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Investigating the performance of coupled WRF-ROMS simulations of Hurricane Irene (2011) in a regional climate modeling framework

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ABSTRACT

Hurricane Irene (2011) was a category 3 tropical storm that resulted in severe flooding, causing at least 40 deaths and more than $15 billion in damaged property along the US northeastern seaboard (Avila and Cangialosi, 2011). This work analyzes the sensitivity of numerical simulations of this devastating storm to the physical parameterizations in the Weather Research and Forecasting (WRF) model and a coupled modeling framework (WRF and the Regional Ocean Modeling System). Simulations were conducted in two 16-member physics ensembles, each included two radiation schemes, two cumulus schemes, two microphysics schemes, and two planetary boundary layer schemes. The simulations were evaluated primarily on the accuracy of the simulated track and the intensity of the storm compared to observations over a period of 5 days centered on the storm's maximum intensity. Cumulus and planetary boundary layer parameterizations were the most influential physics schemes with radiation and microphysics having much smaller effects. The simulated track, intensity, translational speed, and rainfall rate were particularly sensitive to cumulus schemes given the differences in representation of shallow convection. Tracks and rainfall rates also showed sensitivity to the inclusion or exclusion of local effects in the parameterization of planetary boundary layer processes. Using a grid spacing of 12 km, coupling an ocean model to WRF affected the storm track (with increased sensitivity to the cumulus scheme selected) and translational speed, but had very little effect on the rainfall rate or intensity of the storm. In terms of track accuracy, the optimal combination of physics parameterizations for WRF is not necessarily optimal for the coupled WRF-ROMS system.

1. Introduction

Tropical cyclones (TCs) present some of the greatest threats to life (Doocy et al., 2013) and damage to property (Blake et al., 2011). Consequently, the present and future climatology of TCs has been the subject of numerous modeling studies (Zhu and Zhang, 2006; Bender et al., 2010; Done et al., 2013; Doi et al., 2013; Strazzo et al., 2013; Park et al., 2014; Holland and Bruyère, 2014), many of which suggest that tropical storms will change in terms of frequency of occurrence, track, and intensity as a result of future climate change. While most climate models predict increases in intensity of the strongest storms, they also tend to predict an overall decrease in the total number of TCs (Walsh et al., 2016). Additionally, a number of studies have focused on analyzing systematic changes to TC characteristics such as intensity, wind speed, precipitation rate, translational speeds, and tracks (e.g. Kossin et al., 2016; Parker et al., 2018; Gutmann et al., 2018). These studies suggest that there could be significant changes to TC characteristics with climate change. However, the predictions are variable and sensitive to basins and TC cases. Furthermore, the reliability of these results remain a subject of debate due to the uncertainties in observed TC data and known deficiencies in the models used for predicting the future climatology of TCs. One of the greatest deficiencies in regional climate models for future predictions is a lack of coupling between atmosphere and ocean models (Chen et al., 2007).

Sea surface temperatures (SSTs) are a primary factor in cyclogenesis and a major contributor to the subsequent intensification of a TC (e.g. Bruyère et al., 2012). SSTs play an important role in the life cycle of a TC. However, TCs also have an important impact on the ocean surface.

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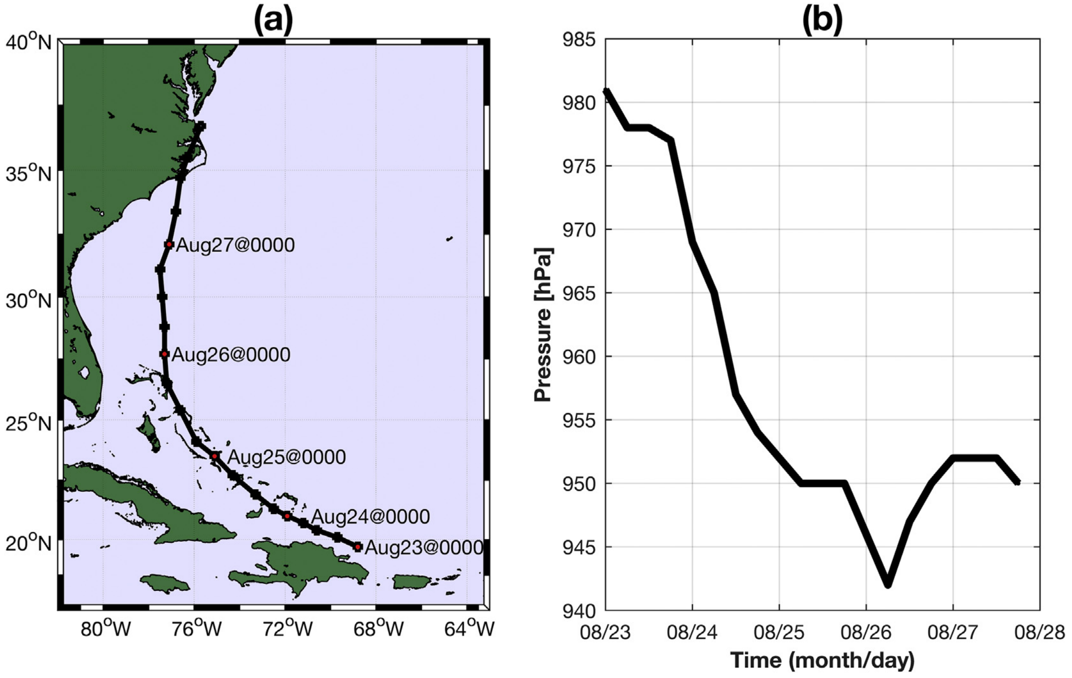

Fig. 1. (a). Map showing the best track positions of hurricane Irene obtained from the US National Hurricane Centers (Avila and Cangialosi, 2011). (b) Observed sea level pressure in hPa (hurricane intensity) for hurricane Irene.

TCs can cool the SST by up to 9 °C (Lin et al., 2003) and leave behind cold wakes that can extend for hundreds of kilometers adjacent to the storm track (Dare and McBride, 2011). These SSTs often recover to their climatological values within 30 days (Dare and McBride, 2011), but can take up to 60 days (Hart et al., 2007). Lingering cold wakes can impact further seasonal TC activity due to interaction with later storms and possibly dampening intensification (Balaguru et al., 2014). This additional mixing may also be important on longer time scales through its impact on the large-scale, slowly varying ocean overturning circulation, and may affect the long-term climatology of TCs (Dare and McBride, 2011). Thus, the impact of individual TCs on the ocean surface can have an impact on subsequent TCs on seasonal to decadal time scales. Using coupled atmosphere-ocean models in regional climate studies of TCs is essential for capturing the dynamic interactions between the atmosphere and the ocean during and long after the passage of a TC.

While coupling has been used in numerical weather prediction of TCs (e.g. Bender and Ginis, 2000; Bender et al., 2007; Bao et al., 2000; Chen et al., 2007), it is in its infancy in regional climate modeling. The poor representation of atmosphere-ocean interactions is largely due to the high computational costs of running coupled simulations over long periods of time covering very large domains, e.g., the North Atlantic basin. Prior to application of a coupled atmosphere-ocean modeling system to regional climate studies of TCs, it is necessary to understand the strengths and limitations of the coupled system so that accurate conclusions can be drawn from such studies. Precursor studies are also essential for identifying optimal configurations of the regional climate model. However, carrying out multiple, long-term, coupled atmosphere-ocean simulations for the purpose of identifying optimal configurations involving multiple models is computationally intensive and expensive. Several authors (e.g. Jankov et al., 2005; Evans et al., 2012) have addressed this difficulty of computational expense by investigating one or more short-term, extreme events with multiple simulations using different model configurations. This experimental methodology produces a more comprehensive evaluation of different model configurations while minimizing computational time.

This study applies the event-based approach to investigate the suitability of a coupled WRF-ROMS modeling system to regional climate studies of TCs. Thirty-two simulations of TC Irene (2011) have been produced; the first sixteen simulations use only the WRF model while the other sixteen use the coupled WRF-ROMS system.

TC Irene was chosen as the test case because the air-sea interactions were important for forecasting the intensity of Irene. Details of TC Irene are provided in the following section. Section 3 describes the regional climate model and coupled model setup, initialization and forcing data together with the observed data used for model evaluation. Section 4 presents the results while Sections 5 and 6 summarize the results and describe our conclusions. This study adds to the current understanding of the strengths and limitations of ocean coupling for simulating the climatology of TCs in the North Atlantic with a coupled WRF-ROMS modeling system. Additionally, this work demonstrates how coupling interacts with the parameterization of atmospheric processes in WRF and how this can have disparate effects on simulation outcome.

2. Case study

Hurricane Irene has been the subject of some previous studies (Mooney et al., 2016; Yablonsky et al., 2015; Klausmann, 2014) because of the scale of its impact on people and property. While its maximum intensity did not exceed category 3 on the Saffir-Simpson scale, it was a very large storm. Hurricane force winds extended nearly 150 km from the center, which had major environmental and societal impacts. Irene is an example of a TC whose track was forecast with good accuracy by the US National Hurricane Center, but whose intensity did not reach forecast values, primarily because the forecast model underestimated the hurricane-induced upper-ocean cooling (Glenn et al., 2016). In this study, Irene is simulated from the 23rd to the 28th of August 2011. During this period, Irene intensified from approximately 980 hPa to its maximum intensity of approximately 940 hPa. Fig. 1(a) and (b) show the best observed track and pressure for this time, which were obtained from the US National Hurricane Center's reports (Avila and Cangialosi, 2011). By the 23rd of August 2011 Irene had reached hurricane status, and on the 24th of August 2011 it strengthened into a category 3 hurricane when it was between Mayaguana and Grand Inagua in the Bahamas. Irene weakened slightly as it moved over Long Island, Bahamas on the 25th of August at 0000 UTC and turned north-northwest and eventually north around 0600 UTC. This change in