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Evaluating the 3D nonlinear tropical cyclone boundary layer (TCBL) model by idealized simulation

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SUMMARY:
In the hierarchy of diagnosis tropical cyclone boundary layer (TCBL) models, the 3D nonlinear model (Kepert and Wang, 2001) is viewed to be the most rigorous. Its application is expected to enhance performance-based wind engineering for tropical cyclones. To guide future TCBL simulation in practice, the accuracy and uncertainty of this model are evaluated by idealized simulation exhausting its configurations, inputs, and parameter models. The model is first coded and validated against the results of typical examples. The effects of three model setups are investigated, including the horizontal diffusion (with vs. without), algorithm's order (1st vs. 3rd), and thermal effects (initial profiles and thermal equations). By comparing the simulation results of typical and extensive examples associated with different setups, their effects and interactions are revealed and quantified, highlighting the 3rd algorithm with horizontal diffusion. This optimal setup is further utilized to conduct the sensitivity analysis, in which eight combinations of temperature profiles, thirteen vertical diffusion models, and seven drag coefficient models are investigated. A comparison of the simulation results reveals the approximate equivalence between some models of different complexity and the applicable conditions of the simplified ones. The results of this study thus could serve as the basis for selecting appropriate model setups and parameters.

Keywords: tropical cyclones; boundary layer models; idealized simulation

1. INTRODUCTION

In the Monte Carlo simulation of tropical cyclones (TC), the TC boundary layer (TCBL) model is the key component that converts the TC track information into surface wind fields. Therefore, its accuracy and uncertainty may significantly influence the reliability of simulation and the related risk assessment or performance-based wind engineering.

The TCBL models aim at solving the primitive equations describing TC dynamics and thermodynamics. A hierarchy of diagnosis models was proposed in TC meteorology and has been utilized in wind engineering, from the approximate closed-form solutions to the simulation-based numerical solutions. The models could be 1D-plume, 2D-slab, or 3D and could be fully nonlinear or linear. Theoretically, the 3D nonlinear TCBL model proposed by Kepert and Wang (2001, KW01 hereafter) is the most rigorous in the hierarchy, which leads to results that have been shown to reflect more TC physics than other models. In other words, other models are simplified from the 3D nonlinear model but with various degrees of approximation. In this context, they could not outperform the KW01 model in terms of accuracy. However, the applications of the KW01 model (e.g., Hu and Kareem, 2021) are so far much less than the frequently-utilized 2D-slab (e.g., Vickery et al, 2009) or the 3D linear models. A possible reason for this situation is that the KW01 model is more complex, while its capabilities and merits have not yet been fully understood. Towards extending its future applications, this study aims at analyzing the effect of the model's setup and parameters on the accuracy and uncertainty of the idealized simulation results.

2. THE MODEL

The primitive equation system involves two momentum equations and one thermal equation, as well as the TKE equation, hydrostatic equation, and continuity equation. In this study, the 3D nonlinear model (KW01) is programmed, which utilizes the three-stage (advection, adjustment, and diffusion) time-split integration method to solve the equation system on cylindrical gridding within the radius of 300km and height of 2km. The grid contains 1081 nodes with a size of 5km and 20 °. The radiation and Neumann conditions apply to the lateral and top boundaries. The model is forced by an axisymmetric pressure profile characterized by the Holland-*B* but with polynomial revision inside the RMW (radius to maximum wind). Overall, the numerical details of this model follow the ones presented in KW01.

3. MODEL VALIDATION

As the purpose of this study is for idealized simulation, the coded model is validated against the benchmark consisting of results of typical numerical examples given in KW01. Fig. 1 shows the close agreement between the results provided by the model in this study and the ones in KW01. However, the deviation above 1 km is also apparent, particularly the Richardson number. Fortunately, that part of the simulated wind field is of little importance in wind engineering applications.

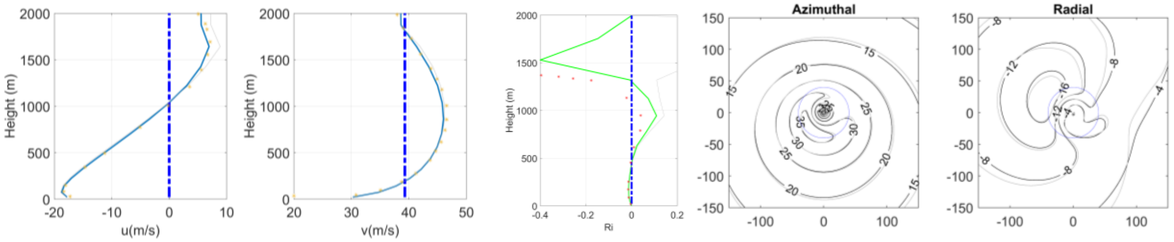

Figure 1. Validation against typical results [Figs. 5, 8, and 10 in Kepert and Wang (2001)].

4. MODEL SETUP ANALYSIS

Configurations of the 3D TCBL model may influence the simulation results. In this section, three types of setups are investigated, including: with or without horizontal diffusion, third-order or first-order upwinding scheme; five different thermal setups (horizontally uniform potential/absolute temperature, solving/fixing temperature profiles, and uniform temperature all the way). By mixing these setups, there are 20 combinations. The effects of these setups are first analyzed by the typical examples, and the results in KW01 are utilized as the baseline. The primary horizontal and vertical distribution patterns of the effects are also observed. Further, an extensive set of numerical examples are utilized as the TC parameters may influence the effects of setups. The RMW is fixed as 40km, while the other three parameters vary within their physically-feasible ranges: maximum wind speed ($V_{\max}$ =[25, 40, 55, 70, 85]m/s), translation wind speed (V_T =[0, 5, 10, 15]m/s), and Holland-*B* parameter (*B*=[1, 1.3, 1.6, 2.1, 2.4]). The combination of these parameters consists of 100 cases; together with the 20 setups, 2,000 simulations were thus carried out. The results are then analyzed by the variation of the difference between different setups along with the parameters.

The difference is quantified by four indicators: The relative difference in the overall and surface maximum horizontal wind speed, and the mean absolute error (MAE) of the difference of surface and overall wind speeds within different radial regions ([0.5-1, 1-1.5 and 1.5-2.5] RMW). The critical values of the three parameters that maximize the effect of setups are also identified. Finally, the influence of the gridding size and RMW is evaluated by repeating the above analysis with the grid of 2km and 10 °and with RMW = 60 and 80km.

Figure 2 shows some examples of the setup analysis. Major conclusions of such an analysis include: The effect of horizontal diffusion could be as significant as 13% and helps stabilize the computation, and increases as *B* and V_T increase; the third-order algorithm could increase the maximum wind speed by 20% over the first-order algorithm, and maximizes at *B*=1.3; the thermal setups generally produce less than 5% peak difference in wind speed that is mainly not influenced significantly by the three parameters. These effects may be slightly decreased by refining the gridding or equivalently by increasing RMW.

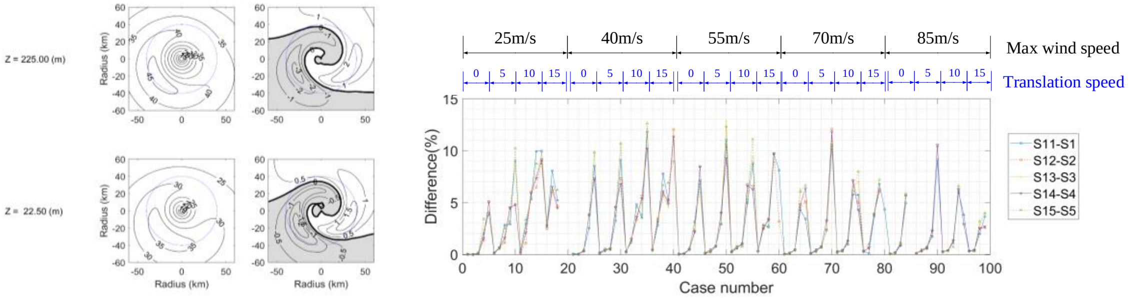

Figure 2. Examples of setup analysis. Left: difference in the azimuthal wind speed due to the order's effect; right: relative difference in maximum total horizontal wind speed due to the effect of horizontal diffusion.

5. SENSITIVITY ANALYSIS

5.1. Temperature Profiles

The preceding section discusses the effect of uniform temperature profiles in the thermal setup. However, the vertical and horizontal thermal profiles of real TCs are much more complex, which may influence the horizontal air density profile, vertical variation of pressure gradient, and stratification, forming the thermal winds. Therefore, the effects of four horizontal thermal profiles estimated from the flight level measurement data (Figure 3a) and two vertical profiles (fixed SST and fixed lapse rate) are investigated. In total, 3072 simulations were carried out by fixing or computing the thermal equation. This extensive investigation reveals that the algorithm's order slightly influences the thermal effects. The combination of fixed SST and the two envelopes in Figure 3a yields a similar difference from the uniform profile, which could be as large as 22%. The thermal effect decreases significantly as $V_{\max}$ increases; when $V_{\max} = 55\text{m/s}$ its maximum is less than 10%.

5.2. Vertical Diffusion Models

A series of vertical diffusion models fit the 3D TCBL model. Although the stationary TC wind fields simulated by various vertical diffusion models have been compared before, it was primarily focused on physics and based on only one typical TC. This study investigates the effects of 14 vertical diffusion models: Mellor-Yamada level-2.25 model (MY, with three different mixing lengths), neutral MY, Louis model (LU), neutral LU, K-profile model (KPP) with fixed/radiallydependent TCBL height, mixing length model (MX), Bulk-Hi-Res (BLK), and three constants (50, 75, 100). With 120 cases of TC parameters and eight combinations of thermal profiles/setups, 18720 simulations were carried out and analyzed. By this investigation, the equivalence between LU and MY is confirmed, and the deviation between the BLK and other models is revealed. The KPP and MX models are discovered as reasonable approximations of MY, given the atmosphere keeps close to neutral. The three constant K values may produce a difference larger than 20% from MY, which is particularly true for high winds (e.g., Figure 3b).

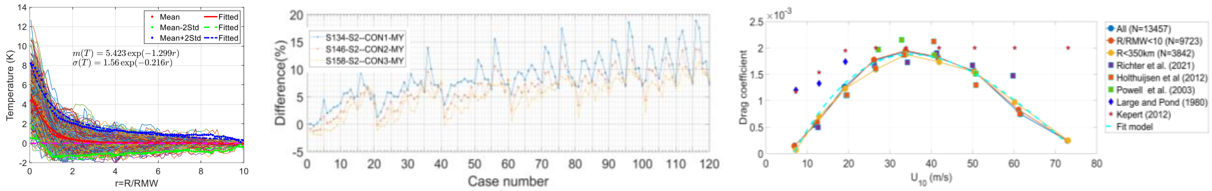

Figure 3. From left to right: (a) radial temperature profiles; (b) example of relative difference between results of constant K and the MY model; (c) drag coefficient model fitted from dropsonde measurements.

5.3. Drag Coefficient Models

Various drag coefficient models reflect the wind speed dependency over ocean, some of which even represent the decay at high winds. Seven drag models are investigated in this study (Figure 3c): Vickery's model (VK), COARE procedure (CA), Kepert's model (KP), the model fitted from up-to-date dropsonde measurement data (FT), and three constant values (0.0015, 0.002, and 0.0025). The VK model is regarded as the baseline because it is frequently employed in existing research. The same cases and thermal profiles in Sec. 5.3 are utilized but with the MY and K=50 models, yielding 13440 simulations. Results show that the constant value of 0.002 approximates VK with less than 8% and 5% differences in the maximum and MAE, respectively. Note this good agreement is based on statistics and does not apply to all the radial coordinates. The KP yields almost the same results as VK, while the CA underestimates and FT overestimates by around 20%-30% in the surface wind speed.

6. CONCLUDING REMARKS

This paper summarizes the validation, algorithm setup, and parameter model sensitivity analysis of the 3D nonlinear TCBL model. The extensive examination yields the effects of various factors on the TC wind field simulated by this model over the complete set of TC characteristics. In the future, the results of the idealized simulation will be validated by practical simulation against field measurement data such as the benchmark dataset established by Hu and Kareem (2022). Consequently, it would provide the simulation with reliable guidance for parameter determination and model selection.

7. REFERENCES

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