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 conditions to improve the forecasts of tropical cyclone (TC) intensity and

• Develop and implement a new parameterization of the effects of roll vortices (rolls) 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 rolls in TC models.

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

• To investigate 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 rolls is to embed a 2-D Single-grid Roll-resolving Model (SRM) into multiple locations of the 3-D TC model. The fundamental 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, 2015). Our proposed numerical system can explicitly resolve the two-way interactions between rolls and the large-scale hurricane flow.
WORK COMPLETED

Tasks completed:

• We have successfully implemented the SRM into COAMPS-TC in close collaboration with the NRL COAMPS-TC group led by Dr. James Doyle.

• The impacts of rolls on the development of axisymmetric TC are investigated and the physical mechanisms involved are explored.

RESULTS

1. Experimental design

The strategy of embedding the SRM mesh into the COAMPS-TC mesh is illustrated in Figure 1. The larger-size mesh with a coarse-resolution represents the mesh in COAMPS-TC, and the smaller-size mesh with a high-resolution represents the mesh in the SRM. At each horizontal grid point, the SRM mesh is oriented perpendicular to the direction of the wind vector averaged within the lowest 1 km layer, with the along-roll axis is in the direction of the vertically-averaged wind vector. SRM and COAMPS-TC exchange information at each of the selected horizontal grid point: COAMPS-TC provides SRM with the vertical profiles of the horizontal winds, potential temperature and water vapor mixing ratio as the mean flow variables for rolls; and SRM provides COAMPS-TC with the roll-induced vertical fluxes of momentum, potential temperature, and water vapor mixing ratio, which are all horizontally averaged in the SRM domain.

Based on the coupled SRM and COAMPS-TC modeling system, the impacts of rolls on the development of the TC is evaluated through a series of experiments. For simplicity, we assume that the TC is stationary and axisymmetric on the f-plane (20°N) and over the ocean with constant sea surface temperature (30°C). The COAMPS-TC is first run for 70 h without SRM to spin up a TC-like vortex. The spunup TC is used as the initial condition for the experiments with the effects of rolls and the elapsed time is reset to 0 h. A summary of these experiments is provided in Table 1. In all experiments, except CTRL, the SRM is embedded at selected horizontal grid points. All other COAMPS-TC configurations are the same as in the spin-up run. Experiments ROLL and CTRL are designed to demonstrate how rolls affect the structure and intensity of the TC. The only difference between the two experiments is that ROLL has SRM embedded into COAMPS-TC, but CTRL does not. Figure 2 shows the horizontal grid points where SRM is embedded in experiment ROLL. Two groups of sensitivity experiments are also conducted. In Group A we investigate which components of the roll-induced fluxes are most important in affecting the development of the TC. In each experiment, only one component of the roll-induced fluxes is provided to COAMPS-TC. In Group B we investigate the effects of rolls formed at different radius ranges on the development of the TC. In each of these experiments, SRM is only embedded at the horizontal grid points within a 5 km range of the specified radius.
Figure 1. Schematic diagram illustrating how SRM is embedded at selected horizontal grid points in the COAMPS-TC domain. The larger-size mesh with relative coarse resolution represents the mesh for COAMPS-TC, and the smaller-size mesh with relative high resolution represents the mesh for the SRM. In this diagram, the SRM meshes are embedded at two horizontal grid points in the COAMPS-TC mesh, labeled as $(X_1, Y_1)$ and $(X_2, Y_2)$.

Figure 2. A map showing the horizontal grid points where SRM is embedded in experiment ROLL. The background color represents the tangential wind at 3 km height. “+” represents the horizontal grid point where SRM is embedded. The two dashed contours represent radius $= 15$ km and 50 km, respectively.
Table 1. A summary of the numerical experiments performed in this study.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td>Control experiment without the effects of rolls.</td>
</tr>
<tr>
<td>ROLL</td>
<td>SRM embedded at the grid points in the radius range 15–50 km.</td>
</tr>
<tr>
<td>Group A</td>
<td></td>
</tr>
<tr>
<td>ROLL-U</td>
<td>Only the roll-induced radial momentum flux is applied to the TC.</td>
</tr>
<tr>
<td>ROLL-V</td>
<td>Only the roll-induced tangential momentum flux is applied to the TC.</td>
</tr>
<tr>
<td>ROLL-Θ</td>
<td>Only the roll-induced potential temperature flux is applied to the TC.</td>
</tr>
<tr>
<td>ROLL-Q</td>
<td>Only the roll-induced water vapor mixing ratio flux is applied to the TC.</td>
</tr>
<tr>
<td>Group B</td>
<td></td>
</tr>
<tr>
<td>ROLL-R20</td>
<td>SRM embedded at the grid points in the radius range 17.5–22.5 km.</td>
</tr>
<tr>
<td>ROLL-R25</td>
<td>SRM embedded at the grid points in the radius range 22.5–27.5 km.</td>
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<tr>
<td>ROLL-R30</td>
<td>SRM embedded at the grid points in the radius range 27.5–32.5 km.</td>
</tr>
<tr>
<td>ROLL-R35</td>
<td>SRM embedded at the grid points in the radius range 32.5–37.5 km.</td>
</tr>
<tr>
<td>ROLL-R40</td>
<td>SRM embedded at the grid points in the radius range 37.5–42.5 km.</td>
</tr>
<tr>
<td>ROLL-R45</td>
<td>SRM embedded at the grid points in the radius range 42.5–47.5 km.</td>
</tr>
</tbody>
</table>

2. Roll-induced vertical fluxes

Figure 3 shows a series of consecutive snapshots of the roll-induced cross-roll momentum flux \( w' u' \) at \( z = 300 \) m. Each pixel represents a single horizontal grid point in the COAMPS-TC domain. The grid points where rolls are generated have non-zero fluxes. Rolls are first formed at some horizontal grid points at the outer (~50 km) and inner (~20 km) radii, and with time they are formed at more and more locations. Figure 4 shows the vertical profiles of the azimuthally-averaged roll-induced vertical fluxes at radius = 25 km, as well as the parameterized turbulent fluxes for comparison. The profiles of the roll-induced radial and tangential momentum fluxes are consistent with those in Gao and Ginis (2015). The shapes of the vertical distributions of roll-induced radial momentum flux and the turbulent radial momentum flux are similar below 1 km. This distribution occurs because the rolls generated by the inflection point instability induce cross-roll momentum flux, which is approximately the radial momentum flux, negatively correlated with the mean wind shear (Figure 5). On the contrary, the vertical distributions of the roll-induced tangential momentum flux and the turbulent tangential momentum flux are very different. This is because the roll-induced along-roll momentum flux, which is approximately the tangential momentum flux, is not dependent on the mean wind shear, as discussed in Gao and Ginis (2015). The roll-induced heat and moisture fluxes have much stronger magnitudes than the corresponding parameterized turbulent fluxes at lower levels \( (z < \sim 1 \text{ km}) \), suggesting that rolls tend to enhance the vertical mixing of heat and moisture in the TCBL.
Figure 3. The horizontal distributions of the roll-induced cross-roll momentum flux \( (m^2 s^{-2}) \) at (a) 4 h, (b) 5 h, (c) 6 h, (d) 7 h in experiment ROLL. The height is 300 m. Each pixel represents a single horizontal grid point in the COAMPS-TC domain. The horizontal grid points where rolls are formed have non-zero flux.

Figure 4. Representative vertical profiles of the roll-induced fluxes (red) and the parameterized turbulent fluxes (black): (a) radial momentum flux, (b) tangential momentum flux, (c) potential temperature flux and (d) the water vapor mixing ratio flux. These profiles are time (6-7 h) and azimuthally averaged, and at radius = 25 km.
3. Effect of rolls on the TC intensity development

To investigate the effect of rolls on the TC structure and intensity, we compare experiments ROLL and CTRL. We use the maximum $<V>$ at $z = 5$ km (far away from the TCBL) to represent the overall TC intensity. Figure 5 shows the time series of the maximum $<V>$ at $z = 5$ km in group A and B experiments, as well as in CTRL and ROLL, for comparison. Interestingly, only the TC in ROLL-V experiment has a similar intensification rate as the TC in ROLL experiment, while the TC intensification rates in other group A experiments are similar to that in CTRL experiment (Figure 5a). This suggests that the roll-induced tangential momentum flux is primarily responsible for the enhanced TC intensification. All the TCs in group B experiments have stronger intensification rates than the TC in CTRL, indicating that rolls at different radii (within the range considered in this study) all have positive contributions to the TC intensity (Figure 5b). The TCs in the group B experiments are weaker than the TC in ROLL, suggesting the enhanced TC intensity in ROLL is very likely due to the collective contributions of rolls at different radii.

![Figure 5](image)

Figure 5. (a) Time series of the maximum azimuthally-averaged tangential wind at $z = 5$ km in the group A experiments. (b) As in (a), but for the group B experiments.

4. Dynamical interpretation

Next we analyze the physical mechanism through which rolls affect the TC structure and intensity. Specifically, we focus on (a) how the roll-induced vertical fluxes, particularly the tangential momentum flux, affect the TCBL structure and (b) how the roll-induced changes in the TCBL affect the entire TC. Our analysis is based on ROLL-R45 because the rolls in this experiment are generated in a limited radius range, and therefore it is easier to identify their local and nonlocal impacts.
4.1 Effect of rolls in the TCBL

To gain a physical insight of the impacts of roll-induced momentum fluxes in the TCBL, we analyze the azimuthally-averaged momentum budgets, which are written as follows (the horizontal diffusion terms are weak and therefore neglected).

\[
\frac{d <U>}{dt} = -\left( \frac{1}{\rho} \frac{\partial P}{\partial r} \right) + \left( f + \frac{<V>}{r} \right) <V> - \left( \frac{\partial WV}{\partial z} \right) + \left( \frac{\partial}{\partial z} (K_m \frac{\partial U}{\partial z}) \right) \tag{1}
\]

\[
\frac{\partial <V>}{\partial t} = -\left( f + \frac{<V>}{r} + \frac{\partial <V>}{\partial r} \right) <U> - \left( \frac{\partial WV}{\partial z} \right) + \left( \frac{\partial}{\partial z} (K_m \frac{\partial V}{\partial z}) \right) - W \frac{\partial <V>}{\partial z} \tag{2}
\]

The physical meaning of the terms in (1) is (from left to right): the net acceleration in the radial direction (that is the material derivative of \(<U>\)); IMB – the gradient wind imbalance, which is the imbalance between the pressure gradient force and the sum of Coriolis and centrifugal forces; and UBL – the total sub-grid momentum tendencies in the radial direction, which consists of the roll-induced tendency (hereafter \(<R_{v}>\)) and the turbulent tendency (hereafter \(<T_{v}>\)). The physical meaning of the terms in (1) is (from left to right): the local time-changing rate of \(<V>\); ANG – the acceleration due to the radial advection of the absolute angular momentum (defined as \(1/2 f r^2 + Vr\)); VBL – the total sub-grid momentum tendencies in the tangential direction, which consists of the roll-induced tendency (hereafter \(<R_{\phi}>\)) and the turbulent tendency (hereafter \(<T_{\phi}>\)); and the vertical advection effect.

To further explore how the roll-induced tangential momentum tendency \(<R_{\phi}>\) affects the TCBL dynamical structures, we derive the differences between the momentum budget terms in (1) and (2) in ROLL-R45 and CTRL. The vertical distribution and time evolution of these differences, denoted by \(\delta\), are shown in Figure 6, which help reveal the chain of responses in the TCBL to \(<R_{v}>\) at the location where rolls are generated.

i) The vertical distribution of \(\delta VBL\) suggests that rolls redistribute the tangential momentum vertically, and thus have a direct effect on the local \(<V>\) profile. Rolls tend to increase \(<V>\) at lower levels and decrease \(<V>\) at the upper levels [see equation (1)].

ii) The vertical distribution of \(\delta IMB\) reflects the effects of rolls on the local \(<V>\) profile: \(\delta IMB\) is positive near surface where rolls tend to increase \(<V>\), and \(\delta IMB\) is negative at upper levels where rolls tend to decrease \(<V>\).

iii) The distribution of \(\delta d<U>/dt\) is similar to \(\delta IMB\), suggesting that the change in IMB directly affects the net radial acceleration, and therefore affects the local \(<U>\) profile.

iv) The changes in \(<U>\) and \(<V>\) result in the change in ANG term (note negative \(\delta ANG\)). Under the impact of rolls, the local wind profiles adjust to a state in which \(\delta ANG\) in nearly in balance with \(\delta VBL\).

The effect of rolls on the TCBL wind is not limited to the location where the rolls are generated. Figure 7 shows the height-radius distribution of the radial (\(\delta <U>\)) and tangential (\(\delta <V>\)) wind changes (ROLL-R45 – CTRL), averaged during 3-4 h. While the roll-induced momentum fluxes only exist in the vicinity of a 45 km radius in ROLL-R45, the wind changes are spread in the radial and
vertical directions. During this time period, there are no changes in the upper-level vortex structure above 3 km (not shown). Thus the observed wind changes are only due to the TCBL local response to the roll-induced momentum fluxes and the advection by the TC mean wind circulation.

Figure 6. Hovmöller diagrams of the changes (ROLL-R45 – CTRL) in (a) the net radial acceleration term, (b) the gradient wind imbalance term, (c) the radial advection of absolute angular momentum term (with a negative sign) and (d) the total sub-grid tangential momentum tendency term.

Figure 7. Height-radius distributions of the changes (ROLL-R45 – CTRL) in azimuthally-averaged (a) radial and (b) tangential winds, time averaged during 3-4 h. The contours in (a) represent <U> in CTRL (bold contour – 0 m s\(^{-1}\); dashed contours – inflow; solid contours – outflow; contour interval – 5 m s\(^{-1}\)) and the contours in (b) represent <V> in CTRL (bold contour – 40 m s\(^{-1}\); contour interval – 10 m s\(^{-1}\)).

4.2 Effect of rolls on the deep eyewall convection

We now explore how the wind changes in TCBL induced by rolls contribute to the intensity of the entire TC. Here we hypothesize that rolls affect the entire TC through the following mechanism: the roll-induced radial wind changes in the TCBL enhance the deep eyewall convection by enhancing the
mass convergence in the TCBL. The enhanced deep eyewall convection therefore contributes to the intensity of the entire TC. The following analysis aims to validate above hypothesis by considering the two main aspects of the deep convection: the upward vertical velocity ($<W>$) and the diabatic heating rate ($<H>$) associated with the thermo-dynamical processes.

We first demonstrate that the change in eyewall updraft ($\delta<W>$) is primarily caused by the change of TCBL mass convergence triggered by rolls. The vertical velocity in COAMPS-TC is calculated as a function of the buoyancy of the air and some other factors, but is not calculated directly based on the mass convergence. To highlight the contribution of the TCBL mass convergence on the eyewall updraft, we diagnose the vertical velocity at the lower levels of the TC ($z < 3$ km) based on the following formula:

$$<W>_e = \int_0^z (-\frac{1}{r} \frac{\partial <U>}{\partial r})dz,$$

where $<W>_e$ represents the diagnosed vertical velocity. According to (3), $<W>_e$ is only determined by the mass convergence, which only depends on the distribution of the radial wind. $<W>$, in ROLL-R45 and CTRL can be diagnosed based on the lower-level $<U>$ distributions in these experiments, and $\delta<W>_e$ (ROLL-R45 – CTRL) can then be derived.

Figure 8 shows the time evolution of $\delta<W>_e$, $\delta<W>$ and $\delta<H>$ (ROLL-R45 – CTRL), vertically averaged within the lowest 3 km. The contours represent the vertically-averaged $<W>_e$, $<W>$ and $<H>$ in CTRL, and the bold contours roughly mark the radial boundaries of the deep eyewall convection. Figure 8b,c demonstrates that the deep eyewall convection in ROLL-R45 is more active than in CTRL. The time evolutions of $\delta<W>_e$ and $\delta<W>$ are similar, confirming that the change in the TCBL mass convergence induced by rolls is largely responsible for the change in the eyewall updraft. The magnitude of $\delta<W>_e$ is apparently weaker than $\delta<W>$ after time = 6 h, which is very likely because the change in the latent heat release also contributes to $\delta<W>$. Figure 8c shows the change in the diabatic heating rate ($\delta<H>$) calculated from the COAMPS-TC simulations (ROLL-R45 – CTRL). $\delta<H>$ has a similar distribution as $\delta<W>_e$ and $\delta<W>$, suggesting that the change in the latent heat release is due to the change of updraft and the associated change of moist air supply to the condensation levels. Thus we have confirmed that the rolls can indeed enhance the eyewall convection via the proposed mechanism. The more active eyewall convection in ROLL-R45 is responsible for a stronger TC. The same mechanism is responsible for the stronger TCs in experiment ROLL and also other group B experiments.

5. Summary

In summary, we have investigated the effects of boundary layer rolls on the structure and intensity of the axisymmetric TC. We have found that the roll-induced wind changes in the boundary layer lead to an increase of the TC intensity. The rolls affect the TC intensity mainly via the induced vertical transport of the tangential momentum. The proposed mechanism is as follows. By enhancing the vertical tangential momentum exchange, the rolls trigger a chain of dynamical responses in the boundary layer, increasing the mass convergence and inducing a more active deep eyewall convection, which leads to the enhanced TC intensity.
**Figure 8.** Hovmöller diagrams of the changes (ROLL-R45 – CTRL) in azimuthally- and vertically- (within the lowest 3 km) averaged (a) vertical velocity diagnosed based on mass convergence (b) actual vertical velocity from COAMPS-TC and (c) diabatic heating rate. The contours represent (a) $\delta \langle W \rangle_e$, (b) $\langle W \rangle$ and (c) $\langle H \rangle$ in experiment CTRL: in (a) and (b) the bold contour is 0.1 m s$^{-1}$ and the contour interval is 0.5 m s$^{-1}$; in (c) the bold contour is 0.01 K s$^{-1}$ and the contour interval is 0.03 K s$^{-1}$.

**IMPACT/APPLICATIONS**

The coupled SRM and COAMPS-TC numerical system developed under this project can be applied to model and predict the development of real world TCs with explicit consideration of the effect of roll vortices. This research program will advance the understanding and parameterization of the atmospheric boundary layer in TC conditions as a route toward skillful prediction of TC intensity and structure.

**RELATED PROJECTS**

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

**REFERENCES**

