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Climate Projections of Spatial Variations in Coastal Storm Surges Along the Gulf of Mexico and U.S. East Coast

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Abstract Using statistically downscaled atmospheric forcing, we performed a numerical investigation to evaluate future climate's impact on storm surges along the Gulf of Mexico and U.S. east coast. The focus is on the impact of climatic changes in wind pattern and surface pressure while neglecting sea level rise and other factors. We adapted the regional ocean model system (ROMS) to the study region with a mesh grid size of 7–10 km in horizontal and 18 vertical layers. The model was validated by a hindcast of the coastal sea levels in the winter of 2008. Model's robustness was confirmed by the good agreement between model-simulated and observed sea levels at 37 tidal gages. Two 10-year forecasts, one for the IPCC Pre-Industry (PI) and the other for the A1FI scenario, were conducted. The differences in model-simulated surge heights under the two climate scenarios were analyzed. We identified three types of responses in extreme surge heights to future climate: a clear decrease in Middle Atlantic Bight, an increase in the western Gulf of Mexico, and non-significant response for the remaining area. Such spatial pattern is also consistent with previous projections of sea surface winds and ocean wave heights.

Key words storm surge; sea surface winds; climate change; regional ocean

1 Introduction

Under global warming condition, a rising sea level off U.S. east coast is expected to occur due to the thermal expansions effect, glacial melting (Stocker *et al.*, 2013), and a dynamical adjustment of sea level to the possible slowdown of Atlantic Meridional Overturning Circulation (AMOC) (Yin *et al.*, 2009; Ezer *et al.*, 2013). The sea level rising trend makes the U.S. east coast vulnerable to storm-surge flooding (Tebaldi *et al.*, 2012; Ezer and Atkinson, 2014; Lin *et al.*, 2012), especially in low-lying regions with dense population. The potential socioeconomic consequences of extreme storm surge events could be significant.

Associated with a warming climate, the frequency of strong storms, such as winter extratropical cyclones may increase toward the end of this century (Solomon *et al.*, 2007; Allen *et al.*, 2014). A poleward shift of storm tracks in the north hemisphere is also possible (Woollings *et al.*, 2012; Bengtsson *et al.*, 2006, 2009; Stocker *et al.*, 2013). Projected changes in the intensity, frequency, or tracks of winter cyclones can have a direct impact on storm surge and coastal flooding. The situation may become even worse when sea level rise (SLR) is considered (Ezer and Atkinson, 2014; Goddard *et al.*, 2015; Little *et al.*, 2015). Such an impact would be location-dependent due to local geomorphological factors, which further complicate the assessment of impact of climate change along the U.S. east coast (Wells, 1997).

Previous studies of coastal flooding projections for the U.S. east coast were mainly based on statistical methods or numerical models with relative course horizontal resolution (Nicholls, 2004; Kirshen *et al.*, 2008a, 2008b). In this study we apply a high-resolution regional ocean circulation model, driven by newly statistically-downscaled atmospheric forcing to assess variability of winter storm surges under different IPCC scenarios. Here we focus on the impact of wind forcing on coastal surges in the winter season while neglecting other factors. In particular, future sea level rise due to thermal expansions, glacial melting,

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and a dynamical adjustment (*e.g.*, Gulf stream slowdown (Ezer *et al.*, 2013)) can significantly increase coastal damage when it is added to the wind-driven storm surge (Ezer and Atkinson, 2014). Such effect is not included in this paper and will be investigated in our future study.

2 Data and Methods

2.1 Climate Data and Statistical Downscaling

The atmospheric forcing data (surface wind and pressure) were statistically downscaled from the daily output of GFDL (Geophysical Fluid Dynamic Laboratory) CM2.1 global climate model (Delworth *et al.*, 2006). We chose this dataset because ‘it realistically simulate many features of the climate system and has been assessed systematically’ (Gleckler *et al.*, 2008). Given that actual emissions since 2000 have exceeded all SRES (Special Report on Emission Scenarios) emission scenarios, we here examined the worst-case emission scenario (*i.e.*, A1FI SRES) (Schneider, 2009) by comparing with the Pre-Industrial scenario. The A1FI scenario is characterized by intensive fossil fuel usage, rapid economic growth and a global population that peaks in the mid-21 century and then declines. The concentrations of atmospheric carbon dioxide in A1FI scenario could reach up to 940 parts per million (ppm) by 2100, more than the triple of the Pre-Industrial levels (IPCC, 2000).

Although GFDL CM2.1 projection provides valuable information on future large-scale atmospheric circulation, its horizontal resolution is 2.5˚ and thus is too coarse to resolve conditions in the costal ocean. To solve this problem, in a previous study we applied a multivariate statistical model to downscale the daily CM2.1 data of the northwest Atlantic Ocean into a 0.25˚ horizontal resolution. The statistical relationship was built upon the linear regressions between the empirical orthogonal function (EOF) spaces of a high-resolution predictand and coarse resolution predictor (Goubanova *et al.*, 2011). The performance of the statistical downscaling has been validated by the good agreement between downscaled wind fields against *in-situ* observations at 16 National Data Buoy Center (NDBC) buoys for the period of 1992–1999. A total of 100 year (2001–2100) statistical downscaling was performed on wind and pressure fields. Detailed information and the validation of the statistical downscaling method can be found in Yao *et al.* (2016). We noted that although the spatial resolution of climate projections can be improved through a statistical downscaling, the temporal resolution set by the GFDL CM2.1 output (daily) remained the same. This imposes a limitation to use regional downscaled product to resolve fast-moving storm systems through the study area.

2.2 Storm Surge Model

We adapted the Regional Ocean Modeling System (ROMS) (Shchepetkin and McWilliams, 2003, 2005; Haidvogel *et al.*, 2008) to the northwest Atlantic Ocean. ROMS is a 3-dimensional, hydrostatic, free-surface model that has been widely used to study coastal circulation and storm surges (Wang *et al.*, 2008; Li *et al.*, 2006). The model domain encompasses the Caribbean Sea, Gulf of Mexico, and U.S. east coast (Fig.1). The model has a horizontal resolution of 7–10 km, and 18 terrain-following vertical layers. Model bathymetry was extracted and smoothed from the 2-minute ETOPO2 topography dataset using the linear programming method by (Sikiric *et al.*, 2009). A long-term (10-year) average of global HYCOM/NCODA (Chassignet *et al.*, 2009) output was used to prescribe open boundary and initial conditions. Specifically, we used an Orlanski-type radiation condition in conjunction with relaxation (Marchesiello *et al.*, 2001) for temperature, salinity and baroclinic velocity, and the method of Flather (1976) for free surface and depth-averaged velocity. By such settings the remote influence from Atlantic Ocean climate variations is excluded and not considered in this paper.

Because extreme storm-surge often occurs coincidentally with spring tides, we extracted tidal forcing (7 tide constituents M_2, S_2, N_2, K_2, O_1, K_1, Q_1) from the ADCIRC database (Luettich Jr. *et al.*, 1992) and interpolated them along the lateral boundary. Two experiments were carried out: Experiment 1 included both downscaled wind and sea level pressure and tidal forcing, while Experiment 2 only considered tidal forcing. Following the same approach used by Flather and Williams (2000), the coastal subtidal surge heights were defined as the differences in sea level between the two experiments.

Before applying the ocean model to future climate scenarios, we evaluated the model’s performance via a hindcast of coastal sea level variations in the winter of 2008. The hindcast simulation covers the period of August 2008 to April 2009 and was driven by wind and sea level pressure from the 3 hourly North America Regional Reanalysis with a 32-km horizontal resolution (NARR) (Mesinger *et al.*, 2005). Observed water level data from 35 tidal gauges operated by the NOAA National Ocean Service (positions shown in Fig.1) were used to evaluate model’s performance. A 36-hour lowpass filter was applied to both observed and simulated time series to focus on the subtidal sea level variations induced by winter storms.

Fig.2 shows time series comparisons together with Root-Mean-Square Error (RMSE) and correlation coefficients between observed and model-simulated surge heights at six stations: Charleston, Fort Pulaski, Naples, Clearwater Beach, Cedar Key and Panama City. The model reproduced temporal and spatial variations of coastal sea levels reasonably well. The RMS between the model and data are: 6.3 cm, 6.0 cm, 7.5 cm, 7.2 cm, 9.7 cm, and 6.9 cm, respectively. A similar comparison was performed at the rest 30 stations spanning over the study domain. RMSE statistics are provided in Table 1. We note that the model performed better during strong storm events (such as Hurricane Hanna and Ike in early September) than during relative calm weather conditions (*e.g.*, at Charleston and Naples in September and October). While more accurate storm surge simulation requires a higher spatial resolution (Kerr *et al.*, 2013; Chen *et al.*, 2013), we found the ocean model we used can reproduce shelf-wide sea level response reasonably well, giving us the confidence to use this model to study the trend and spatial patterns of storm surges in future climate scenarios.

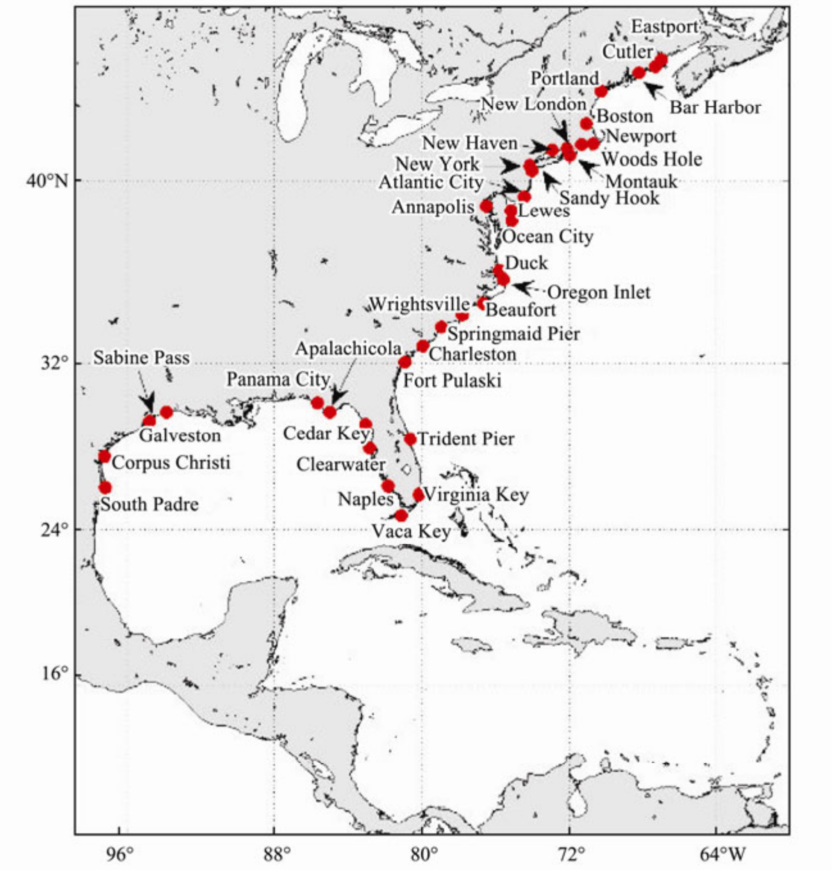

Fig.1 Model domain and location of tidal gages (red circles).

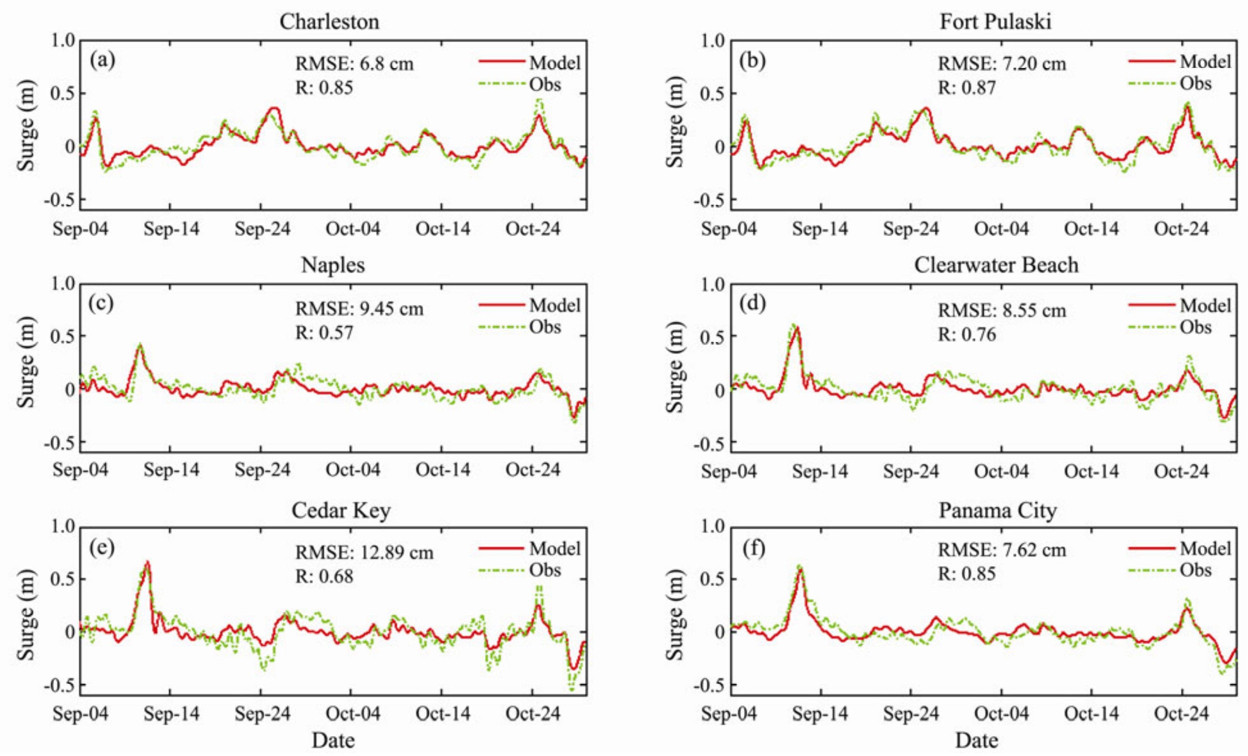

Fig.2 Comparison of the simulated (red) and observed surge (green) for (a) Charleston, (b) Fort Pulaski, (c) Naples, (d) Clearwater Beach, (e) Cedar Key, (f) Panama City.

Table 1 RMS error statistics of the surge elevation between model and observation

Station name	Longitude (°E)	Latitude (°N)	RMSE (cm)
Eastport	−66.9817	44.9033	6.0
Cutler Naval Base	−67.2967	44.6417	6.1
Bar Harbor	−68.2050	44.3917	6.2
Portland	−70.2467	43.6567	6.6
Boston	−71.0533	42.3533	7.3
Woods Hole	−70.6717	41.5233	7.1
Newport	−71.3267	41.5050	6.8
New London	−72.0900	41.3600	7.2
Montauk	−71.9600	41.0483	7.8
New Haven	−72.9083	41.2833	7.8
New York	−74.1417	40.6367	8.2
Atlantic City	−74.4183	39.3550	10.0
Lewes	−75.1200	38.7817	10.7
Ocean City	−75.0917	38.3283	8.4
Annapolis	−76.4800	38.9833	10.5
Duck	−75.7467	36.1833	11.9
Beaufort	−76.6700	34.7200	6.8
Wrightsville Beach	−77.7867	34.2133	5.9
Springmaid Pier	−78.9183	33.6550	6.5
Charleston	−79.9250	32.7817	6.3
Fort Pulaski	−80.9017	32.0333	6.0
Trident Pier	−80.5917	28.4150	5.5
Virginia Key	−80.1617	25.7300	6.4
Vaca Key	−81.1050	24.7117	6.2
Naples	−81.8067	26.1317	7.5
Clearwater Beach	−82.8317	27.9783	7.2
Cedar Key	−83.0317	29.1350	9.7
Panama City	−85.6667	30.1517	6.9
Galveston	−94.7883	29.2850	13.1
Corpus Christi	−97.2167	27.5800	8.9

3 Results

Using the 0.25° downscaled wind and sea level pressure data, we performed two climate scenario experiments, one for the Pre-Industrial (PI) scenario as a control run and the other for the A1FI scenario as the sensitivity run. In each experiment, the model simulation lasts for 10 years (from year 170 to 180 for the PI experiment and from 2069 to 2079 for the A1FI one, GFDL CM2.1 timescale). Sea level differences between the two experiments were examined at the 35 tidal gauge stations listed in Fig.1. The statistics of the difference in surge heights between the two experiments are summarized in Table 2.

The results show an overall decreasing in the extremes (99% percentile) of surge heights in the study domain. The most striking feature is found in the Middle Atlantic Bight (MAB) region, especially from New Haven to Ocean City where the simulated changes in extreme surge heights can be up to 36%. Similar decreasing trend can also be found outside the MAB, except for some sites in the Gulf of Mexico. For the maximum surge height, the changes are very variable but those sites in the MAB still show a large decrease. To assess the significant level of any changes in extreme events, we performed a significant test for the above results. As the extreme events in the PI and A1F1 experiments are generally not normally distributed, a Wilcoxon rank sum test was applied to the number of days with extreme values in a single year. The null hypothesis was that the extreme surge events for both experiments were extracted from the same population. Theoretically, one can rejects this null hypothesis if the *P*-value is smaller than or equal to the significance level (10% for our case) and conclude that the difference of extreme surge events in the two experiments were statistically significant. The *P*-value in Table 2 indicates that difference in extreme surge events between the two experiments is significant only in the MAB region and off the coast of western Gulf of Mexico.

Table 2 Statistics analysis of the surge elevation difference between the future and control run

Station name	99 percentile % change	Maximum surge % change	*P*-value of the Wilcoxon rank sum test
Eastport	−1.32	19.83	0.47
Cutler Naval Base	0.01	8.69	0.43
Bar Harbor	−0.27	3.72	0.31
Portland	−1.66	3.46	0.21
Boston	−8.29	−3.57	0.85
Woods Hole	−11.14	−28.68	0.38
Newport	−16.82	−38.75	0.08
New London	−20.92	−44.63	0.03
Montauk	−20.66	−42.86	0.12
New Haven	−25.63	−35.79	0.03
New York	−28.07	−57.80	0.03
Sandy Hook	−29.06	−58.07	0.03
Atlantic City	−34.10	−45.53	0.01
Lewes	−36.48	−30.91	0.03
Ocean City	−36.19	−27.94	0.02
Annapolis	−20.82	−36.73	0.05
Duck	−23.84	−14.05	0.14
Oregon Inlet	−17.96	−18.81	0.27
Beaufort	−6.43	−0.99	0.27
Wrightsville Beach	−7.26	33.37	0.31
Springmaid Pier	−7.94	31.75	0.38
Charleston	−12.08	29.41	0.21
Fort Pulaski	−16.95	20.39	0.16
Trident Pier	−5.73	−2.10	0.97
Virginia Key	−4.04	0.10	0.73
Vaca Key	−0.58	1.21	0.34
Naples	−0.10	−11.80	0.97
Clearwater Beach	0.89	−10.16	0.97
Cedar Key	3.14	−15.78	0.91
Apalachicola	2.80	−11.17	0.91
Panama City	3.03	−2.45	0.91
Sabine Pass North	5.69	6.28	0.14
Galveston	6.36	18.76	0.06
Corpus Christi	5.18	2.17	0.19
South Padre	3.38	2.39	0.21

We plot the histogram of the surge heights at three sites: *i.e.*, New York, Charleston, and Galveston as the representatives of MAB, SAB and the western Gulf of Mexico, respectively in Fig.3(a–c), which generally confirm our findings in Table 2. The significant decrease in New York and slight increase in Galveston for extreme surge heights are also consistent with the analysis of surface winds in Yao *et al.* (2016).

To further investigate the extreme events, the surge elevations are fitted using a Generalized Extreme Value distribution GEV (l, r, j) (Lionello *et al.*, 2012), where l is the location parameter, r is the scale parameter and j is the shape parameter. All these parameters are estimated by the maximum likelihood method. Long terms series are required for reliable estimates of these parameters. In this study, as the 10-year integration is still not long enough for the long-term return period estimation, we analyzed the 10 largest maxima per year following Wang *et al.* (2008). A 48-h time window (typical time for winter storm durations) was applied to make sure the independence of each data sample for the selection of the yearly maxima. The cumulative probability of the GEV distribution was calculated for the same three sites shown in Fig.3(a–c), and the results are shown in Fig.3(d–f). It is necessary to keep in mind that such probability is based on the annual maximum surge heights. A clear decrease in the extreme surge heights can be found for New York, while an increasing trend exists for Galveston and a weak difference for Charleston, which is also consistent with the finding of histogram plots.

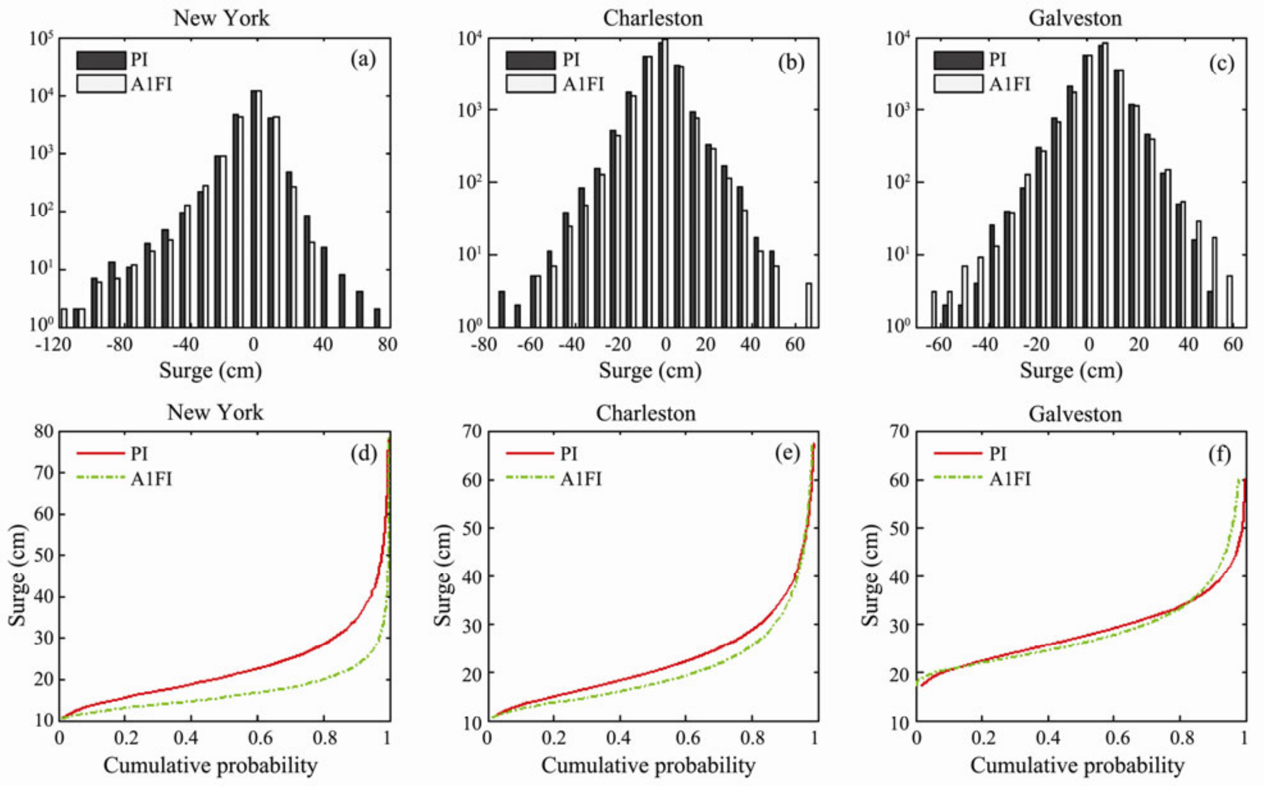

Fig.3 Upper panel: Histogram distribution of the surge events for (a) New York, (b) Charleston, (c) Galveston; Lower panel: Cumulative probability distribution of the annual extreme surge for (d) New York, (e) Charleston, (f) Galveston.

4 Summary and Discussion

Using statistically downscaled atmospheric forcing, we performed a numerical investigation to evaluate the impact of future climate on storm surges along the Gulf of Mexico and U.S. east coast. The regional ocean model was adapted from ROMS with a mesh grid size of 7–10 km, and the model domain encompassed the Caribbean Sea, the Gulf of Mexico, and U.S. east coast. Before the climate application, the model was validated in a hindcast mode to reproduce coastal sea levels in the winter of 2008. The good agreement between model-simulated and observed sea level variations gives us the confidence to use this model as a tool to evaluate surge heights under future climate conditions.

Two climate scenario experiments, including the PI as a control run and the A1FI as a sensitivity one, were performed for a period of 10 years, respectively. The simulated changes (A1FI relative to PI case) in surge heights were analyzed, which identified three types of responses in extreme surge heights under the warming climate: a clear decrease in MAB, an increase in the western Gulf of Mexico and non-significant response for the remaining area. Sea surface winds should be responsible for the above changes in surge heights, which can be further confirmed by the spatially coherent pattern between simulated surge heights in this study and that of the sea surface winds in Yao *et al.* (2016). This result highlights the important role of sea surface winds in climate studies. Another indirect evidence to support our finding comes from Wang *et al.* (2014), who indicated that the ocean wave height is also largely modulated by sea surface winds. Based on multi-model CMIP5 simulation, the variation of wave height as well as its spatial distribution due to a changing climate shows a very similar pattern to our results in this study. Under a warming climate sea surface winds may experience some changes depending on their location, thereby causing adjustments via various dynamic processes. Similarity may be exhibited in responses for various fields due to dynamic linkage, as shown in wave height (Wang *et al.*, 2014) and storm surge in this study. However, as one of the most important factor, the impact of sea surface winds due to global warming still needs to be fully assessed combining both dynamic and thermal processes, especially considering the complexity over coastal regions.

In this study we focus on sea surface winds in order to emphasize its role in storm surges. We understand that many other factors may also play important parts in regulating the storm surge heights, such as sea level rise, changes in ocean circulation, North Atlantic Oscillation (NAO), Atlantic Meridional Overturning Circulation (AMOC), *etc.* For example, Ezer *et al.* (2013) reported an accelerated sea level rising due to the slowdown of Gulf Stream. Goddard *et al.* (2015) pointed out a significant SLR off the Northeast of North America due to the combined effects of AMOC and NAO, with an extremely 128 mm jump around the New York City. Ezer and Aktinson (2014) reported an accelerated flooding along the U.S. east coast induced jointly by SLR, Gulf Stream system, NAO, and others processes. In reality, intensity of storm surge is determined by all factors, and a comprehensive assessment cannot be obtained unless all associated physical processes are considered. Yet the complexity and nonlinearity would make such an assessment less credible especially considering the interactions between these factors. Thus it may be a practical solution to isolate one factor from the others in order to simplify the problem. As one of the most important variables in climate studies, sea surface winds exert both thermal and dynamic effects on ocean, and in this study the impact is isolated by ignoring other factors and then assessed using numerical experiments under different climate scenarios. It should be emphasized that the real response may be different from the above solution when the roles of other factors are included. For example, Little *et al.* (2015) showed a significant increase in storm surge energy when SLR is included. The need of a more comprehensive study is manifested for better understanding the impact of global warming on coastal surge heights.

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