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THE IMPACT OF AIR-SEA INTERACTIONS ON TYPHOON STRUCTURE

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Abstract: In this work, the results of a coupled experiment and an uncoupled experiment conducted in one of our former works are used to analyze the impact of air-sea interactions on the structure of typhoons. Results reveal that typhoon-induced SST decreases to reduce the latent heat fluxes transporting from the ocean to the atmosphere and cause the flux of sensible heat to transfer downward from the atmosphere to the ocean. Such SST reduction also has remarkable impacts on the typhoon structure by making the typhoon more axisymmetric, especially in the middle and high levels. This study also analyzes the basic characteristics of symmetric typhoon structure.

Key words: air-sea interactions; typhoon structure; SST reduction

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1 INTRODUCTION

Over the recent years, the asymmetric structure of tropical cyclones (TCs) has drawn much concern. For the mechanism of its formation, Yang et al.[1] argued that dynamic factors inside the TC results in its asymmetric structure. Ross et al.[2] and Wang[3, 4] showed in numerical simulations that the asymmetric structure is related with the β effect. Shapiro[5], Li et al.[6], and Bender[7] indicated that large-scale environmental flow fields give rise to the asymmetric structure. As shown in the result of an analysis on dynamics, a two-dimensional stationary asymmetric flow field is mainly subject to non-linear advection factors and the β effect[8]. It was then further verified by a numerical experiment[9]. Diabatic heating is another important factor in forming, maintaining and affecting the asymmetric structure of TCs. With simple, quasi-geostrophic and barotropic vorticity equations model, Lei[10] showed that diabatic heating results in the asymmetric distribution of the tangential wind speed and gravitational geopotential field of the TC. A three-level quasi-geostationary baroclinic model was used to study the TC structure in the environmental diabatic heating field and an associated numerical experiment showed that diabatic heating has large impacts on the horizontal and vertical structures of the TC (Chen et al.[11]). In an ideal numerical experiment, a hurricane vortex was incorporated with asymmetric, diabatic heating and both the structure and intensity of the TC was shown to undertake substantial change. In our earlier work[13], MM5, a mesoscale atmospheric model, was coupled with Princeton Ocean Model (POM), a regional ocean model, to set up a mesoscale air-sea coupled model. Then this model, also called a coupling experiment, and MM5, also known as an uncoupled experiment, were used to simulate the change in the intensity of Typhoon Krovanh. The results showed that the typhoon intensity simulated by the coupling experiment was consistent with the observation while that modelled by the uncoupling experiment, with fixed sea surface temperature (SST) data, was much larger. During the typhoon, the SST is lowered with the extent larger to the right of the track than to the left, due to processes of entrainment and pumping by which cold water is transferred to the mixed layer on the one hand, as feedback to the TC, the reduced SST causes the ocean to decrease its supply of latent and sensible heat to the TC, resulting in the weakening of the TC, on the other. At present, there is little research on the effect of air-sea interactions on the TC structure and quite a number of issues remain to be

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worked on in detail. For instance, do changes in the distribution of latent and sensible heat fluxes induced by decreased SST affect the structure of TC? By analyzing the effect of the SST fall on the TC structure, this study attempts to investigate into the role of the asymmetric structure due to such SST drop in the weakening of TC intensity.

2 ANALYSIS OF THE STRUCTURE

Figure 1 presents the distribution of wind speed at the lowest model level (σ=0.995 and at a height of 36 m) for two points of time as simulated by the coupling and uncoupling experiments. At hour 6 of the integration (figure omitted), the two experiments are basically the same in wind speed and distribution pattern, with wind speed being the maximum at the northeast quadrant to the right of the eye and the minimum at the southwest quadrant. Studies showed that TCs in this asymmetric distribution pattern usually move west at high speeds[14], being consistent with the westward movement of Typhoon Krovanh. At hour 18 of the integration (Figs. 1a & 1b), the wind speed simulated by both experiments is the maximum at the north quadrant and shows significant asymmetry, which is mainly in the core of the TC. For the maximum wind speed, however, the coupling experiment is smaller (38 m/s) than the uncoupling experiment (41 m/s) and is more of asymmetric distribution. The difference is more pronounced at hour 30 of the integration (Figs. 1c & 1d), at which the coupling experiment has much smaller maximum wind speed (42 m/s) than the uncoupling experiment does (51 m/s), indicating an increased asymmetric wind field in the former experiment.

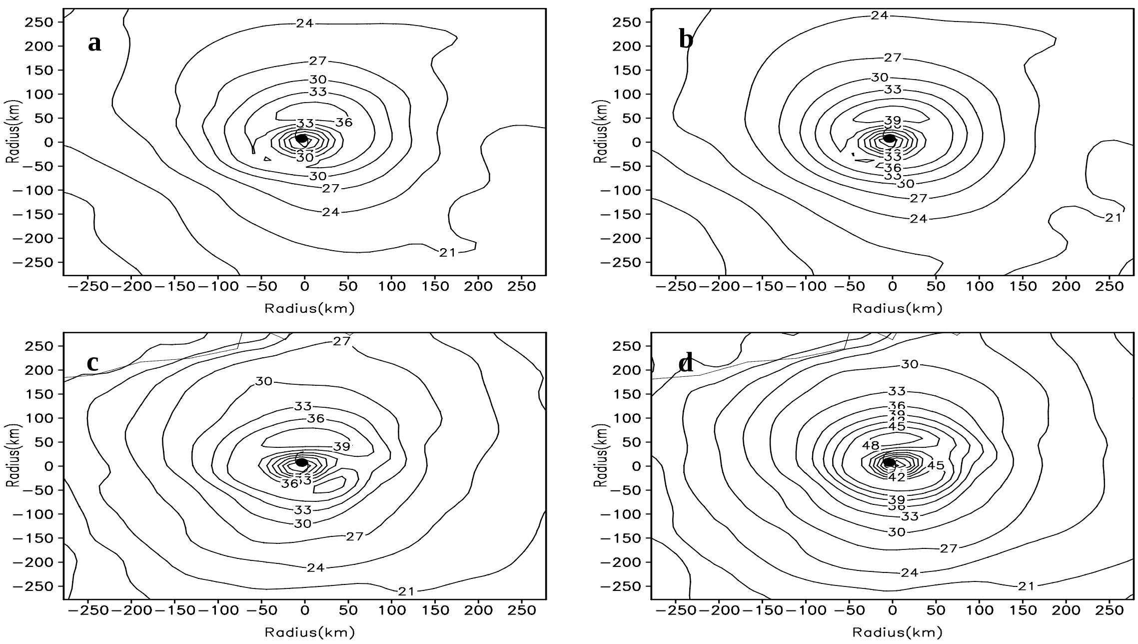

Fig. 1. TC wind speed simulated by the coupling experiment (a, c) and uncoupling experiment (b, d) at 1800 Coordinated Universal Time (UTC) on August 23 (a, b) and at 0600 UTC on August 24 (c, d). The symbol of TC indicates the position of the eye at the corresponding time.

The exchange of sensible and latent heat and momentum between land and sea are essential in the formation and evolution of TCs. Latent heat flux is the basic condition for the TC to develop and is thus more important. A mature TC depends mainly on the release of latent heat for its main source of energy, with 10%–20% of the energy coming from the water vapor in the underlying surface of the ocean. Water vapor converges and rises in the boundary layer and releases a large amount of latent heat from condensation, providing energy for the maintenance and evolution of the TC[15]. Fig. 2 and Fig. 3 show the distribution of the fluxes of latent and sensible heat at two moments of time in the two experiments. In both the experiments, the values of latent heat flux in both experiments are positive over the ocean and land, and their magnitude is much larger than that of sensible heat flux, indicating a larger role of latent heat flux in the evolution and maintenance of the TC. In the uncoupling experiment, the distribution of latent heat flux (Figs. 3a & 3c) is similar to that of wind speed (Figs. 1b & 1d), in that the values are relatively small near the eye, gradually increase outward from the eye, and then reach the minimum in the proximity of the radius of maximum wind speed before decreasing slowly outward. The flux of latent heat north of the eye is relatively large. In the coupling experiment (Figs. 2a & 2c), however, latent heat flux distributes in a highly asymmetric way and is small at the right rear portion from the eye, as it is affected by air-sea temperature difference. At hour 30 of the integration of the coupling experiment, the maximum latent heat flux is 600 W/m^2, much smaller than that of the uncoupling experiment (1 100 W/m^2). The two experiments differ greatly in the distribution of sensible heat flux; its magnitude depends on the temperature difference between the sea and air and the magnitude of wind speed, with the direction of transportation determined by this temperature difference. For the uncoupling experiment, the distribution of latent heat flux (Figs. 3b & 3d) is also similar to that of wind speed (Figs. 1b & 1d); it is generally positive over the ocean, i.e., the ocean transports sensible heat flux to the atmosphere by magnitudes that increase with the wind speed. For the coupling experiment (Figs. 2b & 2d), however, the sensible heat flux, being negative, is transported from the atmospheric boundary layer to the ocean, making vortex-shaped symmetric distribution absent in the sensible heat flux, and leading to a pattern which does not look like that of wind speed at all, due to the SST fall being taken into account in the experiment and air temperature being warmer to the right of the TC than SST.

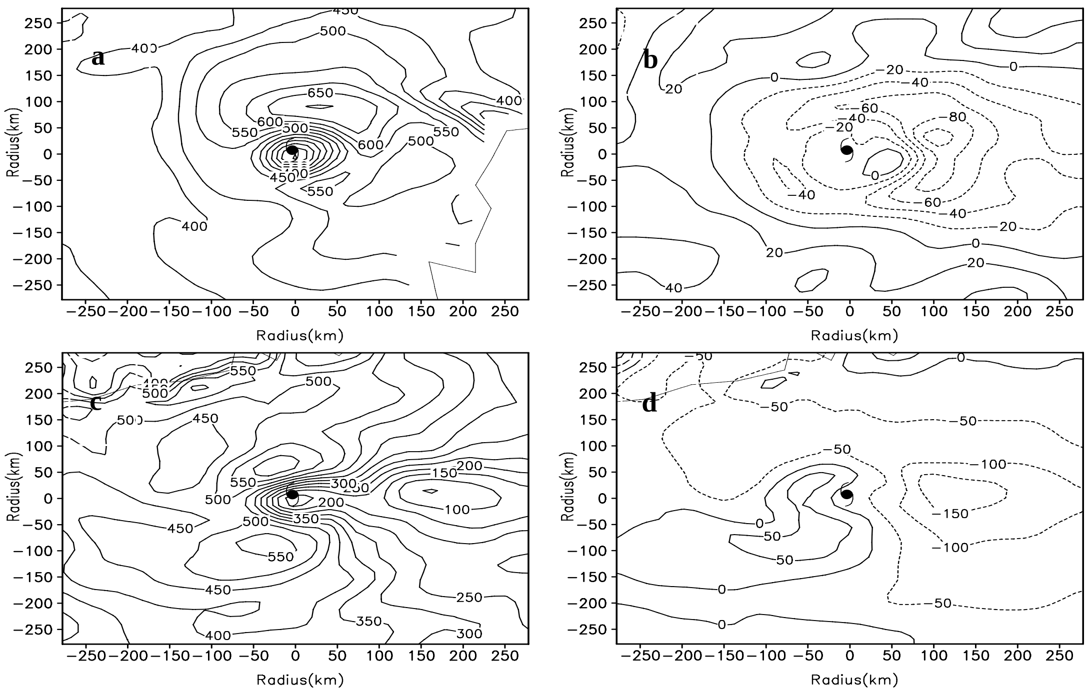

Fig. 2. Latent heat flux (a, c) and sensible heat flux (b, d) simulated by the coupling experiment at 1800 UTC on August 23 (a, b) and at 0600 UTC on August 24 (c, d). The symbol of TC indicates the position of the eye.

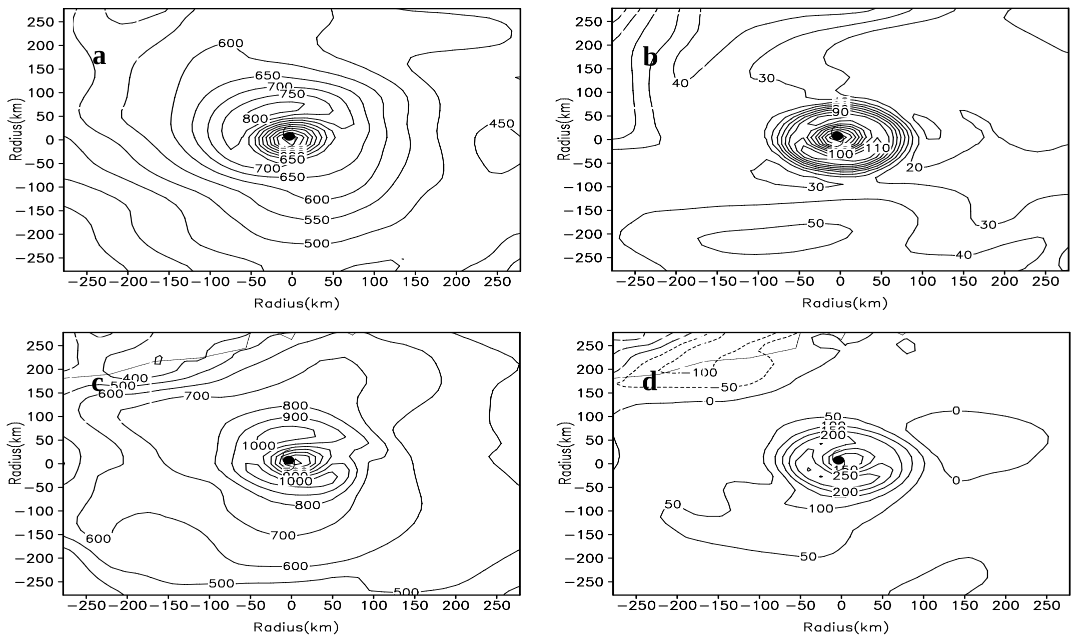

Fig. 3. Same as Fig. 2 but for the uncoupling experiment

Because of the scarcity of observations about surface flux in high wind speeds, opinions are divided on how large the effect of sensible heat flux on the TC can be and in which direction sensible heat flux is transported. Most of the previous studies hold that it is toward the atmosphere that the ocean transports the sensible heat flux during a TC process. As shown in observational studies in recent years, sensible heat flux can be transported downward to the ocean in some of the TC processes. Based on the measurements of the Marex buoys, data from surveys for profiles across the sea and from island stations in Xisha Islands provided by South China Sea branch of the State Oceanological Administration, Wu et al.[16] computed the exchanges of heat across the air-sea interface within the TC circulation regimes. The studies showed that the heat exchange across the interface between the sea and air within the TC circulation systems are very intense, which is mainly contributed by latent heat flux; negative sensible heat flux appears in the TC circulation of summer. With data from a CBLAST (Coupled Boundary Layer Air-Sea Transfer) project, Desflots et al.[17] computed the surface flux (of both latent heat and sensible heat) for Typhoon Frances (2004), with results showing that the surface heat flux is asymmetrically distributed around the eye and extremely low at the right rear quadrant of the storm. As the TC reduces much SST at its right rear portion, the heat flux is the lowest at the corresponding quadrant. With observations, Black et al.[18] computed the flux of latent heat and sensible heat under the condition of Typhoon Kerry (1979). Results showed that the air temperature was higher than SST and the sensible heat flux was transported downward to the ocean at a rate of about 100 W/m^2. As shown in the numerical simulation of this study, the TC-related temperature decrease reduces greatly the latent heat flux transported from the ocean to the atmosphere and causes the downward transfer of sensible heat flux to the ocean. In addition, asymmetric distribution is significant in the heat flux.

3 MESOSCALE WAVES WITHIN THE TC VORTEX

To decompose the axisymmetric and non-axisymmetric components of the physical quantity field of the TC, the results simulated by the model on regional rectangular coordinates at 15-km grid intervals were converted to a polar coordinates mesh taking the eye as the polar point. To conduct Fourier decomposition as well as to make the resolution close to each other between the two coordinates, the grid interval takes 15 km and the amplitude angle takes 5° on the radial direction in the polar coordinates. With the model physical quantity field converted to the polar coordinates, the part on the cylindrical coordinates (r, θ, z) is subdivided into an axisymmetric (X_s) and a non-axisymmetric (X_a) portions, where

$$X_s(r,z) = \frac{1}{2\pi}\int_0^{2\pi} X(r,\theta,z)\,\mathrm{d}\theta ,$$

$$X_a(r,\theta,z) = X - X_s .$$

For the horizontal wind, the method in Liu et al.[19] was first followed to deduce the regional mean wind in deep layers as in

$$V_m = \frac{\int_{900\,\mathrm{hPa}}^{150\,\mathrm{hPa}}\int_0^{2\pi}\int_0^{150\,\mathrm{km}} Vr\,\mathrm{d}r\,\mathrm{d}\theta\,\mathrm{d}p}{\int_{900\,\mathrm{hPa}}^{150\,\mathrm{hPa}}\int_0^{2\pi}\int_0^{150\,\mathrm{km}} r\,\mathrm{d}r\,\mathrm{d}\theta\,\mathrm{d}p} .$$

Then, $V' = V - V_m$ is obtained by computation. According to the axisymmetricity index, $I_{SA} = X_s^2 / X^2$, as defined by Xu et al.[20], X is the field of a particular element, and X_s is axisymmetric part of the element field. Apparently, $I_{SA} \le 1$; when $I_{SA} = 1$, the element field is fully axisymmetric; the closer I_{SA} approaches 1, the more axisymmetric is of the structure. Fig. 4 gives the curve of the altitude-dependent variation of the axisymmetricity index of wind speed averaged over hours 18–36 of model integration. Although the axisymmetricity index fluctuates with the change in altitude, the axisymmetricity itself is the basic character of the simulated fields of elements in both the coupling and uncoupling experiments. Compared with those of the uncoupling experiment, the coupling experiment, with the increase of altitude, has a slightly smaller axisymmetricity index at layers beneath 6 km while having a faster decreasing rate in layers above 6 km. It indicates that the TC-reduced SST has feedback in the TC so that the axisymmetricity of its structure is decreased but the asymmetricity is increased, especially so at the middle and higher levels of the TC.

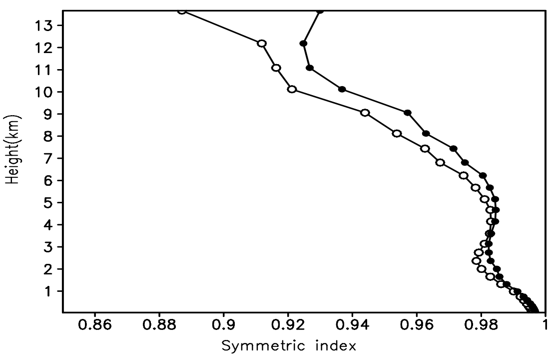

Fig. 4. Curves of the variation with altitude of the axisymmetricity index of wind speed averaged over hours 18–36 of model integration in the coupling experiment (hollow circle) and the uncoupling experiment (solid circle)

Figure 5 shows that the temporal variation of the intensity of Wave 1 of the asymmetric wind speed (indicated by the average for the area surrounding the eye). The general tendency of variation corresponds well with the intensity of TC (expressed by the minimum pressure near the eye), especially with Wave 1 of the coupling model. When the intensity of Wave 1 decreases, the TC intensity increases and vice verse. The enhancement of the TC is accompanied by the reduction of the asymmetricity of the TC.

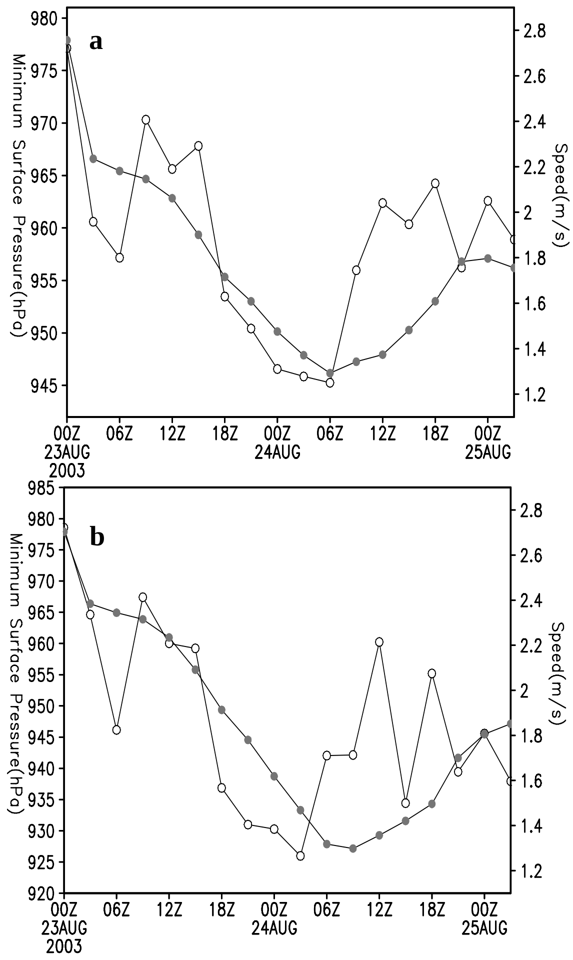

Fig. 5. Variation tendency of the intensity of the axisymmetric wind speed (hollow circle) and TC intensity (solid circle) in the coupling experiment (a) and uncoupling experiment (b)

4 SUMMARY

(1) The TC-related SST fall has remarkably reduced the latent heat flux transporting from the ocean to the atmosphere, enabling the downward transport of sensible heat flux to the ocean. Additionally, heat flux is more of asymmetric distribution. As feedback to the TC, the TC-reduced SST decreases the axisymmetricity of its structure but increases the asymmetricity of the TC, especially in the middle and higher levels.

(2) The results of an ideal numerical experiment[12] shows that minor changes in factors governing convection (such as the underlying ocean surface) can affect the TC structure and via this process exert an impact on its intensity. However, as real TCs are just too complicated, no numerical experiments or analysis were carried out with real cases of TCs. According to previous works on the mechanisms through which the TC-reduced SST is shown to have an impact on the TC intensity, the decreased SST lessens the flux of latent and sensible heat that is supplied to the TC by the ocean. As shown in this study, such reduction indeed has great impacts on the structure and intensity of the TC. According to the conclusion of Möller et al.[12], the TC-reduced SST may affect the intensity of TC through an entirely different mechanism. It needs extensive study in the future.

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