurricanes is caused by the interactions of wind-generated waves and the underlying surge – with radiation stresses from wave processes playing a significant role in the surge, and the combined wave-current bottom boundary dynamics being important for both the wave and surge processes. Highly-sophisticated numerical models that separately simulate surge and wave processes have been developed and validated at NOAA over the last decade (the ADCIRC-based ESTOFS system for the surge modeling and WAVEWATCH III Global Multi-1 system for wave modeling). Apart from having state-of-the-art physics, these models can be run in unstructured grid formulation, a key requirement for seamlessly simulating inundation processes at small spatial scales along the coast. The hydrodynamic part of the NSEM is coupled three-way between wave, ocean, and hydrology model components, using the flexible Earth System Modeling Framework (ESMF)/National Unified Operational Prediction Capability (NUOPC) coupling framework, consistent with NOAA's Unified Forecast System (UFS). In the COASTAL Act and within the NEMS framework, the two modeling systems (storm surge and wave) are dynamically coupled to exchange physical processes so as to obtain accurate estimates of total wave–surge induced inundation (coupling to hydrological model is under development).

The hydro part is forced by a blended atmospheric field, made up of the atmospheric model output from regional scale to the downscaled results over the impacted area. Within this framework, the performance of atmospheric products is evaluated and blended fields are generated on a high-resolution grid, using a master blend recipe (see section iv).

WAVEWATCH III:

WAVEWATCH III (https://github.com/noaa-emc/ww3) is a community wave modeling framework that includes the latest scientific advancements in the field of wind-wave modeling and dynamics. The core of the framework consists of the WAVEWATCH III third-generation wave model (WAVE-height, WATer depth, and Current Hindcasting), developed at NOAA/NCEP.

WAVEWATCH III solves the random phase spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of this equation is that properties of medium (water depth and current), as well as the wave field itself, vary on time and space scales that are much larger than the variation scales of a single wave. The model includes options for shallow-water (surf zone) applications, as well as wetting and drying of grid points. The wave model is a sophisticated modeling system with numerous developments that have been added in recent years (wave – hurricane interaction physics, new wave growth and dissipation physics packages, wave – mud, wave – vegetation, and wave – bottom interaction physics to name a few) (Abdolali et. al 2019 (https://doi.org/10.1016/j.coastaleng.2020.103656)).

ADCIRC:

The ADvanced CIRCulation model (ADCIRC (http://doi.org/10.3390/jmse8050308)) is a finite element hydrodynamic community model. Its natural finite element unstructured mesh capability, and several modules specifically address various aspects of the coastal flooding and tropical cyclone forcing, making it one of the best tools available for coastal inundation studies. ADCIRC operates in either two-dimensional depth-integrated depth-averaged (2D barotropic) and three-dimensional (baroclinic) modes. In the 2D mode, it solves equations for both water surface elevation and the depth-averaged velocity fields.

National Water Model:

NOAA's National Water Model (NWM (http://doi.org/10.1029/2019JC015822)) is the foundation for the nationally consistent operational hydro forecasting and source of inland hydrologic information. NWM provides river channel discharge within the CONUS areas including coastal zones. The model is coupled to the Extratropical Surge and Tide Operational Forecast System (ESTOFS) and Advanced Circulation Model (ADCIRC) in the Coastal Zones.

Other components:

Surge Wave Grid Development:

New grids have been generated with refinement in the nearshore and overland areas to improve the NSEM's ability to meet the COASTAL Act's requirements, as determined by model testing. The grid are adjusted to (1) better represent features in regions vulnerable to inundation and (2) incorporate and better reflect new bathymetry and topography made available through COASTAL Act Bathymetry/Topography dataset.

Bathy-Topo DEM

Within the COASTAL Act, NCEI with support from NOAA's Office for Coastal Management (OCM), identified and evaluated existing coastal elevation datasets, including source data (i.e. lidar surveys) and derivative products (i.e. DEMs). The gap analysis included assessing the data quality, spatial extent and date of acquisition and/or creation (in the case of DEMs). The products are developed and tested under the Disaster Relief Appropriation for Hurricane Sandy to build the suite of seamless topographic-bathymetric and bathymetric high-resolution telescoping DEMs for the identified areas of interest. DEMs developed along the coast have a spatial resolution of 1/9 arc-second (~3m) and coarsen to 1/3 arc-second (~10m) offshore.

CWWED Database:

The CWWED serves as an interactive database that provides access to all “Covered Data”, both by the Named Storm Event Model (NSEM) as well as relevant stakeholders, and serves as an accessible repository for the NSEM output so it can be referenced by FEMA and all relevant stakeholders.

III- END-TO-END WORKFLOW AND VALIDATION METHODOLOGIES

[VIDEO] https://res.cloudinary.com/amuze-interactive/video/upload/vc_auto/v1638807196/agu-fm2021/10-AA-1E-D3-10-C2-2D-83-1D-02-C0-1C-2C-AD-B4-F1/Video/workflow_cropped_vcupv2.mp4

Video 1- COASTAL Act end-to-end workflow (For Official Use Only - Pre-decisional information).

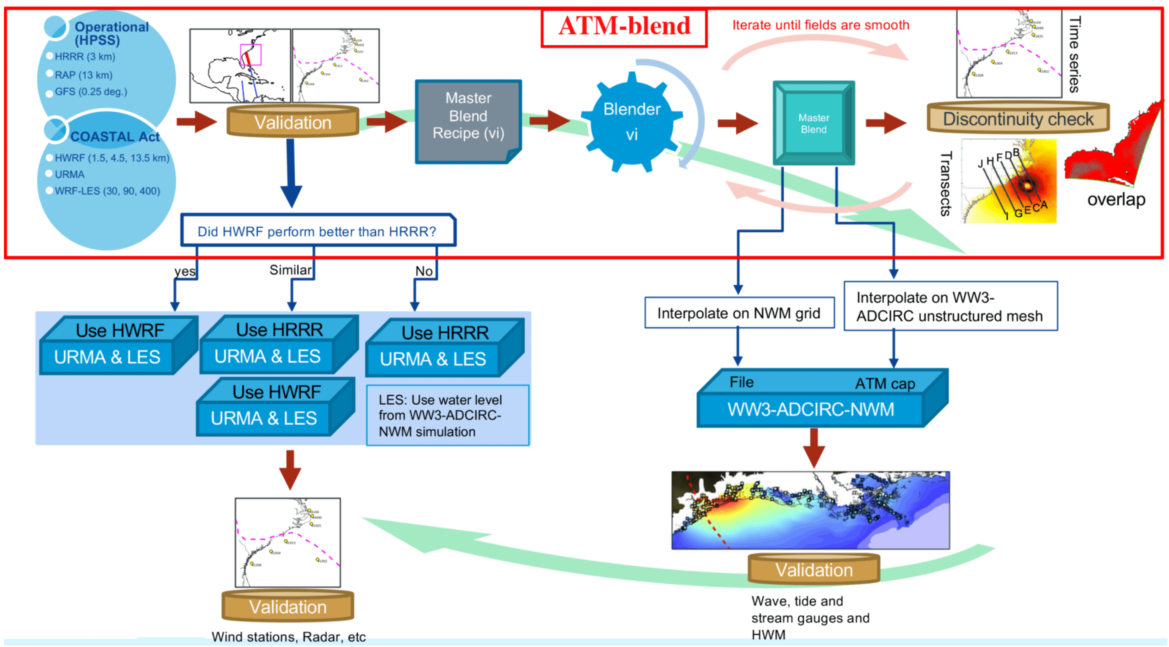


Figure 3- COASTAL Act end-to-end workflow (For Official Use Only - Pre-decisional information).

Observations

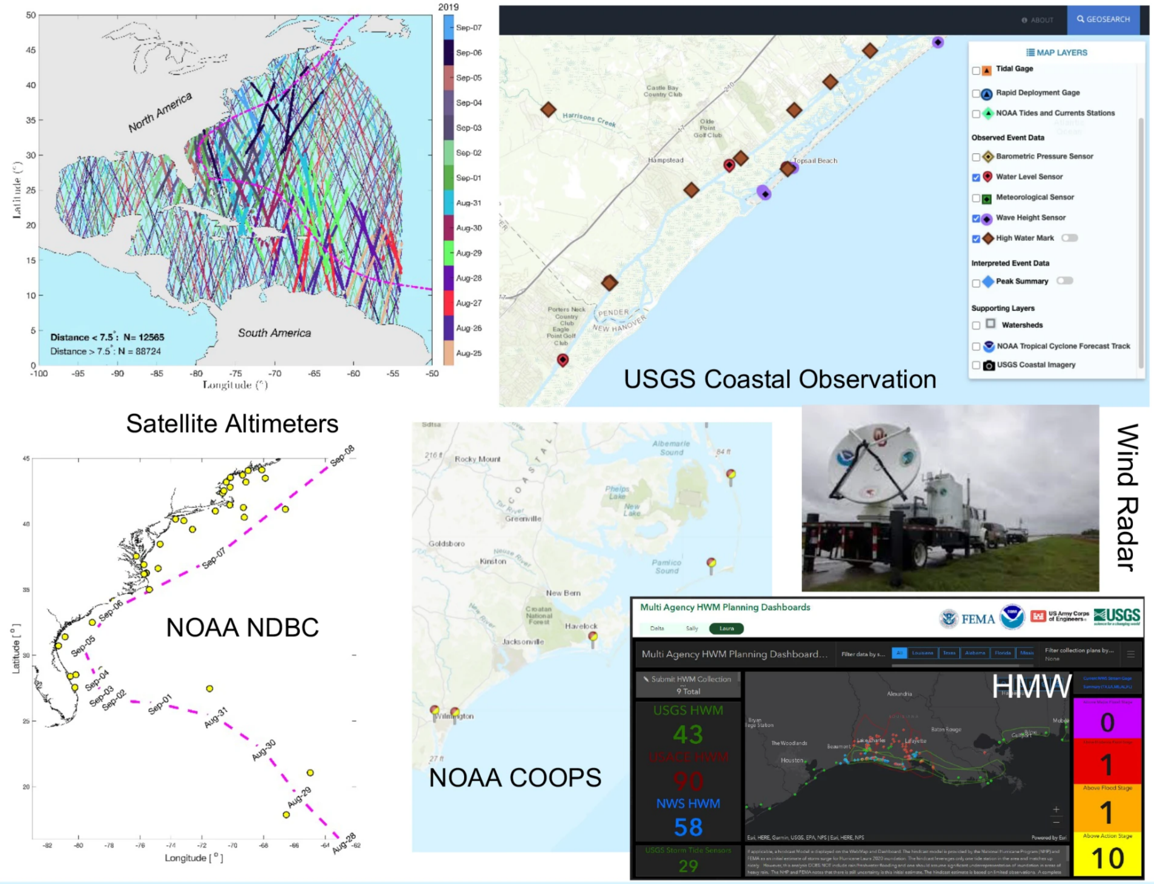


Figure 4 - Observations for COASTAL Act validation suite (For Official Use Only - Pre-decisional information).

Wind, pressure, and gust validation:

- Wind Radars
- Land-Based Methetological Stations
- NDBC meteorological data (offshore obs)
- Satellite Altimeters (offshore obs)
- ...

Wave validation:

- NDBC buoy
- Satellite Altimeters
- USGS wave gages
- ...

Water Level Validation:

- CO-OPS tide gauges
- High Water Marks
- USGS water level gages
- ...

River Discharges:

- NOAA Streamgages
- USGS Streamgages
- ...

Validation

The wind and hydro products are evaluated against offshore and coastal wave-buoys, nearshore water level stations, radars, and satellite altimeters, as well as USGS rapid-deployment water level and wave gauges placed in the nearshore regions and overland.

TIER 1:

The overall performance of each individual model over the entire model domain and for the whole simulated time is evaluated. This validation is critical for tier 2 validation.

TIER 2:

The outputs of the atmospheric models and coupled WAVEWATCH III-ADCIRC-NWM modeling system are validated for 10 m wind, gust, and total water level as a combination of storm surge, tides, and wave activity. During the development of the NSEM model, the analysis is done for previous hurricane events for which (1) damage from the storm's inundation led to incidents of buildings being destroyed to their foundation (i.e. "slab" scenarios), and (2) more data on total water level recordings are available to validate the model performance. The skill assessment techniques and criteria are determined via two methods: paired t-test for time series comparison with available observations and 2) ensemble modeling for areas with no observations. These methodologies are consistent with the goal of the COASTAL Act to have the determination of model performance for the 90% accuracy evaluation.

Accuracy assessment with paired t-test:

For a given model run, the modeled time series are compared to the observation. The aim is to test whether a given level of accuracy (i.e. 90%) is reached (equivalently an error level of 10%). Considering the natural variability in the observed phenomenon (e.g., wind U10 wave height Hs) and observational error, it is unreasonably strict to require that every model data point has an error of less than 10%. Therefore, the accuracy assessment will focus on the mean relative difference between the modeled and observed time series, and test whether this mean difference is below 10%. The paired t-test accounts for observational uncertainty as well as the expected differences due to model errors. Since the model and observation both describe the same process (e.g., wind speed or wave height), there is a dependence between the modeled and observed time series variables. In this setting, the paired t-test hypothesis is applied to test whether the mean difference between the two time series is less than 10% or not. The following null hypothesis H0 and alternative hypothesis Ha:

H_0: $\mu d < 0.1$

H_a: $\mu d > 0.1$

where the mean relative difference is defined as d_i = (Xi,model − Xi,obs)/Xi,obs, and Xi is the model variable at time i being tested. Since the alternative hypothesis states that the relative difference is greater than 0.1, this constitutes an upper-tailed test. This test has the following assumptions:

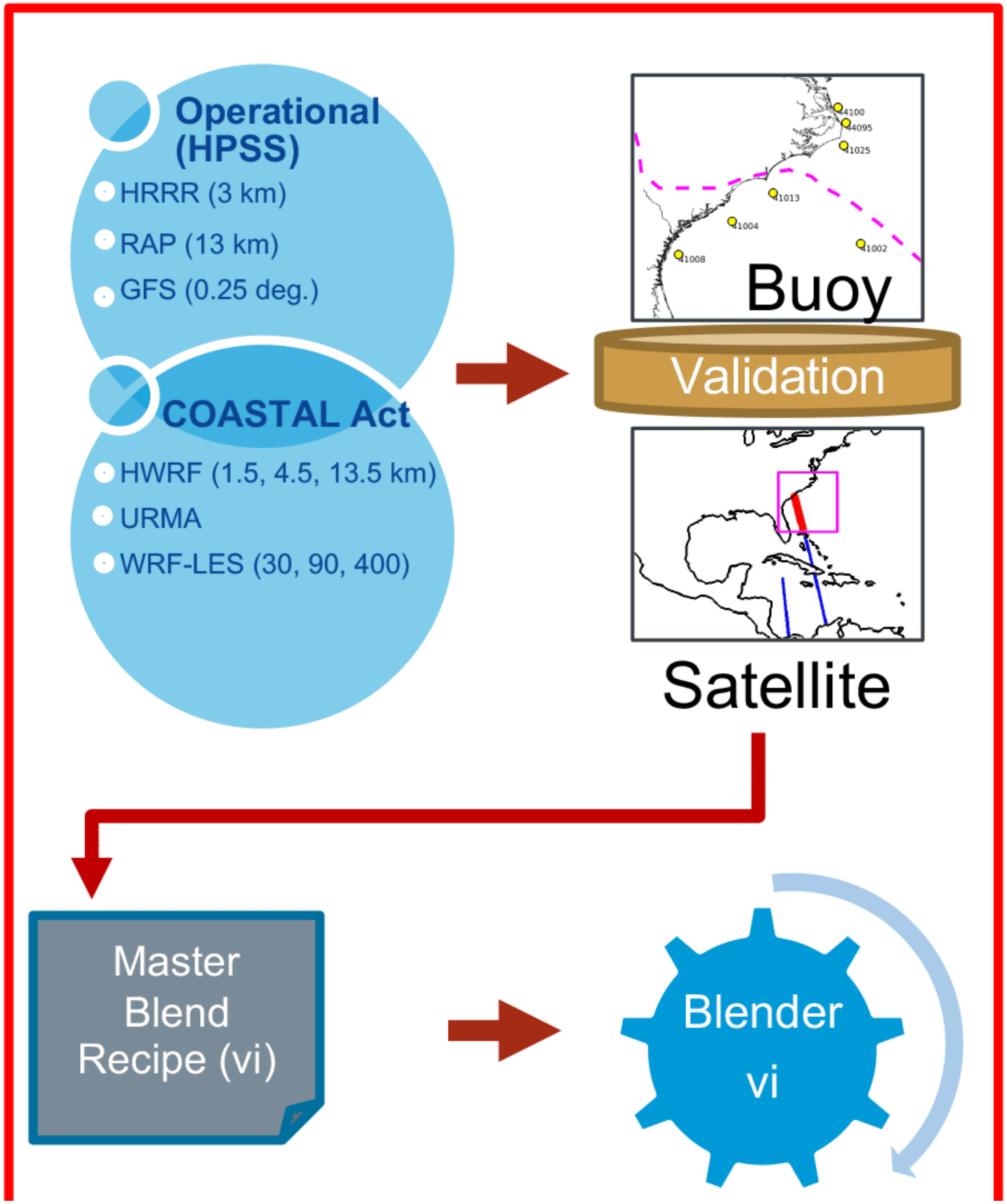
- That the sampling distribution of d_i is a normal distribution.
- That the d_i samples are independent.

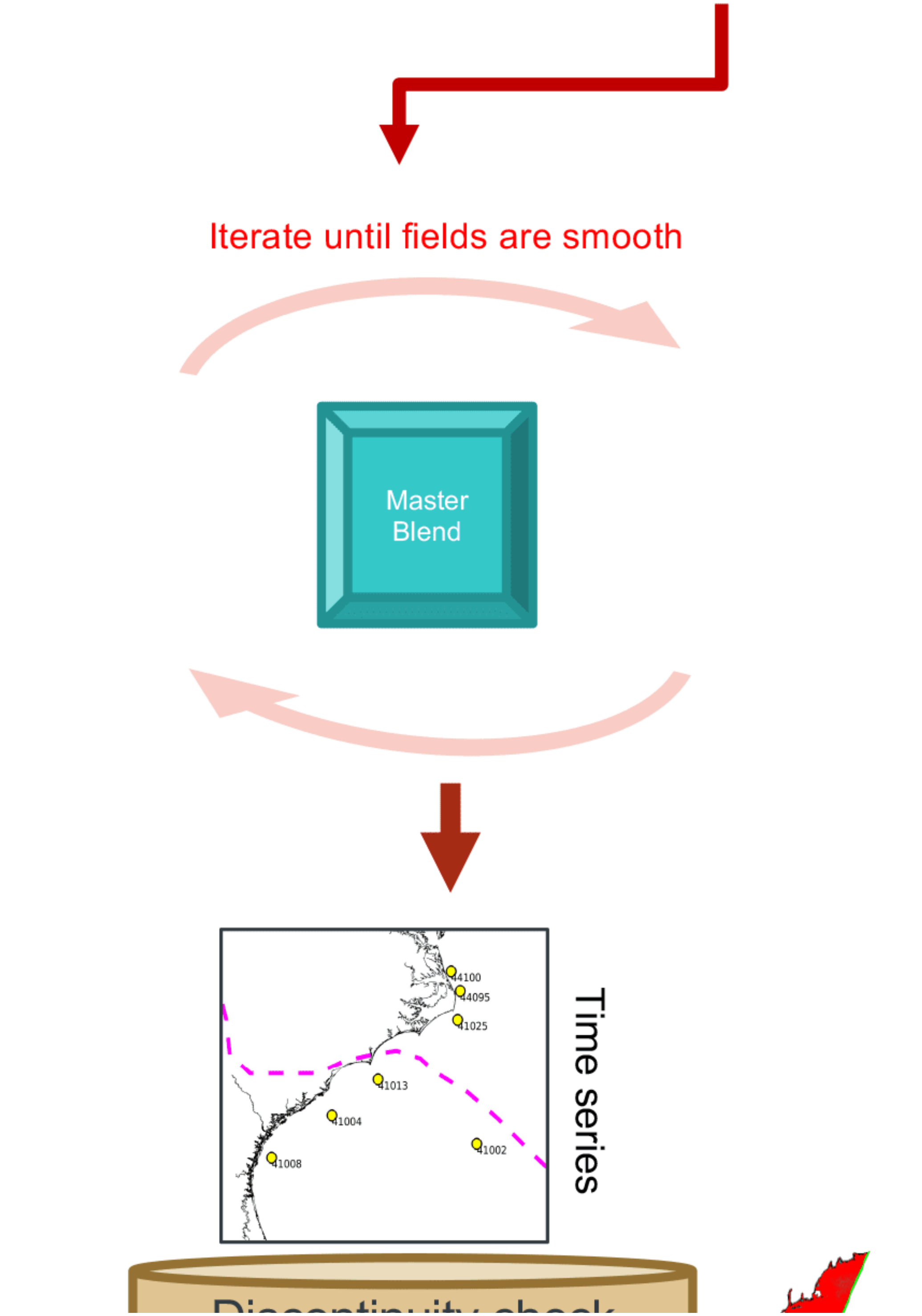
The hypothesis test is conducted at the standard level of significance of $\alpha = 0.05$. This means that the null hypothesis that the mean difference between two time series at a given station is less than 0.1 (or 10%) should be rejected if the p-value of this statistical test is < 0.05. In practical terms, this means that the probability of erroneously rejecting the null hypothesis (that 90% accuracy is met), given that it is true, is less than 5%. See Abdolali et. al (2021) for more info.

Uncertainty Evaluation via ensemble modeling:

Conventionally, the time series of observations at fixed in situ locations such as meteorological stations, wave buoys, tide and stream gauges, and Spatio-temporal along-track satellite data are used to assess the accuracy of atmospheric, wave, and surge models. However, these data are sparse, often not covering the area of interest where the damage needs to be determined and sometimes unavailable within the landfall time window. To fill this gap, the models run on a given number of ensemble members and the spread of results as an estimate of model uncertainty is calculated. These data can be used as a measure of the model's accuracy over the entire model domain, notably in regions away from the available observations. See Abdolali et. al (2021) for more info.

IV- ATM-BLENDING




Iterate until fields are smooth
Master Blend
Time series
44100
44095
41025
41013
41004
41002
41008

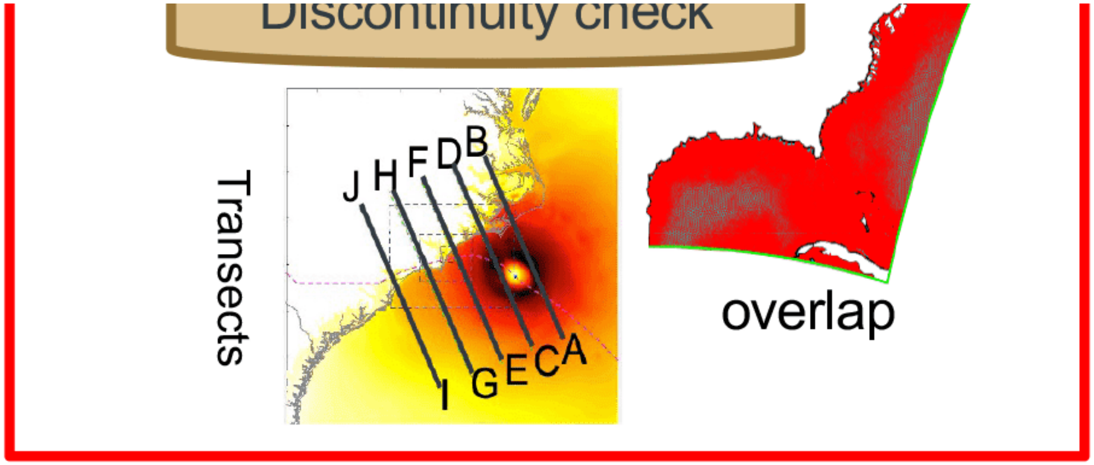


Figure 5- atm-blending workflow (For Official Use Only - Pre-decisional information).

The Hurricane Weather Research and Forecasting (HWRF) model serves as the main atmospheric engine to provide high resolution forcing along the hurricane track and at reduced resolution away from the storm. The HWRF data is available from the genesis of the hurricane to a few cycles after the landfall till the end of the storm life cycle and it covers the entire hydrodynamic domain on moving inner nested grids (core, storm, synoptic). The other COASTAL Act atmospheric model (Weather Research and Forecasting-Large Eddy Simulation WRF-LES) has a much smaller spatiotemporal coverage (~ 1 day near the landfall time and in the impacted area). The COASTAL Act utilizes other NOAA operational atmospheric models listed in Table 1.

Table 1- Temporal and spatial coverage of the existing atmospheric models in use in the atm-blend.

ATM Model	**Spatial Resolution**	**Spatial Coverage**	**Temporal Coverage**
WRF-LES	30/90/400 m	Impacted Area	~1 day (landfall)
HWRF	Moving (1.5/4.5/13.5 km)	Hurricane Track	Hurricane Genesis-Landfall
HRRR	3 km	CONUS	24/7
Rapid Refresh (RAP)	13.5 km		24/7
GFS	0.25 degrees	Global	24/7

Based on the requirements identified by downstream models in COASTAL Act, 8 variables, listed in Table 2, are required.

Table 2- Forcing variables

Variable Name (Standard)	**Variable Name (Master Blend)**	**Long Name**	**Unit**	**Receiving Model**
UGRD_10maboveground	U2D	U-Component of Wind 10 m above ground	m/s	WW3/ADCIRC/NWM
VGRD_10maboveground	V2D	V-Component of Wind 10 m above ground	m/s	WW3/ADCIRC/NWM
PRES_surface	PSFC	Surface Pressure	Pa	NWM
PRMSL_meansealevel	P	Pressure Reduced to MSL	Pa	WW3/ADCIRC
TMP_2maboveground	T2D	Temperature 2 m above ground	K	NWM
SPFH_2maboveground	Q2D	Specific Humidity 2 m above ground	kg/kg	NWM
PRATE_surface	RAINRATE	Precipitation Rate at surface	kg/m^2/s	NWM
DSWRF_surface	DSWRF	Downward Short-Wave Radiation Flux at surface	W/m^2	NWM
DLWRF_surface	DLWRF	Downward Long-Wave Radiation Flux at surface	W/m^2	NWM

An atm-blending tool for blending the required fields is developed at NOAA for atmospheric models listed in Table 1. The blended product (Master Blend) is on a 0.015 degree resolution regular grid covering the entire WW3-ADCIRC-NWS domains in NetCDF (shown in Figure 6).

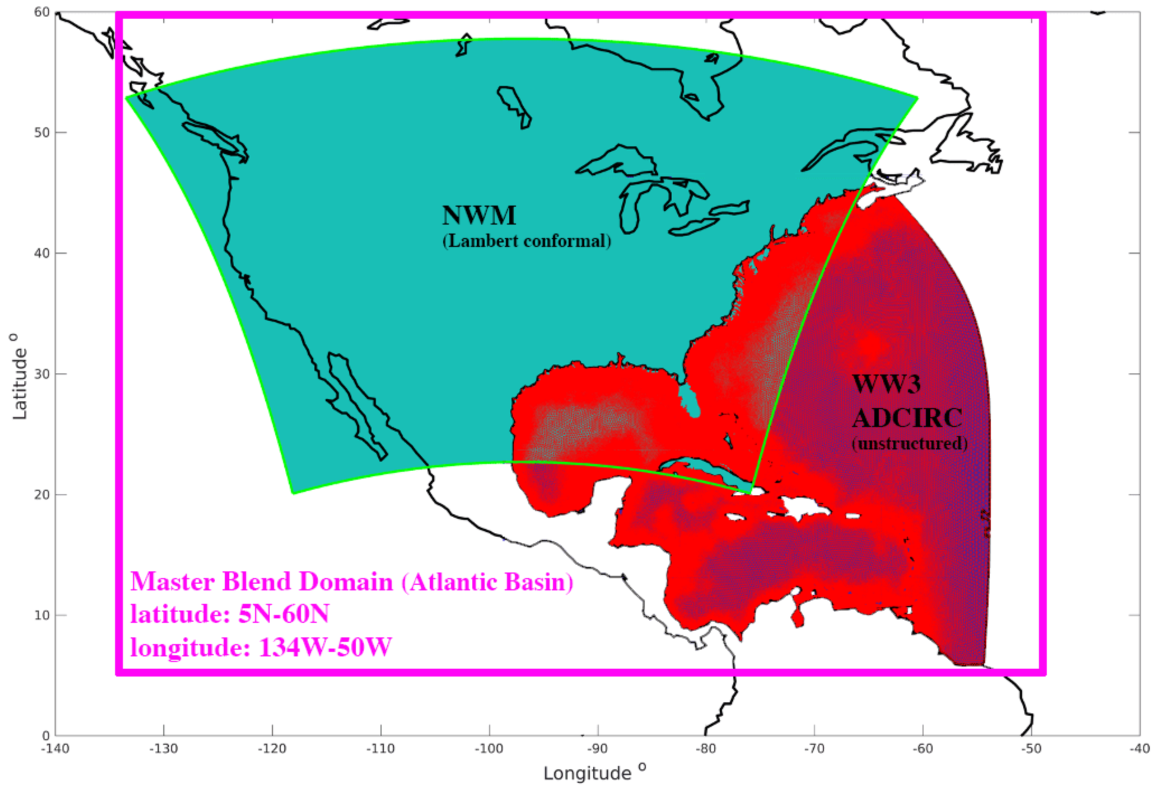


Figure 6- WW3-ADCIRC, NWM, and master blend domains (For Official Use Only - Pre-decisional information).

The tool retrieves, interpolates and blends specific operational atmospheric forcings (GFS, HWRF, RAP, HRRR) for specified variables for a domain of interest (Figure 5). A numerical recipe based on evaluating the blended fields against in situ (stations) and remote met observations (satellite altimeters) is then optimized for finalizing blended fields (Figure 6, 7). These fields can then be interpolated from structured grids to triangular unstructured meshes for downstream models.

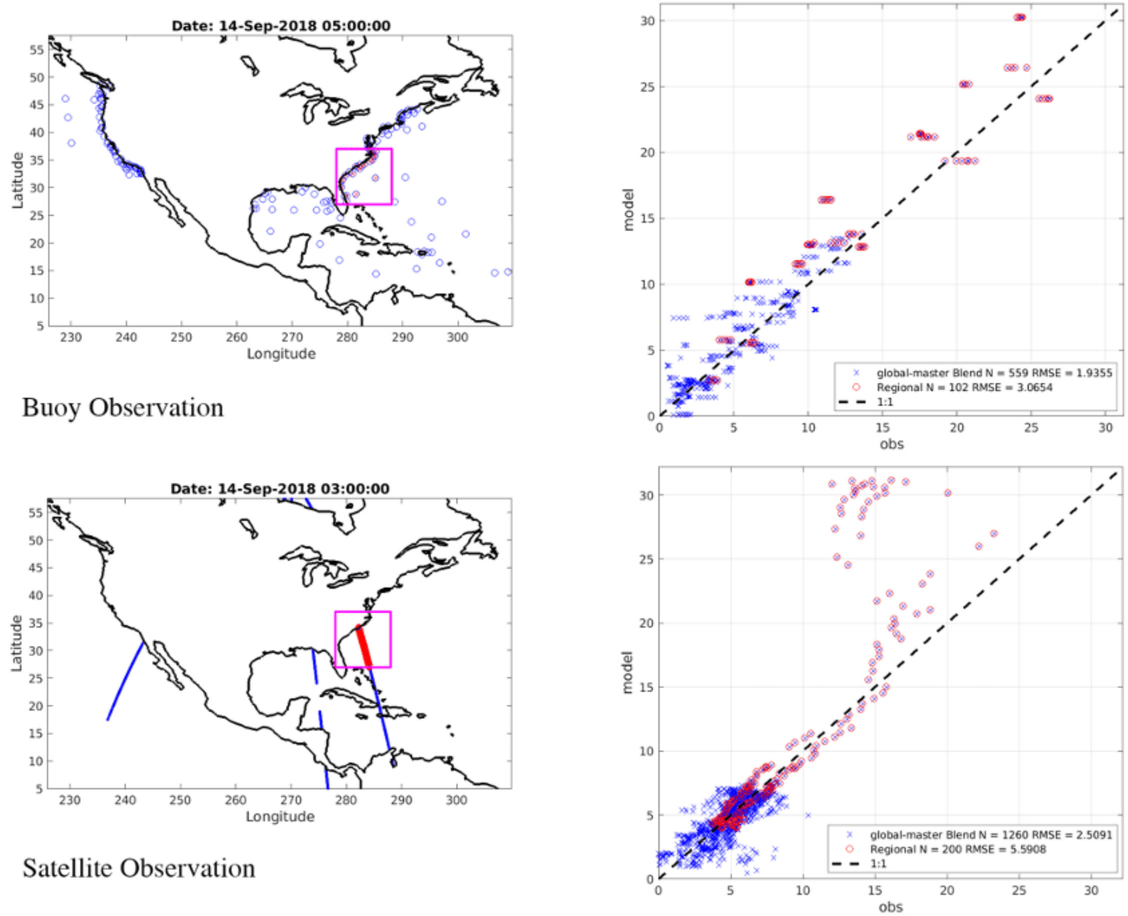
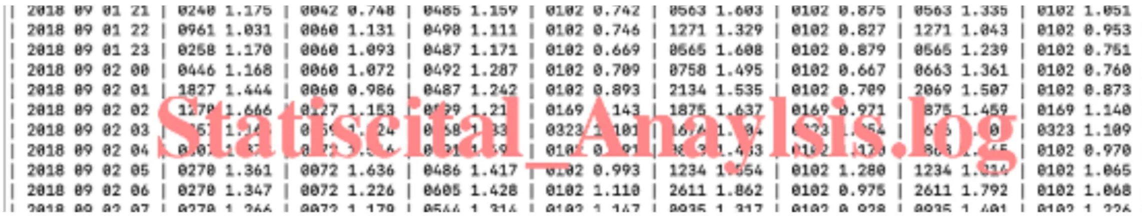


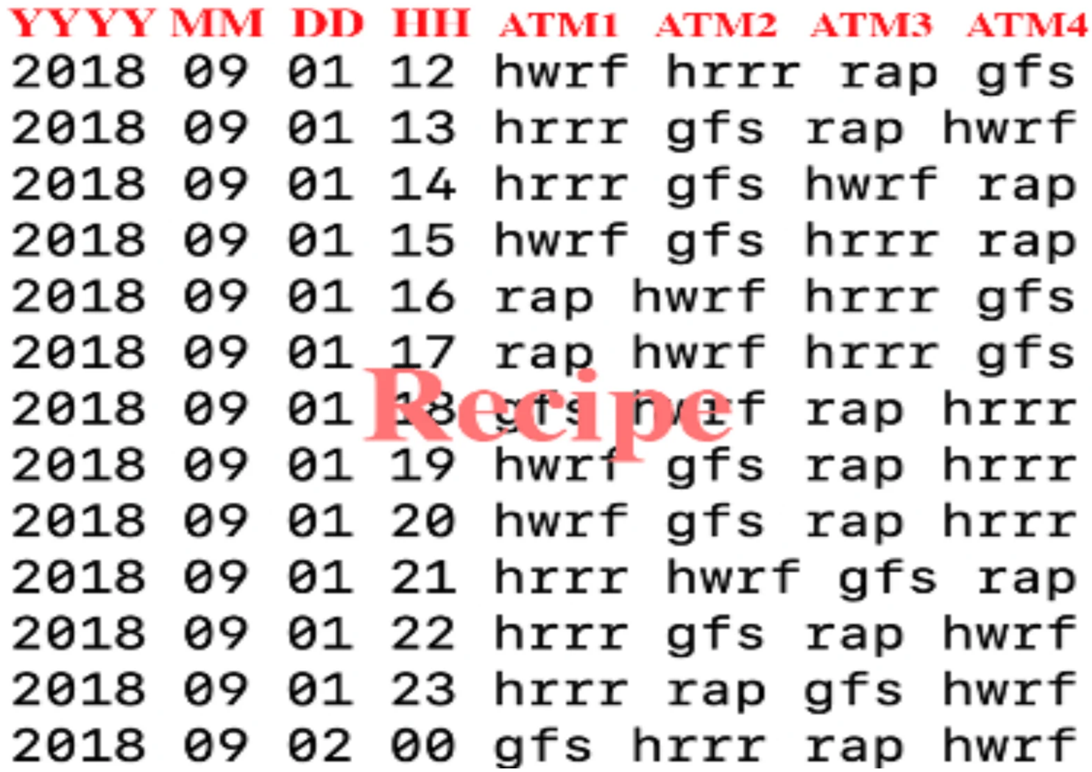
Figure 7- Satellite and buoy data comparison with atm-model components within the master blend and impacted area (For Official Use Only - Pre-decisional information).

lon_min 278.000 lon_max 288.000 lan_min 27.000 lat_max 37.000

Date	hwrf				hrrr				gfs				rap			
	Global		Regional		Global		Regional		Global		Regional		Global		Regional	
YYYY MM DD HH	no	error	no	error	no	error	no	error	no	error	no	error	no	error	no	error
2018 09 01 12	0873	1.143	0042	0.870	0670	1.490	0102	1.316	1435	1.343	0102	1.430	1385	1.305	0102	1.351
2018 09 01 13	0240	1.168	0042	0.942	0678	1.316	0102	0.881	1004	1.361	0102	0.890	1004	1.352	0102	0.909
2018 09 01 14	1694	1.399	0042	0.906	0681	1.607	0101	0.832	2229	1.513	0101	0.984	2229	1.505	0101	1.034
2018 09 01 15	0536	1.205	0042	0.670	1032	1.206	0102	0.965	1656	1.526	0102	0.934	1656	1.707	0102	1.062
2018 09 01 16	0240	0.999	0042	0.732	0771	1.715	0194	0.777	1545	1.560	0194	0.844	1545	1.706	0194	0.728
2018 09 01 17	0239	1.088	0041	0.892	0505	1.598	0101	0.995	0917	1.613	0101	1.044	0917	1.920	0101	0.860
2018 09 01 18	0240	1.225	0042	0.817	0674	1.804	0102	0.884	1283	1.443	0102	0.782	1283	2.166	0102	0.862
2018 09 01 19	0240	1.111	0042	0.513	0843	1.222	0102	1.045	1529	1.381	0102	0.628	1529	1.192	0102	0.882
2018 09 01 20	0240	1.049	0042	0.565	0492	1.263	0102	0.931	0570	1.646	0102	0.781	0570	1.305	0102	0.930



Atmospheric Models' performance Summary



YYYY	MM	DD	HH	ATM1	ATM2	ATM3	ATM4
2018	09	01	12	hwrf	hrrr	rap	gfs
2018	09	01	13	hrrr	gfs	rap	hwrf
2018	09	01	14	hrrr	gfs	hwrf	rap
2018	09	01	15	hwrf	gfs	hrrr	rap
2018	09	01	16	rap	hwrf	hrrr	gfs
2018	09	01	17	rap	hwrf	hrrr	gfs
2018	09	01	18	gfs	hwrf	rap	hrrr
2018	09	01	19	hwrf	gfs	rap	hrrr
2018	09	01	20	hwrf	gfs	rap	hrrr
2018	09	01	21	hrrr	hwrf	gfs	rap
2018	09	01	22	hrrr	gfs	rap	hwrf
2018	09	01	23	hrrr	rap	gfs	hwrf
2018	09	02	00	gfs	hrrr	rap	hwrf

Sample Recipe for Hurricane Florence (2018)

Figure 8 - Model Performance Summary and Master Blend Recipe (For Official Use Only - Pre-decisional information).

The execution of the atm-blend is semi-automated in the following hierarchical order:

1. ATM Data Retrieval from HPSS archive (HWRF, HRRR, GFS, RAP).

2. Variables extraction (entire Table 2) from the GRIB2 files, interpolate on the master blend domain and write in NetCDF format.
3. Observation Data Retrieval for stationary meteorological stations and along satellite altimeters tracks.
4. Statistical Analysis of each model performance over the entire master blend domain and in the impacted area (Figure 2).
5. Recipe preparation based on the model performances (Figure 3).
6. Master Blend Preparation based on the recipe.
7. Interpolation from the structured lat-lon grid to triangular unstructured mesh for WW3-ADCIRC and to Lambert conformal regular grid for NWM.

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DISCLOSURES

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ABSTRACT

The Named Storm Event Model (NSEM) which includes the atmospheric suite (HWRF[1][1 (https://www.mdpi.com/2073-4433/11/9/888)], HRRR[2], RTMA-URMA[3] and WRF-LES[4]), the coupled wave-surge-riverine modeling system (WW3[5]-ADCIRC[6]-NWM[7]) [2 (%20https://doi.org/10.1029/2019JC015822),3 (https://doi.org/10.3390/jmse8050308)] and a validation suite has been developed to provide definitive estimates of wind and water variables of major landfalling hurricanes, in compliance with the United States COASTAL Act of 2012. Within this framework, the performance of atmospheric products is evaluated and blended fields are generated on a high-resolution grid, using a master blend recipe. The atmospheric data forces the downstream hydro-coupled component which includes the wave (WAVEWATCH III (https://github.com/NOAA-emc/ww3) [4 (https://doi.org/10.1016/j.coastaleng.2020.103656),5 (https://doi.org/10.1007/s10236-020-01426-9)]), ocean circulation (ADCIRC) and hydrological models (NWM). These have been coupled using the community-based National Unified Operational Prediction Capability (NUOPC) layer based on the Earth Systems Modeling Framework (ESMF).

The wind and hydro products are evaluated against offshore and coastal wave buoys, nearshore water level stations, radars and satellite altimeters, as well as USGS rapid-deployment water level and wave gauges placed in the nearshore regions and overland. The NSEM workflow will be presented at the conference, highlighting the advantages of ESMF in model performance improvement and challenges for upstream atmospheric model blending, model coupling, and validation against observations.

1- HWRF (Hurricane Weather Research and Forecasting)

2- HRRR (High-Resolution Rapid Refresh)

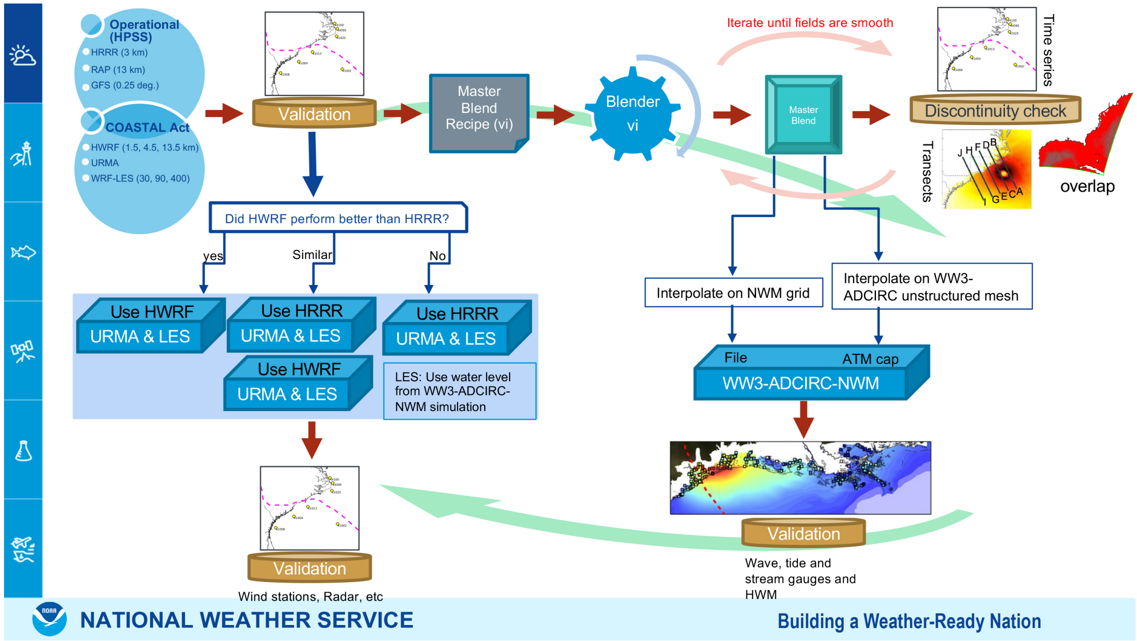
3- RTMA-URMA (Real Time Mesoscale Analysis-UnRestricted Mesoscale Analysis)

4- WRF-LES (Weather Research and Forecasting-Large Eddy Simulation)

5- WAVEWATCH III (WAVE-height, WATer depth and Current Hindcasting)

6- ADCIRC (The ADvanced CIRCulation model)

7- NWM (National Water Model)



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