A sea drag relation for hurricane wind speeds

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[1] For the determination of the stress at the air-sea interface and the near-surface wind speed, numerical weather prediction (NWP) models commonly use a drag coefficient. Generally, the Charnock relation is used, which gives an increase in the drag coefficient for increasing near-surface wind speeds. According to observations, however, the magnitude of the drag coefficient levels off at a wind speed of approximately 30 m s^{-1}, and decreases with a further increase of the wind speed. Consequently, the surface drag is overestimated in NWP models for hurricane wind speeds and the intensity of hurricane winds is underestimated in forecasts. In this study, a parameterization that gives a decrease in the surface drag is tested in an NWP model. Two hurricanes in the Caribbean are modeled: Ivan (2004) and Katrina (2005). The results show that this drag parameterization leads to much stronger hurricanes in forecasts, and are in good agreement with observations.
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1. Introduction

[2] The understanding and proper description of energy and momentum exchange at the air-sea interface are of primary importance for hurricane forecasting and modeling. The exchange at the air-sea interface is a two-way coupling. The air-sea exchanges of heat and moisture determine how hurricanes gain their strength from the ocean, while on the other hand the exchange of momentum determines the ocean response. Although in time the prediction of hurricane tracks has improved considerably, the prediction of hurricane intensity is still poor, i.e. the strength of hurricanes is often underestimated [*Black et al.*, 2007]. It was shown by *Emanuel* [1995] that hurricanes can only attain their intensity for a certain ratio of the exchange coefficients of the total enthalpy flux C_k to the momentum flux C_D. Based on this concept, the intensity of hurricanes in model simulations is enhanced by either increasing the latent and sensible heat fluxes [see, e.g., *Andreas et al.*, 2008] or by decreasing the surface drag in order to stabilize the surface momentum flux. In the present study, the description of the surface momentum flux for hurricane wind speeds is studied. The computation of the momentum flux in numerical weather prediction (NWP) models and oceanographic applications involves a formulation for the drag coefficient, which is commonly based on the Charnock relation [*Charnock*, 1955]. According to this relation (see section 2), the drag coefficient increases with increasing wind speed. However, the relation overestimates the magnitude of the drag coefficient for hurricane wind speeds. Indirect evidence that the drag coefficient does not increase with increasing wind speed in hurricane conditions, was given by *Emanuel* [1995]. He concluded that $C_k/C_D \sim$ 1.0–1.5 for hurricane wind speeds. With traditional drag formulations, this ratio would be smaller. Emanuel argued that his results were not consistent with smaller C_k/C_D; then, the wind speeds would be much weaker than observed. Moreover, experimental evidence has been given by analyses of observational data. *Powell et al.* [2003] analyzed wind profiles, which were obtained by releasing Global Positioning System (GPS) drop sondes in tropical cyclones. They showed that the drag coefficient levels off at a wind speed of 33 m s^{-1} and starts to decrease with further increase in the wind speed. Furthermore, *Jarosz et al.* [2007] showed a similar result. Analyzing surface wind speed and current measurements in the water column along the pathway of hurricane Ivan in 2004, they computed the magnitude of the drag coefficient from the along-shelf momentum balance. It was shown that the magnitude of the drag coefficient increases for wind speeds up to around 30 m s^{-1} and then decreases with further increase in the wind speed. The decrease in the drag coefficient for hurricane wind speeds is contrary to the current drag formulations that are used in models, which in general give a monotonic increase with increasing wind speed.

[3] The observed saturation in the surface drag is strongly related to the intensive wave breaking in hurricane conditions. Due to actively breaking waves, the foam coverage at the air-sea interface is enhanced. *Powell et al.* [2003] speculated that this results in the formation of a 'slip' surface, which leads to the reduction of the surface drag for hurricane wind speeds. Moreover, the generation of sea spray is assumed to affect the transfer of momentum significantly. When wave crests are torn off by strong winds, spray droplets are injected into the atmospheric flow. Then, the impact of spray droplets can be described by the theory of the motion of suspended particles in a turbulent flow of incompressible fluid. The essential concept then is that the spray droplets embedded in the atmospheric flow form a stably stratified layer that suppresses the turbulent mixing, which results into acceleration of the flow [see *Kudryavtsev and Makin*, 2010].

[4] *Makin* [2005] suggested that from wind speeds of ~30 m s^{-1} and higher a thin layer adjacent to the sea surface turns to a regime of limited saturation by suspended spray droplets. Then, the Richardson number in this thin layer reaches its critical value, which leads to a reduction in the surface drag and acceleration of the air flow. From the theory of suspended particles in a fluid, Makin was able to explain the observed reduction in the sea drag and he proposed a drag parameterization that accounts for this reduction. In the present study, a drag parameterization that is based on the relation proposed by *Makin* [2005] is tested in a numerical weather prediction model. The impact of this

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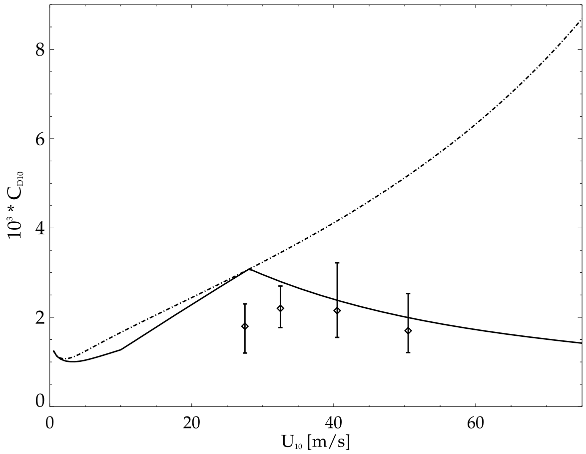

Figure 1. The drag coefficient at 10-meter height as a function of 10-meter wind speed, for the common Charnock relation in (1) (dashed-dotted line) and the new drag parameterization in (2) (solid line). Observational data by *Powell et al.* [2003] are indicated by diamonds.

parameterization on the prediction of the hurricane track and hurricane intensity is examined; a comparison is made to results obtained with the common Charnock formulation. The case studies are hurricanes Ivan (2004) and Katrina (2005), which were in the Gulf of Mexico.

[5] The outline of the paper is the following. In section 2 the parameterization is introduced and more details are given about the simulations. In section 3 the results are presented, followed by a concluding section.

2. Methodology

2.1. Parameterization

[6] In numerical weather prediction models and oceanographic applications, the drag formulation is commonly based on the Charnock relation

$$z_0 = z_* \frac{u_*^2}{g}, \quad (1)$$

with g the acceleration due to gravity, u_* the friction velocity defined according to $u_* = \sqrt{\tau/\rho}$ with τ the surface momentum flux (or stress) and ρ the near-surface air density, and z_* the dimensionless roughness, known as the Charnock parameter. In general the Charnock relation has proven to work well in many applications. However, for very high wind speeds the magnitude of the drag coefficient is overestimated considerably. Consequently, the Charnock relation might not be accurate for surface momentum flux computation in hurricane conditions. Therefore, *Makin* [2005] proposed a drag formulation, based on the common Charnock relation, according to which the surface drag decreases for wind speeds higher than ~33 m s^{-1}. The formulation is given by

$$z_0 = {c_l}^{1-1/\omega} {c_{z_0}}^{1/\omega} \frac{{u_*}^2}{g}, \quad (2)$$

with c_l a constant, c_{z0} represents the Charnock parameter and $\omega = a/\kappa u_*$, with a the fall velocity of spray droplets. For wind speeds up to ~33 m s^{-1} the impact of spray can be neglected ($\omega = 1$) and the relation reduces to the common Charnock relation. For higher wind speeds, the impact of spray droplets becomes significant. A stably stratified suspension layer arises at the air-sea interface, which results into acceleration of the atmospheric flow and reduction of the surface drag. The critical fall velocity (a_{crit}) is reached, which translates into $\omega < 1$.

[7] In the present study, a parameterization based on (2) is tested. We use a wind speed dependent Charnock parameter that was proposed by *Makin* [2003] that also takes into account the effects of air-flow separation:

$$c_{z_0} = c + f_{U_{10}}, \quad (3)$$

with

$$f_{U_{10}} = 0.02[\max[0, \tanh(0.075 U_{10} - 0.75)]], \quad (4)$$

with c a constant. In our parameterization c = 0.0075, which means that the value of c_{z0} converges to a value of 0.025 with increasing reference wind speed at 10-meter height U_{10}. The parameterization is tested in the NWP model HIRLAM (see section 2.2) that uses (1) with z_* = 0.025. We take c_l = 10 and a_{crit} = 0.64 m s^{-1} [see *Makin*, 2005]. Then, the surface drag starts to decrease from U_{10} ~ 28 m s^{-1} and is in fair agreement with the observational data by *Powell et al.* [2003] (see Figure 1). With the same c_{z0}, a decrease in the surface drag from U_{10} ~ 32–33 m s^{-1} could also be realized with a different choice for a_{crit}, but then the drag coefficient would be larger and nearly outside the range of the observational data. On the other hand, a Charnock parameter of 0.010 as suggested by *Makin* [2005] would be much smaller than the model standard value of 0.025.

2.2. Simulations

[8] Hurricanes Ivan (2004) and Katrina (2005) were simulated with the NWP model HIRLAM (High Resolution Limited Area Model, see http://hirlam.org/https://webaccess.knmi.nl/exchweb/bin/redir.asp?URL=http://hirlam.org/ for more information), both with the standard Charnock formulation in (1) with z_* = 0.025 and the new drag parameterization in (2). The hurricanes were modeled on a grid with 0.05 degree resolution that covers the entire Gulf of Mexico. Then, the performance of the parameterization was investigated in two ways. First, experiments were carried out in which analyses and forecasts were performed on a six-hours interval. Here, the initial condition was an analysis from the European Centre (ECMWF). All other subsequent analyses were HIRLAM analyses. The ECMWF analyses were not mixed in, as the extreme conditions during hurricanes are underestimated severely in the ECMWF analysis. During the HIRLAM analyses, which were based on every previous forecast, observational data were assimilated in the HIRLAM 3D-VAR assimilation scheme. Moreover, lateral boundary conditions from the ECMWF were used. The locations of these boundaries were chosen such that they did not affect the hurricanes that were modeled inside the domain. The duration of these simulations was approximately five days.

[9] Secondly, the impact of the drag parameterization was investigated by performing long-term forecasts. The length of the forecasts varied between +48h and +96h. The initial conditions were HIRLAM analyses, which were obtained by

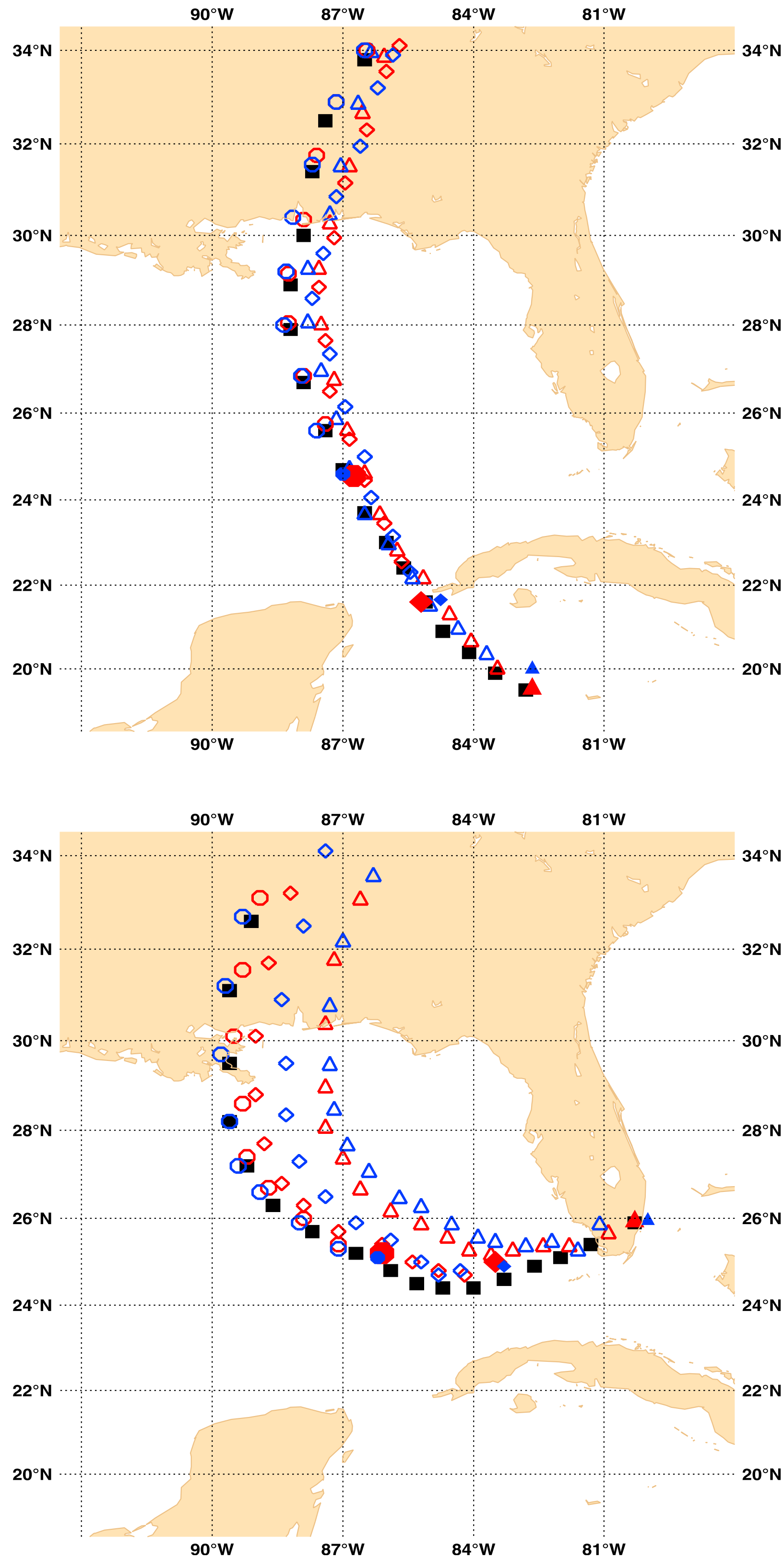

Figure 2. Hurricane track for (top) Ivan and (bottom) Katrina with the Charnock relation (red) and the new drag parameterization (blue; see text), in the +48h (circles), +72h (diamonds) and +96h (triangles) HIRLAM forecasts. Observed tracks according to the National Hurricane Centre are shown in black.

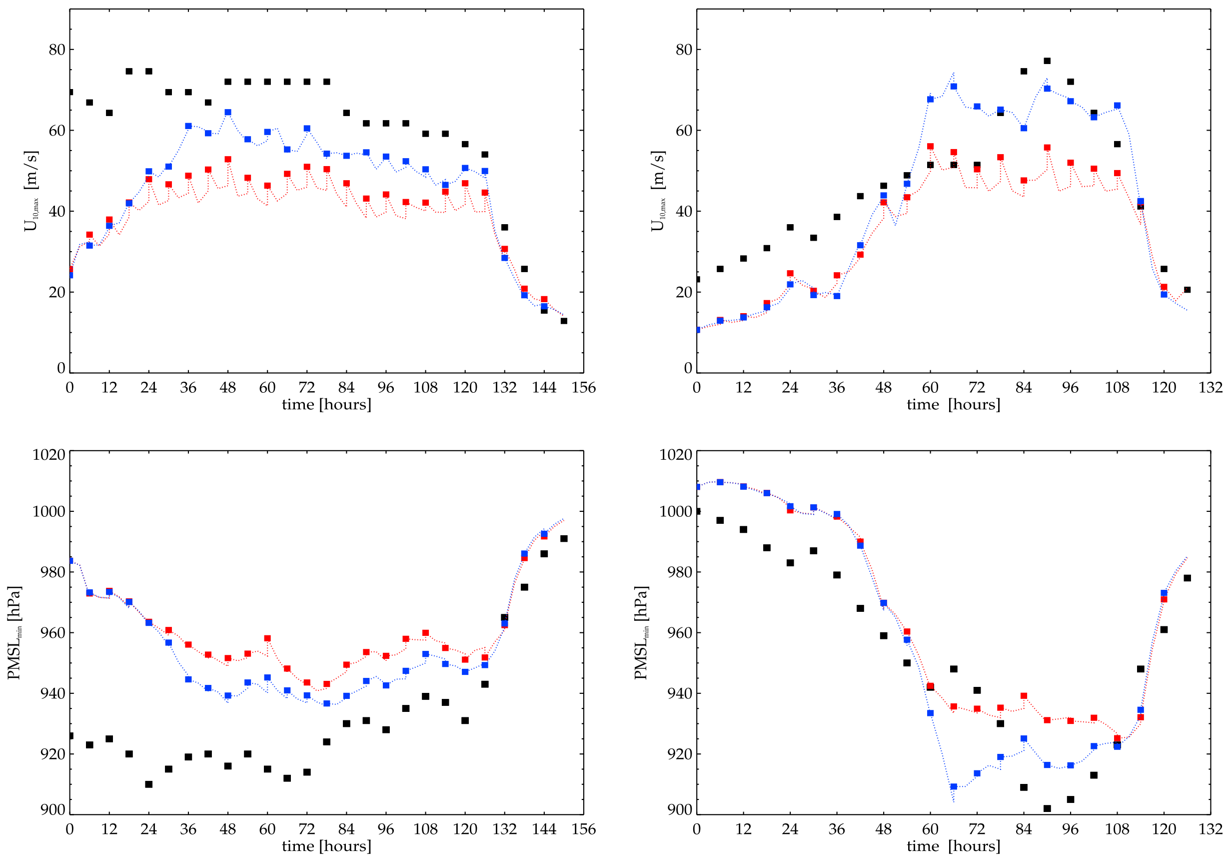

Figure 3. (top) Maximum 10-meter wind speed and (bottom) central pressure for (left) Ivan and (right) Katrina. See Figure 2 for explanation of the colors. The HIRLAM analyses are indicated by squares; $t = 0$ corresponds to 11 September 2004 (Ivan) and to 25 August 2005 (Katrina).

doing a three days spin-up simulation with data assimilation as is described above.

3. Results

[10] In Figure 2 the predicted tracks are shown for hurricanes Katrina and Ivan, for the +48h, +72h and +96h forecasts. The track in Figure 2 is based on the trajectory of the lowest 10-meter wind speed in the hurricane's eye. The observed track according to the National Hurricane Center (NHC; Tropical Cyclone Reports from http://www.nhc.noaa.gov/https://webaccess.knmi.nl/exchweb/bin/redir.asp?URL=http://www.nhc.noaa.gov/ were used) (NHC) is shown as well. As is shown in the figure, with the new drag parameterization the track is nearly unchanged in comparison to the track from the common Charnock relation.

[11] In Figure 3 the maximum wind speed and the central pressure are shown as a function of time, for both Ivan and Katrina, from the experiments with analysis cycles. As is shown in the figure, HIRLAM is much more capable in simulating the hurricanes with the new drag parameterization than with the common Charnock relation. With the Charnock formulation in HIRLAM, the hurricanes can not fully develop into major hurricanes. During almost every analysis, the hurricanes are stronger than in the preceding +6h forecast ($\delta U_{10} \sim$ 5–10 m s^{-1}), which both reflects the positive impact of the data assimilation and the negative impact of the drag formulation on the forecasts. The wind speed during Katrina peaks (during an analysis) at 55 m s^{-1}. On the contrary, with the new drag parameterization HIRLAM *is* able to produce a major hurricane. The difference between the maximum 10-meter wind speed from an analysis and its preceding +6h forecast is much smaller than the difference stated above ($\delta U_{10} \leq 2$ m s^{-1}). According to observations, on 28 August the 10-meter wind speed and the central pressure peak at 77 m s^{-1} and 902 hPa, respectively. HIRLAM is able to model this intensification; with the new parameterization, these extremes are 73 m s^{-1} and 916 hPa, respectively. Peculiar, however, is the intensification of Katrina on 27 August with the new parameterization. In the NHC report it is stated that during this day the intensity leveled off at about 51 m s^{-1}, due to the fact that the inner eyewall deteriorated and a new outer eyewall was formed. With the new parameterization, HIRLAM seems to be unable to model the observed atmospheric conditions during this stage.

[12] In the long forecasts, the hurricanes are not intense enough compared to observed wind speed and sea level pressure extremes, with the standard Charnock relation in HIRLAM (see Figure 4). During Katrina, the lowest central pressure is realistic with 906 hPa. However, the 10-meter wind speed peaks at 57 m s^{-1}. With the new drag parameterization, Katrina becomes an enormous hurricane in the long-term forecasts: in the 4-day forecast the 10-meter wind speed and central pressure reach the impressive values of 98 m s^{-1} and 872 hPa, respectively. This is probably due to the modeled rapid intensification on 27 August (see Figure 4), as discussed previously. For hurricane Ivan, the observed

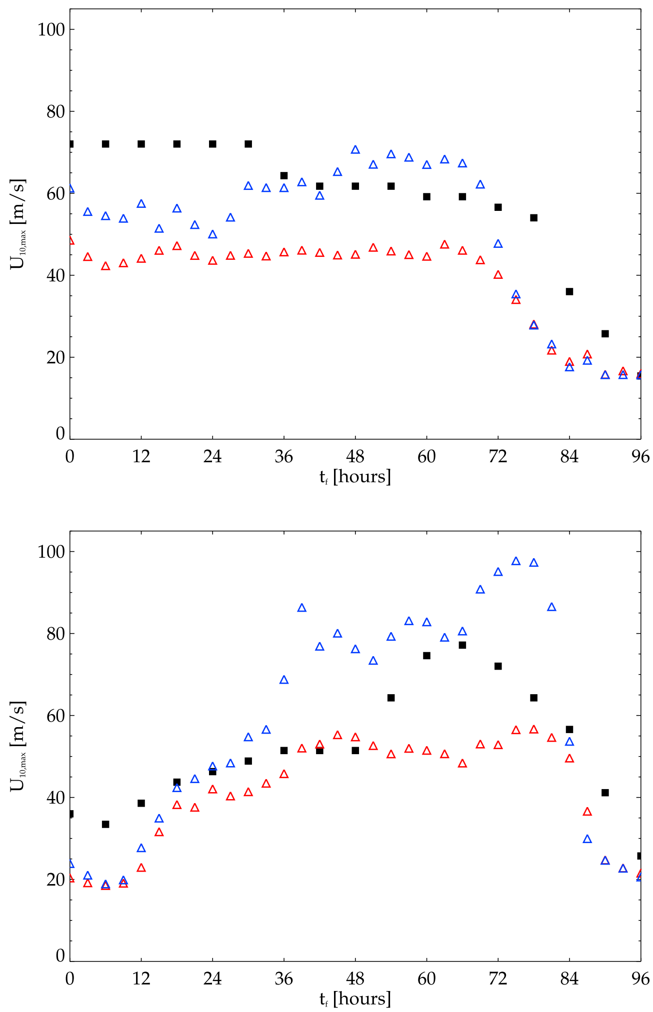

Figure 4. The highest 10-meter wind speed during (top) Ivan and (bottom) Katrina during the +96h forecast. See Figure 2 for explanation of the colors. Time t = 0 corresponds to 13 September 2004 (Ivan) and to 26 August 2005 (Katrina).

highest wind speed is a rather stable 60 m s^{-1} on the day before landfall. With the Charnock relation, the highest wind speed in the 4-day forecast is only approximately 45–47 m s^{-1}. With the new parameterization, the highest wind speed during this stage varies between 67 and 70 m s^{-1}.

4. Conclusion

[13] A drag parameterization that gives the observed decrease in the drag coefficient for hurricane wind speeds was tested in the NWP model HIRLAM, in which traditionally the common Charnock relation is used. With both drag relations, two hurricanes in the Gulf of Mexico were simulated: Ivan (2004) and Katrina (2005). The impact of the new drag parameterization on hurricane track, 10-meter wind speed and sea level pressure was examined. To that end, we ran several simulations in which observational data were assimilated in analysis cycles. Long forecasts up to four days ahead were carried out as well.

[14] While the prediction of the hurricane track is nearly unchanged with the new parameterization, the intensity of the hurricanes changes quite dramatically. The severe hurricane winds are underestimated when the common Charnock relation is used. This is concluded from the direct comparison between observations from the National Hurricane Center and the model results, but also from the comparison of analyses with preceding +6h forecasts. Assimilating observations, HIRLAM tends to keep the simulated hurricanes in the analyses close to the conditions observed, but then the hurricanes rapidly lose their intensity in the forecasts. With the new drag parameterization, however, the intensity of hurricane winds is comparable to the observed intensity of the hurricanes, both in the analyses and the forecasts. For example, the simulated maximum 10-meter wind speed during Katrina is 73 m s^{-1}, which is much closer to the reported 77 m s^{-1} (NHC) than the value of 55 m s^{-1} with the Charnock relation. Additionally, the difference between any analysis and its preceding +6h forecast is much smaller: ~2 m s^{-1} vs. 5–10 m s^{-1} with the Charnock relation. In the long-term forecasts up to 4 days ahead, the new drag parameterization has proven to work and it seems to perform better than the Charnock relation, although Katrina becomes too intense in the 4-day forecast.

[15] The results for hurricane Katrina are slightly better than for hurricane Ivan, in the simulations with data assimilation. Since this could be due to the initial condition in the simulations for Ivan, we also simulated Ivan starting two days earlier. This has negligible impact, because of the interaction with land (Jamaica), which causes Ivan to weaken severely.

[16] The results from this study can be compared to the results from *Moon et al.* [2007]. In that study a roughness parameterization was tested, which yields a drag coefficient that levels off, rather than decreases with increasing wind speed. Simulating several hurricanes, including Ivan, *Moon et al.* [2007] found that the prediction of the wind speed improved with their parameterization. The prediction of the central pressure in hurricanes did not improve, in contrast to our simulations.

[17] We have investigated the impact of using the ECMWF analyses in the experiments with data assimilation. In that case, the hurricanes could not develop properly; they became much weaker than we have presented in this paper. Moreover, with ECMWF analyses as initial condition for the long-term forecasts, the track prediction for Katrina deteriorated, while for Ivan the track prediction was slightly better.

[18] In future studies, it should be investigated whether the results in this paper are in agreement with the concepts of Emanuel, who suggested that the ratio of the exchange coefficients of the enthalpy flux to the momentum flux should have a certain value in the hurricane wind speed regime.

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