Estimates for Surface Exchange Coefficients and Turbulence Length Scales Using Numerical Simulations

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Motivation:

• Progress in forecasting and understanding hurricanes is being hindered by uncertain settings in parameterization schemes (especially boundary-layer and surface-layer schemes).

• This study aims to reduce this uncertainty by evaluating a large set of simulations that systematically vary the surface drag coefficient and the length scales in a turbulence/PBL parameterization.

• The model output is evaluated using several simple yet well-observed metrics of hurricane intensity and structure.

Methodology:

More details available in Bryan (2012a)

Due to the large number of simulations (> 400) most results are from an axisymmetric model.

Comparison of axisymmetric simulations and 3D simulations is shown in Fig 11.

• Model: CM1 (http://www.mmm.ucar.edu/people/bryan/cm1/)

• Domain: 1500 km x 25 km

• Grid spacing: 1 km horizontal grid spacing, 123 vertical levels (17 levels below 1 km).

• Initial conditions: Dunion (2011) moist-tropical (MT) sounding; 29 °C sea-surface temperature (SST); initial vortex from Rotunno and Emanuel (1987).

• Microphysics: Morrison (2009) double-moment scheme

• Horizontal and vertical turbulence schemes: same as Bryan and Rotunno (2009);
  • Intensity of horizontal diffusion is proportional to l_h
  • Intensity of vertical diffusion is proportional to l_v

• To allow for straightforward comparison with theory, surface enthalpy coefficient C_k is held fixed at 1.2×10^{-3}

• Surface drag coefficient C_d is also held fixed for each simulation, but is varied from one simulation to another.

Method to determine analysis time

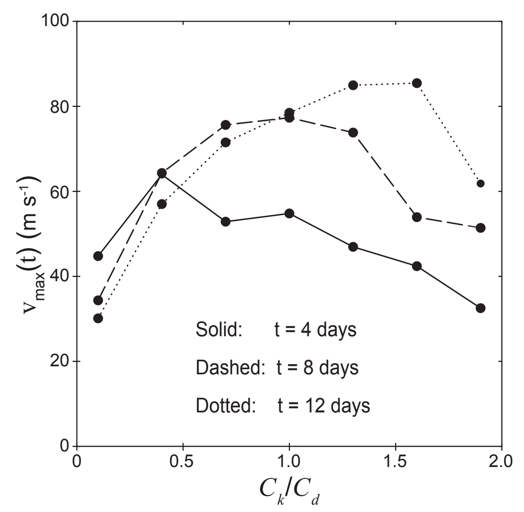


Fig. 1: Maximum tangential velocity $v_{max}(t)$ from 3d simulations using l_h = 1000 m and l_v = 40 m at t = 4 days (solid), t = 8 days (dashed), and t = 12 days (dotted).

• Conclusions about the dependence of v_{max} on C_k/C_d can depend on the time chosen; see Bryan (2012b) for more details.

• The methodology below (Fig 2) avoids this problem.

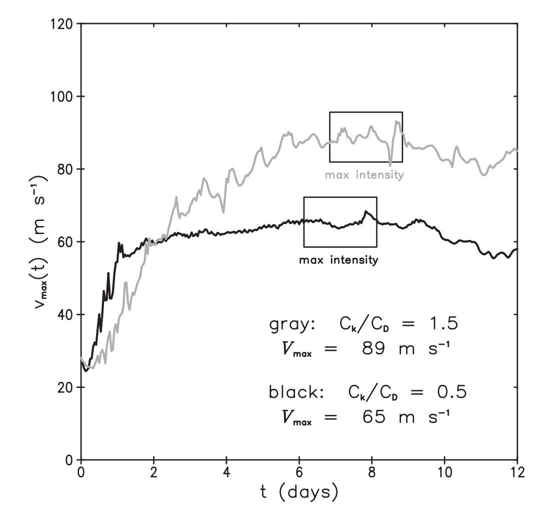


Fig. 2: Time series of maximum tangential velocity $v_{max}(t)$ from two simulations: C_k/C_d = 0.5 (black) and C_k/C_d = 1.5 (gray).

• Boxes denote maximum 2-day-average value of v_{max}.

• This objectively determined time can be different for each simulation.

• All results shown in Figs 3-11 are averaged over these 2-day periods.

Maximum Intensity

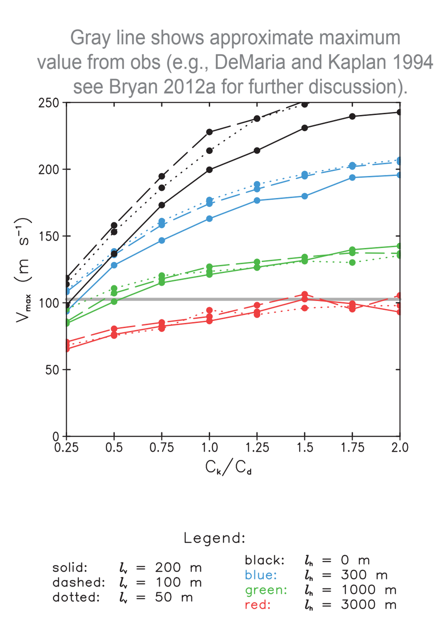


Fig. 3: Maximum tangential velocity V_{max} (from any level) as a function of C_k/C_d.

• Model V_{max} is reasonable when l_h = 1000 m and C_k/C_d = 0.5 (i.e., where green lines intersect gray line).

• Model V_{max} is also reasonable for C_k/C_d = 0.25 when l_h = 0 or 300 m; however, recent studies (e.g., Donelan et al. 2004, Drennan et al 2007, Haus et al 2010, Bell 2010) suggest C_k/C_d is higher in intense hurricanes: probably about 0.5-0.6.

• Vertical length scale l_v has little effect on maximum intensity (note solid vs dashed vs dotted lines).

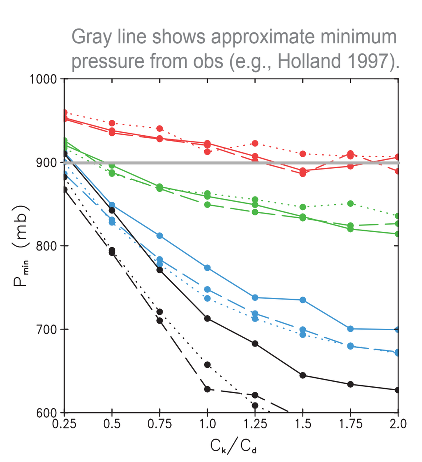


Fig. 4: Minimum surface pressure (mb), P_{min}.

• Analysis of P_{min} yields the same conclusions.

Hurricane size

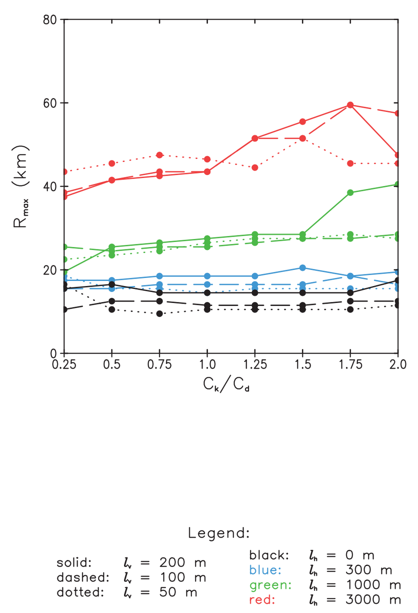


Fig. 5. The radius (km) of maximum azimuthal velocity, R_{max}.

• R_{max} remains essentially unchanged for changes in C_k/C_d and/or l_v.

• R_{max} is very sensitive to changes in horizontal length scale l_h because horizontal diffusion is a major contributor to the angular-momentum budget in the eyewall boundary layer of simulated hurricanes, and thus limits frontal collapse in the eyewall; see Rotunno and Bryan (2012) for further analysis.

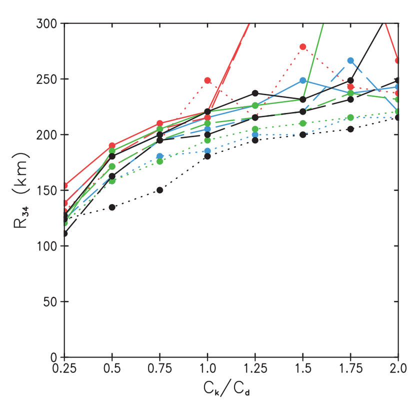


Fig. 6. The radius (km) of gale-force winds at 10 m MSL, R_{34}.

• R_{34} is weakly dependent on l_h and l_v.

• R_{34} increases as C_k/C_d increases.

• Most observed storms have R_{34} < 200 km (e.g., Dean et al. 2009); model results are consistent for C_k/C_d < 1.

Boundary-Layer Structure

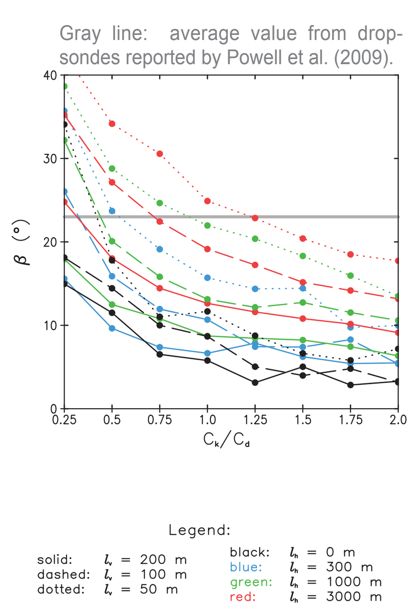


Fig. 7. Inflow angle (degrees) at 10 m MSL at the location of maximum winds.

• Inflow angle is unreasonably small for $C_k/C_d \geq 1$.

• Inflow angle usually increases as l_h increases.

• Inflow angle usually increase as l_v decreases.

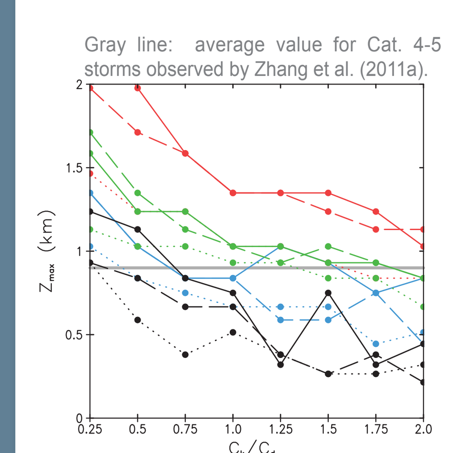


Fig. 8. The height (km) of maximum tangential velocity, z_{max}.

• z_{max} increases as l_h increases.

• z_{max} increases as l_v increases.

• z_{max} has a high bias for $l_h \geq 1000$ m. This bias is attributable to the use of constant l_v for these simulations; see Fig. 9.

Sensitivity to formulation of l_v

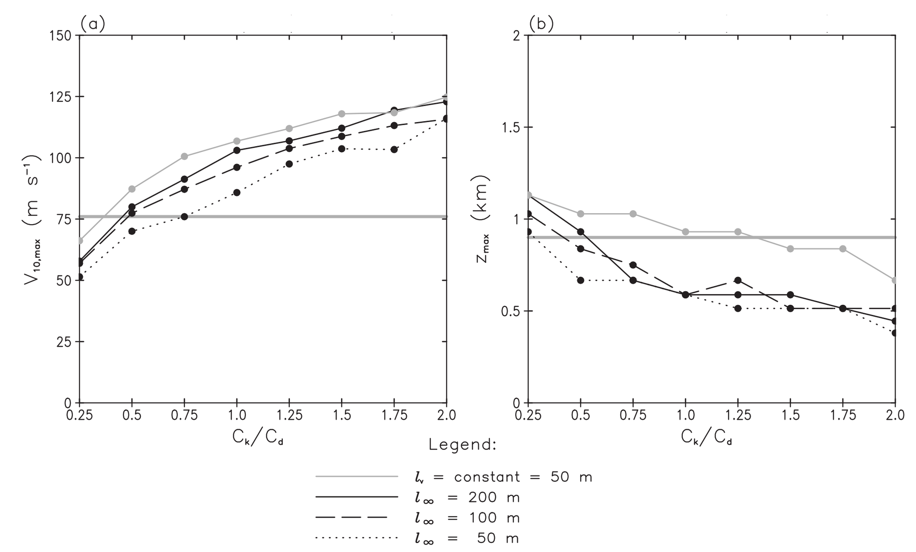
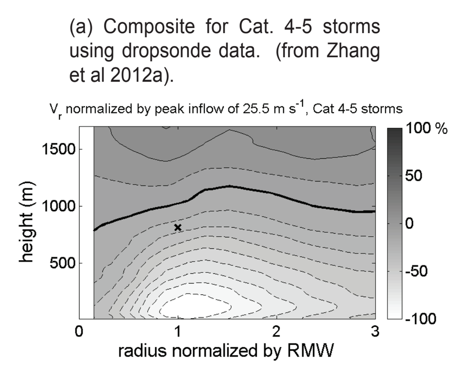
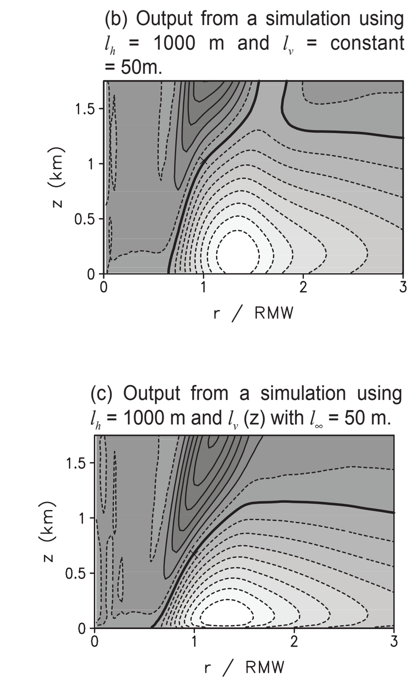


Fig. 9: Comparison of simulations using constant l_v (gray line) and simulations using l_v that increases with height following Blackadar (1962); three different values are used for the asymptotic length scale l_∞ (see Legend). (a) Maximum 10-m windspeed (m s^{-1}), and (b) height (km) of maximum azimuthal velocity. (Using l_h = 1000 m.)

Fig. 10: Radial velocity normalized by maximum value, as a function of radius (normalized by RMW) and height MSL.





Comparison to 3D simulations

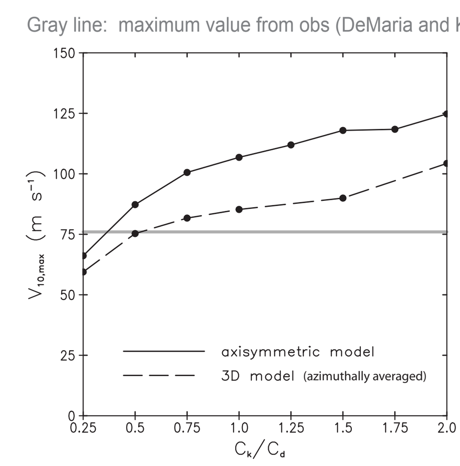


Fig. 11. Maximum 10-m wind speed (m s^{-1}) using l_h = 1000 m and l_v = 50 m.

• The 3D model produces weaker (by ~20%) sustained winds than the axisymmetric model.

• The settings l_h = 1000 and l_v = 50 m still produce reasonable intensity (Fig 11) and structure (not shown).

Summary

• The model settings $l_h \approx 1000$ m, $l_v \approx 50$ m, $C_k \approx 1.2\times10^{-3}$, and $C_d \approx 2.4\times10^{-3}$ yield the most reasonable combination of maximum winds, minimum pressure, height of maximum winds, and surface inflow angle compared to obs.

• These values for l_h, l_v, C_k, C_d are consistent with recent observational and laboratory studies, e.g., Donelan et al. (2004), Drennan et al. (2007), Haus et al. (2010), Bell (2010), Zhang et al. (2011b), Zhang and Montgomery (2012)

• The model produces the theoretical result, $V_{max} \sim (C_k/C_d)^{0.5}$, only when horizontal diffusion is weak (l_h < 100 m) (black lines in Fig 3).

• For l_h = 1000 m, the model produces $V_{max} \sim (C_k/C_d)^{0.2}$ (green lines in Fig 3).

• The often-cited result ... Cat. 4+ hurricanes do not occur unless $C_k/C_d \geq 0.75$ ... appears to be a model-specific result (requiring large l_h and/or low SST).

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