Super-parameterization of boundary layer roll vortices in tropical cyclone models

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LONG-TERM GOALS

The long term goals of this effort are to

• Advance the parameterization of the atmospheric boundary layer in high wind conditons to improve the forcasts of tropical cyclone (TC) intensity and

• Develop and implement a new parameterization of the effects of roll vortices into the U.S. Navy’s operational COAMPS-TC prediction system.

OBJECTIVES

The objectives of this project are:

• To develop a new methodology for explicit representation of roll vortices in TC models.

• To investigate the mechanisms leading to the formation of roll vortices in TC conditions and to assess their effects on the structure and intensity of TCs.

• To inverstigate the interaction between the surface processes and the BL processes and to assess their effects on TC intensity and structure predictions.

APPROACH

Our approach to represent roll vortices (rolls) in a TC model resembles the “super-parameterization” approach used represent cloud processes in general circulation models (GCMs). The basic idea is to embed a 2-D high-resolution roll-resolving model into multiple locations of the 3-D TC model. The fundametal assumption behind this approach is that rolls in the boundary layer are separable from the large-scale flow because of their small spatial scale. The decomposition of the full atmospheric equations into two sets of coupled equations for the mean flow and rolls is described in detail by Gao and Ginis et al. (2014). Our proposed numerical system can explicitly resolve the two-way interactions between rolls and the large-scale hurricane flow.
WORK COMPLETED

Tasks completed:

- A 2-D high-resolution Single-grid Roll-resolving Model (SRM) has been developed. SRM can be used to explicitly resolve rolls and represent the roll-induced mixing effects in a tropical cyclone model.

- We have embedded the SRM into an idealized tropical cyclone boundary layer (TCBL) model. Some key aspects of rolls have been investigated based on this idealized framework, including the formation mechanism of rolls, the effects of environmental factors on rolls, the distribution of roll-induced fluxes, and the impact of rolls on the mean winds. A paper summarizing the linear analyses is accepted for publication in the *Journal of Atmospheric Sciences (JAS)*. A follow-up manuscript summarizing the nonlinear analysis is under preparation and will be submitted to *JAS* in the near future.

- We have successfully implemented the SRM into COAMPS-TC in close collaboration with the NRL COAMPS-TC group led by Dr. Jim Doyle. We are currently investigating the dynamics and impacts of rolls on hurricane intensity and structure in a realistic TC environment.

RESULTS

1. Results from idealized TCBL simulations

A group of idealized experiments have been conducted to investigate the effect of stratification, particularly the mixed layer height on the evolution and structure of rolls. In these experiments, SRM is embedded at the Radius of Maximum Wind (RMW) of the idealized TCBL model. The coupled SRM-TCBL model is run until rolls reach a quasi-equilibrium state. The initial stratification profiles are prescribed, in which the mixed layer height is varied from 200 m to 600 m.

a. Effect of the mixed layer height on the characteristics of rolls

Fig. 1 shows the representative structures of the rolls for the mixed layer heights 300 m (left) and 600 m (right), respectively. The two snapshots are taken at the quasi-equilibrium state. There are substantial differences in the upper levels (z > 1 km) between the two cases. The streamlines and contours of \(\omega^i\) are inclined from the vertical in the higher mixed layer case, which suggests internal gravity waves co-exist with rolls. These waves are generated because the rolls keep perturbing the stably stratified layer above while propagating horizontally. The triggered waves are phase-locked with the rolls; they have the same horizontal wavenumber and angular frequency. Internal gravity waves are not very effectively triggered in the lower mixed layer case. We conclude that under a higher mixed layer, the roll vortices can more effectively trigger vertically propagating internal waves in the stably stratified layer above.

Fig. 2 shows the horizontally averaged momentum fluxes in all experiments. These fluxes represent the net vertical transports of momentum by rolls and internal waves. The roll-induced momentum fluxes are concentrated in the lower levels (z<1 km). The roll-induced fluxes have similar distribution in different experiments, but the magnitude increases with the mixed layer height. The momentum flux
\( \overline{w'u'} \) at the upper levels \((z>1 \text{ km})\) is generated by the vertically propagating internal waves. As the mixed layer height increases, the internal waves become more efficient in radiating more momentum flux vertically.

**Figure 1.** Representative structures of the rolls under a mixed layer height of 300 m (left) and 600 m (right). The colored background represents vertical velocity \( w' \). Contours are streamlines: solid (dashed) contours represent clockwise (counterclockwise) circulations.

**Figure 2.** Horizontally-averaged momentum fluxes (left: cross-roll momentum flux \( \overline{w'u'} \); right: along-roll momentum flux \( \overline{w'v'} \)). The mixed layer height used in different experiments are indicated in the figure.

\textbf{b. Characteristics of roll-induced momentum fluxes}

We have examined the correlation between the roll-induced momentum fluxes and the mean wind shear. The traditional way to parameterize the sub-grid-scale fluxes is the flux-gradient approach, often called the \( K \)-theory. The \( K \)-theory assumes that the vertical flux induced by the sub-grid-scale motions depends on the vertical gradient of the mean, and can be represented as \( \overline{w'\phi'} = -K_\phi \frac{\partial \phi}{\partial z} \), where \( \phi \) can be an arbitrary variable and \( K_\phi \) is the parameterized mixing coefficient for \( \phi \). To examine whether the roll-induced fluxes can be represented by the \( K \)-theory, we calculate the mixing coefficients that are needed to represent the roll-induced fluxes. Specifically, the effective \( K \) for the cross-roll
momentum and along-roll momentum are calculated according to following formulas: 

\[ K_u = -\frac{\partial u}{w u} \]

and 

\[ K_v = -\frac{\partial v}{w v} \]

As shown in Fig. 3, \( K_u \) has a very different vertical distribution from \( K_v \): \( K_u \) in these experiments is mostly positive and have limited values, but \( K_v \) reaches infinity around \( z \approx 0.4 \) km. The different distribution of \( K_u \) and \( K_v \) suggest that the rolls transport the cross-roll momentum and the along-roll momentum by different mechanisms. While the roll-induced cross-roll momentum flux depends on the local gradient, the along-roll momentum flux does not. The traditional K-theory doesn’t distinguish the momentum transport in the two directions and therefore cannot be used to represent the roll-induced momentum fluxes. The SRM explicitly resolves the momentum perturbations caused by rolls, and it is computationally efficient. Therefore, embedding the SRM into hurricane models is a potentially sensible approach to capture the roll-induced mixing effects.

**Figure 3.** Profiles of the effective K derived based on the roll-induced momentum fluxes and the mean wind shear.

c. Effect of rolls on the mean wind distributions

Fig. 4 illustrates the impacts of the rolls on the mean winds in the TCBL. Overall, the changes of the mean wind profiles in all the experiment are qualitatively similar. Rolls with stronger magnitude have a larger impact on the wind profiles. The rolls reduce the inflow near surface and increase the inflow at upper level (the inflow layer is enhanced by rolls). The azimuthal maximum wind, i.e. the super-gradient jet, is slightly weakened by rolls. As shown in Fig. 4 (c) and (d), the changes in the mean radial wind are more apparent than the changes in the mean azimuthal wind.

We conducted an additional experiment to investigate the impact of the rolls on the overall distribution of mean winds in the TCBL. In the additional experiment, SRM is embedded at all locations of the mean TCBL model. The same stratification profile is used at all locations and the mixed layer height is
set as 600 m. Fig. 5 illustrates the height-radius distribution of the net changes induced by the rolls. The result is consistent with the findings from the experiments shown in Fig. 4: the rolls decrease the inflow near the surface, broaden the inflow layer and weaken the super-gradient jet.

Figure 4. Comparison of the mean wind profiles before and after rolls are introduced. The mean wind profiles without the impact of rolls (initial wind profiles) are shown as the dashed lines in (a) and (b). The mean wind profiles under the impact of rolls from the five experiments are shown as solid lines in (a) and (b). The net change of the mean winds induced by rolls are shown in (c) and (d).

Figure 5. Radius-height distribution of the net change of the mean winds induced by rolls. Contours show the mean wind distribution without rolls. The dashed contours represent the inflow, and solid contours represent the outflow in (a).
2. Results from COAMPS-TC simulations

We have successfully implemented the SRM into the COAMPS-TC model and investigated the generation and effects of rolls on the development of the hurricane. An idealized simulation without rolls is first conducted to spin up the TC and provide the initial condition for the coupled TC-roll model. In this idealized simulation, the TC is assumed to be stationary and SST is assumed to be constant. After 70 hr of the initial TC spinup, SRM is turned on at 400 horizontal grid locations to resolve rolls and provide the roll-induced tendencies to COAMPS-TC. Fig. 6 illustrates the locations where SRM is embedded.

![Figure 6](image_url)

**Figure 6.** Horizontal distribution of the wind field in the idealized TC simulation at z ~ 3km at 70 hr. The background color represents the wind speed. The white ‘+’ represent the locations where SRM is embedded.

The result suggests that roll can be generated at most of the selected locations. Fig. 7 shows the horizontal distribution of roll-induced fluxes 5hr after the SRM is turned on. Each pixel represents a single location. The locations where rolls are generated have non-zero fluxes. The rolls can induce significant vertical fluxes of momentum, heat and moisture in the TCBL. Fig. 8 shows the distribution of roll-induced fluxes and the parameterized turbulent fluxes at the radius of maximum wind to the right of the storm center. Only the roll-induced radial momentum flux ($v_r$) resembles the parameterized turbulent flux. The roll-induced azimuthal momentum, heat and moisture fluxes have very different vertical distributions and magnitudes from the parameterized turbulent fluxes.
Figure 7. The horizontal distributions of roll-induced fluxes near surface (z=30m), 5 hr after SRM is turned on. Each pixel represents a single grid of the TC model. The grids with rolls formed have non-zero fluxes.

Figure 8. Profiles of the roll-induced fluxes and parameterized turbulent fluxes at the radius of maximum wind, to the right of the storm center. The roll-induced fluxes (shown as black lines) are explicitly resolved by the SRM, and the turbulent fluxes (shown as red lines) are parameterized based on the standard K-theory. The profiles shown are 1hr-averaged.
The roll-induced fluxes in the boundary layer can significantly affect the TC structure. To highlight the effect of rolls Fig. 9 shows the differences between the experiment with rolls and without rolls. The experiment with rolls has a higher inflow layer, suggesting rolls can affect the radial advection of angular momentum and moisture into the storm center. Moreover, the impacts of rolls are not only limited in the boundary layer (roughly $z < 2 \text{ km}$). There are also significant changes in vertical updraft associated with the deep convection above 2 km. We conclude that rolls can play an important role in the overall TC structure and intensification process. The mechanism by which the rolls affect the TC development, as well as the sensitivity of the TC structure to the rolls generated at different radius will be investigated in the future.

**Figure 9.** Upper-panel: azimuthal-averaged radius-height distribution of the wind fields in the experiment with rolls, 5 hr after SRM is turned on. Middle-panel: azimuthal-averaged radius-height distribution of the wind fields in the experiment without rolls, at the same time as the upper-panel; Lower-panel: the differences of the wind fields in the two experiments. The black contours in the upper and middle panels represent the same values.

**IMPACT/APPLICATIONS**

This research program will advance the understanding and parameterization of the atmospheric boundary layer in tropical cyclone conditions as a route toward skillful prediction of tropical cyclone
intensity and structure. A new 2-D high-resolution Single-grid Roll-resolving Model (SRM) is being developed and implemented into the U.S. Navy’s operational COAMPS-TC prediction system.

RELATED PROJECTS

Other ONR DRI “Unified Parameterization for extended Range Prediction” projects.

REFERENCES


Gao, K. and I. Ginis, 2014: A numerical study of the interactions between roll vortices, internal waves and mean flow in the hurricane boundary layer. To be submitted to J. Atmos. Sci..