Article ID: 1006-8775(2016) 03-0287-09

IMPACT OF AIR-SEA INTERACTION ON THE GENESIS OF TROPICAL INCIPIENT VORTEX OVER SOUTH CHINA SEA: A CASE STUDY

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Abstract: Based on 6-hourly sensible heat flux and latent heat flux from the NCEP Climate Forecast System Reanalysis (CFSR) and circulation data from the Japanese 25-year Reanalysis (JRA-25), the initial developing process of tropical cyclone Mindulle (1005) in 2010 has been diagnosed to reveal the impact of air-sea interaction over the South China Sea (SCS) on the genesis of its incipient vortex. The results show that the incipient vortex first occurred east of the Luzon Island on 0000 UTC 20 August, suggesting that the topographic forcing of the Luzon Island for easterly winds over the western Pacific might be one of the factors responsible for the formation of the incipient vortex. During the formation stage of the incipient vortex, strong southeasterlies over the SCS caused warm water of the middle and eastern SCS to flow toward the Luzon Island due to Ekman transport resulting from wind stress, leading to an increase of the sea surface temperature and sensible heat flux into the atmosphere. Although the anomalous sensible heating favored surface pressure to reduce, it was not conducive to the increase of local vorticity associated with the vortex above the heating area because, according to the atmospheric thermal adaptation theory, the anticyclonic vorticity would be created in the lower troposphere due to the decreased vertical gradient of the sensible heating. However, the ascending motions occurred over the eastern area of the anomalous sensible heating due to the augmentation of the vorticity advection with increasing height, causing water vapor to condense in the middle and upper troposphere. In turn, cyclonic vorticity was generated in the lower troposphere due to the increased vertical gradient of the condensation latent heating, resulting in the formation and further growth of the incipient vortex. Therefore, the vorticity creation due to the condensation heating played a dominant role during the subsequent enhancing stage of the incipient vortex.

Key words: tropical cyclogenesis; air-sea interaction; incipient vortex; sensible heating

CLC number: P444 **Document code:** A

doi: 10.16555/j.1006-8775.2016.03.003

1 INTRODUCTION

The tropical cyclone (TC) is an intensely convective system occurring in the tropical ocean, with its activities relying largely on thermodynamic conditions such as sea surface temperature (SST), mid-tropospheric humidity, and atmospheric stability together with dynamical factors including large-scale cyclonic vorticity in the low-level, vertical wind shear, and Coriolis force (Gray[1]). The genesis of the incipient vortex of a TC has been found to depend on favorable large-scale circulation (Wang et al.[2]; Sun et al.[3]; Tian et al.[4]) especially on the middle and lower tropospheric circulation as well as air-sea interaction (Zhang et al.[5]; Chen et al.[6]; Jiang et al.[7]; Jiang et al.[8]; He et al.[9]; Wu et al.[10]; Li et al.[11]). According to the well-known WISHE (Wind Induced Surface Heat Exchange) mechanism (Emanuel[12]), a weak initial disturbance can directly acquire some energy from warm ocean so that the wind speed of the disturbance becomes stronger with air pressure to reduce further. The disturbance obtains much more energy from the ocean through such a positive feedback, and eventually evolves into a strong TC. Note that the WISHE mechanism is valid for the intensification of the initial disturbance already reaching to certain degree. So far, there are no commonly accepted theories regarding how the initial disturbance arises and develops. In terms of internal dynamics of TC genesis over recent decades, the top-down (Ritchie and Holland [13]; Simpson et al. [14]) versus bottom-up (Montgomery and Enagonio [15]; Hendricks et al. [16]; Reasor et al. [17]; Sippel et al. [18]; Montgomery et al. [19]; Tory [20]) views have been two dominant theories. Both views recognize the importance of Mesoscale Convective System (MCS) dynamics in driving the genesis process in middle troposphere, and establish conceptual models of incipient vortex enhancement leading to TC genesis. These theories focus on internal

Received 2014-02-17; **Revised** 2016-05-04; **Accepted** 2016-07-15

Foundation item: National Basic Research Program of China (2011CB403505, 2010CB950402); National Natural Science Foundation of China (40975052, 41175059)

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influences on TC genesis (Gray [21]), but for the role of air-sea ex changes played in the genesis of the initial disturbance, it has not yet received much attention.

The TC interacts constantly with underlying ocean. At its formation stage with very weak intensity, the oceanic impact on the TC developing may be more important (Waliser and Graham[22]; Chen and Houze[23]). Therefore, it is necessary to comprehensively examine the impact of air-sea heat fluxes on the genesis and development of the initial disturbance.

The South China Sea (SCS) is the largest marginal sea among tropical Pacific Ocean. It is also one of the source areas of TC genesis. The TC that generates locally in the SCS usually migrates northwestward and makes landfall in the coastal regions of southeastern China, leading to severe economic loss. Thus studying the formation and development of the TC in the SCS is of great significance (Chia and Ropelewski[24]; Zhang et al.[25]; Zhang and Lin[26]; Wu et al.[27]; Lau et al.[28]). Based on QuickSCAT sea surface winds for the period 1997-2006, Wang et al.[29] found that all TCs are formed in the northern SCS during summer monsoon. In investigating the spatial-temporal distributions of air-sea heat fluxes, Wang et al. also suggested that during summer, sea surface latent heat fluxes transporting into the atmosphere are much larger in southern SCS than in the northern SCS, while surface sensible heat fluxes are less in central SCS than in both northern and southern SCS[30]. These studies imply that the cyclogenesis in the SCS may be related to the local heat fluxes, with sensible heat fluxes being a dominant factor.

Therefore, the objective of present study is to reveal the impact of anomalous sensible heat fluxes on the genesis of incipient vortex in the SCS based on a case of moderate TC Mindulle that occurred in August 2010. In this work, the incipient vortex of a TC is defined as one for the period during which an initial disturbance arises and then develops into a tropical depression issued by the Joint Typhoon Warning Center (JTWC). According to this definition, the genesis stage of the incipient vortex of Mindulle was the period from 0000 UTC 20 August to 1200 UTC 22 August. Within this stage, the incipient vortex would certainly acquire external energy from the SCS in the form of sensible heating to intensify continually.

Section 2 introduces data and methods related to diabatic heating. Section 3 describes the developing process of the incipient vortex of Mindulle and characteristics of air-sea heat fluxes. The impacts of surface sensible heating and condensation latent heating on the incipient vortex are examined respectively in Sections 4 and 5. A summary and discussion are given in Section 6.

2 DATA AND METHODS

(1) The best tracks of TCs in 2010 are derived from the JTWC (http://weather.unisys.com/hurricane/w_pacific/2010/index.php). (2) 6-hourly sea surface sensible heat fluxes and latent heat fluxes as well as upper oceanic (5-meter depth below the surface) currents are extracted from Climate Forecast System Reanalysis (CFSR) products (Saha et al.[31]). Positive fluxes refer to upward heat transfer from ocean into atmosphere. (3) 6-hourly atmospheric variables from Japanese 25-year Reanalysis (JRA-25) include mainly sea level pressure, 10-m winds, as well as air temperature and wind components at different isobaric surfaces (Onogic et al.[32]). (4) Daily OISST with very high resolution of 0.25° latitude × 0.25° longitude are obtained from NOAA Na tional Climate Data Center (Reynolds et al.[33]).

Based on Ertel potential vorticity theory (Ertel[34]), the complete form of vertical vorticity tendency equation derived from Wu and Liu can be expressed as[35]

$$\frac{D\zeta_z}{Dt}+\beta v+(f+\zeta_z)\nabla\bullet\vec{V}=\frac{1}{\theta_z}\left[P_E\frac{D}{Dt}\left(\frac{1}{\theta_z}\right)-\frac{D}{Dt}C_D\right]+\frac{1}{\theta_z}\nabla\theta\bullet\vec{F}_\varsigma+\frac{1}{\theta_z}\vec{\varsigma}_a\bullet\nabla Q \qquad (\theta_z\neq 0) \tag{1}$$

where ζ_z is vertical component of absolute vorticity, β is Rossby parameter, θ is potential temperature, $\theta_z=\frac{\partial\theta}{\partial z}$ is vertical gradient of potential temperature, $P_E=\alpha\vec{\varsigma}_a\bullet\nabla\theta$ is Ertel potential vorticity, $\vec{\varsigma}_a$ is vector of absolute vorticity, $C_D=\frac{\alpha}{\theta_z}\zeta_s\theta_s$, $(\theta_z\neq 0)$ is a thermal parameter, which represents an projection of horizontal vorticity component onto the vertical vorticity component under the constraint of P_E conservation due to slantwise θ surface, ζ_s is horizontal component of absolute vorticity, $\theta_s=\frac{\partial\theta}{\partial s}$ is horizontal gradient of potential temperature, and Q is diabatic heat.

It turns out from Eq. (1) that the local change rate of vertical vorticity depends on atmospheric convective stability, vertical wind shear, non-uniform diabatic heating, and frictional dissipation. When only considering external thermal forcing, Eq. (1) can be simplified as

$$\frac{\partial\zeta_z}{\partial t}=-\vec{V}\bullet\nabla\zeta_z-\beta v+(1-k)(f+\zeta_z)\frac{\omega}{p}-(f+\zeta_z)\frac{1}{\theta}\frac{1}{d\theta}+\frac{1}{\theta_z}\vec{\varsigma}_a\bullet\nabla Q \tag{2}$$

where $\frac{1}{\theta_z}\vec{\varsigma}_a \bullet \nabla Q = \frac{1}{\theta_z}\left[(f+\zeta_z)\frac{\partial Q}{\partial z} - \frac{\partial v}{\partial z}\frac{\partial Q}{\partial x} + \frac{\partial u}{\partial z}\frac{\partial Q}{\partial y}\right], (\theta_z \neq 0)$

A scaling analysis shows that the vorticity variation forced by vertical inhomogeneous heat is 1-2 order of magnitude greater than that forced by horizontal non-uniform heat (Wu et al.[36]). In present study, only examined is the vertical inhomogeneous heat ($\frac{1}{\theta_z}(f+\zeta_z)\frac{\partial Q}{\partial z}$) contributing to the creation of relative vorticity. The total diabatic heating is estimated using apparent heat source (Q_1), which is expressed as (Yanai et al.[37])

$$Q_1 = C_p\left(\frac{P}{P_0}\right)^k\left(\frac{\partial \theta}{\partial t} + \vec{V} \bullet \nabla\theta + \omega\frac{\partial \theta}{\partial p}\right) \quad (3)$$

where $\omega = \frac{dp}{dt}$ is vertical velocity in p coordinate, and p_0 =1 000 hPa.

The ω-equation is from Zhu et al.[38].

$$\left(\delta\nabla^2 + f^2\frac{\partial^2}{\partial p^2}\right)\omega = f\frac{\partial}{\partial p}\left[\vec{V_g} \bullet \nabla(f+\zeta_g)\right] - \nabla^2\left(\vec{V_g} \bullet \nabla\frac{\partial \varphi}{\partial p}\right) - \frac{R}{c_p p}\nabla^2\frac{dQ}{dt} \quad (4)$$

3 GENESIS PROCECESS OF MINDULLE AND AIR–SEA FLUXES IN THE SCS

3.1 *Genesis process of Mindulle*

The fifth tropical cyclone was developed in central SCS on 1200 UTC 22 August during the 2010 western Pacific typhoon season, and the JTWC classified it as tropical depression (named "Mindulle"). The tropical depression subsequently moved northwestward and intensified into a tropical storm on 1200 UTC 23 August. Finally, it made landfall in northern Vietnam on 1200 UTC 24 August. It also brought about heavy rainfall over Hainan Island and southern Guangxi Region in China.

Figure 1 shows the evolution of the sea surface pressure (SLP) and 10-m wind fields during the genesis stage of incipient vortex of Mindulle. At 0000 UTC 20 August, strong easterlies were observed to prevail over the northern SCS and Philippine Sea (Fig. 1a). The easterlies veered southward when they encountered the continent of Luzon Island, forming a weak cyclonic circulation with the center (16°N, 123°E) locating east of Philippines (Fig.1b). Meanwhile, the SLP also dropped to below 1 009 hPa. 12 hour later, the SLP reduced further to 1 007 hPa, with cyclonic center moving to the west of Luzon Island (Fig.1c). These indicated the incipient vortex having already formed at this time. On the other hand, the southward-recurving of easterlies on eastern coast of the Luzon Island implied that the formation of such an incipient vortex depended to a great extent on the topographic forcing of Luzon Island. With enhanced southwesterlies converging toward the incipient vortex center, the SLP dropped significantly to below 1 006 hPa from 1200 UTC 21 August to 0000 UTC 22 August (Figs. 1d and 1e). Subsequently, the incipient vortex rapidly intensified within 12 hours to reach critical intensity of a tropical depression, with minimum SLP even below 998 hPa, thus the JTWC named it as Mindulle (Fig.1f). Note that during this period the incipient vortex of Mindulle had already moved into western SCS. Afterwards, Mindulle continued migrating westward and eventually made landfall (Fig.1f).

3.2 *Variations of sea surface sensible heat fluxes*

On 19 August prior to the genesis of the incipient vortex of Mindulle, the SST was observed to be colder in the west of Luzon Island than in its east although the SST wholly exceeded 28℃ in the entire SCS and western Pacific (Fig.2a). Strong surface southeasterlies were noted to prevail over the Philippine Sea, which led warmer water to flow westward into eastern SCS due to Ekman transport caused by wind stress (Fig.2c), favoring the SST increase west of Luzon Island. These indicate the impact of wind fields on local SST increasing.

As compared to previous day, the SST increased by 0.5℃ in eastern SCS on 20 August (Fig.2c), with actual SST all exceeding 29℃ (Fig.2b). Such warmer SST would enhance local temperature differences in the air-sea interface, thereby increasing surface sensible heat fluxes from the upper ocean into the lower atmosphere (Fig.2d). Corresponding to the area (13°-20°N, 115°-126° E) with the SST warming significantly, the sensible heat fluxes on 20 August also increased by 4 W m^{-2} compared to those on 19 August. The warmed air would ascend in the lower troposphere due to surface sensible heating, thus surrounding air certainly converged toward the region of maximum sensible heat fluxes. Consequently, a cyclonic circulation was formed evidently in the vicinity of the Luzon Island on 20 August (Fig.2b), with circulation center locating around 16°N and 121°E.

4 IMPACT OF SURFACE SENSIBLE HEAT ON THE GENESIS OF THE INCIPIENT VORTEX

According to the thermal adaption theory, anomalous upward sensible heating leads a cyclonic circulation to form in the layer of near sea surface (in the form of the first step of thermal adaption) (Wu and Liu[39]; Wu et al.[40]). Such a heat-induced circulation can be seen from Fig.3. Over the area (13°-20°N, 115°-126° E) of significantly increased sensible heat fluxes (Fig. 2d), an anomalous cyclonic circulation was observed

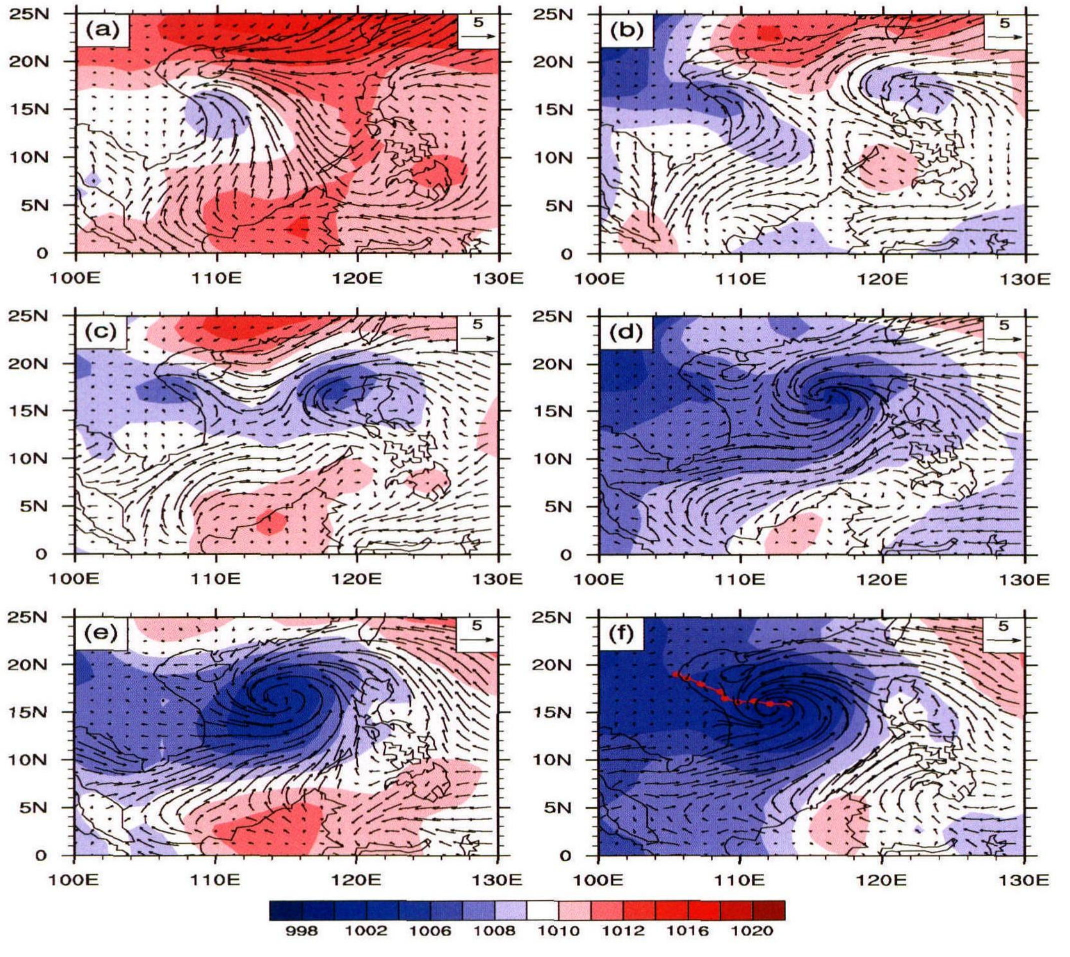

Figure 1. Evolution of the sea surface pressure (shading, hPa) and 10-m wind (vectors, m s^{-1}) fields during the genesis stage of incipient vortex of Mindulle. (a) 0000 UTC on 20 August, (b) 1200 UTC on 20 August, (c) 0000 UTC on 21 August, (d) 1200 UTC on 21 August, (e) 0000 UTC on 22 August, (f) 1200 UTC on 22 August (Red curve indicates the track of Mindulle after it had been named by the JTWC).

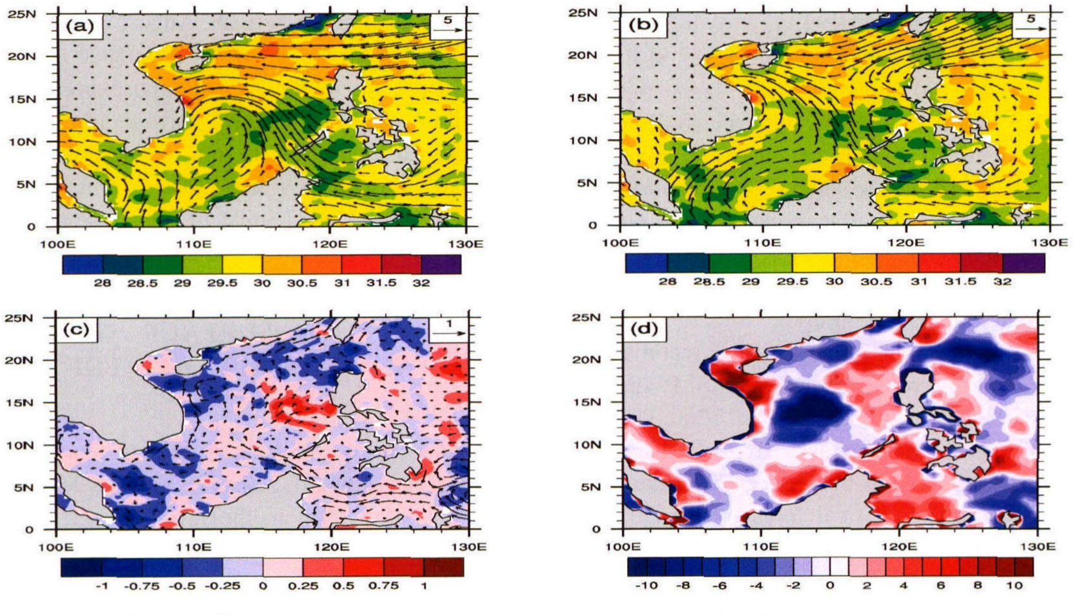

Figure 2. Daily SST (shading, ℃) and 10-m winds (vectors, m s^{-1}) on (a) 19 and (b) 20 August 2010. (c) Upper oceanic current under 5-m depth on 19 August and SST differences (shading, ℃) between 20 and 19 August. (d) Daily sea surface sensible heat flux differences (shading, W m^{-2}) between 20 and 19 August.

at 1 000 hPa (Fig.3a), with an increase of 2.5×10^{-5} s^{-1} in relative vorticity from 1800 UTC 19 August to 0600 UTC 20 August (Fig.3a), indicating that upward sea surface sensible heating fluxes favored the genesis of the incipient vortex in near sea surface layer. Indeed, distinct ascending motions existed at 1 000 hPa over the anomalous sensible heat area between 116°E and 126°E (Fig.3d), which helped the SLP drop further (Figs.1b and 1c).

Note that anomalous surface sensible heat was conducive to the formation of the incipient vortex only in near sea surface layer, but it did not facilitate the development of the incipient vortex into higher layers in the initial stage. Positive diabatic heating was present only around and below 1 000 hPa between 115°E and 124° E, while above 900 hPa was negative diabatic heating (Fig.3d). As a dominant diabatic heating component in the lower troposphere, the surface sensible heat decreased with increasing height ($\frac{\partial Q_{SH}}{\partial_Z} <$ 0). According to Eq. (2), negative relative vortictiy would be created in lower troposphere above 1 000 hPa, namely $\frac{\partial \varsigma_z}{\partial t} \propto \frac{1}{\theta_z}(f+\zeta_z)\frac{\partial Q_{SH}}{\partial z} < 0$. The relative vorticity tendency along 15° N due to the vertical gradient of non-uniform diabatic heating was displayed in Fig.4a, in which the local change rate of relative vorticity was calculated directly from the term $\frac{1}{\theta_Z}(f+\zeta_Z)\frac{\partial Q_1}{\partial_Z}$. Over the area of anomalous surface sensible heat between 115°E and 124°E, negative relative vortictiy tendency indeed existed in middle and lower troposphere (Fig. 3b), with dominant negative differences of relative vorticity at 500 hPa between 0600 UTC 20 August and 1800 UTC 19 August (Fig.3b), accompanied by an anomalous anticyclone. Note also that absolute vorticity advection decreased with increasing height in middle and lower troposphere (Fig. 3c). Based on Eq. (4), descending motion ($\omega > 0$) would be produced above 1 000 hPa over the anomalous sensible heat area (Fig.3d).

Although the first step of thermal adaption associated with negative gradient of vertical sensible heating in lower troposphere was not conducive to the development of the incipient vortex from near sea surface into higher layers, the second step of thermal adaption [40] related to vertically inhomogeneous condensation latent heating over the eastern area of anomalous sensible heating favored the deepening of the incipient vortex. Note from Fig.3c that over the eastern portion (10°-20°N, 124°-128°E) of anomalous sensible heating, absolute vorticity advection at 500 hPa was larger than that at 1 000 hPa, indicating positive absolute vorticity advection with increasing height. According to Eq. (4), ascending motions would be generated ($\omega < 0$). Strong ascending motions were actually present between 1 000 and 500 hPa (Fig.3d), forming deep convection. Subsequently, the impact of condensation latent heating resulting from the ascending motions on the incipient vortex genesis was thus examined.

5 IMPACT OF CONDESATION LATENT HEAT ON THE GENESIS OF THE INCIPIENT VORTEX

Over the area of higher SST, besides increased sensible heat fluxes, sea surface latent heat fluxes could also be enhanced due to vaporizing much more moisture into atmosphere. Although the surface latent heat fluxes did not directly heat up the lower tropospheric atmosphere, some of them would be released in the form of condensation latent heating through ascending motions, and then conduced to further developing of the incipient vortex.

Figure 3d shows that over the eastern area (122° -126° E) of anomalous sensible heating, the forced ascending motions were accompanied by positive diabatic heating, with maximum heating locating around 500 hPa. Obviously, condensation latent heating was the dominant heating component of such non-uniform diabatic heating in the vertical. According to Eq. (2), below 500 hPa positive relative vorticity would be increased due to vorticity creation by positive vertical gradient of condensation latent heating ($\frac{\partial Q_1}{\partial_Z} > 0$). As shown in Fig.4a, positive relative vorticity tendency was indeed present in middle and lower troposphere (1 000-500 hPa) over eastern Luzon Island, with maximum tendency greater than 1×10^{-9} s^{-2} in lower layers. The incipient vortex was thus formed and rapidly grown over eastern Luzon Island.

Twenty-four hours later (Fig.4b), the incipient vortex not only moved evidently westward into the SCS but also became stronger and deeper due to much larger vorticity creation of vertically inhomogeneous condensation latent heating between 1 000 and 500 hPa, with maximum vorticity creation exceeding 5×10^{-9} s^{-2} in lower troposphere (1 000-850 hPa). Such a large vorticity creation was even comparable with the local change rate of total relative vorticity in near sea surface layer (Fig.5a), suggesting that condensation latent heating and related vorticity creation played a dominant role in intensification of the incipient vortex.

By 0000 UTC 21 August (Fig.5c), strong condensation latent heating existed over the SCS from lower to upper troposphere, with maximum heating locating around 500-400 hPa in excess of 14×10^{-5} K s^{-1}. Because positive relative vorticity were created due to condensation latent heating enhancing with increasing height in middle and lower troposphere ($\frac{\partial Q_1}{\partial_Z} > 0$), significant increase of relative vorticity occurred in middle troposphere around 500 hPa (Fig.5b), with

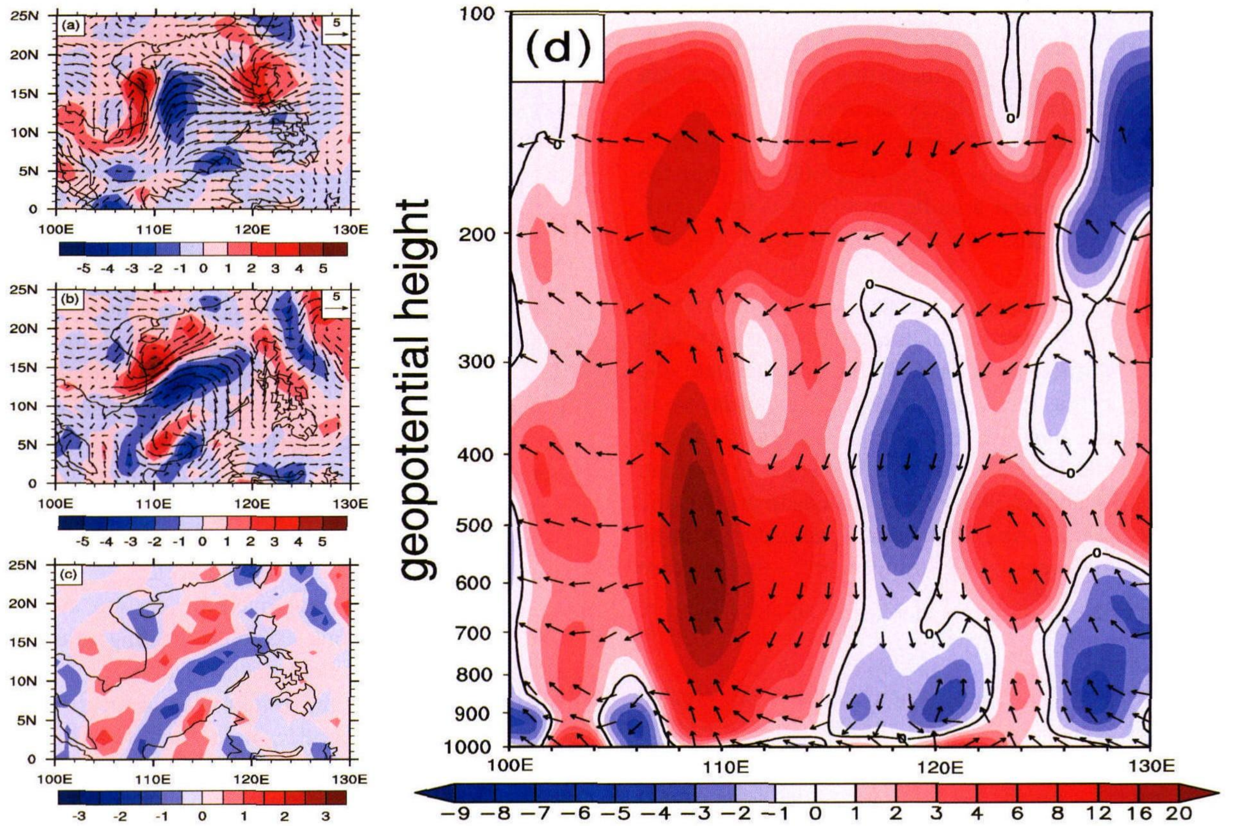

Figure 3. (a) Relative vorticity differences (shading, 10^{-5} s^{-1}) and wind differences (vectors, m s^{-1}) at 1 000 hPa between 0600 UTC on 20 August and 1800 UTC on 19 August. (b) As in (a) but for at 500 hPa. (c) Absolute vorticity advection differences (shading, 10^{-9} s^{-2}) between 500 hPa and 1 000 hPa at 0000 UTC on 20 August. (d) Pressure-longitude cross section along 15°N of diabatic heating Q_1 (shading, 10^{-5} K s^{-1}) and zonal circulation (vectors, u in m s^{-1}, and ω in hPa s^{-1}).

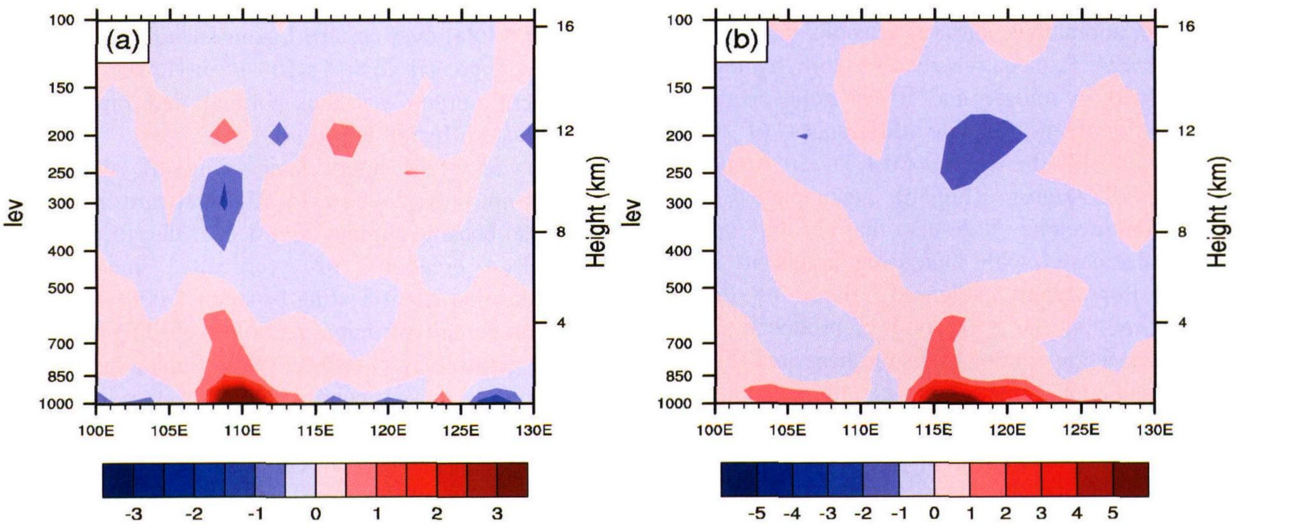

Figure 4. (a) Pressure-longitude cross section along 15°N of relative vorticity tendency (shading, 10^{-9} s^{-2}) resulted from vertical gradient of non-uniform diabatic heating Q_1 at 0000 UTC on 20 August 2010. (b) As in (a) but for along 16°N at 0000 UTC on 21 August 2010.

maximum increase reaching 5×10^{-5} s^{-1} within 12 hours from 1800 UTC 20 August to 0600 UTC 21 August. Similarly, positive relative vorticity were increased in lower troposphere at 1 000 hPa (Fig.5a). In addition, anomalous sensible heating over the northeastern SCS (15°-19°N, 116°-120°E) also contributed to the increase of positive relative vorticity in near sea surface layer. Subsequently, ascending motions strengthened further as the incipient vortex intensified, releasing much more condensation latent heating and leading the maximum heating to higher altitudes, thus strong positive relative vorticity were created constantly. Such positive

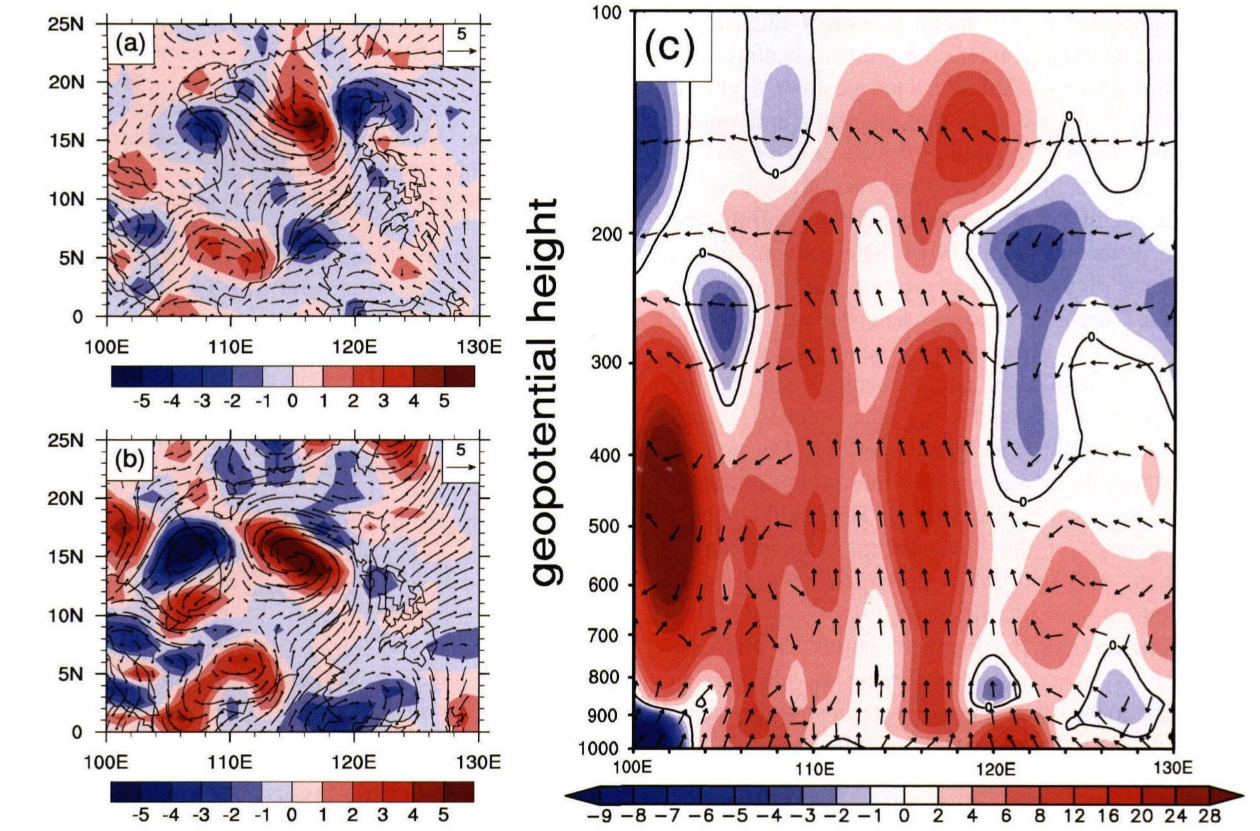

Figure 5. (a) Relative vorticity differences (shading, 10^{-5} s^{-1}) and wind differences (vectors, m s^{-1}) at 1 000 hPa between 0600 UTC on 21 August and 1800 UTC on 20 August. (b) As in (a) but for at 500 hPa. (c) Pressure-longitude cross section along 16°N of diabatic heating Q_1 (shading, 10^{-5} K s^{-1}) and zonal circulation (vectors, u in m s^{-1}, and ω in hPa s^{-1}).

feedback led the incipient vortex to further intensify and finally developed into the TC Mindulle (Figs.1d and 1f).

6 SUMMARY AND DISCUSSION

Although the fifth tropical depression (named "Mindulle") was issued to form in central SCS on 1200 UTC 22 August during the 2010 western Pacific typhoon season, its incipient vortex firstly occurred in lower troposphere east of Luzon Island. At 0000 UTC 20 August, strong easterlies over the northern SCS and Philippine Sea veered southward when they encountered the continent of Luzon Island, a weak cyclonic circulation was thus formed, implying that the topographic forcing of Luzon Island on easterly winds over western Pacific might be one of mechanisms responsible for the genesis of the incipient vortex.

During the initial stage of the genesis of the incipient vortex, strong surface southeasterlies led warmer water to flow westward into eastern SCS due to Ekman transport caused by wind stress, favoring the SST increase west of Luzon Island, thus enlarging air-sea temperature differences. Consequently, upward surface sensible heat fluxes into lower tropospheric atmosphere were enhanced over eastern SCS and east of Luzon Island. Such strong surface sensible heating induced ascending motions to appear in near sea surface layer, re sulting in the SLP drop and occurrence of a cyclonic disturbance.

For the period from 0000 UTC 20 August to 0000 UTC 21 August, although the creation of negative vorticity due to vertical gradient of anomalous sensible heating in lower troposphere over eastern SCS and east of Luzon Island was inconducive to the development of the incipient vortex from near sea surface into higher layers, the dynamical effect associated with positive vertical gradient of vorticity advection facilitated to produce ascending motions over the eastern area of anomalous sensible heating.

Over the eastern area of anomalous sensible heating, the maximum condensation latent heating were located in middle troposphere around 500 hPa. Thus positive relative vorticity were created due to positive vertical gradient of condensation latent heating in middle and lower troposphere. The incipient vortex was thus formed and rapidly grown over eastern Luzon Island.

During the enhancing stage of the incipient vortex, the creation of positive relative vorticity by vertically increased condensation latent heating was largely greater than that of negative relative vorticity by vertically decreased sensible heating in middle and lower troposphere. Consequently, ascending motions strengthened further as the incipient vortex intensified, releasing much more condensation latent heating and creating more positive vorticity. Such positive feedback led the incipient vortex to further intensify and finally developed into the TC Mindulle.

It should be mentioned that the present study investigated mainly the air-sea conditions during the initial stage of the incipient vortex. The oceanic impact on the genesis of the incipient vortex was highlighted from surface sensible heating perspective, with an emphasis on the important roles of vertically non-uniform condensation latent heating and related vorticity creation played in the genesis and intensification of the incipient vortex. During its formation stage, there was another low pressure system in upstream region around 110° E. How and to what extent the genesis of the downstream incipient vortex was associated with such a low pressure system deserve further investigation in the future.

The formation of the incipient vortex in this case study involved in continental forcing of the Luzon Island on the lower tropospheric easterlies. Under what conditions in SST and atmospheric circulation is the incipient vortex generated by such forcing of the Island on the large-scale circulation? These issues will be validated through analyzing more cases and numerical modeling.

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Citation: HAO Sai, MAO Jiang-yu and WU Guo-xiong. Impact of air-sea interaction on the genesis of tropical incipient vortex over South China Sea: A case study [J]. J Trop Meteorol, 2016, 22(3): 287-295.