Deep-Sea Research Part I xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Deep-Sea Research Part I

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

Air-sea interactions during rapid intensification of typhoon Fengshen (2008)

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ARTICLE INFO

Keywords:
Rapid intensification
Tropical cyclone heat potential
Convective burst
Latent heat release

ABSTRACT

Typhoon (TY) Fengshen (2008) rapidly intensified from 35 to 70 kt (about 18–36 m/s) in 24 h between 0000 UTC 19 June and 0000 UTC 20 June 2008 east of the Philippines. Based on multi-platform observations, the oceanic and atmospheric processes responsible for its rapid intensification (RI) is investigated in this study. We find that the anomalously high tropical cyclone heat potential (110–200 kJ/cm^2) (TCHP) exerts a great influence on RI of Fengshen compared with other atmospheric environmental factors. In 24 h of RI, TY Fengshen moves over the abnormally warm ocean where the maximum isotherm depth of 26 °C is 200 m which is 80 m deeper than that under the climatological condition. The thick and warm mixed layer restrains the sea surface cooling by limiting entrainment of the cold thermocline water, and thus enhances the ocean to atmosphere heat transfer. In areas of abnormally high TCHP, the occurrence of convective bursts (CBs) results in extra latent heat release (LHR). During the RI phase, abundant LHR causes the warm anomaly of the middle and upper troposphere around the eye, and thereby results in RI of Fengshen. In addition, we also find that the role of high TCHP in CBs and the following RI may be different between asymmetric and axisymmetric processes.

1. Introduction

Rapid intensification (RI) in the tropical cyclone (TC) is traditionally defined as the intensity increase of about 30 knots in 24 h in the western North Pacific (WNP; Shu et al., 2012) and North Atlantic (Kaplan and DeMaria, 2003). The RI of a TC is a complex nonlinear process which often involves multiple competing and synergistic factors. Due to lack of reliable datasets, the multi-scale air-sea interactions during TC passage are not clear, and thus the understanding on the RI of a TC is quite limited. In general, weak vertical wind shear (VWS), high relative humidity (RHUM) in the low and middle level troposphere, weak forcing from upper level troughs, and warm sea surface temperature (SST) are favorable environment conditions for the RI of a TC (e.g., Kaplan and DeMaria, 2003, 2010; Shu et al., 2012; Wang et al., 2015; Wang et al., 2017).

The RI of a TC is one of the unsolved problems in TC forecasts. It is well known that SST higher than 26 °C is needed for TC genesis and development. However, SST is not a critical parameter in forecasting intensity, particularly in forecasting RI (Schade and Emmanuel, 1999; Law and Hobgood, 2007). In contrast, the TC heat potential (TCHP), defined as the integrated heat content from the sea surface to the depth of 26 °C isotherm (Leipper and Volgenau, 1972), is a much better predictor than only SST in the statistical intensity prediction scheme (Law and Hobgood, 2007) since it is an estimation of the heat available for TC to convert into latent heat (Wada and Usui, 2007; Shay and Brewster, 2010). The RI of a TC needs heat energy from the warm ocean with a deep mixed layer, which is modulated by mesoscale ocean processes such as mesoscale eddies, rings and fronts (Lin et al., 2005, 2008, 2009a, 2009b; Wada and Usui, 2007; Shay and Brewster, 2010; Wada, 2015b). In addition, TC-induced SST cooling can negatively feed back to the TC intensification (e.g., Schade and Emanuel, 1999; Cione and Uhlhorn, 2003). Without additional energy supply, the TC self-induced SST cooling exceeding 2.5 °C is regarded as unsuitable condition for the intensification (Lin et al., 2008). Warmer and thicker mixed

Abbreviations: CCMP, A new Cross-Calibrated Multi-Platform; AMSU, Advanced Microwave Sounding Unit; CBs, Convective bursts; GFS, Global Forecast System; GPCP, Global Precipitation Climatology Project; JMA, Japan Meteorological Agency; LHR, Latent heat release; MSW, Maximum sustained wind; MWR, Maximum wind radius; PWP, Price-Weller-Pinkel; RI, Rapid intensification; RHUM, Relative humidity; SSHA, Sea surface height anomaly; SSS, Sea surface salinity; SST, Sea surface temperature; TCHP, Tropical cyclone heat potential; TC, Tropical cyclone; TY, Typhoon; VWS, Vertical wind shear; WNP, Western North Pacific

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https://doi.org/10.1016/j.dsr.2018.08.009
Received 31 May 2017; Received in revised form 23 August 2018; Accepted 23 August 2018
0967-0637/

layer reduces TC-induced SST cooling, which can cause an increase in the enthalpy flux from ocean to atmosphere, and consequently favors the intensification of a TC (Lin et al., 2005, 2008, 2009a, 2009b). Since the intensification of a TC depends on the availability of oceanic energy, understanding the interactions between mesoscale ocean processes and TC is critical for improving prediction of the TC intensity.

The processes by which heat is extracted by a TC from ocean and converted into kinetic energy are complex and not fully understood (Black et al., 2007; Price, 2009; Zhang, 2010; Cione et al., 2013). Previous studies have found that the convective bursts (CBs) or hot towers near the TC eye are closely associated with the TC intensification and play an important role in the RI process of a TC (e.g., Simpson et al., 1998; Kelley et al., 2004, 2005; Rogers, 2010; Guimond et al., 2010). The CBs in the inner core are closely linked to the latent heat release (LHR) (e.g., Hennon, 2006; Kelley and Halverson, 2011; Jiang, 2012, 2013), and thus can boost the formation and development of the upper-level tropospheric warm core in a TC eye (Vigh and Schubert, 2009; Zhang and Chen, 2012). The upper-level warm core is hydrostatically more efficient to induce the onset of RI, and is sensitive to the underlying SST (Chen and Zhang, 2013).

Typhoon (TY) Fengshen is ranked as the seventh deadliest Philippines TY since 1947. An estimated 1743,815 persons are affected by TY-induced landslides and flooding with damage to agriculture, infrastructure, health, education and environment. Damage exceeds $252 million with over 300,000 houses destroyed (Yumul et al., 2012). Most of properties loss and casualties produced by the storm may be attributed to the RI of TY Fengshen. Thus, the purpose of this study is to examine the atmospheric and oceanic processes responsible for the RI of TY Fengshen.

The rest of the paper is organized as follows. Section 2 presents the datasets used for the study. Section 3 describes the oceanic response and feedback to TY Fengshen during RI, and investigates the effects of subsurface warm ocean anomalies on the RI using the observational data and a 1-dimensional ocean mixed layer model. Section 4 examines the large-scale atmospheric characteristics and analyzes the convective-scale process during RI of TY Fengshen. Section 5 discusses the relationships among TCHP, CBs and RI. Section 6 presents the summary.

2. Data and methods

The Japan Meteorological Agency (JMA) TY best track data is used to locate 6-hourly positions and maximum sustained wind (MSW) speeds for TY Fengshen. The large-scale background atmospheric conditions during TY Fengshen's passage, such as the VWS between 850 and 200hPa, and averaged relative humidity of 750–850 hPa are examined using the six-hourly Global Forecast System (GFS) analysis data with horizontal resolution of 0.5° × 0.5°.

Hydrographic observations from the two Argo floats with daily temporal resolution (WMO ID: 5901580 and 5901581), merged sea surface height anomaly (SSHA) from satellite altimeter distributed by AVISO (Ducet et al., 2000; Pujol et al., 2016), and SST from Reynolds Version 2 (Reynolds et al., 2007) are used to investigate the synoptic ocean features responsible for the RI and the oceanic responses to TY Fengshen. The SSHA and SST datasets have 0.25° × 0.25° spatial resolution and daily temporal resolution.

The Cross-Calibrated, Multi-Platform (CCMP) ocean surface wind dataset is produced by combining all ocean surface wind speed observations from SSM/I, AMSR-E and TMI, and all ocean surface wind vector observations from QuikSCAT and SeaWinds (Atlas et al., 2011). It has the spatial resolution of 0.25° × 0.25° and the temporal resolution of 6 h. Daily precipitation with 1° spatial resolution is obtained from Global Precipitation Climatology Project (GPCP) (Huffman et al., 2001). Daily evaporation data with 1° spatial resolution is from OAFlux (Yu and Weller, 2007). The Price-Weller-Pinkel (PWP) one-dimensional mixed layer ocean model (Price et al., 1986) is forced by these datasets to examine the influence of warm ocean anomaly on air-sea flux during Fengshen RI.

The geostationary infrared brightness temperature data (Knapp and Kossin, 2007) is used to examine the evolution of CBs during the RI. LHR profiles are from the Earth Observation Research Center, Japan Aerospace Exploration Agency (Shige et al., 2004, 2007). The LHR grid data consists of 720 × 148 longitude-latitude elements corresponding to a 0.5 × 0.5° grid that covers the TRMM region from 37°S to 37°N. Advanced Microwave Sounding Unit (AMSU) temperature data (Demuth et al., 2004) is used to investigate the vertical structure evolution of the temperature of TY Fengshen during RI. The plots are provided by the website: http://rammb.cira.colostate.edu/products/tc_realtime/about.asp#AMSUPLOT.

The TCHP is defined by (Leipper and Volgenau, 1972),

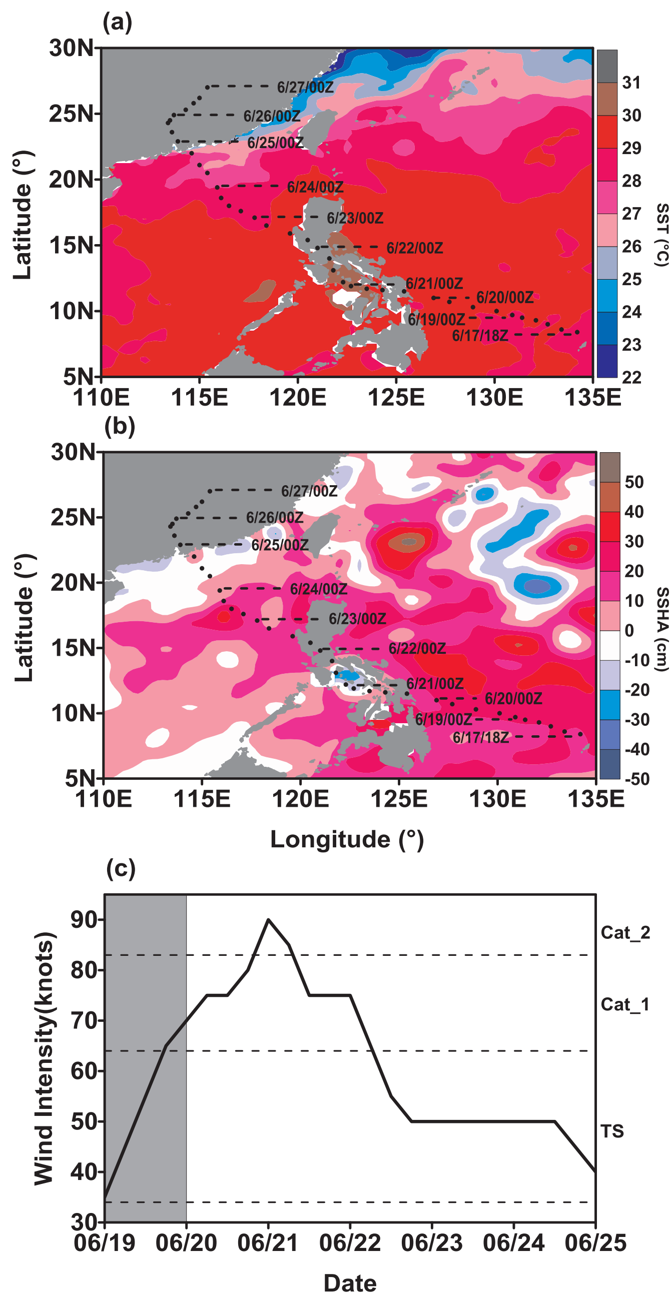

Fig. 1. Horizontal distributions of (a) SST (°C) and (b) SSHA (cm) on 16 June 2008 prior to TY Fengshen genesis, (c) time evolution of MSW of TY Fengshen. The track of TY Fengshen is overlaid in (a) and (b). The shade in (c) indicates the period of rapid intensification for TY Fengshen.