Comments on “Sensitivity of tropical-cyclone models to the surface drag coefficient”

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1. Introduction

In a recent numerical modeling study, Montgomery *et al.* (2010, hereafter MSN10) examined the sensitivity of tropical cyclone (TC) intensity to the surface drag coefficient. As part of their study, MSN10 compared their model results to previous theoretical and modeling studies. This comparison should have been done more carefully because there is a significant difference in methodology between MSN10's simulations and some previous studies. The primary purpose of this Comment is to document this key difference, and to demonstrate how this different methodology can lead to different conclusions. I also offer an alternative hypothesis for how vortices can intensify in numerical models in the absence of surface drag.

The theoretical relationship evaluated by MSN10 is technically the *maximum possible intensity* (or potential intensity, PI) for TCs. PI is usually considered to be proportional to the surface exchange coefficient for enthalpy C_k because, all else being equal, larger C_k results in larger surface heat flux (which is the ultimate source of energy for TCs). Furthermore, PI is usually considered to be *inversely* proportional to the surface exchange coefficient for momentum C_d because, all else being equal, larger C_d (i.e., surface drag) results in larger kinetic energy dissipation. More specifically, some theoretical studies have determined that maximum tangential velocity $V_{\max}$ should vary as follows:

$$V_{\max} \sim \left(\frac{C_k}{C_d}\right)^{1/2} \qquad (1)$$

[e.g., Emanuel (2004) and references therein]. It is important to note that (1) applies to the *maximum possible* tangential velocity for a specified environment (e.g., sea surface temperature, atmospheric moisture/temperature profile, etc), assuming all else held fixed. Furthermore, (1) is derived from equations assuming *steady* flow (i.e., Eulerian time-tendency terms are negligible).

Some support for (1) was found in numerical modeling studies by Emanuel (1995) and Bryan and Rotunno (2009). Using two different axisymmetric models (one based on gradient-wind balance and the other a primitive-equation model), Emanuel (1995) evaluated (1) by integrating these models "for long enough that quasi-steady mature model storms were achieved" (p. 3972). Using a different primitive-equation axisymmetric model, Bryan and Rotunno (2009) integrated numerical simulations for 12 days in order to achieve "an approximately steady state" (p. 1775). Both of these studies showed that numerical models could produce the relationship, (1). [Bryan and Rotunno (2009) also showed cases in which the numerical model *did not* produce (1), especially when their model had large horizontal diffusion.] Some differences between the simulations by Emanuel (1995) and Bryan and Rotunno (2009) are documented in the recent study by Bryan (2012).

In their modeling study, MSN10 did not find any support for (1). However, there is one key difference in their methodology: instead of running their simulations to approximate steady state, they evaluated intensity primarily at an arbitrary time of 4 days into the model integrations. [According to MSN10 (pg. 1949) this choice was made because "... longer time experiments may admit new evolutionary pathways for the hurricane vortex (such as secondary eyewall formation and subsequent evolution) that lie outside the scope of the present paper ...."] No evidence was provided by MSN10 to suggest that their simulations were approximately steady at $t = 4$ days or that their simulated tropical cyclones had reached *maximum* intensity. Therefore, some of MSN10's conclusions are questionable, especially their evaluation of (1) and their comparison to simulations by Emanuel (1995) and Bryan and Rotunno (2009).

To evaluate how the length of MSN10's simulations might affect their conclusions, I have conducted a very similar set of numerical simulations for this article. The numerical model is the three-dimensional version of CM1 (Bryan and Rotunno 2009; Bryan *et al.* 2010). Most model settings are identical to those of MSN10. For example: the initial sounding is from Rotunno and Emanuel (1987); the sea-surface temperature is 27 °C; the Coriolis parameter is constant, valid at 20 °N; the domain is square with a length of 5400 km and grid spacing of 45 km far away from the tropical cyclone; a square fine mesh is included in the center of the domain that has length of 600 km and grid spacing of 5 km; the Kessler liquid-only microphysics scheme is used; Newtonian relaxation is applied to potential temperature to crudely account for atmospheric radiation; dissipative heating is neglected; C_k has a constant value of 1.3×10^{-3} for all simulations; and each simulation has a constant value of C_d.

There are a few differences from the simulations of MSN10, including the use of different numerical models (CM1 instead of MM5). The CM1 simulations have 62 vertical levels (instead of 24), where the first model level is at 10 m above sea level, and the vertical grid spacing varies from 20 m at the surface to 500 m at the top of the domain. The horizontal diffusion schemes are different. CM1 uses a Smagorinsky-type scheme, and simulations herein have a horizontal length scale l_h = 1000 m. MM5 uses a ∇^4 diffusion scheme with a two-part diffusion coefficient: one part is a constant (proportional to horizontal grid spacing) and the second part is deformation-dependent (with a length scale proportional to horizontal grid spacing). There are some small differences in the vertical diffusion (i.e., PBL) schemes, but both are simple downgradient-diffusion-type schemes that diagnose the diffusion coefficient based on local deformation and static stability; the simulations herein use the same vertical length scale as the "bulk PBL" scheme in MM5: l_v = 40 m. The initial vortex is from Rotunno and Emanuel (1987).

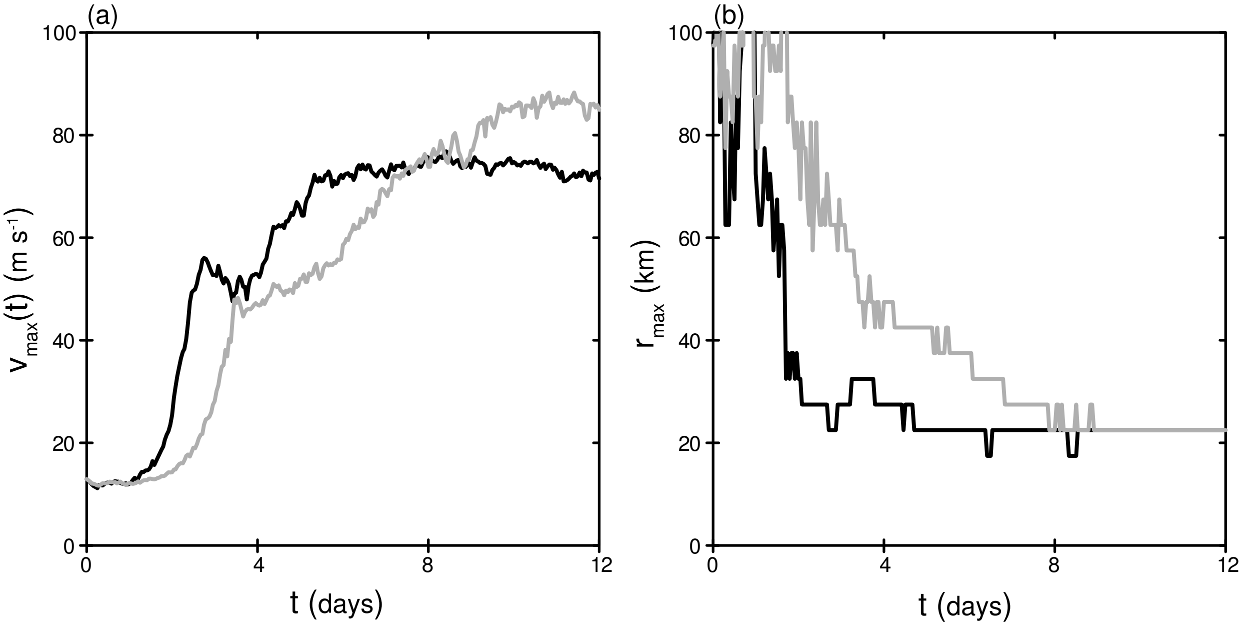

Figure 1. Time series of (a) maximum tangential velocity, $v_{\max}(t)$, and (b) radius of maximum tangential velocity, $r_{\max}$, from simulations with C_k/C_d = 0.7 (black) and C_k/C_d = 1.3 (gray).

None of these differences in model setup is expected to yield substantially different results, compared to MSN10's simulations. However, there is one significant difference: the simulations herein are integrated for 18 days (rather than 4 days).

Maximum intensity at any given time is calculated in a similar manner as MSN10: that is, $v_{\max}(t)$ is the maximum azimuthally averaged value of tangential velocity v. The storm center is defined herein as the gridpoint (from anywhere in the domain) that yields the maximum possible value of $v_{\max}(t)$. The height of $v_{\max}(t)$ is always between 0.5–1.0 km above the surface (where lower values of C_k/C_d yield the higher heights, and vice versa). The radius of maximum winds, $r_{\max}$, is defined as the radius of $v_{\max}(t)$.

Time series of $v_{\max}(t)$ and $r_{\max}(t)$ from two simulations are shown in Fig.1. At t = 4 days, results are qualitatively similar to those of MSN10: for C_k/C_d of 0.7 (black lines in Fig.1), $v_{\max}(t) \approx 55$ m s^{-1} and $r_{\max}(t) \approx 30$ km; and for C_k/C_d of 1.3 (gray lines in Fig.1), $v_{\max}(t)$ is smaller ($\approx$ 45 m s^{-1}) and $r_{\max}(t)$ is larger ($\approx$ 50 km). Small differences from MSN10's results are, of course, attributable to the use of different numerical models and/or settings. Nevertheless, it is clear from Fig. 1 that these types of simulations — i.e., simulations that start with a broad, weak, and subsaturated initial vortex — have not yet reached maximum intensity after only 4 days. It takes roughly 10 days for the C_k/C_d = 1.3 simulation to produce a quasi-steady value of $v_{\max}(t)$, and at this time both simulated cyclones have the same value of $r_{\max}$ (22 km). For $t > 10$ days, $v_{\max}$ is inversely proportional to C_d, which is qualitatively consistent with (1); the opposite conclusion reached by MSN10 seems to be attributable to their relatively short integration time of 4 days.

Fig. 2 shows the instantaneous value of $v_{\max}(t)$ as a function of C_k/C_d at three different times. At t = 4 days (solid line), the simulations herein yield a maximum value of $v_{\max}(t)$ for C_k/C_d = 0.4, consistent with MSN10's results. However, at t = 8 days (dashed line) the maximum value of $v_{\max}(t)$ occurs for C_k/C_d = 1.0, and at t = 12 days (dotted line) the maximum value of $v_{\max}(t)$ occurs for C_k/C_d = 1.6.

In their Section 3.4, MSN10 compare their results to previous modeling studies, but they did not explain their different results in the context of their much shorter integration time. Fig. 3 herein shows $T_{\max}$, which is the time at which the maximum value of $v_{\max}(t)$ occurs in

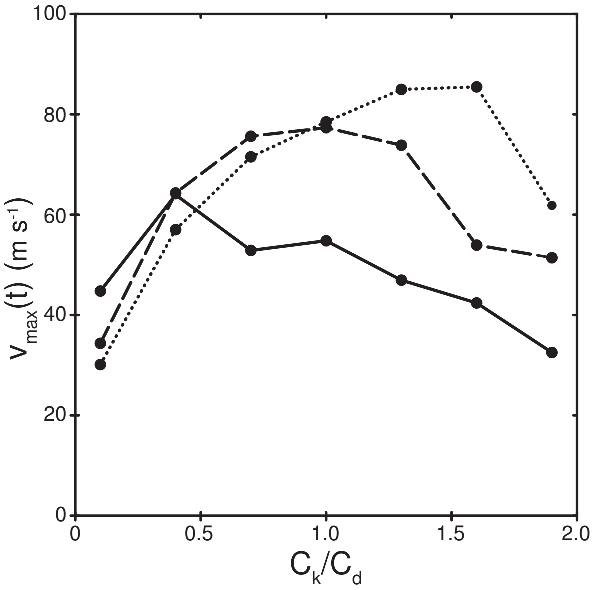

Figure 2. Instantaneous values of $v_{\max}(t)$ as a function of C_k/C_d at three different times: t = 4 days (solid, the final time examined by MSN10); t = 8 days (dashed); and t = 12 days (dotted).

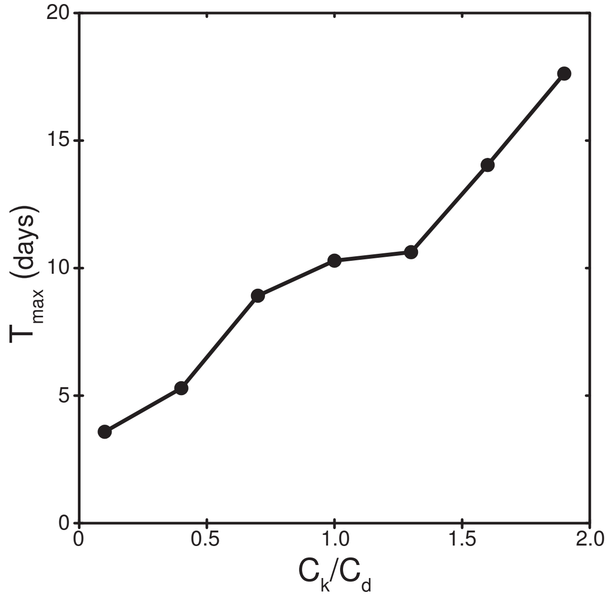

Figure 3. Time (days) required to reach maximum intensity as a function of C_k/C_d.

the 18-day CM1 simulations. Simulations with $C_k/C_d > 1$ require more than 10 days to reach maximum intensity for this idealized setup. The physical reasoning for this result is fairly straightforward; larger values of C_d yield stronger radial inflow in the boundary layer (owing to greater gradient-wind imbalance, as discussed by MSN10, e.g., pg. 1950). With stronger radial inflow, the initially subsaturated vortex can moisten more rapidly, and the initially broad vortex can contract to smaller radius earlier.

The conclusions drawn herein are consistent with other modeling studies, including ones that used axisymmetric models and coarser resolution. For example, Rosenthal (1971) used an axisymmetric model and found the same overall result shown herein: that is, *maximum* intensity is inversely proportional to C_d, and the time required to reach maximum intensity is also inversely proportional to C_d. Rosenthal's simulations were integrated for 12–18 days (depending on time needed to reach maximum intensity).

For readers that are curious about the very long time (>10 days) required for some simulations to reach maximum intensity, this result suggests at least two artificial aspects of these simulations. First, recent observational and laboratory studies have found the ratio C_k/C_d is likely ∼0.5–0.7 in intense tropical cyclones (e.g., Black *et al.* 2007; Haus *et al.* 2010; Bell 2010); therefore, the 10–18 day values for $C_k/C_d > 1$ in Fig. 3 are likely not relevant to tropical cyclones (TCs) in nature. Second, as mentioned several times herein, the initial conditions for these simulations are subsaturated everywhere; several days are required to reach saturation, after which the rapid intensification begins (e.g., Fig. 1). A more realistic set of simulations that are more directly applicable to TCs in nature should probably start from saturated vortices, although it seems unlikely that the resulting simulations would show a major difference in the response of $V_{\max}$ to C_k/C_d.

In summary, it seems likely, based on the simulations shown herein, that the different conclusions between MSN10's study and other similar modeling studies (e.g., Emanuel 1995; Bryan and Rotunno 2009) are attributable to the relatively short integration time of MSN10's simulations. Their simulated tropical cyclones are probably not quasi-steady after 4 days of integration, and the values of maximum winds likely do not represent the *maximum possible* values. Hence, MSN10's conclusions about the theoretical relation for maximum intensity, (1), are probably specious because this relation technically applies to steady flow (and not necessarily to storms undergoing intensification). Some previous studies that have shown support for (1) have allowed their simulations to reach an approximately steady state of maximum intensity.

Finally, regarding the limit of $C_d = 0$ (i.e., no surface friction), MSN10 argued that no intensification should be expected for this configuration, and concluded that the intensification reported with $C_d = 0$ by Craig and Gray (1996) was attributable to coarse vertical grid spacing in their axisymmetric numerical model. However, radial inflow in the boundary layer due to gradient-wind imbalance (which was correctly identified by MSN10 as an important process for TC intensification) does not necessarily require surface friction; in principle, radial inflow can be induced by any mechanism that reduces tangential velocity v near the surface while keeping the radial pressure gradient unmodified. For the numerical model used by Craig and Gray (1996), the mechanism for reducing v appears to be the subgrid turbulence (i.e., PBL) parameterization, which has a static-stability-dependent term that is designed to activate the scheme in unstable layers. Surface heat fluxes can create a statically unstable thermodynamic profile near the surface, which seems likely to have activated near-surface vertical diffusion. Because v decreases with height, the turbulence model decreases v near the surface (and increases v aloft). Assuming the radial pressure gradient stays roughly the same, this decrease in v near the surface can lead to radial inflow and thus intensification. In support of this interpretation, I have conducted a set of simulations for this study using the axisymmetric model of Rotunno and Emanuel (1987) (RE87, as configured in that study), which is the same model used by Craig and Gray (1996). With $C_d = 0$, the vortex intensifies; $V_{\max}$ is 90 m s^{-1} after 10 days. By setting $C_d = 0$ *and* removing the stability-dependent term in the subgrid turbulence parameterization (by setting the squared Brunt-Väisälä frequency to zero), the simulated vortex does not intensify, thus supporting the above interpretation of Craig and Gray's simulations.

The reason for the lack of intensification in MSN10's MM5 simulations with $C_d = 0$ may be attributable to inherent differences between axisymmetric and three-dimensional simulations and/or different vertical resolution, as hypothesized by MSN10. Another possible explanation is that the PBL schemes are different between their axisymmetric (RE87) and three-dimensional (MM5) models, with larger diffusion in the RE87 model. In fact, the scheme in the RE87 model uses a larger vertical length scale by default (l_v = 200 m, as opposed to 40 m in MM5) *and* the RE87 model correctly reduces the Brunt-Väisälä frequency in saturated conditions (whereas the MM5 scheme used by MSN10 does not); both differences are expected to increase vertical diffusion in the RE87 model, which supports the alternative explanation proposed here.

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