Air-Sea Interaction in Extreme Weather Conditions

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1. Introduction

The vulnerability of coastal areas, e.g. around the North Sea, for storm surges prompts for accurate forecasts, especially in cases of extreme weather. Over the North Sea wind speeds rarely exceed 25 m/s in the present climate. That means that more conventional descriptions of the boundary layer, like a Charnock relation, are adequate for use in atmospheric and oceanic models.
For higher wind speeds, observational data (e.g. Powell et al. 2003; Holthuijsen et al. 2012) show that a Charnock-type drag relation in which the drag coefficient increases monotonically, is not valid anymore and that the drag coefficient levels off around 32–33 m/s.
In a future warmer climate, autumn storms in mid-latitude areas might well get more intensive (Baatsen et al. 2015), and such wind speeds more prevalent. Models that are currently in use for weather and storm surge forecasting use a Charnock relation for the marine atmospheric boundary layer (MABL), and are not able to properly represent such events.
In this paper we investigate the application of alternative parametrizations for the exchange of momentum, heat and moisture between atmosphere and ocean in a limited area atmospheric model. We will not go into the details of the parametrizations, but focus on the ability to forecast extreme storms. Because such extreme storms do not (yet) occur on the North Sea, the models are tested in the Gulf of Mexico with hurricanes Ivan (2004) and Katrina (2005).

2. A sea drag relation for hurricane wind speeds

To include the effect of spray droplets on the drag, which becomes significant for wind speeds above 33 m/s, and also the effects of air-flow sepraration, the standard Charnock drag relation was extended, see Zweers et al. (2010). The resulting drag coefficient is given in Figure 1, which also shows observed data by Powell et al. (2003) and Holthuijsen et al. (2012).

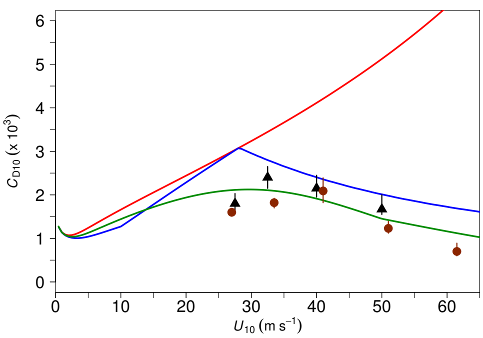

FIG. 1. Drag coefficient as function of the 10-m wind speed. Red is a Charnock relation, blue the extended relation from Section 2, green the parametrization from Section 3. Data points in black are from Powell et al. (2003), in brown from Holthuijsen et al. (2012).

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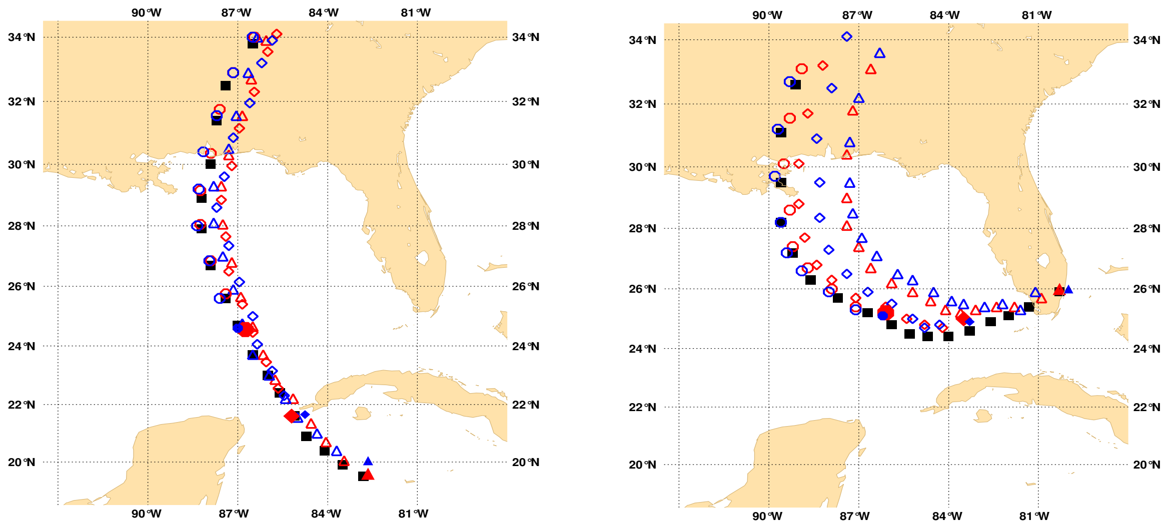

FIG. 2. Hurricane track for Ivan (left) and Katrina (right) with the Charnock relation (red) and the extended drag parameterization (blue), in the 48h (circles), 72h (diamonds) and 96h (triangles) HIRLAM forecasts. Observed tracks according to the National Hurricane Centre are shown in black.

This extended drag relation was built into the NWP model Hirlam and applied in the Gulf of Mexico for hurricanes Ivan (2004) and Katrina (2005). The Hirlam model uses a grid size of 0.05° and 40 vertical levels with the lowest level at approximately 30 m. The dynamics time step is 2 min. Lateral boundary conditions are taken from the European Centre (ECMWF) model archive. Figures 2 and 3 give some key results of these simulations.

The alternative drag parametrization has little effect on the hurricane tracks (Figure 2). The intensity of the storms, however, represented by the maximum 10-m wind speed and the pressure in the centre of the storm, becomes significantly stronger and closer to the observed values from the National Hurricane Center in comparison with a standard Charnock formulation as shown in Figure 3 for the combination of successive Hirlam analyses.

Application to storm surge

The improved hurricane intensity does not automatically lead to higher storm surges, because the increased wind speeds are accompanied by decreased drag. In fact, it can be shown (Zweers et al. 2012) that just decreasing the drag coefficient consistently in the atmospheric and the storm surge model always leads to lower surges.

To test this, the Hirlam simulations for hurricanes Ivan and Katrina were used to drive a 2D-version of the hydrodynamical model Delft3D. Effectively, the wind stress was taken directly from Hirlam, without a separate drag relation in the storm surge model.

Figures 4 and 5 give some time series results for coastal locations. They show indeed that, despite the higher wind speeds with the extended drag relation, the peak of the surge has not increased.

3. The impact of spray-mediated enhanced enthalpy and reduced drag coefficients in the modelling of tropical cyclones

In Section 2, a method was explored that decreases the momentum exchange coefficient in the MABL, but there the ensuing changes in the exchange of heat and moisture are not very large.

This Section will explore a different method, based on Kudryavtsev and Makin (2011), and further developed in Kudryavtsev et al. (2012), in which the impact of spray droplets on the momentum flux is directly accounted for through a spray stress. The model produces a decrease in the drag at very high wind speeds, in agreement with available measurements in these conditions, and the air-sea exchange of enthalpy (heat and moisture) is enhanced. The wind profile is still assumed to be logarithmic with height. In Figure 1 this drag relation is shown in green.

As in Section 2, the new parametrization was implemented in Hirlam and applied to hurricanes Ivan and Katrina.

Sea surface temperatures (SSTs) for the Hirlam surface analysis are taken from the ECMWF archive and remain fixed during the forecast period. This is a valid method in 'normal' weather conditions

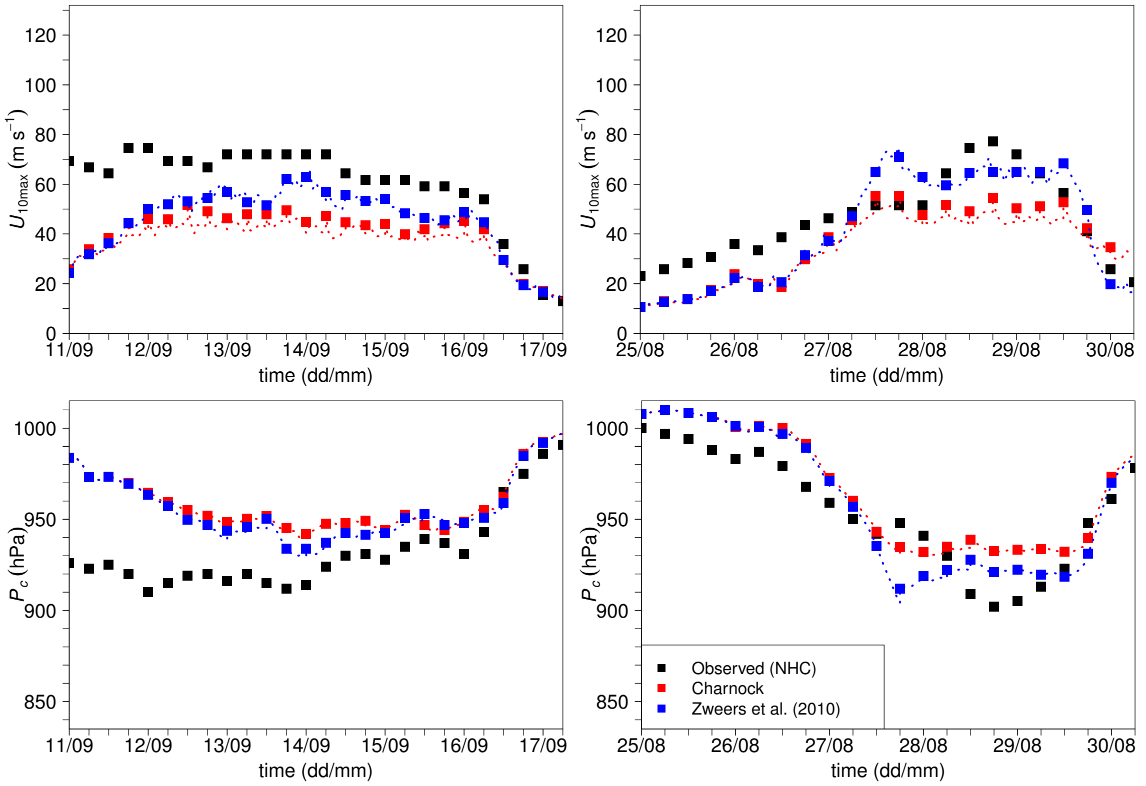

FIG. 3. Maximum 10-meter wind speed (top) and central pressure (bottom) in successive Hirlam analyses for hurricanes Ivan (left) and Katrina (right). Colors are as in Figure 2.

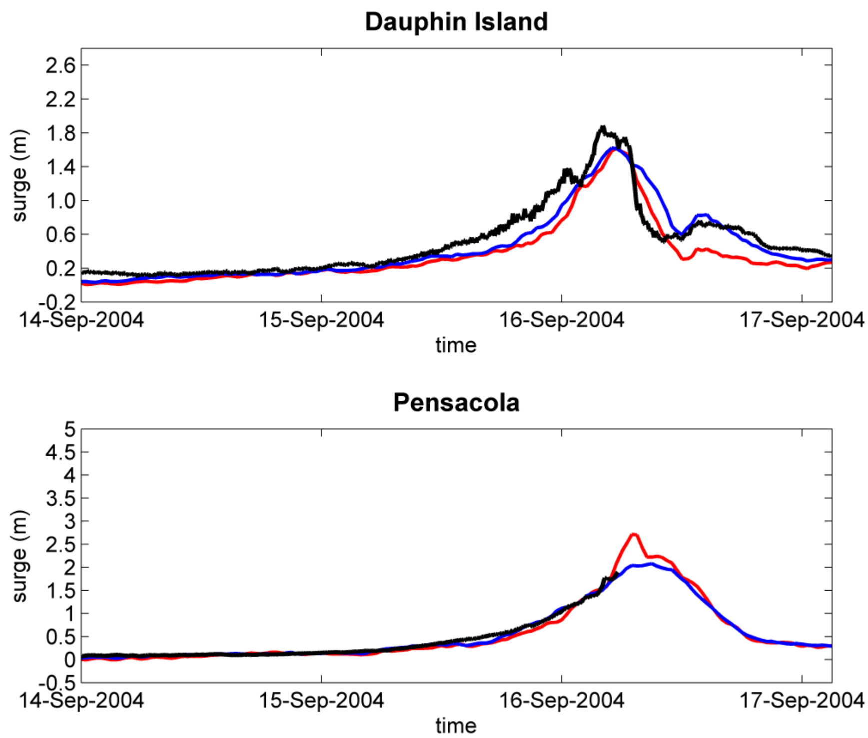

FIG. 4. Storm surges simulated with Delft3D in Dauphin Island and Pensacola during hurricane Ivan. Colors are as in Figure 2, black: observations.

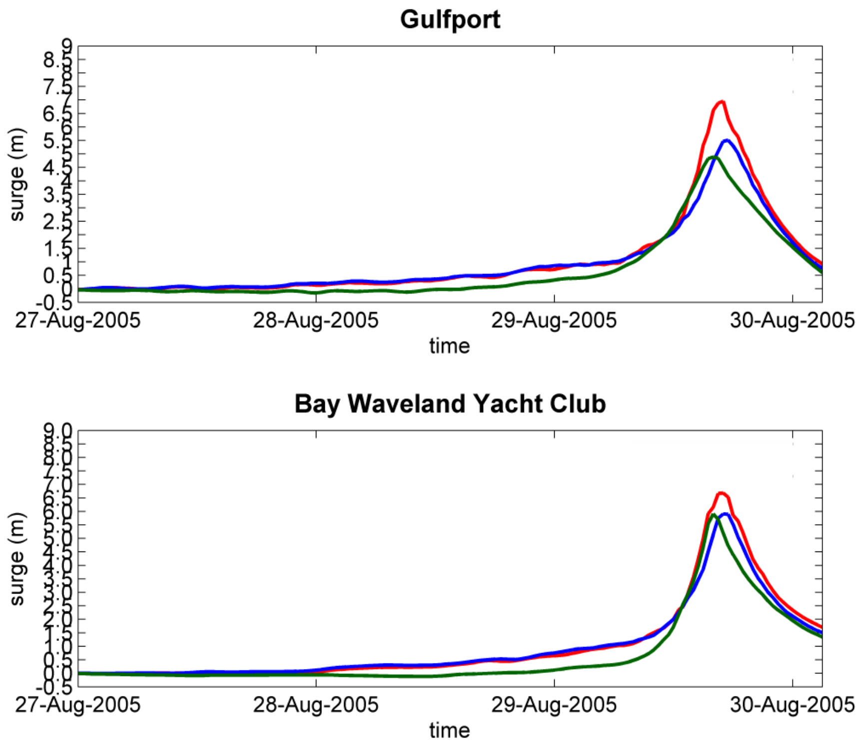

FIG. 5. Storm surges simulated with Delft3D in Gulfport and Bay Waveland Yacht Club during hurricane Katrina. Colors are as in Figure 2, the green curves are driven by the H*wind analysis of the Hurricane Research Division with the extended drag relation.

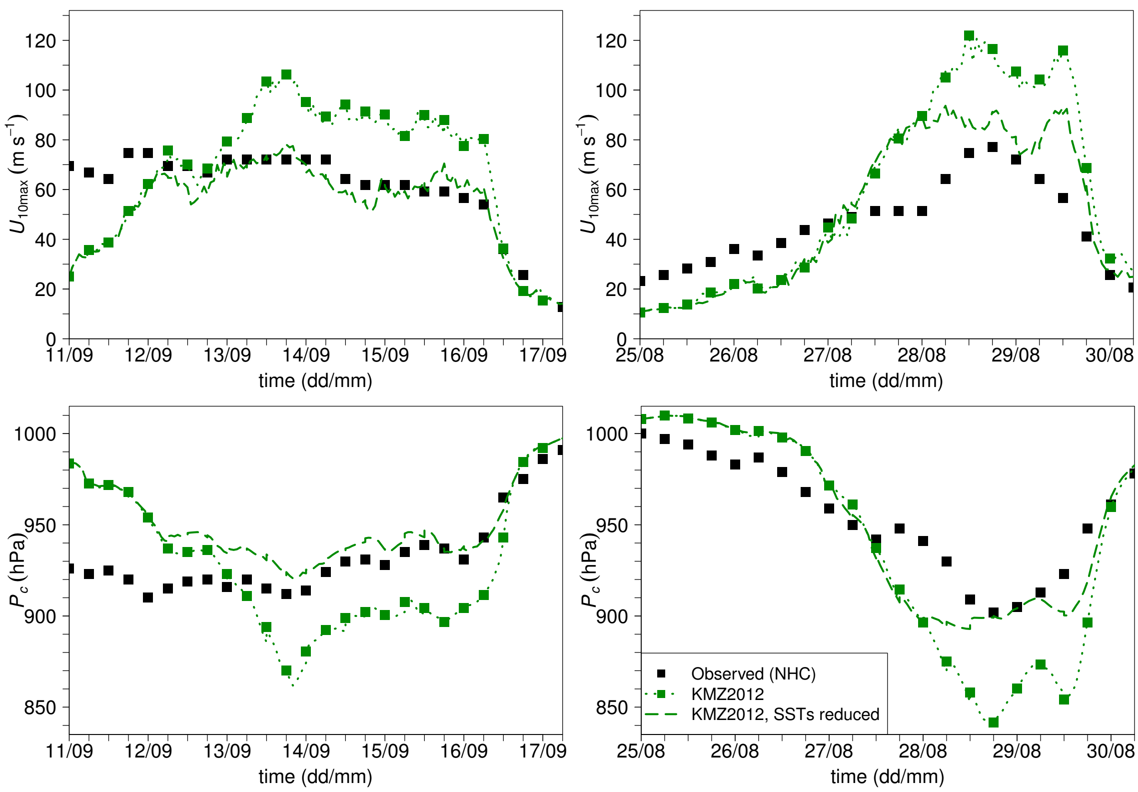

FIG. 6. Maximum 10-meter wind speed (top) and central pressure (bottom) in successive Hirlam analyses for hurricanes Ivan (left) and Katrina (right). Calculations with default SSTs (block-dotted) and reduced SSTs (dashed).

where SSTs do not change rapidly. In hurricane conditions, however, upwelling, currents generated in the upper layer of the ocean and heat uptake by the tropical cyclone, locally reduce the SSTs. This in turn affects the enthalpy exchange and therefore the intensity of the storm.
To account for this, an alternative scenario was also tested in which the SSTs were reduced with 2 K / 12 h in grid points where the 10-m wind speed exceeded 33 m/s.
Results for the maximum wind speed and central pressure in hurricanes Ivan and Katrina are given in Figure 6. This shows simulations with standard handling of the SSTs and also with the reduced SSTs. With the standard SSTs the intensity of the hurricanes are overestimated, but the rather simple reduction of the SSTs underneath the cyclones leads to much more realistic results.

4. Conclusions

For a realistic representation of the intensity of tropical cyclones in a Limited Area NWP model, the drag needs to level off for high wind speeds. Simultaneous increase of the heat and moisture exchange with unaltered SSTs, however, leads to overestimation of tropical-cyclone intensity. But even a simple reduction of SSTs underneath the cyclone leads to much more realistic results.
This suggests that a coupled NWP-ocean model is necessary for proper forecasts of extreme storms.

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