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A novel analytical model for wind field simulation under typhoon boundary layer considering multi-field correlation and height-dependency

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A R T I C L E I N F O

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A B S T R A C T

On the basis of the measured atmospheric pressure distribution rule fitted by on-the-spot near-ground observation data, the typhoon's height-dependent pressure field was developed with the aid of gas state and hydrostatic balance equations. Probabilistic correlation among mesoscale typhoon field parameters was taken into account. A reduced calculation pattern was proposed by carrying out the scale analysis of three dimensional Navier-Stokes equations to solve the wind velocity field in the typhoon boundary layer. A novel typhoon velocity field model suitable for the gradient layer and boundary layer was then established considering the multi-field parameters correlation and terrain effects. The influence of height-dependent eddy viscosity, which was also closely related to the pressure field and terrain type, on the wind speed profiles under the typhoon boundary layer was considered and discussed. An improved iterative loop algorithm introducing the spatial distribution of eddy viscosity at the low-level boundary layer along the vertical and radial directions was utilized. Furtherly, case studies of the specific typhoon wind field was re-illustrated and compared with the observed wind speed profiles averaged from upper-level dropsondes data and low-level profiles measured by meteorological towers. Three typical regions of vertical wind speed profiles were summarized. Wind speed time series observed by meteorological stations and sea surface wind field snapshots of several typhoons obtained from Hurricane Research Division of National Oceanic and Atmospheric Administration American (H*Wind) were also compared. In general, some specific wind environment characteristics such as non-exponential wind profiles in typhoon boundary layers can be re-illustrated with satisfactory precision by these improved algorithms.

1. Introduction

Typhoon-related natural hazards pose serious threats to people's life and productive activities. The safety and reliability of flexible structures in typhoon-prone regions, including long-span bridges and high-rise buildings, need to be estimated during landfalls of the moving strong typhoons. However, typhoon-resistant design and typhoon-related risk prediction, i.e. design wind speed maps, storm surge simulation and disaster early warning, are mainly based on numerically derived typhoon wind fields because of the limited amount of field observation data (Vickery et al., 2009). In order to obtain sufficient wind speed data, an alternative approach, in which extended wind speed samples are generated by the Monte-Carlo algorithm, was first introduced by Russell and Schueller (1974) and improved significantly in some other pioneering studies (Batts et al., 1980; Vickery and Twisdale, 1995, Vickery et al., 2000a,b). For engineering applications, the wind field model should be accurate, efficient and time-saving, so as not the simulation algorithm be too complex.

The most common option for typhoon field modelling in engineering applications is the slab or depth-averaged model (Russell and Schueller, 1974; Batts et al., 1980; Vickery and Twisdale, 1995, Vickery et al., 2000a,b, Vickery et al., 2009), in which the momentum equation is averaged vertically. In this model, the typhoon boundary layer height is usually defined as a constant value and the surface wind speed is estimated by an empirically-based reduction relationship between the gradient and the near ground wind velocity. As a result, a series of studies have been carried out to determine the values of V_{10}/V_G involving average wind speeds at 10m high and gradient height, sea-land transition and gust factors (Vickery et al., 2009). However, the accuracy of the slab model, especially for simulating the typhoon boundary layer, is not

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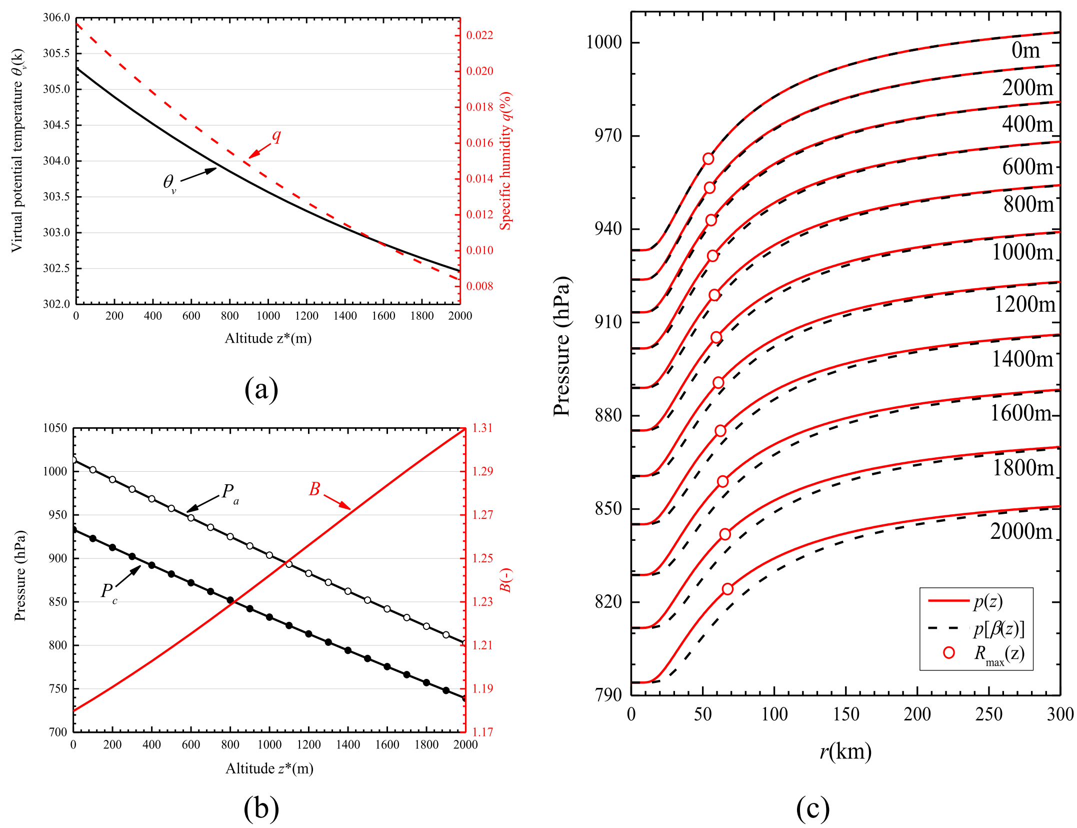

Fig. 1. 3-D pressure model during typhoon conditions: (a) Variation of θ_v and q; (b) Variation of pressure and parameter β; (c) variation of radial pressure.

well-behaved because it relies heavily on modification from observation data and empirical analysis. Furthermore, the spatial velocity distribution in the typhoon boundary layer and the terrain effects are ignored to some extent. The height-resolving model is an improved method for directly solving the Navier-Stokes equation and is based on several simplified semi-analytical algorithms (Meng et al., 1995; Kepert, 2001). The features of the wind field can be described approximately and the terrain types, treated as roughness-related parameters, are included in the updated wind field model. Some literatures (Kepert, 2010) have compared these two kinds of models and demonstrated the inherent superiorities of the height-resolving model.

On the basis of Meng's model, Huang and Xu (2012) developed the height-varying pressure model, taking into account the influence of temperature. Moreover, Snaiki and Wu (2016) introduced temperature and moisture effects into the pressure field, which can be helpful for predicting the wind speed by considering global climate change effects. Furthermore, many research works have shown that correlation among field parameters, which were usually modelled based on sufficient observation data, is stronger (Vickery and Wadhera, 2008). However, in the slab model, this correlation is simply used for determining the gradient wind speed. Besides, some evidence (Vickery and Wadhera, 2008; Xiao et al., 2011; Zhao et al., 2013) suggests that the features of typhoons in the Northwest Pacific Ocean (NPO) and hurricanes in the Northwest Atlantic Ocean (NAO) are quite different, which means statistical models of field parameters in the NAO cannot be easily applied to the NPO directly. It is essential to develop an improved typhoon model suitable for regions in the NPO, especially on the southeast coastlines of China.

In this study, the typhoon wind field was modelled considering the correlation among field parameters observed and fitted for the southeast coastlines of China. With the aid of near-ground observation pressure data of several typical typhoons, a surface pressure field was reproduced by the Holland expression (Holland, 1980), and a spatial height-dependent pressure field was constructed considering the gas state and hydrostatic balance equations, which reflect the variation of pressure at different altitudes. An axisymmetric wind field model was then developed based on the Navier-Stokes equation using a scale analysis that took into account the correlation among field parameters and terrain effects. The spatial distribution function of eddy viscosity in the low-level boundary layer, which was closely related to the pressure field and terrain type, was suggested using an iterative loop method. The method was validated in comparison with observation data, including dropsondes data, low-level wind speed series and sea surface wind field. Furthermore, the numerical typhoon field was reproduced and features of the wind field were discussed.

2. Height-dependent pressure field

The pressure field distribution directly determines the intensity and structure of typhoons and is always prescribed by a simplified model for civil engineering application. Holland (1980) analyzed several field observation data and modified the radial distribution of surface pressure in a typhoon with a fitting profile parameter β expressed as

$$p(r) = p_c + \Delta p \exp\left[-(R_{\max}/r)^{\beta} \right] \tag{1}$$

in which $p(r)$ is atmospheric pressure at radius r from the typhoon center (hPa), p_c is the central pressure (hPa), and Δp is the pressure drop between the central and peripheral pressure, which can be valued as standard atmospheric pressure, 1013.25 hPa. $R_{\max}$ indicates the radius (km) of maximum wind speed, which is a geometric location parameter. However, the radial pressure distribution profiles in the upper air are not exactly same as the surface ones due to the vertical pressure variation relating the effects of temperature and humidity, which cannot be neglected in the typhoon boundary layer. Combining the gas state equation with the hydrostatic balance equation, the pressure of moist air