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 oprational COAMPS-TC prediction system.

OBJECTIVES

The objectives of this project are:

- To develop a new methodology for explict 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 preditions.

APPROACH

Our approach to parameterization of roll vortices in a TC model resembles the "super-parameterization" approach used to simulate cloud physics processes in general circulation models (Grabowski 2001). This methodology includes embedding a roll vortex resolving high-resolution 2-D LES model into the 3-D equation system representing a TC model. The decomposition of a 3-D equation system into two coupled equation systems for the mean flow and convective scale motions (roll vortices) is described in detail by Ginis et al. (2004) for an idealized 2-D mean flow. In this project, we extended this procedure for a general case of a 3-D TC model. The two models are coupled and explicitly solve the two-way interaction between the large-scale flow and roll vortices. The approach is schematically illustrated in Fig. 1. The 2-D LES model numerical meshes are oriented perpendicular to the direction of the mean wind flow generated by the TC model within the lowest ~3 km thickness layer. The exact location of the convective meshes are determined experimentally.

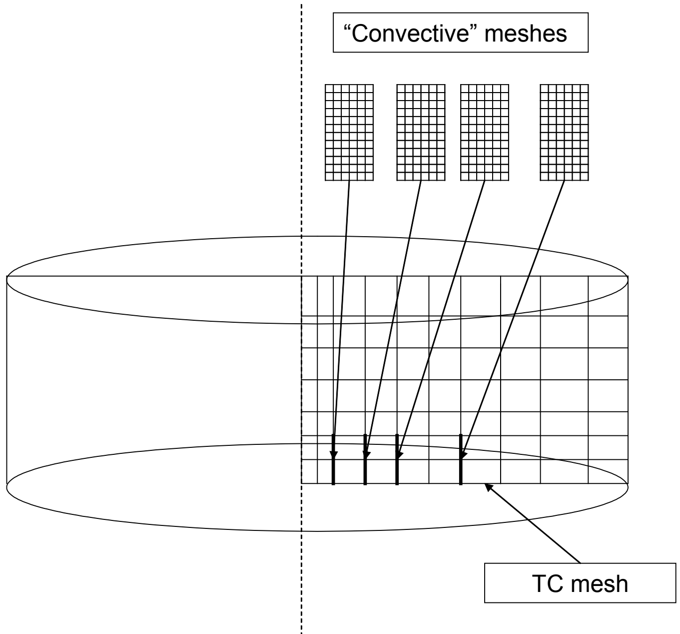


Figure 1. A schematic diagram of the finite grid structure of the coupled TC-2D LES model. The 2D-LES mode lnumerical meshes are placed at different distances from storm center and use the information about the mean-flow vertical temperature, moisture, and wind profiles.

WORK COMPLETED

Tasks completed:

- We coupled the 2D-LES model with an axisymmetric hurricane boundary layer (HBL) model to simulate the generation and evolution of roll vortices, as well as the interactions between rolls and the large-scale wind in HBL.
- We investigated the formation and characteristics of roll vortices due to the inflection point instability in an idealized TC boundary layer.
- We inverstigated the evolution of finite amplitude, nonlinear roll vortices and their potential impacts on the TC boundary layer structure.

RESULTS

The HBL model is initialized from a NOAA/HRD observed multi-storm composite temperature dataset. It is capable of producing a realistic structure of the HBL velocity field. The 2D-LES model is non-hydrostatic and can explicitly simulate large eddies in the HBL, like roll vortices. The model results reveal that the roll vortices can be generated by the inflection point instability of the HBL flow, with the major energy source coming from the vertical shear of the cross-roll mean wind. We have investigated the linear and nonlinear phases of the development and evolution of roll vortices in the hurricane boundary layer. Fig. 2 shows the typical structure of the roll vortices in linear phase generated at 1.0 radius of maximum winds (RMW). The roll vortices in the linear phase have well-organized structures with pairs of counter-rotating cells. It is noticeable that each individual cell is not symmetric: there is a tilt near the surface. The tilt is critical for the roll vortices to gain energy from the mean flow because rolls can induce negative net momentum flux with this kind of structure.

Five experiments were conducted to explore the effect of stable stratification on the inflection point instability. For simplicity, potential temperature profiles with constant lapse rate are used in these experiments. The value of the lapse rate varies from 1K/km to 5K/km. In each experiment, the same potential temperature profile is used at all locations.

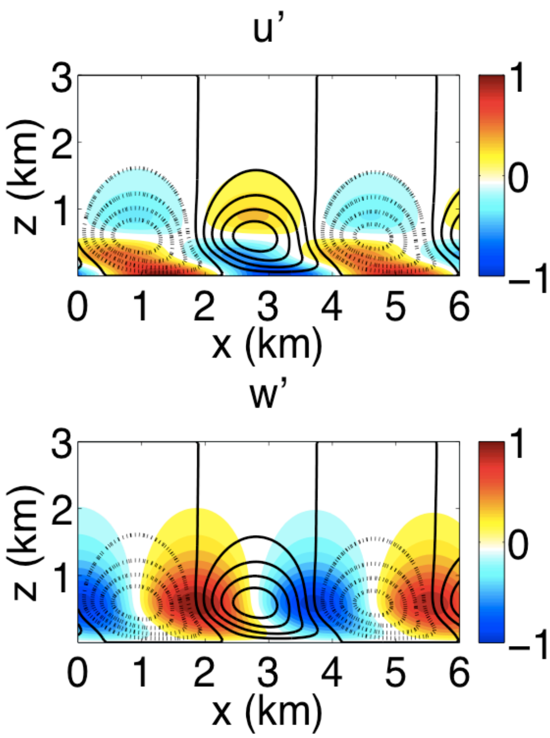
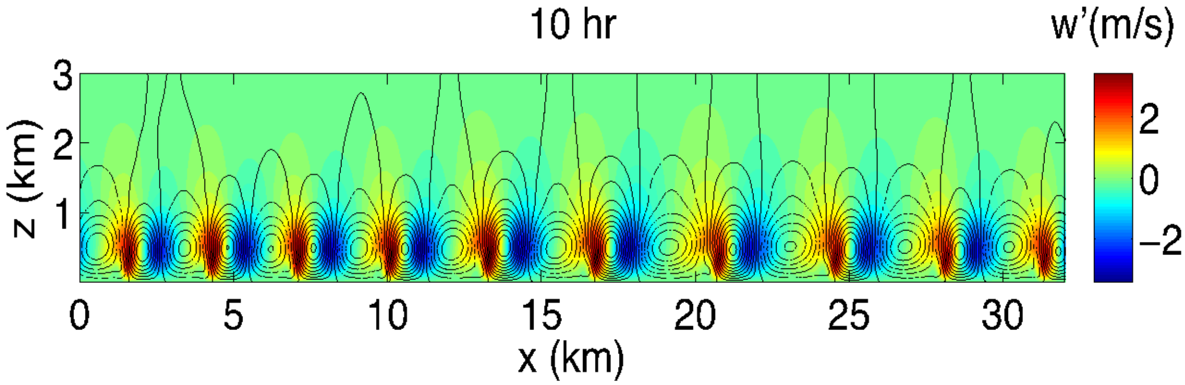


Figure 2. Circulation pattern (upper) and stream function (lower) of roll vortices at 1.0 RMW. Black lines represent zero stream function, which separate different cells. Blue contours represent negative value, corresponding to counter-clockwise circulation. Red contours represent positive value, corresponding to clockwise circulation.

The main findings of the linear phase investigation can be summarized as follows: 1) Under neutral stratification the hurricane boundary layer flow is inherently unstable because of the existence of the inflection point in the radial wind profiles. 2) Roll vortices generated by the inflection point instability are characterized with a tilt in their lower, near surface part. 3) The growth rate of roll vortices decreases with radius due to a decrease of the mean wind shear. On the other hand, the wavelength of roll vortices increases with radius, mainly due to an increase of the characteristic height scale of the HBL flow. 4) Stable stratification can suppress the inflection point instability due to the negative work done by buoyancy.

The investigation of the nonlinear phase has just started. We initially did not consider the effect of stratification, for simplicity. Some preliminary findings of the nonlinear phase investigation can be summarised as follows: 1) Nonlinear rolls may at least have two types structures: a) well-organized single-scale and b) multi-scale. Both types of the structures are illustrated in Fig. 3.

a. Single-scale roll vortices



b. Multi-scale roll vortices

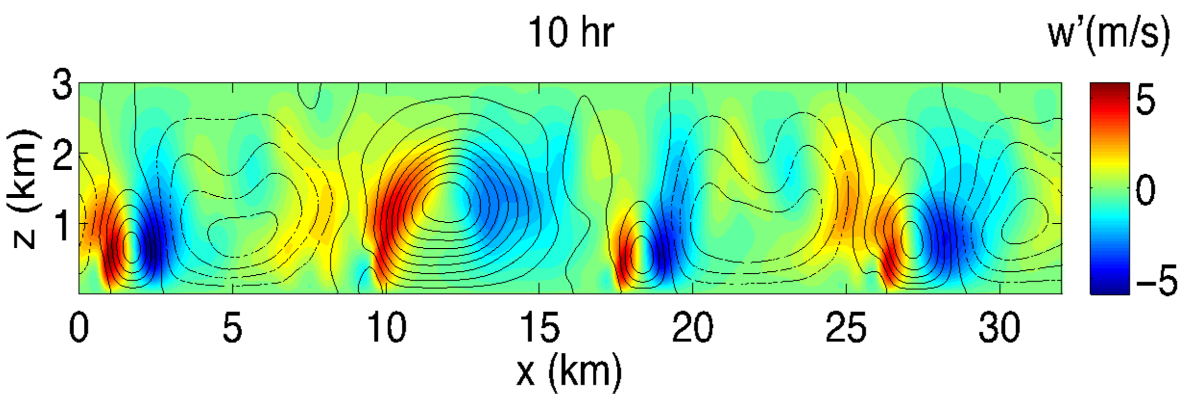


Figure 3. Nonlinear rolls generated at 0.75RMW (top) and 1.0 RMW 9 (bottom) at 10hr. Contours represent the stream function (solid-clockwise, dash-counterclockwise), color indicates the vertical velocity of rolls.

2) The roll-induced momentum flux can significantly modify the HBL structure by reducing the inflow wind speed and increasing the inflow layer height. This result is illustrated in Fig. 4. The overall effect of the roll-induced flux is to better mix the momentum in the HBL.

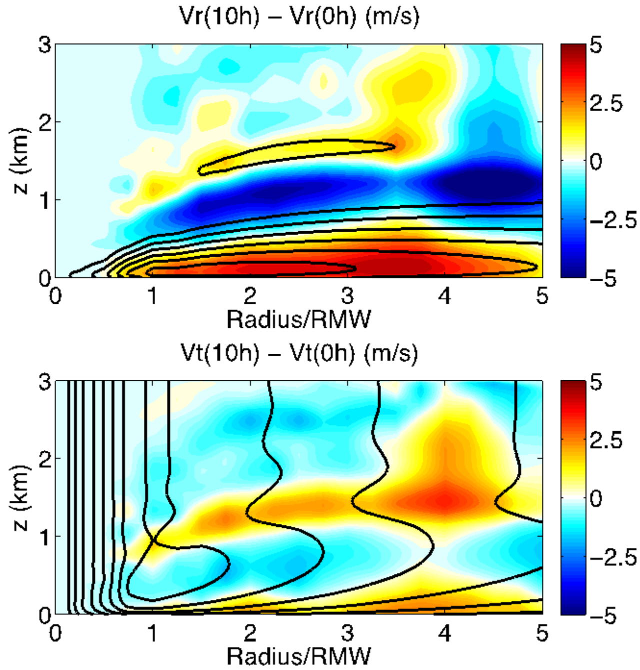


Figure 4. Differences between the HBL radial (top) and tangential (bottom) winds at 10hr and 0hr. Black contours show the initial wind distribution.

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 parameterization of the effect of roll vortices will be developed and implemented into the U.S. Navy's operational COAMPS-TC prediction system.

RELATED PROJECTS

Other ONR DRI "Unified Parameterizaiton for extended Range Prediction" projects.

REFERENCES

Grabowski, W. W., 2001: Coupling cloud processes with the large-scale dynamics using the cloud-resolving convection parameterization (CRCP). *J. Atmos. Sci*., **58**, 978-997.

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