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Observational study on thermodynamic and kinematic structures of Typhoon Vicente (2012) at landfall

Y.C. He [a], P.W. Chan [b], Q.S. Li [a,*]

[a] Dept. of Architecture and Civil Engineering, City University of Hong Kong, Kowloon, Hong Kong
[b] Hong Kong Observatory, Kowloon, Hong Kong

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ABSTRACT

Severe Typhoon Vicente was the strongest tropical cyclone (TC) that has attacked Hong Kong (HK) since 1999. This paper presents a comprehensive observational study on this windstorm during its landfall, based on in-situ measurements from weather radars, radiosonde balloons, wind profilers and other ground-based devices at various meteorological stations in HK. Both its thermodynamic and kinematic structures are investigated to explore the TC characteristics at landfall. The results of this study reflected that the vortex extended to the tropopause around 16 km. Vertical profiles of pressure deficit below TC outflow layer depicted a linear distribution pattern with respect to isobar-expressed altitude, with a slope increasing almost linearly with increasing surface pressure deficit. The inner and outer rainband regions were respectively dominated by stratiform and convective precipitations, and the inner region was vertically separated into two discriminatory layers by the melting layer located at 5.4 km. The sea-air contrast temperature varied noticeably during the landfall process, with an increase of 1–1.5 °C in the TC inner region where sea-air flux exchange strengthened distinctly compared to that at outer areas.

Vertical wind profiles from balloons showed that horizontal wind speed and wind direction experienced a sharp change around the tropopause, above which flow motions were dominated by the anti-cyclone of Tibetan high. The inflow layer depth was found on the order of 2 km, compared to 1–2 km for the atmospheric mixing layer depth. The gradient height, recognized via the maximum horizontal wind, was in the range of 0.5–2.5 km which decreased with decreasing radii prior to landfall. Examination of the results from wind profilers over marine, urban and rugged terrain showed that the wind structures in the TC boundary layer (TCBL) depended upon storm-relative position and underlying terrain features. Vertical profiles of marine winds in the inner rainband region demonstrated a jet feature, with mean speed being logarithmical with height in the lowest 1 km. TCBL winds above rugged areas were influenced severely by topographic effects. The low-level wind maximum, or the gradient speed, changed insignificantly above different sites.

1. Introduction

Tropical cyclones (TCs) can produce destructive winds, high surges, torrential rains and severe floods and cause serious economic losses and casualties (Pielke et al., 2008; Zhang et al., 2009). Thus, knowledge of TCs is of great socio-economic importance especially for the weather forecast and disaster-mitigation practice in TC-prone areas.

Since the 1950's when the first reconnaissance aircraft was put into use, great advancements of knowledge on TCs have been achieved based on updated observational devices and analytical techniques (Aberson et al., 2006). It has been well recognized that a mature TC consists radially of three distinct components: eye, eyewall and rainbands. The eye is normally circular in shape. It has warm and moist air below an inversion, with clear and dry air above (Willoughby, 1998). Surrounding the eye is the eyewall which contains the greatest winds, highest clouds, heaviest precipitations and intense convections. The eyewall usually expands outwards with height and demonstrates a stadium-like structure (Stern and Nolan, 2009). Intense TCs may exhibit two or more concentric eyewalls (Black and Willoughby, 1992), with the loop strap between these eyewalls dominated by a moat that takes on the characteristics of the TC eye (Houze et al., 2007). Rainbands contain mixture of convective and stratiform clouds and precipitations, and often possess storm-relative and wind-shear-relative asymmetries (Hence and Houze, 2012). They exist in the periphery of a TC and move spirally toward the eye, causing

* Corresponding author.
E-mail address: bcqsli@cityu.edu.hk (Q.S. Li).

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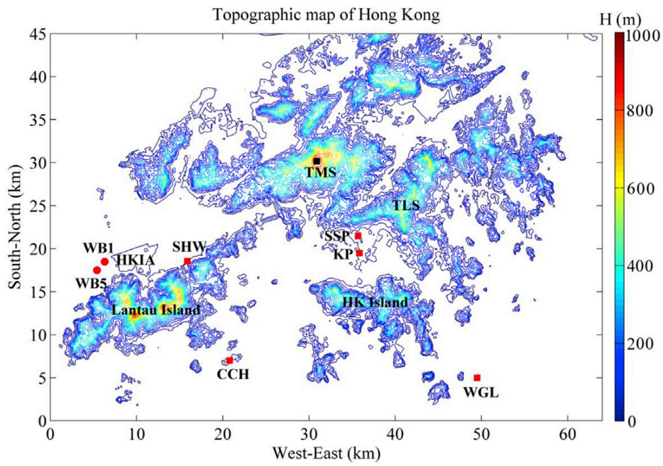

Fig. 1. Topographic map of HK and locations of adopted meteorological stations.

intensification of eyewall convection. Both eyewall and rainbands have convergent airflow in low levels and outflow above.

TCs commonly form and develop over warm tropical oceans in an environment of enhanced vorticity and reduced wind shear. The primary energy source to support and maintain a TC comes from water evaporation. Theoretically, a TC storm may be treated as a huge Carnot heat engine (Emanuel, 1986, 1988), and the maximum intensity it can attain is determined by the surface inflow air temperature, upper outflow air temperature and ocean-atmosphere interaction condition. As a TC forms, it moves along with the steering environment (Chan and Gray, 1982). During the translational process, TCs interact with the environment, with their internal structures evolving accordingly. The TC intensity may be strengthened or weakened, dependent on the combined effect caused by a number of factors such as environmental wind shear (Wong and Chan, 2004) and sea surface temperature (Schade, 2000). Generally, strong wind shear tends to destroy the vortex's warm-core structure, resulting in a decrease of TC intensity; while warmer sea waters and upper-ocean heat contents favor the storm's deepening. Variations of TC intensity also correlate with the dynamics of and interactions of eye, eyewalls and rainbands (Houze et al., 2006). Usually, the storm strengthens as the eyewall contracts. For TCs with concentric eyewall structures, the eyewall replacement acts as another key process in the intensity change (Houze et al., 2007). However, prediction of TC intensity has been still left as a challenging task (Rappaport et al., 2009), owing to its complex correlations with TC internal structures and environmental states.

When a TC makes landfall, the vortex system usually experiences significant changes due to the loss of ocean energy source and the increased friction on land. It starts to weaken and demonstrate apparent asymmetric features. The weakening effect further leads to a redistribution of its significant weather featured by the development of broad regions of stratiform rain (Kepert, 2010). Observational results show that the background environmental flows and storm translation may also influence the TC characteristics severely at landfall (Powell, 1987). The topographic features play another role in the weather-related impacts. For example, orogeny can enhance the already intense rainfall. It may also result in complex flow phenomena such as mountain waves and vortices (Chan, 2012).

The complexity of the TC structure and its somewhat unpredictable evolutions during the lifecycle makes it to be a continuous research focus during the last decades. Among the masses of observational studies, Hawkins and Rubsam (1968) analyzed the horizontal and vertical structures of the inner core of a moderate hurricane, based on aircraft measurements from five flight levels. In a follow-up study, Hawkins and Imbembo (1976) examined the wind and thermal structures at two developing stages of a small hurricane. Jorgensen (1984) presented a case study on the mesoscale motion and thermodynamic fields associated with the eyewall of a mature hurricane, while Frank (1977) conducted a composite study on the large-scale structure of TCs in northwest Pacific region on the basis of 10 years' radiosonde data. Specialized observations on the TC structure in inner core and rainband regions were conducted respectively by Barnes et al. (1983) and Willoughby (1998), among many others. The development of GPS dropsondes broke a new path for the detection of vertical profiles of the TC structure at a greatly improved resolution, which triggered substantial studies on detailed TC characteristics (e.g., Powell et al., 2003; Kepert, 2006; Zhang et al., 2011; Wang et al., 2015).

Despite these numerous studies, observations of TCs throughout the whole troposphere are still limited. Meanwhile, owing to the less availability of aircraft over land, and the low probability of a landfalling TC passing through an equipped site as well as frequent damage of measurement devices during strong winds, observations of landfalling TCs over land are insufficient. Although the development of movable observation masts (e.g., Balderrama et al., 2011) has led to a greater capture rate, such observations only covered an extremely limited portion of the TC depth, leaving most of the TC structure unexplored.

This paper presents a comprehensive observational study on a landfalling typhoon, based on in-situ measurements from weather radars, radiosonde balloons, wind profilers, and ground-based meteorological devices. The primary motivation of this study aims to explore the spatial structure of this landfalling typhoon and identify the possible differences of the TC characteristics before and after landfall. The importance of this study lies in the following two aspects. (1) The observed typhoon was the strongest TC that has attacked Hong Kong (HK) in this century. During its passage, various kinds of meteorological instruments in HK worked properly. Thus, the well archived weather measurements, whose detecting range covered the whole troposphere, provided a valuable opportunity to explore the thermodynamic and kinematic structures of this typhoon. (2) The territory of HK is dominated by complicated topographic features. Consequently, the topographic effects particularly on TC wind fields in the atmospheric boundary layer can be examined.

The remainder of this paper is organized as follows: Section 2 introduces the observational network and the database used in this study. Section 3 presents the measurement results from weather radars and sounding balloons. The TC structure within the whole troposphere is stressed. Sections 4 focuses on detections from Doppler radar wind profilers, with a highlight on the TC characteristics within the atmospheric boundary layer. Section 4 examines the measurements within the surface layer from ground-based meteorological devices. Finally, main findings and conclusions of this study are summarized in Section 5.

2. Observation network and datasets

2.1. Observation network

2.1.1. Site locations

There are over 50 meteorological stations in HK for long-term observations of various weather elements. Eight of them are selected for this study, i.e., CCH, KP, SHW, SSP, TMS, WB1, WB5 and WGL. Their locations are shown in Fig. 1. Among these stations, TMS is located atop the peak of the Tai Mo Shan Mountain (955 m above mean sea level, AMSL). CCH and WGL are respectively located at the zenith of the Cheung Chau Island (72 m) and the Waglan Island (56 m). KP and SSP are situated above a built-up terrain (65/24 m). SHW is located at the foot of the Lantau Island (4.7 m). WB1 and WB5 are two buoys around the Hong Kong International Airport (HKIA). Thus, the measurements from these stations are expected to be able to reflect the TC characteristics at different height levels and above varied terrain.

2.1.2. Instruments installed on masts

Traditional instruments that are widely equipped at the

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