Deficiencies of Slab Models of the Tropical Cyclone Boundary Layer

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1 INTRODUCTION

Diagnostic models of the tropical cyclone boundary layer have important practical uses, including for engineering design and climatological hazard assessment studies, and as components of tropical cyclone potential intensity models. A widely used class of such models has been slab models, in which the governing equations are depth-averaged. Here, a slab model is compared to one which fully resolves height, and it is shown that the vertical averaging leads to substantial differences in the simulations. The slab model produces excessively strong inflow and too great a departure of the boundary-layer mean winds from gradient balance. Given the considerable impact of the vertical averaging in slab models on the simulated flow in the tropical cyclone boundary layer, it is difficult to recommend their further use for applications where quantitative accuracy is important. Other applications will require care to ensure that the results are not unduly affected by the depth-averaging.

2 MODEL FORMULATION

Two diagnostic models of the TCBL are used here, a slab model and a height-resolving model. Each diagnoses the boundary-layer flow as the response to a specified, optionally translating, pressure field representative of a tropical cyclone. Thus each model can be provided with identical forcing, thereby isolating the effects of the boundary-layer representation from the rest of the storm. The slab model is depth-averaged, while the height-resolving model solves the full three-dimensional equations of motion with a simple parameterisation of turbulent diffusion. Both use the same parameterisation of surface drag and, as far as is possible, boundary conditions. The thermodynamics of the boundary layer will not be studied, not because it is unimportant, but because the focus is on getting the flow correct, which is a necessary first step to calculating the flux and advection terms in the thermodynamic budgets. Full details of the models used in this study are in [1].

3 RESULTS

Figure 1 shows the boundary-layer flow in a stationary, axisymmetric cyclone with maximum gradient wind of 40 m s−1 at a radius of 40 km, according to the height-resolving model. The forcing vortex is as in [2] to ease comparison with their slab model results. The depth of the inflow layer decreases rapidly with radius, from about 2 km at 300 km radius to below 400 m in the eye, consistent with observations (e.g. [3] and [4]), and linear models and scaling arguments that show that the boundary layer depth in the core of the storm scales as I−1/2, where I is the inertial stability (e.g [5]). The maximum azimuthal wind is 43.2 m s−1 at a height of 400 m, and is about 8% supergradient. The supergradient flow is mostly within the inflow layer, but does extend upwards into the outflow layer at the top of the boundary layer, and was extensively analysed by [6].

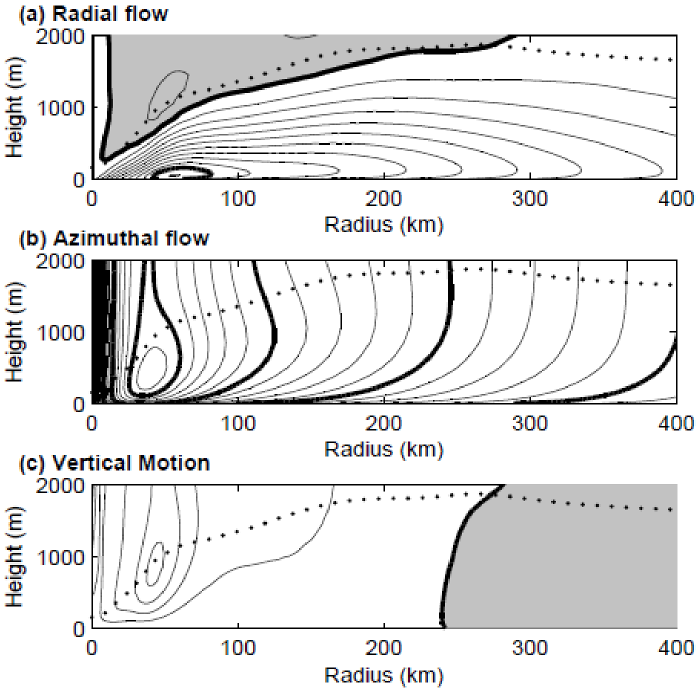


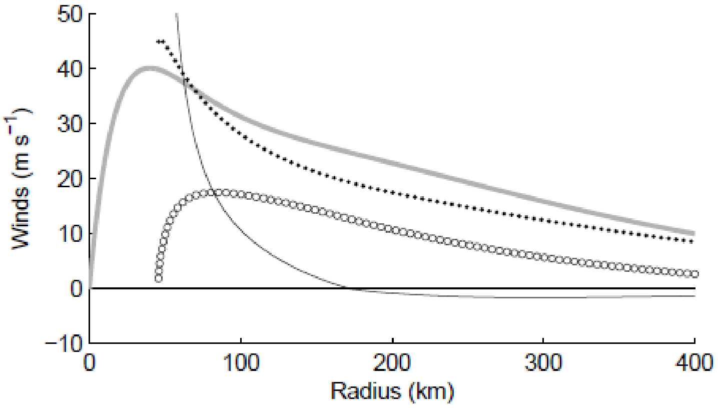
Figure 1: The boundary layer flow in a stationary storm simulated by the height-resolving model. (a) radius-height section of the radial wind, contour interval 1 m s^{-1}, multiples of 10 m s^{-1} shown bold, positive values shaded. (b) radius-height section of azimuthal wind, contour interval 2 m s^{-1}, multiples of 10 m s^{-1} shown bold. (c) radius-height section of the vertical velocity, contour interval 0.05 m s^{-1}, zero line shown bold, subsidence shaded. The dotted line in each panel indicates the level at which the stress magnitude reduces to 20% of its surface value.

The turbulent stress has maximum magnitude at the surface and decreases monotonically with height in this and similar simulations. The dotted lines in Figure 1 show the height at which the momentum flux magnitude falls to 0.2 of its surface value; the value 0.2 was chosen as it roughly coincides with the top of the inflow layer. Clearly the turbulent transport of momentum is a significant part of the dynamics of the outflow layer, consistent with the discussion in [6].

The flows from the slab and height-resolving models are compared in Figure 2. This comparison uses the same forcing vortex and surface drag parameterisation in both models; the flow from the height-resolving model is averaged over the same height range as the prescribed boundary layer depth in the slab model. This height is less than the boundary-layer depth except in the inner core, but as can be inferred from Figure 1, other reasonable choices will not dramatically change the results. The slab model has the stronger inflow except within the eye, most markedly so at and immediately outside of the radius of maximum winds (RMW). Thus the eyewall updraft is very much stronger in the slab model. The frictionally-forced updrafts outside of 250 km radius are more similar, because there the stronger *∂u/∂r* term in the continuity equation compensates for the stronger inflow in the slab model. The height-resolving model has the height-mean azimuthal flow slightly subgradient except in the vicinity of the RMW, where it is slightly supergradient. This situation is in strong contrast to the slab model, which has much larger departures from gradient balance through most of the storm. Observations show that the azimuthal-mean surface inflow angle in tropical cyclones over the sea is usually in the range 20 – 25°. For example, Hurricane Frederic (1979) had an azimuthal-mean surface inflow angle of 21 – 22°, according to the over-water composite analysis of [7]. The height-resolving model simulation shown in Figure 2b has a surface inflow angle of 20 – 25° over most of the domain, reducing to smaller values inside of radius 70 km. Observations of the depth-averaged inflow angle are seldom reported, but can safely be assumed to be less than the surface value. The slab model inflow angle exceeds 20° between 70 and 360 km, and exceeds 30° from 90 to 220 km radius, which is unrealistically large.

One might suspect that the excess inflow in the slab model is because the surface drag there is calculated from the boundary-layer mean wind, whereas the height-resolving model uses the 10-m wind. One can crudely correct for this by reducing the wind speeds in the surface stress calculation by a factor of, say, 0.7 – 0.9, to better represent the surface wind; [8] reduce their surface drag coefficient by 50% for this reason. This adjustment reduces the departure of the boundary-layer flow from the gradient flow at large radii (Figure 3). However, the solution now displays marked oscillations inwards of about 150 km radius, similar to those analysed by [2] (section 4.1) but beginning at much larger radius than they reported.

(a) Slab model



(b) Height−resolving model

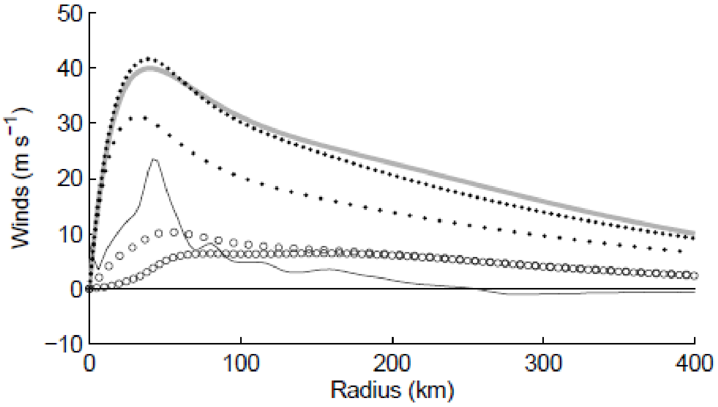


Figure 2: (a) Axisymmetric boundary layer flow according to the slab model. Gradient wind (thick grey), boundary-layer mean azimuthal (dots), inwards (open circles) and upwards (thin black, multiplied by 100) flow components. Parameter values are as in [9], including the boundary-layer height which is fixed at h = 800 m.
(b) Simulation of the same vortex as in (a), except by the height-resolving model, as already shown in Figure 1. Curves with closely-spaced symbols are averaged over the lower 800 m, while those with less dense symbols show the flow at 10-m height. The vertical velocity is at 800-m height.

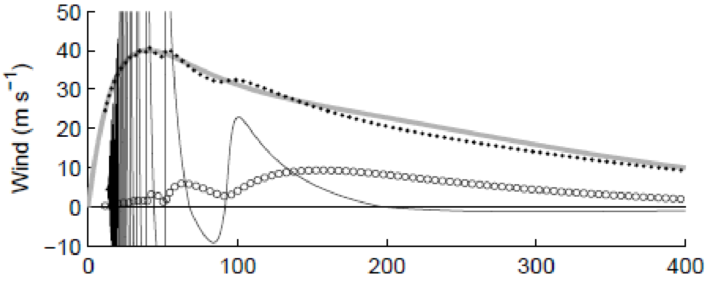


Figure 3: Boundary-layer flow simulated by the slab model as in Fig. 2a, except with C_D halved.

4 DISCUSSION AND CONCLUSIONS

Marked differences in the boundary-layer flow occur between that predicted by a simple slab model and that predicted by a height-resolving model. In addition, the slab model was shown by [1] to exhibit quite pathological behaviour for some reasonable parameter settings, and to have an unphysical sensitivity to *f*. Analysis of the reasons for these properties [10] shows that two factors are responsible: (i) the calculation of the surface drag using the boundary-layer mean wind rather than the surface wind, and (ii) the inaccurate treatment of the nonlinear terms in the depth-averaging. The first of these is problematic at all radii, while the second becomes significant in the inner core. There is some uncertainty in what values of physical parameters should be applied, and arguably a smaller value of C_D can be justified in the slab model since the drag is being applied to the boundary-layer mean wind. This adjustment reduces the excess inflow and subgradient flow in the slab model, but can trigger the quasi-inertial oscillation, so cannot be regarded as an improvement. These results confirm and help explain the recent TCBL model intercomparison by [11], who found that the slab model was significantly less accurate than the linear model of [5] when compared to observational analyses.

Simplified models of the TCBL are useful for a number of purposes, with major applications including climatological risk assessment and engineering design. The considerable inaccuracies demonstrated here and by [1] implies that considerable caution must be applied in future if using slab models for quantitative prediction. Such applications have demonstrated satisfactory agreement between model and observations ([8], [12], [13] & [14]), but the slab model output has in such cases been rather empirically adjusted before comparison with observations. Moreover, most such verifications have been of wind speed, where the biases in radial and azimuthal components will partly cancel, rather than of the wind vector. While these authors are to be commended for their validation efforts, it appears that the tuning of these adjustments has concealed fundamental deficiencies in the model.

Another important application of simplified models has been as a component of tropical cyclone potential intensity (PI) models. Recently, [9] have shown that further approximations within a slab model, including those made in Emanuel's PI model, can produce large changes in the flow. Those differences are of similar magnitude to the differences between slab and height-resolved models demonstrated here. The results in this paper support the conclusion of [9] as to the need to improve the boundary-layer component within existing PI models. However, it is very clear that simply relaxing some approximations but remaining with the slab model approach would be replacing one inaccurate model with another. A better solution could be an extension of the height-parameterised model presented here, to include prediction of the thermodynamic parameters. Research is continuing to develop such a model.

5 REFERENCES

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