COASTAL OCEAN RESPONSE TO EXTRATROPICAL STORMS: A RETROSPECTIVE ANALYSIS USING REGIONAL COASTAL OCEAN MODELS OF THE SOUTHEAST ATLANTIC COASTAL OCEAN OBSERVING SYSTEM (SEACOOS)

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The responses of the U.S. southeast coastal ocean to extratropical storm events that occurred in March 2001 are considered from the perspective of the regional observations and models comprising the Southeast Atlantic Coastal Ocean Observing System (SEACOOS). SEACOOS modeling activities are focused on three sub-regional circulation models (with overlapping domains) being operated by UNC, UM, and USF. Each of these sub-regional models employs a three-dimensional, time-dependent, primitive equation formulation, with free-surface and higher order turbulence closure to simulate the tidal and sub-tidal variability of the currents and sea surface height in response to external forcing. In this paper, the ability of these sub-regional models to hindcast the coastal ocean responses to significant extratropical storms as observed during March 2001 is examined. The model solutions are tested under three scenarios in order to discern the effects of tidal mixing and stratification in their respective sub-domains. Comparisons between model hindcasts and *in-situ* observations are made to evaluate each model's performance and an initial attempt at merging the output from these models to describe the response to a set of strong weather events observed in March 2001 is provided. As a starting point, the following questions are addressed:

1. Can three separate sub-regional ocean models provide a coherent description of the coastal ocean circulation in the SEACOOS domain under relatively coherent but strong forcing from synoptic scale weather events?
2. To what degree can the sub-regional models reproduce *in-situ* observations?
3. What could be done to improve the models' fidelity?

The three models (USF, UM and UNC) are used to hindcast and analyze the SEACOOS sub-regional ocean responses to the extratropical storms of March 2001. To do that, efforts have been made to make the model bottom topography, surface and boundary forcing fields, initial conditions and model parameters consistent. However, some differences remains due to the nature of the numerical schemes of each model, and differences in their implementations of lateral and surface boundary conditions. Table 1 lists the model parameters used by the three models, while Table 2 lists details of the models' lateral and surface boundary conditions

Table 1. Model Parameters

Attributes	**UNC**	**U Miami**	**USF**
Model Resolution	0.1-50 km	2-10 km	2-6 km
Time Step (seconds)	60	Internal: 40 External: 4	Internal: 360 External: 12
Nodes	~40000	~` 13000	~10000
Vertical levels	21sigma	21 sigma	21 sigma
Model	Quoddy	POM	POM
Vertical mixing	MY2.5	MY2.5	MY2.5
Horizontal mixing	Smagorinsky c=0.28*	Smagorinsky c=0.2*	Smagorinsky C=0.1*
Scheme of calculating the wnd Stress	Hsu (1995) scheme	Hsu (1995) scheme	Hsu (1995) scheme
Inverse horizontal Prandtl number	1	0.2	1
Min. water depth	2m	2m	2m
Bottom drag coefficient	0.0025	Depth-dependent minimum =0.0025	Depth-dependent minimum =0.0025
Initial T/S profile	Domain averaged Levitus 98 winter climatology	Domain averaged Levitus 98 winter climatology	Domain averaged March 01 shelf hydrography

*: C is the free parameter used in the *Smagorinsky* (1963) scheme quantifying the horizontal mixing.

Table 2. Surface and Lateral Boundary Conditions

Attributes	**UNC**	**U Miami**	**USF**
Global Tide Models used to extract tidal BC's	FES95D LeProvost	OSU- Topex	CCAR Tierney/Kantha
Number of tidal constituents	M_2, N_2, S_2, O_1, K_1 , P_1, Q_1 (8)	M_2, N_2, S_2, K_2, O_1, K_1, P_1, Q_1 (8)	M_2, N_2, S_2, K_2, O_1, K_1, P_1, Q_1 (8)
Tidal potential	No	Yes	No
Surface fields Momentum and Heat Flux	32 km, 3-hourly NCEP EDAS surface fields	32 km, 3-hourly NCEP EDAS surface fields	32 km, 3-hourly NCEP EDAS surface fields
Satellite AVHRR SST relaxation	Yes	Yes	Yes
BC's Sea Surface Height	Tides	Tides	Tides
External Velocity 2-D OBC	N/A	Radiation	Radiation
Internal 3-D Velocity OBC	N/A	Radiation	Radiation

Events' description. Two significant storms occurred around March 5-9 and March 20-24. The surface wind and pressure fields of these synoptic storms are given by NECP/NCAR reanalyses (Fig. 3). The first storm event is a typical Nor'easter. The storm lasts about 2-days, and then weakens when the low-pressure system moved northeastward. This is a large-scale weather system and the resultant surface atmospheric fields over the SEACOOS domain are relatively coherent.

The second storm is of a different nature. It stems from a low-pressure cyclone originating over the Gulf of Mexico. As the cyclone moves eastward the speed and direction of the surface wind field changes over Georgia and the Carolinas. This storm is of smaller scale and with a more spatially heterogeneous wind field than the first storm.

Summary of models' response. The model experiments are conducted under three scenarios, each with increasing complexity: exclusion or inclusion of tides and the exclusion or inclusion of stratification. The same NCEP atmospheric forcing is used for all scenarios in each of individual sub-regional model runs; the resultant solutions are then compared with observations to assess model performance, discrepancies relative to the field observations, and paths toward model improvements. The table below summarizes the three scenario cases to be considered:

Experiment	**Tide**	**Density**
Case I	No tides	Barotropic (uniform density)
Case II	With tides	Barotropic (uniform density)
Case III	With tides	Stratified (density profile from Levitus winter climatology [UNC and UM] or shelf observations (USF)

Cases I and II are intended to identify the importance of elevated mixing due to tidal currents on the shelf responses to synoptic weather forcing. Of the three sub-regions, the largest tides are in the SAB. Stratification plays an important role in the coastal ocean circulation by suppressing mixing and by reducing bottom friction through baroclinic compensation of the surface pressure field. Density stratification is introduced by using the sub-domain averaged density profiles in Case III. More realistic 3-D density field initialization is not possible because domain-wide hydrographic data are not available for the March 2001 time period.

SAB. Consider first the comparisons made at Fort Pulaski and St. Augustine (Fig. 4). All time series are 40 hr low-pass filtered to focus on the sub-tidal variations induced by the storms. In general, the SAB model captures the sea level changes induced by these extratropical storms. Model sea levels in Case II are essentially the same as model sea levels in Case I. Adding stratification in Case III improves the model performance, especially for the second extratropical storm event, which is likely due to reduced bottom friction.

EFS. Moving south the EFS model is run for the same set of simulations. Comparisons between the modeled and observed sea levels indicate that the model that considers tides and local atmospheric forcing only is insufficient to represent the sub-tidal coastal ocean variability. Some small changes are seen in the correlation coefficients and *rms* misfits between Cases I and II (see Fig. 5). Moreover, adding density stratification in Case III does not improve the model skill (In fact, it appears to worsen the solution). It appears that in order to achieve better shelf solution, sub-tidal sea levels (in particular sea level set-up and set-down along the model open boundaries in the shallow water) must be more properly prescribed, dictating a more dynamically sound nesting approach that couples this models with a larger domain offshore model.

WFS. The WFS, being broad and more locally forced does not have such severe problems. Similar modeled and observed sea level comparisons are provided for the WFS model results (Figure 6) at the Apalachicola, Cedar Key, St. Petersburg, and Naples coastal stations. Data and model comparisons indicate good model skill in capturing the sub-tidal variability, demonstrated by correlation coefficients of ~0.9 and *rms* misfits of ~ 0.06m at all stations. Moreover, Cases I and II reveal similar results. Adding stratification basically produces the same model solutions as barotropic runs using uniform density specifications in Cases I and II, although this finding must be tempered by the fact that the March 2001 stratification is weak.

Summary. The SAB and WFS models demonstrate skill at capturing sub-tidal time scale variations in both sea level and currents. Modeling the EFS is found to be more challenging. This is a result of the EFS's sub-regional complexity due to the relatively narrower shelf and the immediately adjacent strong baroclinic FC in the deep water. Compared to the wide SAB and WFS, the shelf of the EFS is narrow and thus less dissipative, and any error in the OBs propagates into the domain interior and is not smoothed. More accurate open boundary condition specifications will be necessary for this sub-regional model to account for sub-tidal variability. Improving the overall SEACOOS modeling effort will require better specification of open boundary values at sub-tidal time scales. Additionally, better specifications of 3-dimensional baroclinicity and inclusion of deep ocean boundary currents are priorities. As global scale operational models emerge, and as alternative basin scale modeling efforts mature, they provide promise for SEACOOS sub-regional modeling efforts to achieve these goals through model nesting.

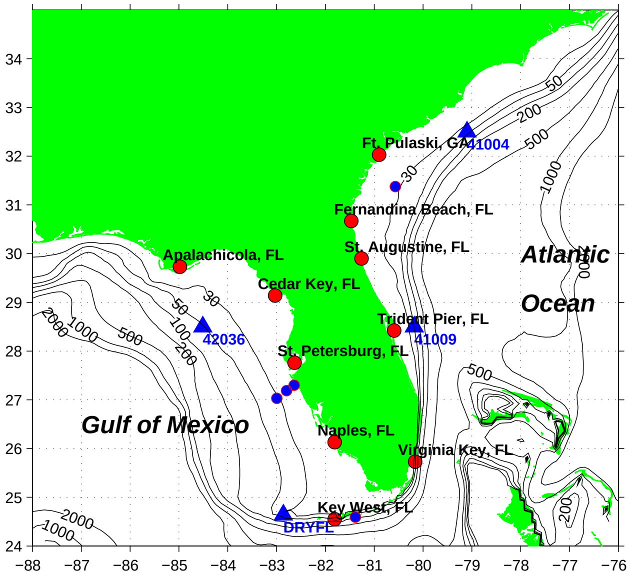

Figure 1. The region of research interest. Coastal tide gauges are denoted by red dots, while NDBC buoys and current stations are indicated by blue triangles and circles, respectively.

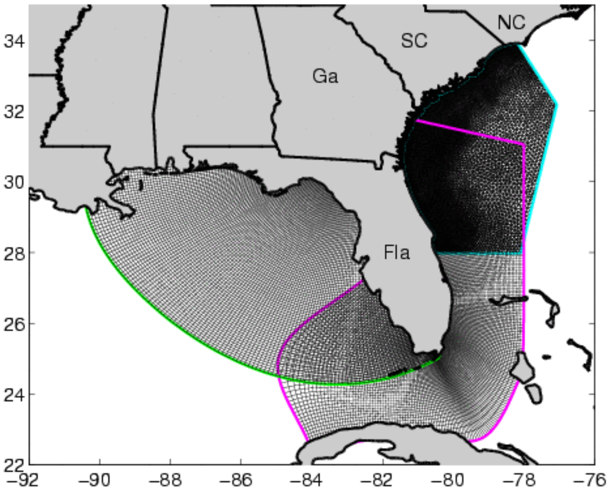

Figure 2. Model grids used to compute circulation on West Florida Shelf (green boundary); East Florida Shelf (magenta); and South Atlantic Bight (cyan for large-scale forcing of red domain where data assimilation is implemented). The grid straddling Cape Hatteras is an extension to include the additional observational sites.

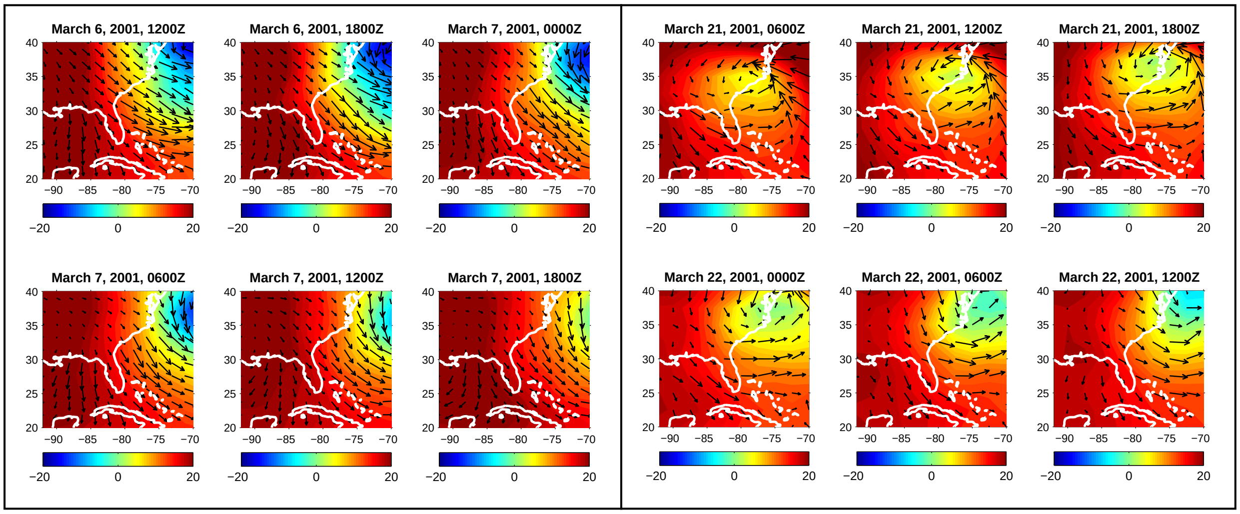

Figure 3. Snapshots of surface wind (indicated by vector) and surface pressure field (subtracted by 1000mb and indicated by color) for extratropical storm 1 (upper six panels) and 2 (lower six panels). Data were obtained from the NCEP/NCAR Reanalysis Project (http://www.cdc.noaa.gov/cdc/reanalysis/reanalysis.shtml).

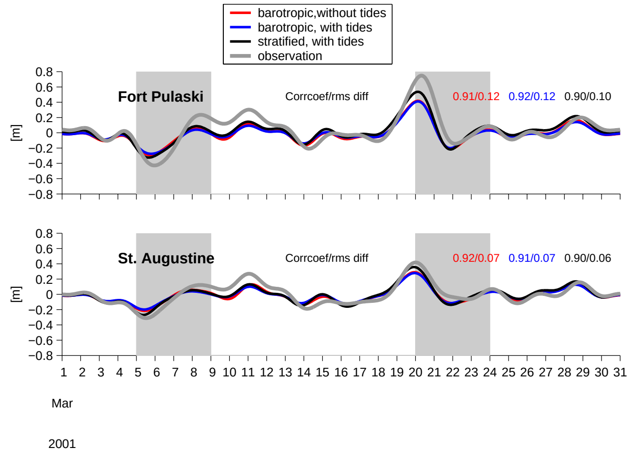

Figure 4. Modeled (from the SAB domain) and observed sea level comparison. Cases I (barotropic, without tides), II (barotropic, with tides), III (stratified with tides) and observations are color-coded with red, blue, black, and gray, respectively. All time series are 40-hr low-pass filtered. The shaded regions indicate storm periods.

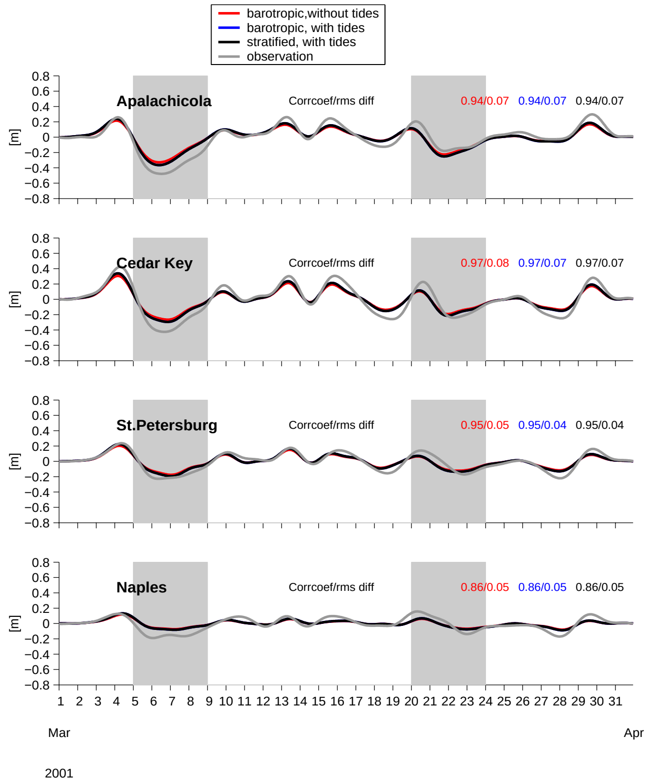

Figure 6. As in Fig. 4 but for the WFS domain. Observed sea level comparison. Cases I (barotropic, without tides), II (barotropic, with tides), III (stratified with tides) and observations are color-coded with red, blue, black, and gray, respectively.

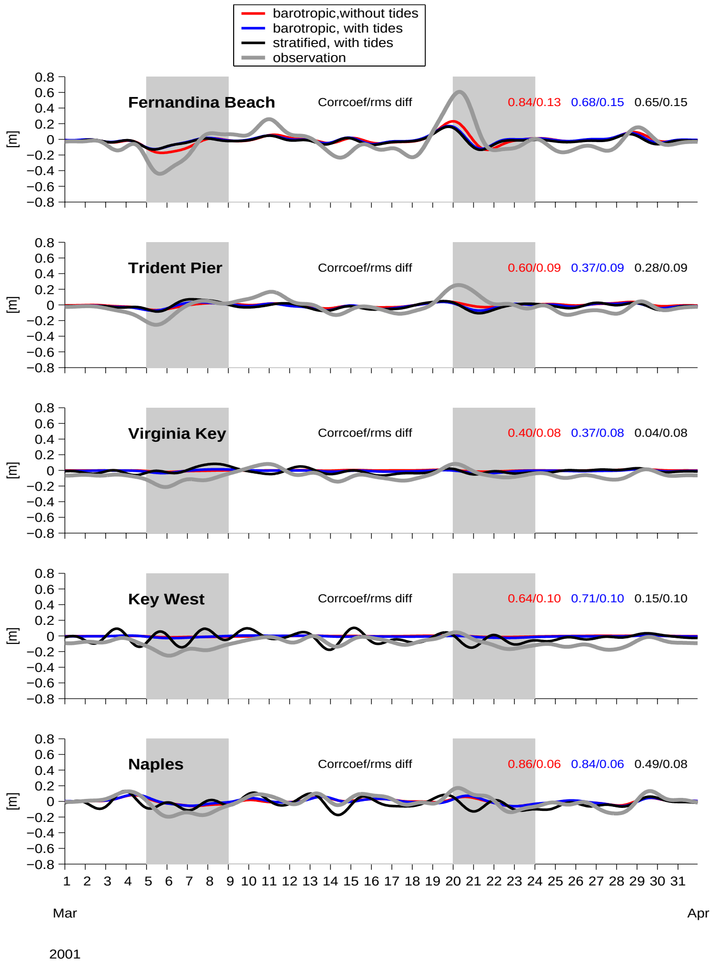

Figure 5. As in Fig. 4 but for the EFS domain. Observed sea level comparison. Cases I (barotropic, without tides), II (barotropic, with tides), III (stratified with tides) and observations are color-coded with red, blue, black, and gray, respectively.