Atmospheric Research 154 (2015) 73–88

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmos

Large-eddy simulation of the hurricane boundary layer: Evaluation of the planetary boundary-layer parametrizations

O. Alizadeh-Choobari *

Institute of Geophysics, University of Tehran, Tehran, Iran

ARTICLE INFO

Article history:
Received 26 May 2014
Received in revised form 14 October 2014
Accepted 5 November 2014
Available online 12 November 2014

Keywords:
Hurricane boundary layer
Large-eddy simulation
Organized roll vortices
Planetary boundary layer

ABSTRACT

The organized roll vortices are the integral part of the hurricane boundary layer (HBL) where they have an important contribution in the vertical transport of momentum, heat and moisture. Large-eddy simulations (LESs) were conducted to explicitly resolve the organized roll vortices in the HBL over the ocean using the Weather Research and Forecasting (WRF) model. The LESs were nested within the WRF mesoscale model to provide two-way up-scale and down-scale exchange at the nest interfaces, and explicitly resolve large eddies. Downdrafts in the organized roll vortices correspond to transport of high-momentum air down to the surface, while updrafts tend to transport low-momentum air upwards. The downdrafts and updrafts therefore lead to a well-organized band-like structure of alternating strong and relatively weak near-surface winds, respectively. The upward legs of the roll vortices are also associated with transport of moist air to the upper levels, while drier air is brought down to the surface in the downward legs. Organized roll vortices contribute a significant [illegible] to the vertical transport of heat and moisture. Three planetary boundary-layer (PBL) parametrizations were examined against the LES. Results indicate that PBL parametrizations cannot capture the band-like structure of alternating strong and relatively weak near-surface winds as they are subgrid scale features, and are unable to adequately represent the surface heat fluxes and wind profiles in the hurricane conditions. PBL parametrizations show ov[illegible]ss variability in the extremes of the wind field.

1. Introduction

It is well known that in the atmospheric boundary layer, in addition to chaotic turbulence, there are convective and dynamic instability mechanisms to generate organized (well defined) roll vortices and coherent vortical structures (here [illegible] large-eddy circulations at or less than a kilometer). The convective instability is basically resulted from thermal convection, while dynamic instability can be driven by the inflection point and parallel instabilities (Brown, 1980). The growth rate of the convective instability is larger than those of inflection and parallel instabilities ([illegible]g and [illegible]n, [illegible]3). The inflection point is the point where the cross-wind profile changes the sign of its curvature and is also the point over which the along-wind vorticity reaches its maximum value. When an inflection point exists, boundary-layer roll circulations may extract energy from the large-scale mean wind shear perpendicular to the roll axis (Stensrud and Shirer, 1988). Extraction of energy by roll circulations through the Coriolis term from the large-scale mean wind shear parallel to the roll axis can also lead to the dynamic instability, which is referred to as parallel instability (Stensrud and Shirer, 1988). To understand the vertical transport processes in the atmospheric boundary layer, large-eddy circulations generated by these instability mechanisms need to be explicitly resolved.

Although the horizontal roll vortices generated by the abovementioned instability mechanisms are somewhat still chaotic and stochastic, they have well-defined structures and can effectively promote the vertical transport in the hurricane boundary layer (HBL). Previous studies have shown that the organized roll vortices are an integral part of the HBL in slightly to moderately unstable stratification combined with sufficiently

* Corresponding author. Institute of Geophysics, University of Tehran, Tehran, Iran.
E-mail address: omid.aliza[illegible]t.ac.ir.

http://dx.doi.org/10.1016/j.atmosres.2014.11.004

strong dynamic instability (Foster, 2005). They may also play a key role in maintaining the high enthalpy fluxes (Morrison et al., 2005) which allow a tropical cyclone to maintain its intensity against frictional dissipation (Emanuel, 2012). The boundary-layer fluxes are also primordial in helping sustain the tropical cyclone secondary circulation and the release of latent heat in the eyewall, which largely arises from condensation.

Using a Doppler radar, Wurman and Winslow (1998) were the first to identify the roll vortices in the HBL, with the wavelength of the rolls found to be approximately 600 m. Recently, much attention has been devoted to such strong roll vortices and their contribution to the vertical circulations in the HBL (e.g. Foster, 2005; Morrison et al., 2005; Nolan, 2005; Lorsolo et al., 2008; Rotunno et al., 2009; Nakanishi and Niino, 2012). For example, the observational studies of Morrison et al. (2005) and Lorsolo et al. (2008) confirmed the existence of roll vortices in the HBL, and the rolls were attributed to the inflection point instability. They found that the roll vortices are nearly aligned with the mean wind direction in the HBL, similar to the results of Li et al. (2013) using the spaceborne synthetic aperture radar. Using wavelet transform, Zhu et al. (2010) demonstrated that the HBL roll vortices form in weak convective conditions outside the eyewall and rainbands, with the cross-wind scale of the rolls estimated to be approximately 1 km at 10-m wind speed of 21 m s^{-1}. They demonstrated that these rolls shift towards larger scales with the increase of wind speed. By developing a nonlinear theory, Foster (2005) showed that the horizontal roll vortices are caused by the inflection point instability in the radial wind profile. He found that a strong near-surface wind shear in the HBL provides a favorable condition for the formation of these roll vortices.

Roll vortices in the HBL are also clearly evident in several recent high resolution numerical simulations. By conducting LESs with the Advanced Research Weather (ARW) model (Skamarock and Klemp, 2008), Rotunno et al. (2009) demonstrated that the tropical cyclone intensity and its maximum wind depend on horizontal roll vortices in the HBL. In his numerical simulation, Zhu (2008) re-produced the organized roll vortices and associated well-defined updrafts and downdrafts in the HBL when Hurricane Ivan (2004) made landfall. He found that explicitly resolved organized turbulent motions in the HBL are responsible for most of the vertical transport of momentum, heat and moisture, while only a small fraction caused by chaotic eddies. The strongest vertical motion associated with roll vortices also found in the middle of the boundary layer, while they have little contribution in the vertical transport processes in the surface layer (Zhu et al., 2010). As noted by Li et al. (2013), most previous studies on roll vortices in the HBL were limited to land-falling storms (e.g. Wurman and Winslow, 1998; Morrison et al., 2005); hence their contribution in the vertical transport processes over the ocean surface where the enthalpy flux is significant remains mostly unexplored.

The scale of a hurricane is of the order of several hundreds of kilometers, but its intensity is affected by different multiple scale processes, ranging from environmental scale (1000 km) to vortex (10–100 km), convective (1 km), small-scale turbulent rolls (10–100 m) and microscales (1–10 m) (Rogers et al., 2012). Contribution of these multi-scale processes causes the difficulty of predicting rapid changes in the hurricane intensity. To better predict the hurricane intensity, the up-scale and down-scale interactions need to be considered in a numerical simulation. This requires very high resolution model simulations that not only include the large-scale features, but also explicitly resolve the organized roll vortices and associated updrafts and downdrafts in the HBL, and parametrize the subgrid scale (SGS) motions.

In mesoscale simulations, grid spacing is not fine enough to explicitly resolve the small-scale turbulent rolls. Instead, their integral impact is expressed through planetary boundary layer (PBL) parametrizations. The PBL parametrizations have been widely evaluated against in situ observations (e.g. Hu et al., 2010; Alizadeh Choobari et al., 2012; Hariprasad et al., 2014; Madala et al., 2014) and in some cases against large-eddy simulations (LESs; e.g. Cuxart et al., 2006 for the stable boundary layer). Comparisons against LESs revealed that most PBL parametrizations are not able to adequately resolve the vertical structure of the boundary layer (Huang et al., 2013). For example, Cuxart et al. (2006) (in a stably stratified boundary layer) and (Huang et al., 2013) studies indicated that PBL parametrizations produce stronger mixing in the boundary layer which leads to a positive friction velocity bias. However, comparisons between LES and PBL parametrizations under strong turbulent motions in the hurricane conditions remain mostly unclear.

A common method to simulate roll vortices in the boundary layer is LES. In LES, a low-pass filter is applied to the time-dependent Navier–Stokes equations, such that large eddies with most energy and fluxes are solved explicitly, while only SGS motions that consist of little energy and fluxes are parametrized. As smaller eddies tend to be more isotropic and homogeneous and less affected by the boundary conditions compared to larger eddies, and they contribute only a small fraction of the total turbulent eddies, parametrization is acceptable. Although the classic LES, used in most of the previous studies, seeks to explicitly resolve the characteristics of roll vortices, it still bears notable deficiencies. It is initialized by the idealized vertical profiles of atmospheric variables and forced by homogeneous large-scale forcing. In addition, it uses the periodic lateral boundary conditions that are suitable over uniform surfaces. However, the hurricane wind changes its speed and direction continuously, and highly asymmetric hurricane vortex structures have been identified (Shapiro, 1990; Reasor et al., 2000). This implies that the large-scale forcing can be substantially inhomogeneous, and it can cause the conditions at the inflow boundary to be quite different from those at the outflow boundary. Therefore, the periodic boundary conditions are not appropriate, implying that the numerical approach and the assumption used by the classic LES are not appropriate for the hurricane conditions.

The present study aims to simulate the organized roll vortices in the HBL over the ocean and understand their influence on the vertical transport of fluxes. To this end, a multi-scale numerical simulation was conducted using the Weather Research and Forecasting (WRF) two-way nesting approach in a hindcasting mode for Hurricane Isaac (2012). To evaluate the boundary-layer parametrizations in re-producing such organized roll vortices to accurately simulate the intensity of a hurricane, additional three mesoscale simulations were conducted, using three different boundary-layer schemes. The results of the mesoscale simulations with the parametrized PBL (all turbulence effects are parametrized) were compared