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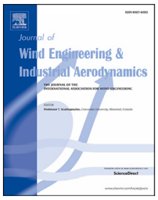

Modeling tropical cyclone boundary layer: Height-resolving pressure and wind fields

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ABSTRACT

The high-accurate wind field of a tropical cyclone boundary layer, which is essentially governed by the Navier-Stokes equations, could be efficiently obtained by predefining the pressure field. Conventionally, the prescribed pressure filed is a 1-D function varying with the distance to the cyclone center (radius). In this study, the pressure field model has been extended to a 2-D function with respect to both radius and height. In addition, a number of field measurements in the tropical cyclone boundary layer indicate rapid variation of the thermodynamic temperature and moisture with time and space. Hence, their effects on the wind field were considered in terms of the virtual temperature, which was integrated in the modeling of pressure field. The analytical solutions of the wind field, as a sum of gradient and frictional wind components, were derived based on a height-resolving scheme using the updated pressure field. Since the tropical cyclone gradient wind and depth of boundary layer are mutually dependent, the iteration approach was utilized in the computation. The proposed height-resolving pressure and wind analytical models have been comprehensively validated with the global positioning system (GPS)-based dropsonde data. The significant importance to consider the height-varying pressure, thermodynamic temperature and moisture in the modeling of the wind field in the tropical cyclone boundary layer were also demonstrated.

1. Introduction

The wind field in the boundary layer region of a mature tropical cyclone is of great significance since a substantial part of economic and life losses result from the events directly or indirectly related to high winds, e.g., wind damage to structures, wind-driven storm surge and wind-rainfall interaction. The situation has become more challenging due to the changing climate and continued escalation of coastal population. While there have been considerable advances in improving the simulation accuracy of tropical cyclone wind field based on the numerical weather prediction models associated with a significant increase of observation data, they are not practical to be employed in the assessments of risk posted by wind-related hazards due to their high computational demands. The state-of-the-art wind hazard risk analysis is essentially based on the Monte Carlo methodology proposed by Russell (1971), where a large number of scenarios need to be carried out. In this context, the parametric, engineering models for tropical cyclone wind fields, based on the prescribed pressure fields, have been popularly utilized.

While several studies have shown that the height-resolving models are superior to the slab (depth-averaged) models that treat the boundary-layer height of the tropical cyclone as a constant, both of these two high-efficient wind field simulation schemes are widely employed in engineering applications. Although the hydrostatic equation simply indicates the pressure field depends on the height, both the slab and height-resolving models conventionally assume the prescribed pressure field is unchanged through the depth of the boundary layer. In particular, the 1-D empirical model introduced by Holland (1980) for pressure, varying with the distance to the cyclone center (radius), has been extensively used due to its simplicity and consistency with field measurements (e.g., Zhao et al., 2013; Mudd et al., 2014). Recently, Huang and Xu (2012) integrated the effects of temperature and variation of central pressure difference with height into the prescribed pressure field for more accurately simulating the typhoon wind field using Meng's model (Meng et al., 1995). Since the gradient wind speed in this refined Meng's model varies with the height from the ground, it is not easy to select the appropriate value in the calculation.

Following the pioneering work of Huang and Xu (2012), the 1-D Holland's empirical pressure model has been extended to a 2-D function with respect to both radius and height in this study. Since a number of

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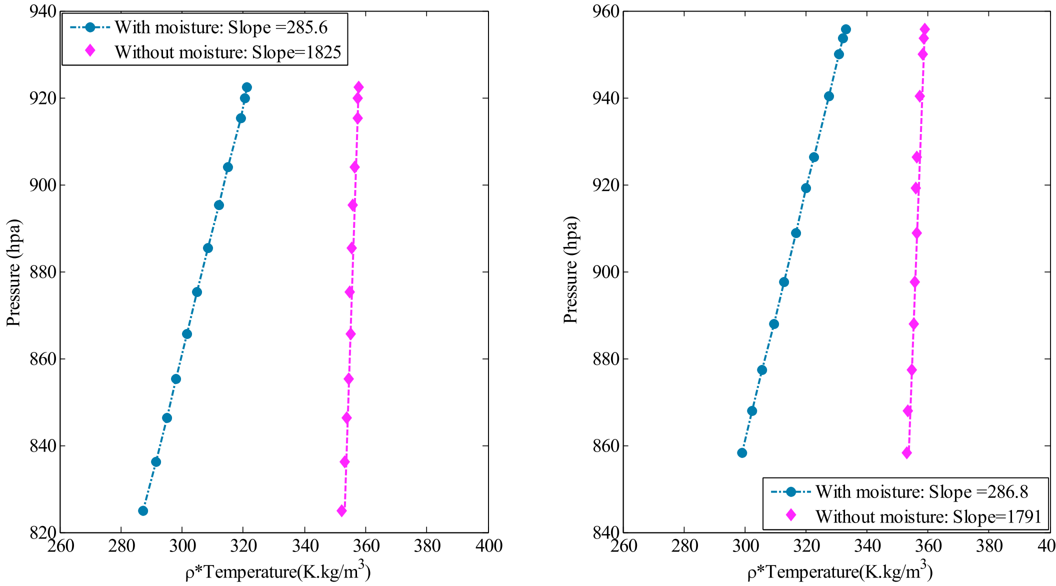

Fig. 1. Moisture effects on the state equation based on two dropsonde measurements during hurricane Katrina (Left: 051926170 and Right: 051926111).

field measurements in the tropical cyclone boundary layer indicate rapid variation of the thermodynamic temperature and moisture with time and space, their effects on the wind field were considered in terms of the virtual temperature, which was integrated in the modeling of pressure field. The obtained 2-D formula for pressure $p(z,r)$ explicitly includes the temperature lapse rate parameter Γ. The global positioning system (GPS)-based dropsonde data (e.g., temperature, humidity, pressure) for the tropical cyclones further demonstrated a heavy dependence of Γ and hence pressure on the moisture content. Furthermore, the proposed 2-D pressure formula indicates the consideration of climate changes (e.g., global warming) may have significant implications to the wind field simulation of a tropical cyclone. The analytical solutions of the wind field were derived based on a recently developed height-resolving scheme (Snaiki and Wu, 2016) using the obtained 2-D pressure field. To select an appropriate height for the calculation of gradient wind speed, the iteration approach was utilized using the depth scale of the tropical cyclone boundary layer as the initial value. The proposed height-resolving pressure and wind analytical models have been comprehensively validated with the GPS-based dropsonde data. The significant importance to consider the height-varying pressure, thermodynamic temperature and moisture in the modeling of the wind field in the tropical cyclone boundary layer were also demonstrated.

2. Height-resolving pressure field

In the simulation of the wind field inside the boundary layer of a tropical cyclone, the surface level pressure profile is typically prescribed to efficiently solve the horizontal momentum equations. In general, the atmospheric pressure can be expressed by the state equation for ideal gas as follows:

$$p = \rho R T \tag{1}$$

where ρ = air density; R = ideal gas constant; and T = temperature.

2.1. Moisture effects

The warm, moist air is considered as the fuel of the tropical cyclones. To simultaneously account for the temperature and moisture effects, a convenient way to proceed would be the use of the virtual temperature T_v which is expressed as follows:

$$T_v = T\left[\frac{R_{noa} + r_v R_v}{R_{noa}(1+r_v)}\right] \tag{2}$$

where r_v = mixing ratio of water vapor; R_v = gas constant of the water vapor; and $R_{noa} \approx 287\ \mathrm{J\ kg^{-1} K^{-1}}$ is the gas constant of mixture of nitrogen (N_2), oxygen (O_2) and argon (Ar). R_{noa} will be denoted subsequently by R for convenience. Accordingly, the state equation can be extended to include the virtual temperature:

$$p = \rho R T_v \tag{3}$$

The importance of moisture consideration in the pressure simulation for a typical tropical cyclone will be illustrated through two dropsonde measurements collected by the National Hurricane Center and Hurricane Research Division during hurricane Katrina. The dropsonde IDs are (051926111) and (051926170), respectively. The dropsondes are usually launched from an altitude of 3 km or higher and provide high-resolution thermodynamics data, namely temperature, pressure, and humidity. To ensure quality control, collected data are post-processed. Fig. 1 presents the pressure p as a function of $\rho_{humid\ \ air}{*}T_v$ and of $\rho_{dry\ \ air}{*}T$, respectively. It is shown the consideration of moisture gives a slope of 285.6 that is close to the gas constant $R \approx 287\ \mathrm{J\ kg^{-1} K^{-1}}$, while the dry assumption results in a slope much larger than this value. This indicates the importance of moisture to accurately simulate the pressure field in the tropical cyclone.

2.2. Pressure formula

To derive the pressure expression, the state equation is first applied on the surface level which gives:

$$p_0 = \rho_0 R T_{v0} \tag{4}$$

where ρ_0 = surface air density; and T_{v0} = surface virtual temperature.

Combining Eqs. (3) and (4) yields the following expression:

$$\frac{p}{p_0} = \frac{\rho T_v}{\rho_0 T_{v0}} \tag{5}$$

The surface pressure is given based on the widely-used Holland's formula: