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Mechanistic Impacts of a Scale-Aware Convection Scheme on Typhoon Intensity: Diagnostics From Minimum Sea-Level Pressure

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ABSTRACT

This study investigates the impact of a scale-aware convective parameterization scheme (CPS) on the simulation of typhoon track and intensity through a series of experiments using the Global-to-Regional Integrated Forecast SysTem (GRIST) model. The results of four typhoon cases show the scale-aware CPS generally reduces the track error by about 15 km and the intensity error by about 10% compared to the default CPS. By analyzing the budget equation of surface pressure tendency, we found the surface pressure fall due to CPS heating is about 0.6 hPa h^{-1} weaker when the scale-aware CPS is used. This is, however, compensated by enhanced microphysics heating, which more than offsets the reduction in CPS and yields a net pressure depression of about 1 hPa h^{-1}. In fact, when parameterized convection is suppressed, the microphysics process takes up the convective instability left over by CPS and stimulates even stronger diabatic heating by 13.8%. The increased microphysics precipitation, along with the intensified grid-scale ascending, further validates the assertion. The results of this study demonstrate the benefits of scale-aware CPS on typhoon modeling.

1 | Introduction

Tropical cyclones (TCs) are one of the most catastrophic weather events, causing severe damage and massive loss of life and property. Accurate forecasting of TCs has long been a pressing need; however, current numerical weather prediction (NWP) models still struggle to predict TCs with sufficient accuracy, despite a fair amount of progress made over the past few decades (Lei et al. 2022; Peng et al. 2017). The challenge arises because a tropical cyclone is characterized by strong multiscale interactions between cumulus convection and large-scale dynamics (Gu et al. 2015; Smith et al. 2017; Tang et al. 2019), thus proper representation of convection and its feedback on large-scale circulations is essential for TC forecasting (Tan et al. 2022; Vitart et al. 2001).

As the horizontal resolution of NWP models extends down to the tens of kilometer scale ("gray zone"), conventional convective parameterization schemes (CPS) become questionable because some

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organized convection can be resolved and convection is no longer a pure subgrid-scale phenomenon (Molinari and Dudek 1992; Arakawa and Wu 2013; Song and Zhang 2018). Some studies simply switched off CPS at this convection-permitting scale and obtained better representation of mesoscale convective systems (Knippertz et al. 2009; Weisman et al. 1997). However, such a strategy makes the under-resolved circulations overenergetic, leading to problems in forecasts such as delayed onset of convection, overprediction of heavy rainfall, and too many strong storms (Bryan and Morrison 2012; Judt et al. 2021; Weisman et al. 1997). CPS is therefore necessary even at the convection-permitting scale.

There are a number of methods for modifying CPS to be scale-aware, including scaling the mass flux using convective fraction (Arakawa and Wu 2013), scaling the convection entrainment rate (Zhao et al. 2024), and scaling the convection adjust time (Zheng et al. 2016). While the influence of scale-aware CPS on general model performance has been investigated in many previous studies (Ahn and Kang 2018; Freitas et al. 2020; Park et al. 2024), there are few studies focusing on its impact on TCs. By comparing typhoon simulations with and without scale-aware CPS, this study aims to answer: to what extent and how does scale-aware CPS improve typhoon modeling? The answer to these questions will help to further understand the impact of scale-aware CPS on model performance, and may also shed light on the pathways toward improvement on typhoon modeling.

2 | Model Description and Experimental Design

2.1 | Model Description

We use the model of Global-to-Regional Integrated Forecast System (GRIST; Li et al. 2022; Zhang et al. 2019), a unified weather and climate modeling system based on unstructured meshes, to explore the impact of scale-aware CPS on typhoon modeling. The dynamical framework of GRIST is based on fully compressible Euler equations, with a vertical acceleration term restored for nonhydrostatic modeling (Zhang et al. 2019). For physics packages, the model includes a bulk mass flux scheme for cumulus convection, originally described by Tiedtke (Tiedtke 1989) and later updated by Bechtold et al. (2008, 2014), the Yonsei University (YSU) scheme for boundary layer turbulence (Hong et al. 2006), the WRF single moment six-class (WSM6) scheme for cloud microphysics, and the Rapid Radiative Transfer Model for GCM Applications (RRTMG; Iacono et al. 2008). To make the TDK CPS scale-aware, we adopt the method of Arakawa and Wu (2013) to scale the mass flux using convective fraction. Details of the implementation are provided in Text S1 in Supporting Information S1.

2.2 | Case Description and Experimental Design

We conducted two experiments for each of the four typhoon cases, including Doksuri (2023), Infa (2021), Lekima (2019) and Soudelor (2015), using CPS with (NEW) and without scale-awareness (CTRL). All these simulations are configured on variable-resolution grids, ranging from a high resolution of 3.5 km centered on eastern China to a coarse resolution of 50 km for the rest of the globe (Figure S1). For Lekima, additional experiments with scale-aware CPS were also conducted using quasi-uniform grids with different horizontal resolutions, that is, 60 km (G7), 30 km (G8), 15 km (G9), 7.5 km (G10) and 3.75 km (G11), where the digital in the grid notation denotes the number of times the icosahedron is recursively bisected (Heikes and Randall 1995). All experiments were initialized using analytical data provided by the National Centers for Environmental Prediction Global Forecast System (GFS) and integrated for 120 h. Details of these experiments are given in Table S1.

3 | Impact of Scale-Aware CPS on Typhoon Track and Intensity

Figure 1 shows the statistical errors of typhoon track and intensity for the four typhoon cases between CTRL and NEW simulations against the observation, which is provided by the China Meteorological Administration. Overall, the track errors increase monotonically with the forecast lead time, from ~50 km before 60 h to ~300 km after 96 h. For either simulations, the mean track errors are slightly smaller than the NWP results for the period 2015–2020 (Yu et al. 2022). It is important to note that our simulations use a real time-varying sea surface temperature (SST), whereas in NWP models, the SST is usually fixed at the initial time. In comparison between CTRL and NEW, the latter further reduces the track error by about 15 km on average. Regarding typhoon intensity, which is measured by the minimum sea-level pressure (p_{min}) and the

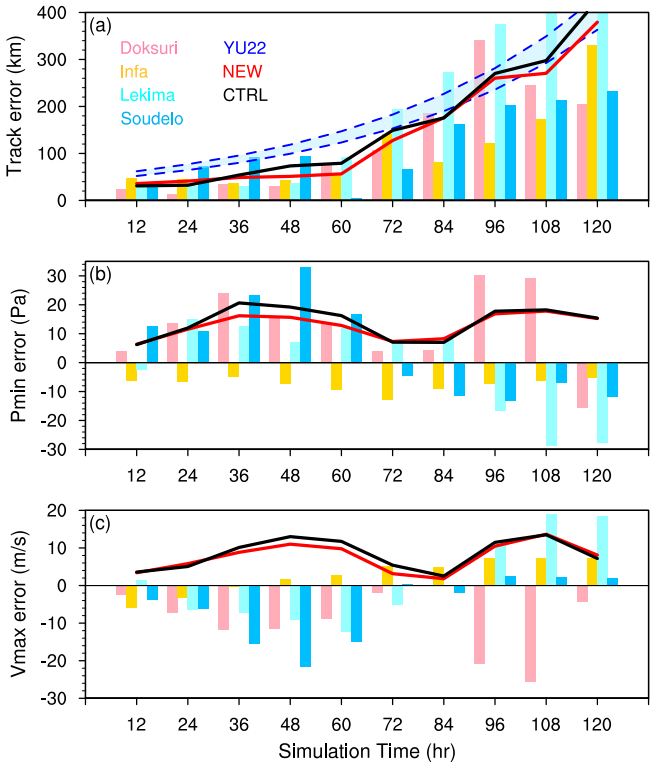


FIGURE 1 | Errors of (a) track, (b) minimum sea level pressure (p_{min}) and (c) maximum 10-m wind speed (v_{max}) of variable-resolution simulations for four typhoon cases with forecast lead time. Red and black lines denote case-averaged absolute errors for simulations with (NEW) and without (CTRL) scale-aware CPS. Bars are for simulations of NEW. Blue lines represent the range of mean fitting errors during 2015–2020 according to Yu et al. (2022).

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maximum 10-m wind speed (v_{max}), the application of scale-aware CPS reduces the error of p_{min} and v_{max} by about 10% on average, although there are still considerable biases. Such improvement is also evident in each typhoon case (Figure S2). In the following, we use Lekima as an example to illustrate the reasons why scale-aware CPS improves typhoon intensity.

Figure 2 gives the observed and simulated track and intensity of typhoon Lekima. In observation, Lekima moved to the northwest and intensified rapidly, with p_{min} dropped by 60 hPa and v_{max} increased by 29 m s^{-1}, reaching a maximum at 60 h. Lekima made landfall at 90 h and then quickly decayed. Both simulations successfully predict the track in the first 36 h, with errors mostly within the range of 50 km. However, they subsequently veered southwest and retraced to the northeast, resulting in failure of landing. In fact, the inability to predict Lekima landfall 3 days in advance is a common problem in many models (Huang et al. 2022; Jia et al. 2020). In contrasting between CTRL and NEW, the latter successfully shifts the track northward with the track error reduced by about 50 km. Further comparison of the 850-hPa geopotential height field (not shown) between CTRL and NEW shows notable discrepancies in the location and intensity of typhoon Krosa (to the east of Lekima), and the Western North Pacific subtropical high, thereby yielding different interactions with Lekima. Such interactions manifest the challenges in typhoon modeling across multiscale processes (Liu et al. 2023, 2024). Regarding the intensity, the CTRL simulation underestimates the intensity, with maximum errors of about 22 hPa and 15 m s^{-1} for p_{min} and v_{max}. The application of scale-aware CPS mitigates the error by about 4 hPa for p_{min} and 3 m s^{-1} for v_{max}, respectively, demonstrating the benefits of scale-aware CPS on typhoon modeling. To examine the performance of scale-aware CPS on uniform grids and to illustrate the extent to which the simulation using variable-resolution grids is comparable to that using uniform grids, we also show in Figure 2 the simulations using uniform grids ranging from 60 km (G7) to 3.75 km (G11). As expected, increasing resolution tends to produce deeper storms, thus improving the intensity performance. This by itself is trivial as TC intensity typically increases as model grid spacing decreases, especially when the grid spacing goes down from 60 to 4 km (Kanada and Wada 2016; Moon et al. 2020). In general, the simulations using variable-resolution grids are similar to those using uniform grids of 3.75 km (G11), with about the same accuracy as high-resolution modeling but at a much lower computational cost. This demonstrates the advantage of variable-resolution grids in typhoon modeling.

4 | Causes of Enhanced Typhoon Intensity With Scale-Aware CPS

4.1 | Analysis of Surface Pressure Tendency Budget Equation

To investigate the reasons why scale-aware CPS improve typhoon intensity, we examined the contributions of different physical processes to the surface pressure tendency (SPT).

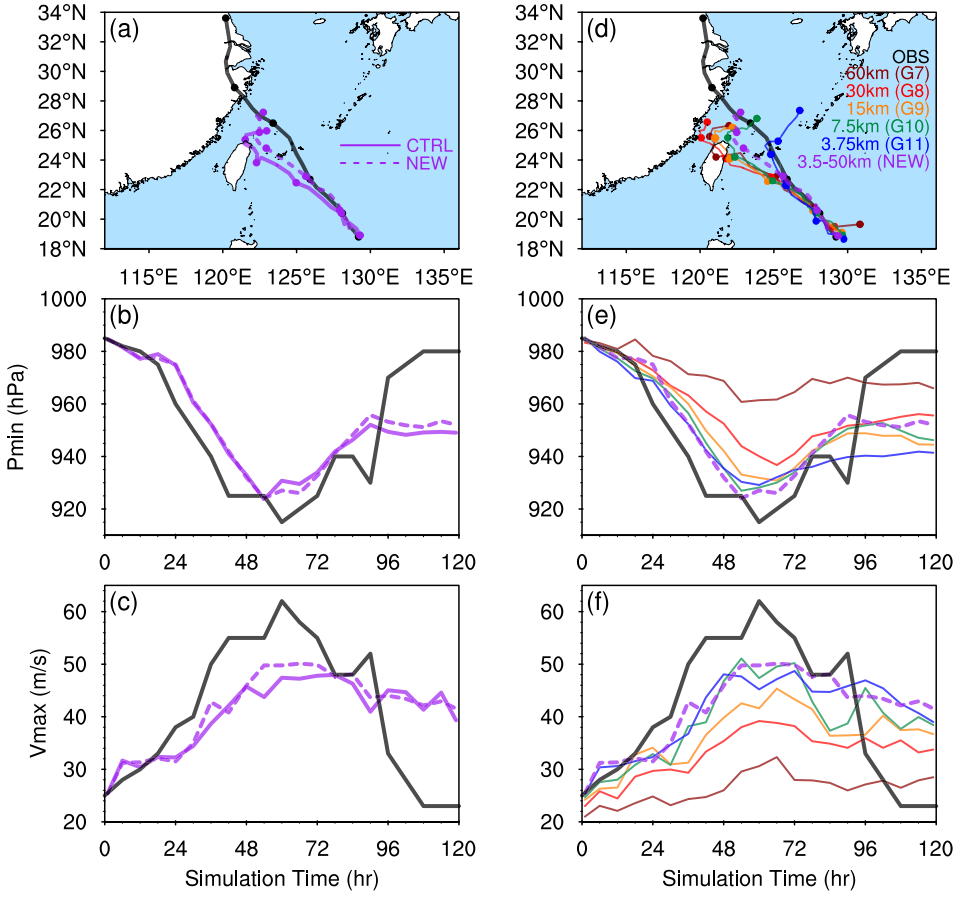


FIGURE 2 | Observed and simulated 120-h (a, d) tracks and evolution of (b, e) p_{min} and (c, f) v_{max} for typhoon Lekima. Dots in (a, d) mark the location each 24-h interval. The left (right) column is for simulations using variable- (uniform-) resolution grids.

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Following Zhang and Ma (2023), the integrated effects of diabatic heating on the surface pressure changes are expressed as:

$$\left.\frac{\partial p_s}{\partial t}\right|_{\text{phy}} = -\frac{g}{R} p_0^{\frac{R}{c_p}} p_s^{1-\frac{R}{c_p}} \int_{z_s}^{z_t} \frac{1}{\theta^2} \dot{Q}_{\text{DIAB}} dz \quad (1)$$

$$\dot{Q}_{\text{DIAB}} = \dot{Q}_{\text{CPS}} + \dot{Q}_{\text{MP}} + \dot{Q}_{\text{RA}} + \dot{Q}_{\text{BL}} \quad (2)$$

where $\dot{Q}_{\text{DIAB}}$ denotes total diabatic heating produced by physical parameterization schemes including CPS, microphysics (MP), radiation (RA), and boundary layer turbulence (BL). The symbol z_s denotes the surface, z_t represents the top of the atmosphere, defined as 15 km following Zhang and Ma (2023). Other symbols in Equation (1) follow conventional meteorological notations. Figure 3 shows the evolution of SPT due to CPS, MP and the sum of contributions from all physical process (DIAB) over an area of 200 km radius centered on the low-pressure center. As noticed, both CPS and MP reduce the surface pressure, due to the fact that heating alters the local potential temperature, causing the air column to stretch horizontally and vertically. The reduction of surface pressure due to CPS in NEW is about 0.6 hPa h^{-1} weaker than that in CTRL because subgrid convection is suppressed in scale-aware CPS. However, the microphysics takes up the convective instability that is left over by CPS (Wang and Zhang 2013). The increase in MP compensates for the decrease in CPS so that the DIAB for the first 48 h is approximately the same in the two runs (red line in Figure 3a). However, during the 48–72 h period, the intensity increase in MP outweighs the reduction in CPS, yielding a net pressure depression of about 1 hPa h^{-1} in the inner-core region. This suggests that the suppression of parameterized convection is in favor of stimulating more intensified microphysics heating, which is responsible for the enhanced typhoon intensity observed in Figure 2b.

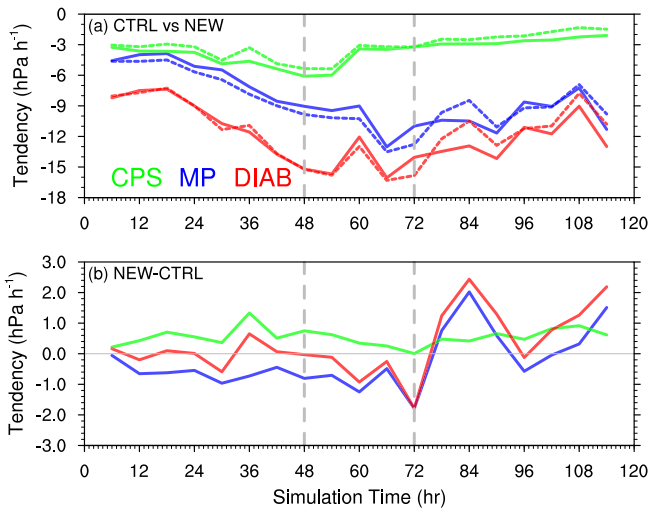


FIGURE 3 | Mean surface pressure tendency (SPT) for an area of 200 km radius centered on the low-pressure center for (a) CTRL (solid lines) and NEW (dashed lines) simulations, and (b) their differences. Green, blue, and red lines denote contributions from subgrid convection (CPS), microphysics (MP) and all physical processes (DIAB).

4.2 | Effects of Scale-Aware CPS on Typhoon Horizontal and Vertical Structure

To investigate the impact of scale-aware CPS on typhoon horizontal structure, Figure 4 shows the spatial distribution of CPS, MP, and total precipitation for CTRL and NEW at 60 h. This classification is widely used in the study of parameterization scheme behavior (e.g., Rulfová et al. 2017; Liu et al. 2018), which is different from the definition in Rogers (2010) that employs reflectivity (dBZ) and vertical velocity to classify precipitation types. Also superimposed is the corresponding contribution of diabatic heating to SPT (contours). In CTRL, the eyewall is characterized by heavy precipitation exceeding 700 mm d^{-1} within a radius of 100 km, with peaks reaching 1000 mm d^{-1}, coinciding with the −50 hPa h^{-1} SPT belt. The type of precipitation in this area is predominantly microphysical. There are three spiral rainbands of more than 100 mm d^{-1} surrounding the eyewall in the outer region, which is dominated by CPS precipitation. In comparison with CTRL, NEW produces a more contracted and intense eyewall MP precipitation, with the maximum exceeding 1500 mm d^{-1}. Accordingly, it produces stronger diabatic heating and thus stronger SPT exceeding −100 hPa h^{-1} in the eyewall and −50 hPa h^{-1} in the surrounding annular rainband. On average, NEW leads to an increase of 14.7 mm d^{-1} in MP precipitation and a corresponding increase of 1.245 hPa h^{-1} in SPT depression, equivalent to an increase of 9.5% and 13.8%, respectively. This enhancement more than offsets the reduction of precipitation (−3.48 mm d^{-1}) and the surface pressure fall (0.348 hPa h^{-1}) of the CPS component, resulting in a net SPT depression of 1 hPa h^{-1} in NEW than in CTRL, as shown in Figure 3b.

To further investigate the impact of scale-aware CPS on typhoon vertical structures, Figure 5 shows the azimuthal averages of heating, temperature anomaly, vertical velocity, and radial winds from CTRL, NEW, and their differences. The CTRL run exhibits a tilting diabatic heating wall extending radially outward, reaching a maximum of 21 K h^{-1} at 8-km altitude (Figure 5a). This causes local warming and forces the air in the eye region to sink (Figure 5d), producing a warm-core structure there. By comparison, NEW produces more diabatic heating than CTRL by about 4 K h^{-1} (Figure 5i), which entirely comes from the microphysics (Figure 5k). In fact, CPS heating is reduced by about 0.5 K h^{-1} compared to CTRL due to the use of scale-aware CPS (Figure 5j). However, this leads to stronger grid-scale ascending in the eyewall region, accompanied by accelerated radial winds (Figure 5l). Specifically, the low-level inflow and upper-level outflow increased by 2 m s^{-1}, resulting in an enhancement of eyewall ascending by 0.2 m s^{-1}. The strengthened secondary circulation takes up the convective instability left over by CPS and produces even stronger diabatic heating of about 4 K h^{-1} via microphysics (Figure 5k). This extra heating further warms the local air and produces a positive temperature anomaly of about 1 K around 5-km height (Figure 5i). In short, by suppressing parameterized convection, the scale-aware CPS intensifies the secondary circulation and the stratiform process, producing stronger diabatic heating and thus enhanced typhoon intensity.

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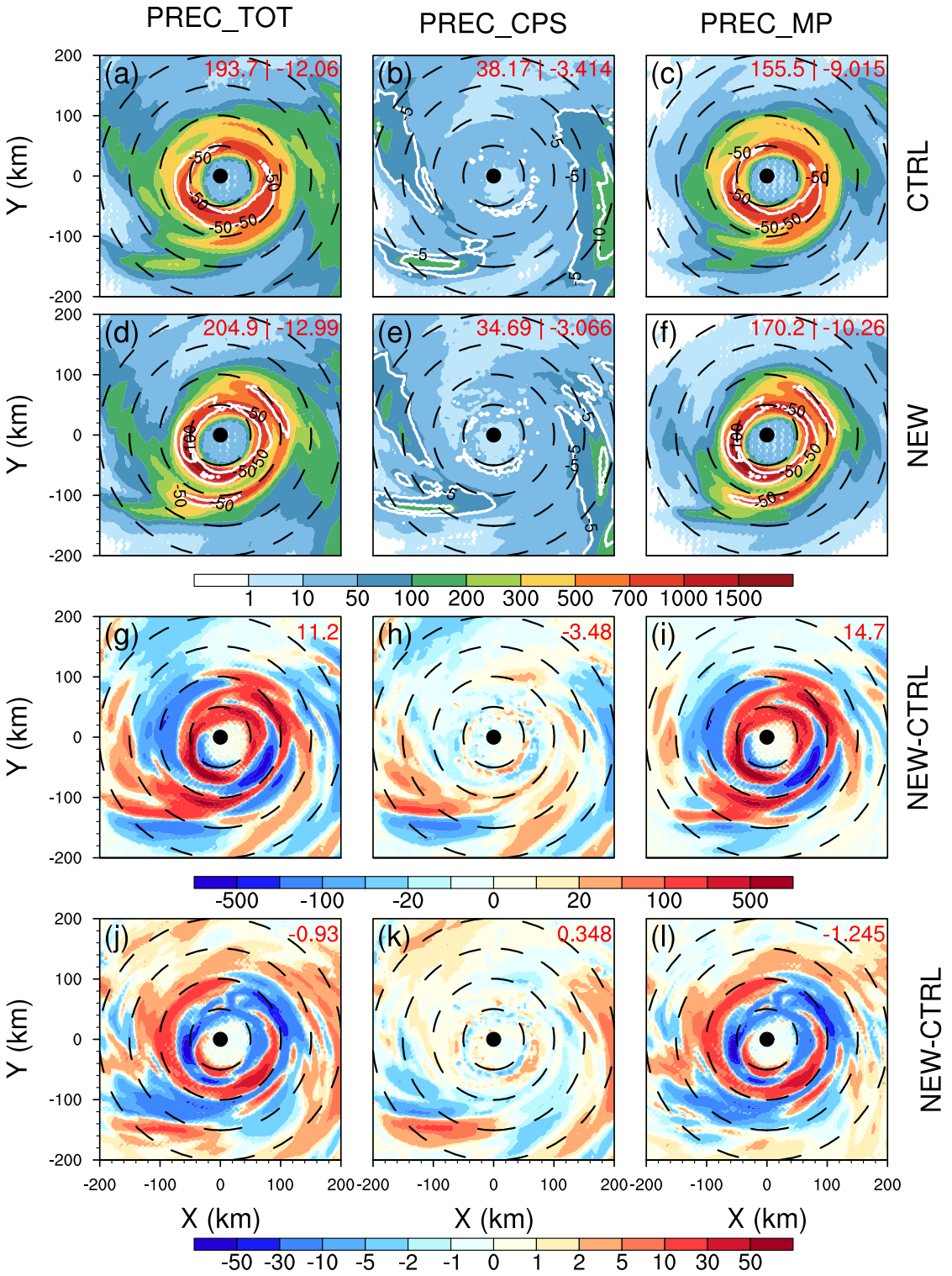


FIGURE 4 | Simulated precipitation and diagnosed SPT at 60 h for CTRL, NEW and their differences. (a–f) Precipitation (shaded, mm d^{-1}) and SPT (contour, hPa h^{-1}), differences between NEW and CTRL for (g–i) precipitation and (j–l) SPT, with the domain mean labeled in the top-right corner. Left, middle and right columns refer to total, CPS and MP precipitation, respectively. Black dashed circles are drawn at 50-km intervals, and the black dots mark the typhoon centers.

5 | Conclusion and Discussion

Through a series of experiments using the GRIST model, we investigate the impact of scale-aware CPS on the simulation of typhoon track and intensity. The results of four typhoon cases show that scale-aware CPS helps to reduce the track error by about 15 km and the intensity error by about 10%, demonstrating the benefits of scale-aware CPS on typhoon modeling.

The Lekima case is then used as an example to illustrate the reasons behind the improved typhoon intensity with scale-aware CPS. By analyzing the budget equation of surface pressure

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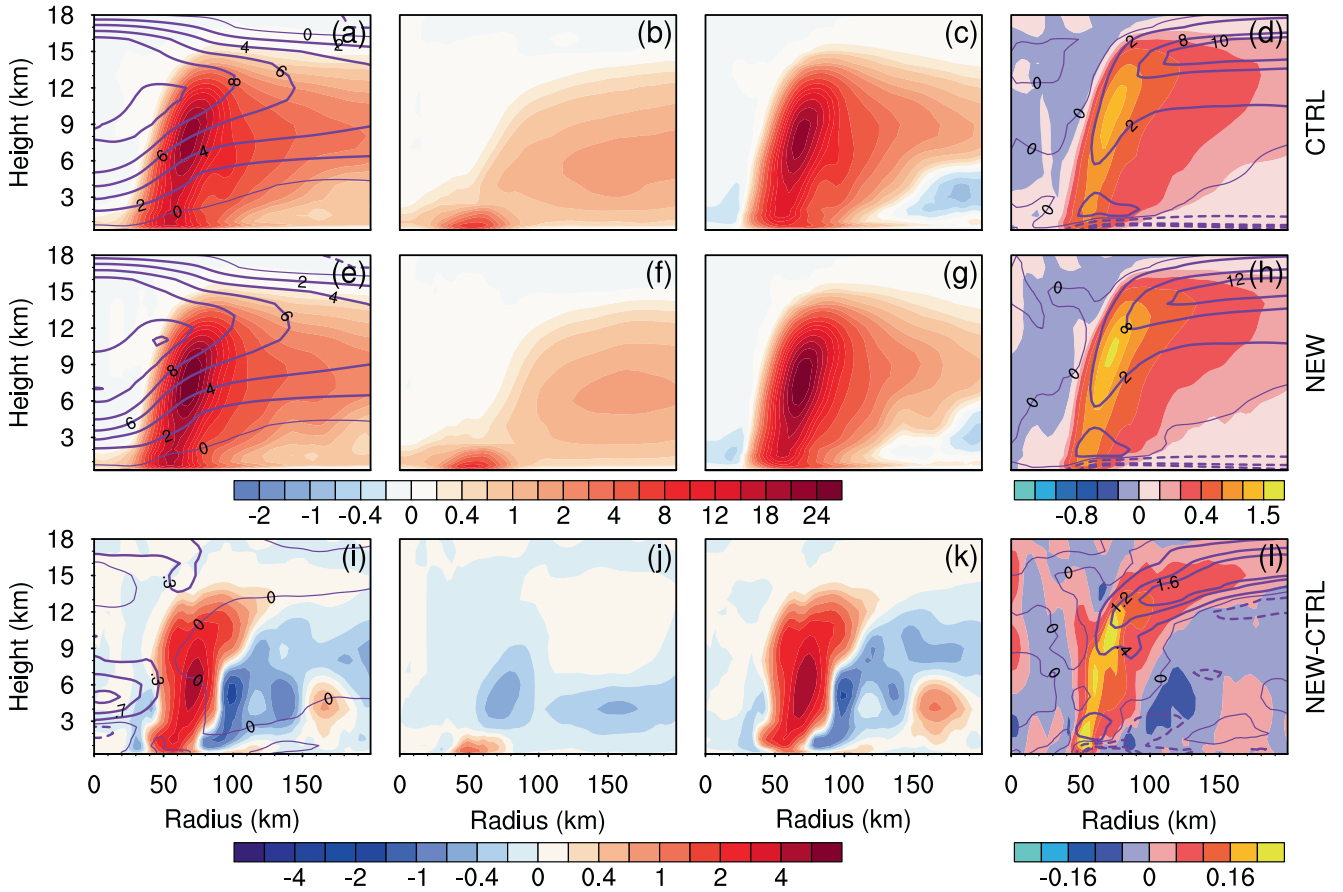


FIGURE 5 | Azimuthal mean of (a, e, i) total diabatic heating (shaded, K h^{-1}) and temperature anomaly (contour, K), (b, f, j) CPS and (c, g, k) MP heating (K h^{-1}), (d, h, l) vertical velocity (shaded, m s^{-1}) and radial winds (contour, m s^{-1}) for CTRL, NEW and their differences during 48–72 h. Solid and dashed contours denote positive and negative values, respectively.

tendency contributed by different physical processes, we found the pressure depression due to CPS heating is about 0.6 hPa h^{-1} weaker when scale-aware CPS is applied. However, the microphysics process takes up the convective instability left over by CPS and outweighs the reduction in parameterized convection, yielding a net pressure depression of about 1 hPa h^{-1}. This suggests the suppression of subgrid convection favors the stimulation of stronger microphysics heating due to stronger grid-scale ascending. Further examination of the inner-core precipitation validates the assertion. Indeed, when the scale-aware CPS is applied, the microphysics precipitation and corresponding diabatic heating in the inner-core region increase by about 9.5% and 13.8% respectively, which more than offsets the decrease in precipitation and diabatic heating of the CPS component. This is accompanied by stronger grid-scale ascending and accelerated radial winds, with the low-level inflow and upper-level outflow increased by about 2 m s^{-1}. In summary, by suppressing subgrid convection and enhancing the microphysics process, the scale-aware CPS intensifies the secondary circulation, producing stronger diabatic heating and thus enhanced typhoon intensity.

Author Contributions

Yanjie Liu: data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft, writing – review and editing. **Xiaocong Wang:** conceptualization, funding acquisition, methodology, software, supervision, validation, writing – original draft, writing – review and editing. **Yimin Liu:** conceptualization, supervision, validation, and writing – review and editing. **Hao Miao:** data curation, software, visualization. **Xuesong Zhu:** resources, software, visualization. **Wei Huang:** resources, software, visualization. **Yaxin Zhao:** software, validation. **Kai Wang:** software, visualization.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

GPM dataset is available at the NASA Goddard Earth Sciences Data and Information Services Center, see https://pmm.nasa.gov/dataaccess/downloads/gpm. The best track data is obtained from The CMA Tropical Cyclone Data center, see http://tcdata.typhoon.org.cn.

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