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Simulation of the Effects of SST Changes Induced by Tropical Cyclones on the Intensity of Tropical Cyclone Bilis (0604)

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Abstract: The effects of sea surface temperature (SST) changes induced by tropical cyclone (TC) Bilis (0604) and its preceding TC, TC Ewiniar (0603), on the intensity of TC Bilis were investigated by using numerical experiments. The observed SST changes induced by TCs Ewiniar (0603) and Bilis (0604) were first separated by using the smooth filtering and cylindrical filtering methods. The maximum SST cooling induced by TC Ewiniar (0603) exceeded 3°C, and that induced by the two TCs, Ewiniar (0603) and Bilis (0604), exceeded 6°C. The simulation results show that the SST cooling induced by TC Ewiniar (0603) and by two TCs reduced the intensity of TC Bilis (0604) by 6.2 m s⁻¹ and 7.6 m s⁻¹ within 60 h, respectively. Without the SST cooling induced by TC Ewiniar (0603), TC Bilis (0604) could have developed into a typhoon. The cold wake induced by TC Ewiniar (0603) was an important factor in inhibiting the intensity of TC Bilis (0604). Based on the analysis of the physical processes of the simulation results, a schematic diagram of the effects of SST changes induced by TCs on the intensity of TC Bilis (0604) was presented. The SST cooling reduced the upward heat flux and moisture flux at the surface of TC mainly within a radius of two latitudes, which in turn decreased the conditional instability and atmospheric moisture in the lower layer of TC, followed by weakening in TC precipitation, TC warm core, the upward vertical velocity of TC, and the inward radial wind in the lower layer of TC. The intensity of TC Bilis (0604) decreased accordingly.

Key words: sea surface temperature cooling; tropical cyclone intensity; spatial filtering; numerical simulation

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1 INTRODUCTION

Tropical cyclones (TCs) are an important weather system in the western North Pacific (WNP) that predominantly occur from June to October every year. The accuracy of TC intensity forecasts has remained limited in the past few decades, especially in cases of rapid intensification (DeMaria et al. [1]; Rogers et al. [2]; Cangialosi et al. [3]). Much of the issue with TC intensity forecasting can be attributed to complex interactions between internal dynamics, TC structure, and surrounding air-sea environments (Emanuel [4]; Wang and Wu [5];

Kaplan et al. [6]). The warm ocean is considered a key energy source for the development of TCs (Schade and Emanuel [7]; Lin et al. [8]). The exchange of air-sea sensible and latent heat fluxes is crucial for the intensity changes of TCs. Sea surface temperature (SST) plays a critical role in controlling energy transfer rates and is a key factor in energy exchange between TCs and the ocean (Emanuel [9]; Merrill [10]; Emanuel et al. [11]; Črnivec et al. [12]; Foltz et al. [13]; Fei et al. [14]; Li et al. [15]). Thus, SST not only affects the rapid intensification of tropical cyclones (Kaplan and DeMaria [16]; Kanada et al. [17]; Chih and Wu [18]), but also affects the maximum intensity of tropical cyclones (DeMaria and Kaplan [19]; Holland [20]). Some studies suggested that there is a significant positive correlation between SST and TC intensity, and the relationship is nonlinear (Emanuel [21]; Baik and Paek [22]; Sun et al. [23]).

Observational studies have shown that TCs usually induce a cooling on SST after passing over the ocean (Price [24]; D'Asaro et al. [25]; Wada et al. [26]), which is closely related to the intrinsic characteristics of TCs and the upper ocean conditions (Lin et al. [27]; Wu et al. [28]; Cui et al. [29]). The primary physical mechanisms contributing to such SST cooling include ocean vertical mixing, Ekman pumping, upwelling, horizontal oceanic advection, and rainfall from TCs (Price [24]; Huang et

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al. [30]; Balaguru et al. [31]). The extent of SST cooling induced by different TCs may vary widely, ranging from less than 1°C to over 10°C (Balaguru et al. [32]; Glenn et al. [33]). Notably, the most pronounced cooling effects may occur a few days after the TC has passed (Wu et al. [34]; Dare and McBride [35]). Such SST cooling will reduce the water vapor flux and heat flux on the sea surface, thereby limiting the intensification of TCs, and acting as a negative feedback mechanism (Emanuel [4]; Seroka et al. [36]; Liu et al. [37]; Zhang et al. [38]). Furthermore, some numerical simulation studies show that the SST cooling induced by TCs (or hurricanes) may cause TCs (or hurricanes) to weaken by more than 20 hPa °C⁻¹ (Holland [20]; Zhu and Zhang [39]).

TC Ewiniar (0603) formed near the equatorial waters of the WNP on June 29, 2006. It initially tracked northwestward, then northward, and finally northeastward after making landfall on the Korean Peninsula. It intensified into a super typhoon in the northeastern waters of the Philippines, inducing a significant drop in the SST in the waters from the northeast of the Philippines to the east of Taiwan Island (Fig. 1 and Fig. 2). As Ewiniar moved to the eastern waters of Taiwan Island, TC Bilis (0604) formed to the north of Ewiniar's generation site on July 8, 2006. Bilis moved mainly northwestward before making landfall, and mainly westward after making landfall. Bilis just passed through the cold SST area induced by Ewiniar, reaching the intensity of a severe tropical storm (Fig. 1 and Fig. 2). Therefore, Bilis is a very typical case of a storm impacted by the cold wake of a preceding TC (Jeong et al. [40]).

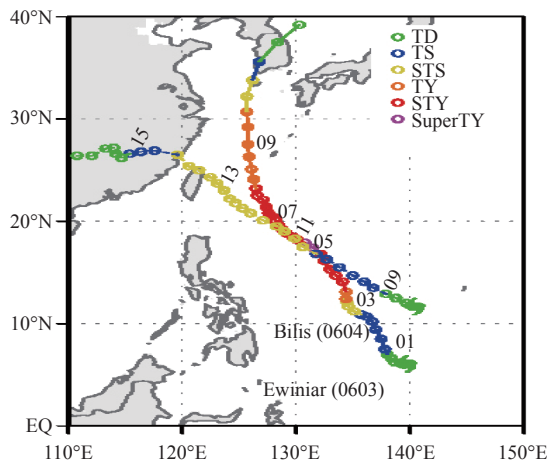


Figure 1. Observed tracks of TCs Ewiniar (0603) and Bilis (0604) at 6-h intervals. A tropical depression (TD) has wind speeds from 10.8 m s⁻¹ to 17.1 m s⁻¹, a tropical storm (TS) from 17.2 m s⁻¹ to 24.4 m s⁻¹, a severe tropical storm (STS) from 24.5 m s⁻¹ to 32.6 m s⁻¹, a typhoon (TY) from 32.7 m s⁻¹ to 41.4 m s⁻¹, a severe typhoon (STY) from 41.5 m s⁻¹ to 50.9 m s⁻¹, and a super typhoon (SuperTY) larger than 50.9 m s⁻¹. The number next to the track is the date in July at 0000 UTC.

However, it is unclear the extent to which SST changes induced by TCs affected the intensity of TC Bilis

(0604). In this study, the SST changes induced by TCs were separated by the smooth filtering and cylindrical filtering methods. Then, the effects of SST changes induced by TCs on the intensity of TC Bilis (0604) were investigated through a series of numerical experiments.

2 DATA AND METHODOLOGY

The 6-h best track data of TCs were derived from the International Best Track Archive for Climate Stewardship (IBTrACS) (Knapp et al. [41]). TC tracks and intensities at 6-h intervals were obtained from the China Meteorological Administration (CMA). TC radii, including the radius of the outermost closed isobar (ROCI) and the radius of 17.5 m s⁻¹ winds at 6-h intervals, came from the Joint Typhoon Warning Center (JTWC).

The daily SST data were derived from microwave and infrared (MW_IR) optimal interpolation (OI) products at 9 km resolution from June 2002 to the present, which were produced by Remote Sensing Systems and sponsored by the National Oceanographic Partnership Program (NOPP) and the National Aeronautics and Space Administration (NASA) Earth Science Physical Oceanography Program.

The atmospheric data were obtained from the National Centers for Environmental Prediction (NCEP) Final (FNL) Operational Global Analysis data, which are available at the surface and 26 pressure levels (from 1000 hPa to 10 hPa) on 1°×1° grids every 6 hours (NOAA/NCEP [42]).

The smooth filtering and cylindrical filtering methods (Kurihara et al. [43]; Yuan et al. [44]) were used for the first time to separate the SST change induced by TC (SST_{TC}) within a radius of 1.5 times the ROCI at 0000, 0600, 1200, and 1800 UTC per day. Firstly, the original SST (SST_O) data with a horizontal resolution of 9 km were averaged by area to obtain the SST data on a 1°×1° grid. Secondly, the large-scale variation of SST (SST_L) on the 1°×1° grid was obtained by performing three-point smoothing in the longitudinal and zonal directions, respectively. The coefficient of three-point smoothing was defined by (Kurihara et al. [43])

$$\alpha = \frac{1}{2} \left(1 - \cos \frac{2\pi}{m} \right)^{-1} \quad (1)$$

where m in Eq. 1 sequentially varies as 2, 3, 4, 2, 5, 6, 7, 2, 8, 9, and 2.

Then, SST_L on the 1°×1° grid was interpolated horizontally to a grid with a horizontal resolution of 9 km. The perturbed SST (SST_p) with a horizontal resolution of 9 km was obtained by subtracting SST_L from SST_O, namely

$$\text{SST}_p = \text{SST}_O - \text{SST}_L \quad (2)$$

Due to the cylindrical effect of TC on the sea surface elements, the SST_{TC} can be separated from SST_p by performing cylindrical filtering on a grid with a horizontal resolution of 9 km as

$$\text{SST}_{TC}(r, \theta) = [1 - E(r)][\text{SST}_p(r, \theta) - \overline{\text{SST}_p(r_0)}] \quad (3)$$

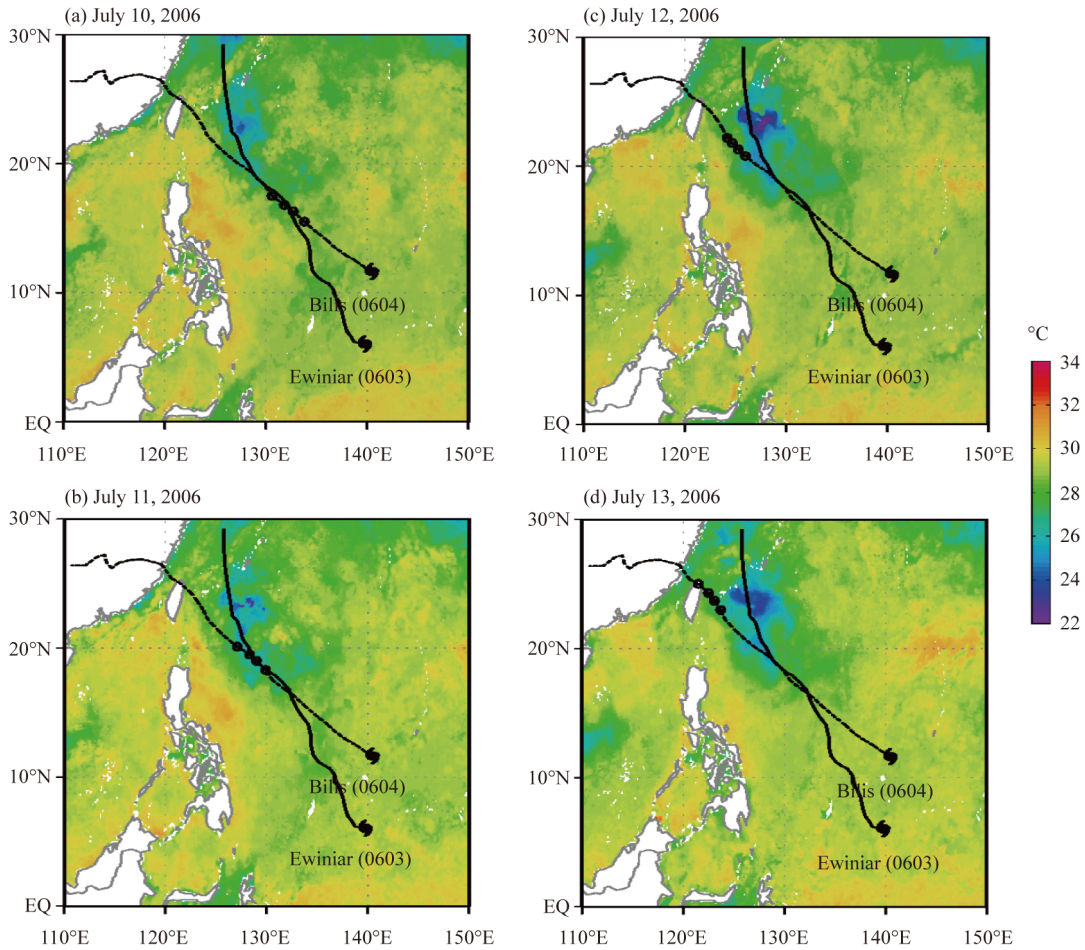


Figure 2. Observed daily SST (shaded, units: °C). (a) July 10, 2006, (b) July 11, 2006, (c) July 12, 2006, and (d) July 13, 2006. The black solid line is the observed track of TC Ewinari (0603). The black dashed line is the observed track of TC Bilis (0604), and the four circles are four observation positions (at 0000, 0600, 1200, and 1800 UTC) for that day.

where $\overline{\text{SST}}_p(r_0)$ is the angular mean of SST_p , at the point of $r_0 = 1.5\text{ROCI}$, and $E(r)$ is a column filter function as

$$E(r) = [e^{-(r_0-r)^2/l^2} - e^{-r_0^2/l^2}] / [1 - e^{-r_0^2/l^2}] \quad (4)$$

where l is a parameter controlling the filtering shape, which takes $l = r_0/5$ in this study.

When multiple TCs passed through the same sea area, the SST change induced by each TC was obtained according to the proportion of the cylindrical filtering value of each TC. Since maximum SST cooling may occur several days after TC has passed (Wu et al. [34]), TCs passing through the same sea area within 10 days was considered.

The simulated TC intensity, namely the maximum wind speed, was obtained by the azimuthal-mean 10-m wind speed.

3 THE MODEL AND EXPERIMENT DESIGN

The Weather Research and Forecasting (WRF) model version 3.8 was employed to conduct numerical experiments in this study. Two nested domains with two-way interactions were adopted. The grid points of the two

domains were 660×420 and 1249×940 , with horizontal resolutions of 9 km and 3 km, respectively. The vertical resolution was 46 layers with a model top of 10 hPa. The new Thompson scheme was employed for microphysics. Other model physics schemes include the Rapid Radiative Transfer Model (RRTM) longwave radiation scheme, the Goddard shortwave radiation scheme, the Monin-Obukhov surface layer scheme, the Noah Land Surface Model land surface scheme, and Yonsei University (YSU) planetary boundary layer scheme.

The initial TC vortex of the model was an asymmetric bogus vortex that was a hydrostatic equilibrium, gradient wind balance, quasi-thermodynamic equilibrium, and conformed to the environmental field. The asymmetric bogus vortex was built by four physical quantities based on the observation, namely, the position of TC, the minimum sea level pressure of TC, the radius of 17.5 m s^{-1} winds of TC, and the initial movement of TC, which was calculated by using two TC positions at an interval of 6 h (Yuan et al. [44]).

The initial and lateral boundary conditions of the model, including the variables such as surface pressure,

surface temperature, geopotential height, wind fields, temperature, and relative humidity, were obtained from the NCEP FNL Operational Global Analysis data, while the SST was provided by the MW_IR data.

The control (CTL) experiment was designed to reproduce the track and intensity of TC Bilis (0604), and SST sensitivity experiments were designed to investigate the effects of SST on the track and intensity of TC Bilis (0604). All simulations started at 1200 UTC on July 10, 2006, and ended at 0000 UTC on July 13, 2006. The lateral boundary conditions and SST were updated every 6 h in all simulations.

The CTL experiment and SST sensitivity experiments differed only in SST. In the CTL experiment, the observed SST was used. The SST sensitivity experiments included the SST_1 experiment and the SST_2 experiment. In the SST_1 experiment, the SST change induced by TC Ewiniar (0603) was removed by using the filtering methods. In the SST_2 experiment, the SST change induced by two TCs, Ewiniar (0603) and Bilis (0604), was removed by using the filtering methods.

4 EFFECTS OF SST CHANGES INDUCED BY TCS ON THE INTENSITY OF TC BILIS (0604)

Figure 3 shows the SST change induced by TC Ewiniar (0603). The results show that the SST change induced by the TC can be well separated by using the smooth filtering and cylindrical filtering methods. The maximum cooling of SST induced by TC Ewiniar (0603) was more than 3°C and was located in the eastern waters of Taiwan Island (Figs. 3a–3c). Furthermore, the maximum cooling of SST induced by two TCs, Ewiniar (0603) and Bilis (0604), was more than 6°C

and was also located in the eastern waters of Taiwan Island (not shown). SST cooling mainly occurred on the right side of the TC track; this right-side asymmetry of cooling was thought to be a characteristic of the homogenous ocean's response to a TC (Cornillon et al. 1995).

The observed and simulated tracks and intensity of TC Bilis (0604) during the period from 1200 UTC July 10, 2006, to 0000 UTC July 13, 2006, are shown in Fig. 4. The simulation results of the CTL experiment show that the simulated track and intensity of TC Bilis (0604) were very close to the observation. The maximum errors of track and intensity of TC Bilis (0604) simulated by the CTL experiment were 133.9 km at 48 h and -2.8 m s^{-1} at 12 h, respectively (Table 1). The simulation results show that the effects of SST changes induced by TCs on the track of TC Bilis (0604) were not very pronounced in the SST_1 and SST_2 experiments compared with the CTL experiment (Fig. 4a). However, the intensity of TC Bilis (0604) increased gradually over time when the SST change induced by TC Ewiniar (0603) was removed (Fig. 4b). The intensity of TC Bilis (0604) was further enhanced when the SST change induced by two TCs Ewiniar (0603) and Bilis (0604) was removed. The maximum increase of the simulated intensity of TC Bilis (0604) was 6.2 m s^{-1} at 48 h (7.6 m s^{-1} at 60 h) when the SST change induced by TC Ewiniar (two TCs Ewiniar and Bilis) was removed. The simulated intensity of TC Bilis (0604) reached the typhoon strength for the first time at 48 h (36 h) when the SST change induced by TC Ewiniar (TCs Ewiniar and Bilis) was removed (Table 1). The simulation results show that the SST cooling induced by TC Ewiniar (0603) was an important reason why the maximum intensity of TC Bilis

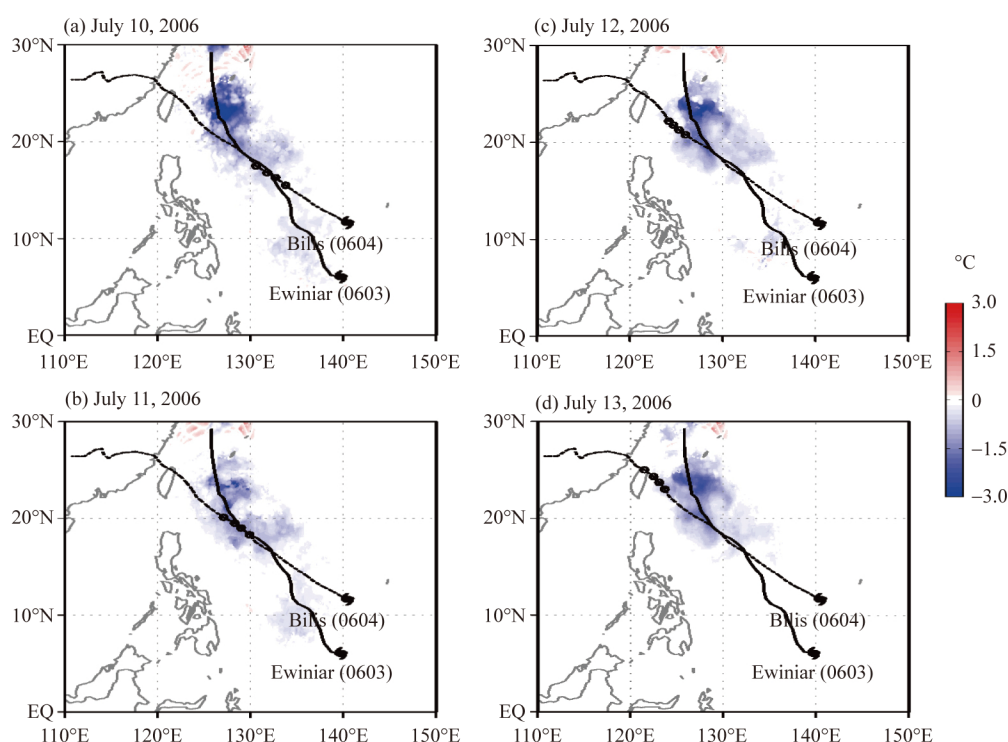


Figure 3. As in Fig. 2, but for SST change (shaded, units: °C) induced by TC Ewiniar (0603).

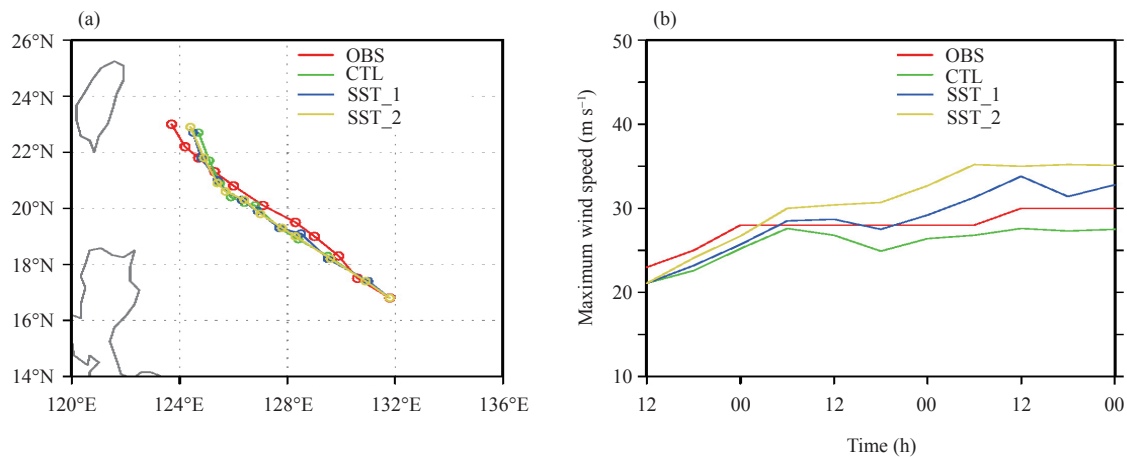


Figure 4. Observed and simulated (a) tracks and (b) intensity (units: m s^{-1}) of TC Bilis (0604) during the period from 1200 UTC July 10, 2006, to 0000 UTC July 13, 2006. OBS is the observation, CTL is the control experiment, and SST_1 and SST_2 are SST sensitivity experiments.

Table 1. Statistics of tracks and intensity of TC Bilis (0604) simulated by using control (CTL) experiment and SST (SST_1 and SST_2) sensitivity experiments. The track and intensity errors are relative to the observation. The intensity change is relative to the CTL experiment. The superscript “*” indicates that the simulated TC reached typhoon strength for the first time.

Experiment		12 h	24 h	36 h	48 h	60 h
CTL	Track error (km)	44.5	70.3	80.2	133.9	116.1
	Intensity error (m s^{-1})	-2.8	-1.2	-1.6	-2.4	-2.5
SST_1	Track error (km)	45.9	70.3	64.8	118.2	95.0
	Intensity change (m s^{-1})	0.5	1.9	2.8	6.2*	5.3
SST_2	Track error (km)	35.2	59.9	71.2	126.8	78.6
	Intensity change (m s^{-1})	1.5	3.6	6.3*	7.4	7.6

(0604) only reached the severe tropical storm category.

Since the effects of SST changes induced by TCs on the track of TC Bilis (0604) were not significant, the subsequent investigation primarily focused on how these SST changes influenced the intensity of Typhoon Bilis (0604).

The high sensible heat flux resulting from high SST favors TC intensification (Kanada et al. [17]). Fig. 5 shows the time evolutions of the radial distribution of the azimuthal-mean simulated upward heat flux at the surface. The large upward heat flux at the surface in the CTL experiment mainly occurred within a radius of two latitudes of TC during the period from 6 h to 60 h (Fig. 5a). The SST_1 (SST_2) experiment had a significant increase in the upward heat flux at the surface within a radius of two latitudes of TC during the period from 6 h to 60 h relative to the CTL (SST_1) experiment (Figs. 5b and 5c). Because the ROCI of the SST change induced by TC Bilis (0604) was larger than that of TC Ewiniar (0603), the radial range of the increase in the upward heat flux at the surface in Fig. 5c was larger than that in Fig. 5b. The TC-induced SST change through the upward heat transport at the surface can affect the stability of the atmospheric boundary layer (Zhu et al. [46]). Large conditional instability of the CTL experiment mainly occurred below 900 hPa (Fig. 6a). Compared with the CTL (SST_1) experiment, the SST_1

(SST_2) experiment had a significant increase in the conditional instability within a radius of two latitudes of TC below 900 hPa (Figs. 6b and 6c).

The large upward moisture flux at the surface of the CTL experiment mainly occurred within a radius of four latitudes of TC during the period from 6 h to 60 h, and the large-value centers were mainly located within a radius of two latitudes (Fig. 7a). Compared with the CTL (SST_1) experiment, the SST_1 (SST_2) experiment had a significant increase in the upward moisture flux at the surface within a radius of two latitudes of TC during the period from 6 h to 60 h (Figs. 7b and 7c). The upward moisture transport at the surface can affect the distribution of water vapor in the atmosphere. The large specific humidity of the CTL experiment occurred near the TC center in the lower layer (not shown). The SST_1 (SST_2) experiment had a significant increase in the specific humidity within a radius of two latitudes in the lower and middle troposphere relative to the CTL (SST_1) experiment (not shown).

The 6-h accumulated precipitation of the CTL experiment mainly occurred within a radius of four latitudes of TC during the period from 6 h to 60 h, and large-value centers of the 6-h accumulated precipitation were mainly located within the radius of one to two latitudes (Fig. 8a). The SST_1 (SST_2) experiment had a

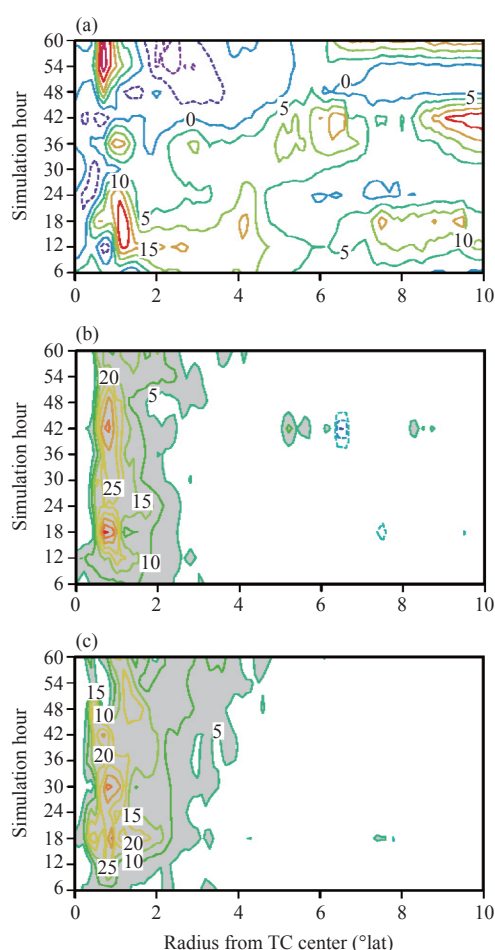


Figure 5. Time evolutions of the radial distribution of the azimuthal-mean simulated upward heat flux at the surface (units: W m^{-2}). (a) Control experiment, (b) the difference between the SST_1 experiment and the CTL experiment, and (c) the difference between the SST_2 experiment and the SST_1 experiment. Gray shading indicates azimuthal-mean simulated upward heat flux greater than 5 W m^{-2} .

significant increase in the 6-h accumulated precipitation within a radius of two latitudes relative to the CTL (SST_1) experiment during the simulation (Figs. 8b and 8c). The increase in precipitation led to the warm core enhancement of TC through the release of the latent heat of condensation and an increase in the upward vertical velocity of TC (not shown).

The inward radial wind in the lower layer within the TC circulation was a part of the secondary circulation of TC. An increase in inward radial wind in the lower layer indicates that the intensity of TC intensified. The large inward radial wind in the lower layer (from 1000 hPa to 850 hPa) of TC mainly occurred within a radius of between about four latitudes and six latitudes at 6 h, then a radius of between about half a latitude and four latitudes during the period from 12 h to 60 h (Fig. 9a). Compared with the CTL (SST_1) experiment, the increased inward radial wind in the lower layer of the SST_1 (SST_2) experiment was mainly located within a radius of between about half a latitude and two latitudes during the period

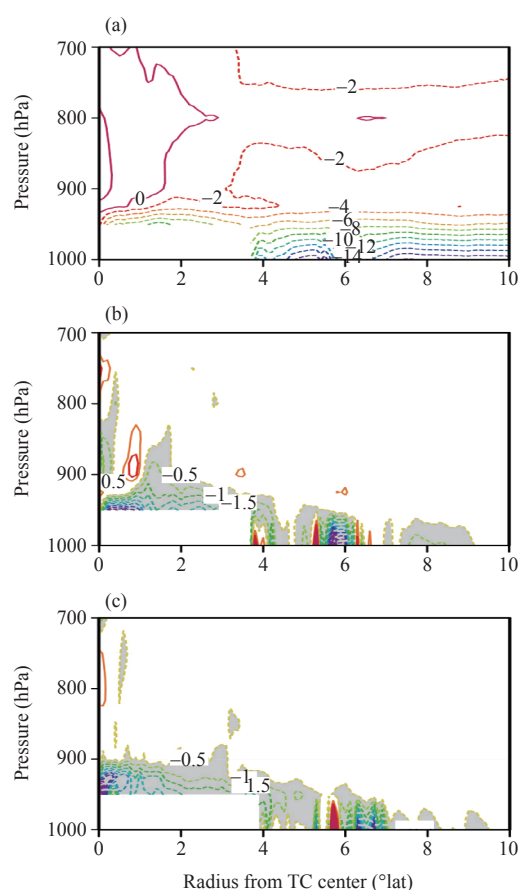


Figure 6. The radial-height distribution of the simulated conditional instability ($\partial\theta_e^*/\partial z$, units: 10^{-3} K m^{-1} , negative values indicate the conditional instability) averaged from 6 h to 60 h. (a) Control experiment, (b) the difference between the SST_1 experiment and the CTL experiment, and (c) the difference between the SST_2 experiment and the SST_1 experiment. Gray shading indicates values less than $-0.5 \times 10^{-3} \text{ K m}^{-1}$. Because the numerical model only gives element values above the ground, the blank in the lower left corner of the figure indicates the missing values below the ground near the center of TC.

from 12 h to 60 h (Figs. 9b and 9c).

Based on the above analysis, a schematic diagram of the effects of SST changes induced by TCs on the intensity of TC Bilis (0604) was summarized in Fig. 10. The SST cooling induced by TCs first led to a decrease in the upward heat flux and moisture flux at the surface of TC mainly within a radius of two latitudes, which in turn caused a decrease in the conditional instability and atmospheric moisture in the lower layer of TC. The decreased conditional instability and atmospheric moisture in the lower layer of TC led to a decrease in TC precipitation, followed by a weakening of TC warm core, a decrease in the upward vertical velocity of TC, a decrease in the inward radial wind in the lower layer of TC, and then a weakening of the intensity of TC Bilis (0604).

5 CONCLUSIONS

In this study, the smooth filtering and cylindrical filtering methods were used for the first time to separate

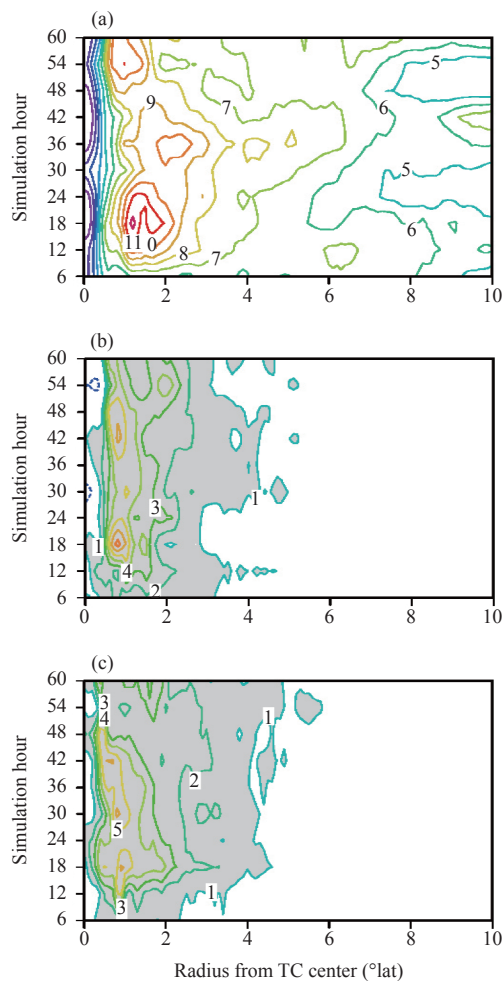


Figure 7. As in Fig. 5, but for upward moisture flux at the surface (units: $10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$). Gray shading indicates values greater than $10^{-5} \text{ kg m}^{-2} \text{ s}^{-1}$.

the SST changes induced by TC Ewiniar (0603) and by two TCs, Ewiniar (0603) and Bilis (0604). The results show that the smooth filtering and cylindrical filtering methods can separate the SST change induced by TC well. The maximum SST cooling induced by TC Ewiniar (0603) and by two TCs, Ewiniar (0603) and Bilis (0604), exceeded 3°C and 6°C , respectively.

The effects of SST changes induced by TCs on the intensity of TC Bilis (0604) were investigated by using the WRF model and numerical experiments. A control experiment and two SST sensitivity experiments were designed to investigate the effects of SST changes induced by TCs on the intensity of TC Bilis (0604). After the control experiment very well simulated the track and intensity of TC Bilis (0604), two SST sensitivity experiments were conducted. The simulation experiments show that the SST cooling induced by TC Ewiniar (0603) and by two TCs Ewiniar (0603) and Bilis (0604) can reduce the intensity of TC Bilis (0604) by 6.2 m s^{-1} and 7.6 m s^{-1} within 60 h, respectively. When the SST cooling induced by TC Ewiniar (0603) and by two TCs, Ewiniar

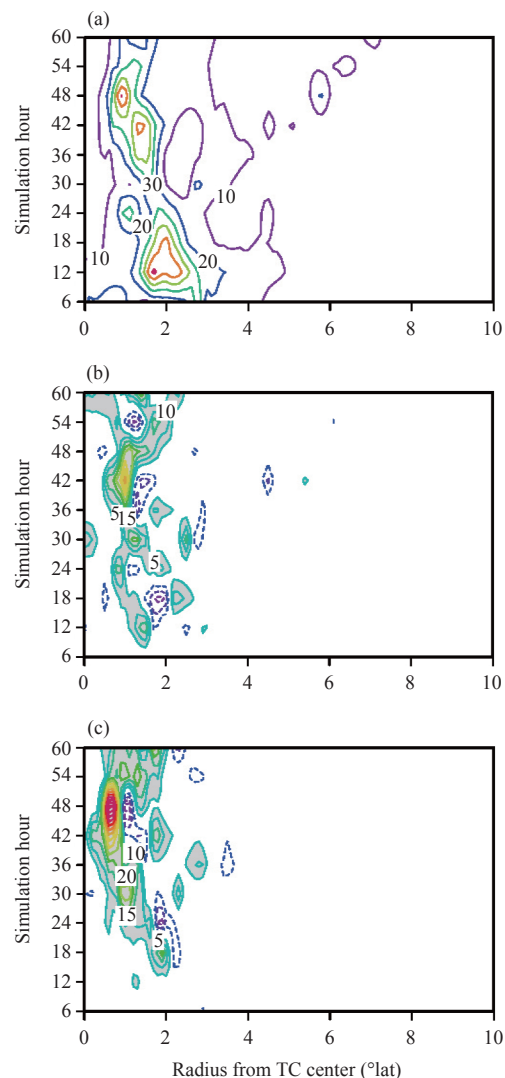


Figure 8. As in Fig. 5, but for 6-h accumulated precipitation (units: mm). Gray shading indicates values greater than 5 mm.

(0603) and Bilis (0604), was removed, TC Bilis (0604) could develop into typhoon category at 48 h and 36 h, respectively. Therefore, the SST cooling induced by TCs was an important factor that inhibits the intensity of TC Bilis (0604).

By analyzing the physical processes of the effects of TC-induced SST cooling on the intensity of TC Bilis (0604), the present study discussed the feedback mechanism of TC-induced SST cooling on the intensity of TC Bilis (0604). The results show that TC-induced SST cooling first led to a decrease in the heat flux and moisture flux at the surface of TC, mainly within a radius of two latitudes, and then a decrease in the conditional instability and atmospheric moisture in the lower layer of TC, followed by a decrease in TC precipitation, a weakening in TC warm core, a decrease in the upward vertical velocity of TC, a decrease in the inward radial wind in the lower layer of TC, and finally a weakening in the intensity of TC Bilis (0604).

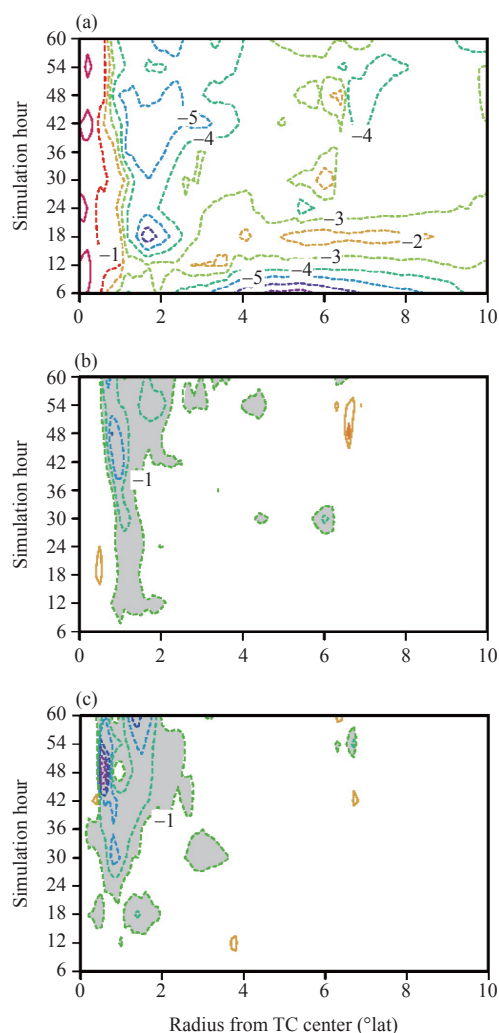


Figure 9. As in Fig. 5, but for radial wind (units: m s^{-1}) averaged from 1000 hPa to 850 hPa and positive outward. Gray shading indicates values less than -1 m s^{-1} .

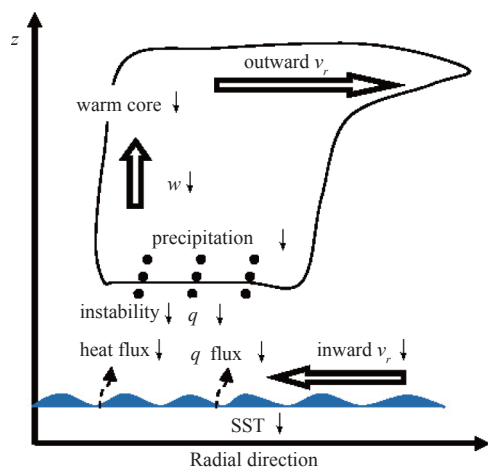


Figure 10. Schematic diagram of the effects of SST changes induced by TCs on the intensity of TC Bilis (0604). “↓” indicates a decrease or weakening. q indicates moisture, w indicates vertical velocity, and v_r indicates radial wind, respectively.

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