Tropical cyclone over the western Pacific triggers the record-breaking ‘21/7’ extreme rainfall in Henan, central-eastern China

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Abstract
During 19–21 July 2021, Henan located in central-eastern China experienced torrential rainfall that caused devastating floods and claimed more than 300 casualties. It remains unclear whether and to what extent this extreme precipitation event is contributed by Typhoon In-Fa (TIF). Here we quantify the contribution of TIF to this record-breaking ‘21/7’ rainfall using an air–sea coupled model with ensemble simulations. The modeling results show that the northwestward moisture transport along the confluence front of TIF and the western Pacific subtropical high (WPSH) contribute mostly to the precipitation extremes across Henan. A sensitivity experiment that removes the TIF effect confirms TIF’s role in shaping extreme rainfall. Specifically, without TIF, WPSH shifts the moisture transport northeastward and causes a heavy rainband over the Korean Peninsula, with much less precipitation over Henan. The water vapor budget over Henan suggests that the TIF-induced moisture advection is nine times greater than the local moisture supply and is effectively converted into clouds therein to reinforce precipitation extremes. The contribution of TIF to the ‘21/7’ Henan torrential rainfall on average could be as large as 42% by comparing the differences between simulated results with and without TIF’s effects.

1. Introduction
Tropical cyclones (TCs) are considered one of the most dangerous natural disasters that affect China (Ren et al 2006, Knight and Davis 2009, Jiang et al 2018, Zhang et al 2018a, Cao et al 2019, Deo et al 2021). Particularly, landfalling TCs can cause serious economic losses, casualties, and ecological damages resulting from the joint influences of torrential rainfall, strong wind, and intense storm surge. As a result, many studies have focused on precipitation extremes associated with landfalling TCs during the past decades from observations and modeling (e.g. Zhang et al 2009, 2019, 2021, Ying et al 2011, Li and Zhou 2015, Khouakhi et al 2017). However, TCs without landfall can also cause record-breaking
rainfall events over inland regions, referred to as TC-induced remote precipitation extremes (TRPEs) (Wang et al 2009, Feng et al 2020). TRPE is usually induced by TC interactions with large-scale or synoptic-scale systems, such as monsoon and upper-level troughs (e.g. Wang et al 2009, Huang and Lin 2014, Yu and Cheng 2014). Bosart and Carr (1978) documented a severe precipitation event resulting from the remote impacts of Hurricane Agnes (1972) and argued that abundant water vapor in the rainy areas was transported from the Atlantic by Agnes’s outer circulation. Farfán and Fogel (2007) analyzed the effects of eastern Pacific TCs’ circulation on the rainfall patterns over Mexico and concluded that TCs can serve as humid air mass sources to support deep convection and trigger precipitation extremes over northwestern Mexico. By utilizing the Weather Research and Forecasting (WRF) model, Wang et al (2009) found that typhoon Songda (2004) caused a remarkable TRPE in Japan. Besides, TCs over the western North Pacific (WNP) can serve as synoptic convective sources to generate quasi-stationary barotropic Rossby wave train, connecting East Asia and the tropical Pacific. The so-called Pacific–Japan or the East Asia–Pacific teleconnection pattern intensifies the moisture supply and warm air advection from the lower latitudes, thereby causing TRPEs over Japan and eastern China (Yamada and Kawamura 2007, Fang and Kuo 2013, Yu and Cheng 2013, Chen and Wu 2016, Feng et al 2020, Luo and Lau 2021).

TRPE is a significant phenomenon in the context of the East Asian summer monsoon and TC interactions (Huang and Lin 2014, Yu and Cheng 2014). On average, 8.8 TCs per year, with a maximum of 17 TCs in 1970, causes TRPEs in the coastal and inland areas of China over the past 59 years (Feng et al 2020). In an earlier study documented by Yu and Cheng (2014), the striking characteristics of TC-enhanced summer monsoonal flow are identified based on six TC cases. It is found that the monsoonal flow which prevails in summer can be strengthened by the outer circulations due to passing TCs, generating TRPEs over eastern China (Yu and Cheng 2014). Although TRPE has a crucial impact on the quantitative precipitation forecast (Wang et al 2009, Chen and Wu 2016), few studies have quantitatively examined the contribution of TCs to the TRPEs to the best of our knowledge.

During 19–21 July 2021, Henan province in central-eastern China was impacted by unprecedented flooding resulting from the prolonged precipitation extremes, with a record-breaking rainfall amount of 201.9 mm occurring in an hour in Zhengzhou (Nie and Sun 2022). This ‘21/7’ rainfall extreme affected 9.3 million people and led to 302 deaths according to provincial authorities as of 2 August. Based on the diagnostic analysis, Ran et al (2021) examined the thermodynamic process of the ‘21/7’ extreme rainfall with the combined effects of the western Pacific subtropical high (WPSH) and Typhoon In-Fa (TIF), and concluded that the mesoscale vortex plays a crucial role in the occurrence of record-breaking rainfall. Yin et al (2022) highlighted the evident effects of the meso-γ-scale convective system on the extreme events over Henan using the WRF model.

However, the above studies have not yet quantitatively examined the role of TIF, which was over 1000 km away from Henan, in the ‘21/7’ extreme rainfall. Whether and to what extent this ‘21/7’ extreme precipitation event is contributed by TIF is still unclear. In this study, we employ the state-of-the-art cloud-resolving air-sea coupled model with ensembles and apply a newly developed moisture budget analysis method to fill the gap in the quantitative contribution of TIF. A quantitative estimation of TIF’s role is critical to the assessment of the ‘21/7’ extreme rainfall disaster of similar TRPE events and also advances the understanding of TRPEs and underlying forcing mechanisms. More importantly, the analysis and modeling framework adopted in this study can be generalized to similar analyses of TRPEs from case-study and climatological perspectives in the future.

2. Data and method

2.1. Dataset

Data from the Global Precipitation Measurement (GPM) Integrated Multi-satellite Retrievals for GPM (IMERG) mission are utilized as the observed rainfall reference. The GPM IMERG is an international satellite mission designed specifically to set a new standard for precipitation measurement (Schwaller and Morris 2011) and can capture the space-time characteristics of above-normal rainfall across China (Guo et al 2016). The China Meteorological Agency (CMA) and International Best Track Archive for Climate Stewardship (IBTrACS) best track data are used to verify the simulated TIF (both track and intensity). And the fifth-generation atmospheric reanalysis of the European Centre for Medium-Range Weather Forecasts (ERAs; Hersbach et al 2020) is employed to verify the modeled atmospheric circulations during the period of ‘21/7’ extreme rainfall event.

2.2. Experimental designs

A modified WRF (version 4.2.2) model is adopted to examine TIF’s effects on the ‘21/7’ rainfall. We modify the WRF model to make it implement both fixed nesting over the rainfall region of Henan and moving nesting over the western Pacific to refine the TIF region. Since TC forecast requires accurate air–sea interaction processes (Yu et al 2022), e.g. the TIF can induce 1°C–2°C sea surface temperature (SST) cooling which greatly changes TIF’s intensity (figures not shown). The WRF model is coupled with the Regional Ocean Modeling System (ROMS) model through the
Model Coupling Toolkit (Jacob et al. 2005, Larson et al. 2005, Warner et al. 2008). The domain setting of the WRF-ROMS coupled model is shown in figure 1(a). The WRF has three fixed domains (fixed in location; D01, D02, and D04) with their respective horizontal resolutions of 12, 4, and 1.3 km and grid sizes of 600 × 480, 1441 × 1081, and 601 × 601, respectively, and one moving nested domain (D03) with a horizontal resolution of 1.3 km and grid size of 601 × 601. The ROMS model has one fixed domain with a horizontal resolution of 3 km. The ROMS model uses equidistant longitude–latitude coordinates to better handle its open boundary conditions and thus has a different domain setting than the WRF model. The parameterization of the WRF-ROMS coupled model is listed in supporting information S1.

We conduct two sets of ten-member ensemble experiments with the WRF-ROMS coupled model, which can facilitate the acquisition of robust numerical simulations. The first set of ensemble experiments is the control simulation (CTRL) in which we have tried to reproduce the temporal and spatial evolution of the ‘21/7’ extreme precipitation over the Henan region as accurately as possible. The second is a sensitivity experiment removing TIF’s impacts (NoTC). The NoTC uses the same WRF setting as CTRL, except that TIF’s vortex is removed from the initial condition by applying a TC-removing scheme documented by Davis and Low-Nam (2001), consequently, no TIF impacts are included during the NoTC integration. The TC removal scheme employed in this study is shown in figure S1 and detailed information on the removal process of In-Fa’s vortex is provided in supplementary materials.

The WRF model was forced by National Centers for Environmental Prediction Global Data Assimilation System reanalysis. And the initial and lateral boundary conditions of the ROMS model are derived from the HYbrid Coordinate Ocean Model reanalysis. The WRF-ROMS coupled model was integrated for 4 d from 0000 UTC 18 July to 0000 22 July 2021. The ensemble mean of simulated results is applied to investigate the contribution of TIF on ‘21/7’ Henan torrential rainfall. Simulated results show that the WRF-ROMS coupled model can simulate In-Fa’s track and intensity better than the atmospheric model alone (figures 1(b), (c) and S2, S3), and the ensemble mean can successfully capture the distribution of precipitation extremes than individual ensemble numbers (figure S4 and S5).

2.3. Water vapor budget method

We develop a water vapor budget method based on Fritz and Wang (2014) to analyze the extreme rainfall over Henan:

\[
\frac{\partial Q_v}{\partial t} = V_1 \cdot \nabla Q_v + Q_{v,ADV} + Q_{v,PBL}
\]

where \( Q_v \) is the water vapor mixing ratio, \( V_1 \) is the 3-dimensional wind vector, and \( \nabla \) is the gradient operator. The term on the left-hand side of equation (1) is the water vapor local change rate or tendency \( Q_{v,ten} \). The three terms, in sequence, on the right-hand side of equation (1) are the moisture advection \( Q_{v,ADV} \), the net water vapor change due to cloud processes \( Q_{v,DIA} \) in which the positive value means condensation and deposition exceeding evaporation and sublimation, and the water vapor change induced by the planetary boundary layer (PBL) process \( Q_{v,PBL} \), respectively. \( Q_{v,ADV} \), \( Q_{v,DIA} \), and \( Q_{v,PBL} \) are output directly from the WRF model, while other terms in equation (1) are derived from the WRF model outputs.

3. Results and discussion

3.1. Model performance in reproducing ‘21/7’ Henan extreme rainfall

The CTRL is used to examine the coupled model performance in reproducing the ‘21/7’ extreme rainfall and associated atmospheric circulation. Since TC’s track and intensity play a crucial role in the TRPE distribution over land (Chen and Wu 2016), we first verify the modeled TIF utilizing the CMA and IBTrACS best track data. The WRF-ROMS coupled model generally reproduces TIF’s track and intensity in CTRL (figures 1(b)–(d)). While modeled TIF is slightly stronger (figures 1(c) and (d)), the trends of the simulated storm’s central minimal pressure and the maximal 10 m wind speed (Vmax) are consistent with the observations during 20–21 July. In addition, the bifurcation of the simulated TIF in the ten ensembles grows with time, e.g. the stand deviation of TIF’s central pressure (maximal 10 m wind) reaches its maximum of 8.1 hPa (8.4 m s\(^{-1}\)) at 0000 22 July (figure 2). Meanwhile, the stand deviation of the simulated rainfall over Henan also grows with time and reaches its maximum of 0.46 mm h\(^{-1}\) in CTRL and 0.51 mm h\(^{-1}\) in NoTC at 0000 22 July (figure 2(g)). The synchronous bifurcation growth in TIF’s intensity and rainfall over Henan implies that TIF may be one of the causes of the rapidly developed rainfall over Henan. The relationship between TIF and the ‘21/7’ torrential precipitation in Henan will be further explored in the following sections.

The model performance in reproducing the ‘21/7’ rainfall is further verified using the IMERG precipitation observation and ERA5 reanalysis data (figure 2). The CTRL in general reproduces the distribution and amount of hourly rain rate compared with the IMERG observation over Henan at 0000 UTC 20 July (figures 2(a) and (b)). The model captures the maximum amount of the rain rate over Henan, although the location of the extremely large rainfall region moves slightly to the south. For moisture transport, the model replicates ERA5’s spatial pattern of water vapor transport and the wind fields at the 850 hPa
3.2. TIF’s role in the ‘21/7’ torrential rainfall

Based on the IMERG observation, the largest accumulated rainfall amount from 18 to 21 July occurs over Henan. Meanwhile, heavy precipitation in TIF’s eyewall, as well as both inner and outer spiral rainbands produced by TIF, are found over the WNP (figure 2(a)). The spatial pattern of atmospheric water vapor transport is consistent with observed precipitation (figures 2(a) and (d)), with more rainfall over central-eastern China primarily located over Henan and the largest moisture fluxes situated over the WNP. It further shows that the low-level (850 hPa) water vapor supplementing and enriching the moisture-laden environment over Henan originated from the north Indian Ocean (NIO; figures 2(d) and (e)). The moisture fluxes that originated from the NIO were first transported into the WNP by the large-scale southwesterly flow. Over the WNP, TIF’s outer circulations are obstructed by WPSH near 30° N and alter the direction of water vapor transport from northeastward to northwestward (figures 2(b) and (e)). Eventually, enhanced water vapor transported

(figure 2(e)), with the largest horizontal moisture fluxes located over the WNP and Henan (figures 2(d) and (e)). The CTRL can generally replicate the temporal variations in precipitation with a maximal rain rate of 2 mm h⁻¹ at 0600 UTC 20 July, the same time as the IMERG observation (figure 2(g)). More importantly, the simulated rainfall in CTRL has a smaller RMSE of 0.42 mm h⁻¹ and a better correlation of 0.73 (P < 0.01) with IMERG observation, compared to that in NoTC with an RMSE of 0.58 mm h⁻¹ and a correlation of 0.47 (P = 0.06).
from WNP and NIO to Henan and the adjacent areas was ensured (figures 2(b) and (e)), providing a more moist environment that is conducive to the occurrences of extreme precipitation (figure 2(g)). Another Typhoon Cempaka located over the southeast coast of China may transport a portion of water vapor to Henan (Ran et al 2021). We also conduct the numerical simulations to separate the weak TC Cempaka and find that Cempaka plays a subtle role in the TIF’s circulations and the atmospheric conditions around the Henan regions, thereby having an insignificant impact on Henan ‘21/7’ torrential rainfall (figure S6). Therefore, we principally focus on the remote contribution of TIF to ‘21/7’ torrential rainfall in Henan in this study.

To highlight the impacts of TIF on TRPE over Henan, we have performed a sensitivity experiment (NoTC) in which the TIF’s effect is removed by zeroing out TIF’s vortex in the WRF model’s initial condition. While the TIF’s features (eyewall and outer spiral rainbands) do not appear in NoTC (figure 2(c)) other environmental circulations, including maximum and average wind speed, are generally coincident with those in CTRL (figure S7), indicating that TIF’s effects are successfully removed. The experiment indicates that the intense accumulated rainfall over Henan approximately disappears in NoTC (figure 2(c)). Given that the summer heavy rainfall bands over East Asia are roughly distributed along the front of WPSH (Kusunoki and Arakawa 2015, Gao et al 2016, Yin et al 2019), the extreme precipitation events are principally concentrated over the Korean Peninsula in the absence of the effects of TIF, coinciding with the distribution of the WPSH front (5880 m geopotential height contour).

The time series of area-averaged precipitation rate over Henan (rectangle box in figure 2) during 18–22 July reconfirms TIF’s role in the ‘21/7’ rainfall (figure 2(g)). The CTRL and NoTC have nearly the same rainfall variations before the TIF enhances on 19 July, while the precipitation rate in CTRL increases rapidly after 19 July when TIF becomes a strong
3. Typhoon. But the precipitation rate in NoTC is small and negligible during the period of 0000 UTC 19 July to 0000 UTC 21 July, with a relatively larger spread of ten ensemble numbers during the period of heaviest rainfall events. One striking feature in NoTC is that the moisture fluxes are advected to Korean Peninsula by southeasterly and southerly winds, with little water vapor transported to Henan (figure 2(f)), consequently, a small amount of rainfall occurs there (figure 2(c)). These changes suggest that the dominating water vapor transport path in NoTC is substantially different from that in CTRL.

3.3. Quantification of the TIF’s contribution
We further carried out a water vapor budget analysis in this subsection to quantify the TIF’s role in the ‘21/7’ extreme rainfall event. The remarkable differences in area-averaged water vapor over Henan (rectangle region in figure 2) between CTRL and NoTC exist during 19–21 July (figure 3(a)). Before 19 July, there exists not much difference in water vapor content between CTRL and NoTC. On 19 July, excessive water vapor is transported to Henan by TIF in CTRL after the TIF intensifies and gets close to the WPSH (figure 2(e)). CTRL has more moisture than NoTC by 5 kg m$^{-2}$ during 19–21 July (figure 3(a)). The highly moistened environment facilitates a fast transition of a large amount of water vapor into precipitation extremes (figure 2(g)), consistent with the decreases in water vapor for both CTRL and NoTC during 19–21 July (figure 3(a)). Meanwhile, the liquid phase cloud (cloud and rain; hereafter referred to as cloud water), which is associated with the microphysical process of precipitation, increases greatly in the period of torrential rainfall in CTRL (figure 3(b)). But in NoTC, it has much less cloud water over the Henan region during 19–21 July (figure 3(b)), which is attributed to the fact that no adequate moisture is transported by TIF from WNP (figure 2(f)).
Figure 4. Quantitative changes in $Q_{v,ADV}$, $Q_{v,DIA}$, $Q_{v,PBL}$, and $Q_{v,TEN}$ over Henan (box region in figures 2(a)–(f)) in CTRL (a) and NoTC (b) during 0000 UTC 19 July to 0000 UTC 21 July. The model results denote the ensemble mean of the seven members.

Water vapor budget analysis demonstrates that water vapor flux ($Q_{v,ADV}$) in CTRL increases from 18 July and peaks with a maximal value of 4 kg m$^{-3}$ h$^{-1}$ at 0200 UTC 20 July, 3 h before the record-breaking rainfall occurs in CTRL (figure 3(c)), but much small $Q_{v,ADV}$ of 2 kg m$^{-3}$ h$^{-1}$ appears in NoTC (figure 3(d)). Of particular importance is that the positive variations of $Q_{v,ADV}$ are coincident with the negative $Q_{v,DIA}$ variations in both CTRL and NoTC (figures 3(c) and (d)), where negative $Q_{v,DIA}$ represents water vapor transforming into cloud water in the atmosphere. The counteraction relation between $Q_{v,ADV}$ and $Q_{v,DIA}$ in both CTRL and NoTC indicates that the excessively accumulated water vapor transported into Henan during 19–21 July can immediately turn into cloud water, and thereby the abundance of liquid water over a sloped region (Taihang mountain) quickly collides and forms torrential rainfall (figures 3(c) and (d)).

Dynamically, the southwesterly airflow of the Huanghuai cyclone and the southeasterly airflow between WPSH and TIF anchor firm control over Henan and the adjacent areas, providing abundant moisture fluxes therein, which further converge and uplift on the windward slopes of the Mount Song and Taihang Mountains (figure S8), resulting in torrential precipitation extremes falling over a longer duration. Moreover, a high rate of water vapor consumption in the rainfall system supplies favorable conditions for the occurrences of extreme precipitation events in Henan. While the local evapotranspiration ($Q_{v,PBL}$) is small and does not show significant differences between CTRL and NoTC, suggesting that $Q_{v,PBL}$ plays a minor role in the occurrence of record-breaking rainfall over Henan (figures 3(c) and (d)).

The aforementioned analyses suggest that the occurrences of the torrential rainfall over Henan during 19–21 July are principally attributable to the excessive moisture, which is transported by TIF from WNP. We further calculate the proportion of each component of the water vapor budget for quantifying the contribution of TIF to the precipitation extremes.
using the budget terms shown in figures 3(d) and (e). As evident in figure 4(a), the amount of moisture flux \( Q_{v,ADV} \) into Henan in CTRL during 19–21 July is 110.24 ± 16.95 kg m\(^{-3}\), accounting for 96% of the \( Q_{v,DIA} \) change, this is much larger than the PBL effect \( Q_{v,PBL} \) of 6.06 ± 0.35 kg m\(^{-3}\) (5%) and the local moisture change \( Q_{v,Ten} \) of −1.28 ± 6.05 kg m\(^{-3}\) (−1%). But in NoTC, because less water vapor was transported into Henan from NWP, a smaller \( Q_{v,ADV} \) of 53.57 ± 20.56 kg m\(^{-3}\) only accounts for 87% of the \( Q_{v,DIA} \) change in NoTC (figure 4(b)). Correspondingly, \( Q_{v,PBL} \) and \( Q_{v,Ten} \) contribute to 6.61 ± 0.47 kg m\(^{-3}\) (11%) and 1.25 ± 5.73 kg m\(^{-3}\) (2%) of the \( Q_{v,DIA} \) changes in NoTC, respectively (figure 4(b)).

Interestingly, although CTRL has much more intense precipitation of 60.69 ± 11.54 kg m\(^{-3}\) than that in NoTC of 35.22 ± 15.24 kg m\(^{-3}\) during 19–21 July (figures 4(a) and (b)), CTRL and NoTC have a similar rainfall efficiency (the ratio of the precipitation rate to cloud water conversion rate (i.e. \( P / \Delta Q_{v,DIA} \)), where \( P \) is the precipitation rate) of 58% (60.69 kg m\(^{-3}\)) in CTRL and 57% (53.57 kg m\(^{-3}\)) in NoTC, respectively. This may be due to CTRL and NoTC having similar local conditions over Henan, where the local weather systems produce favorable conditions for the occurrence and development of record-breaking rainfall events (Ran et al 2021, Yin et al 2022). The large-scale circulations derived from TIF’s effects contribute roughly 96% of moisture fluxes transmitted from outside Henan, together with a 58% cloud water conversion rate caused by local precipitation conditions, resulting in the ‘21/7’ torrential rainfall over Henan in the context of the interactions between TIF and local weather systems. Based on the budget analysis above, the contribution of TIF to the torrential rainfall during 19–21 July over Henan is approximately 42% (60.69 kg m\(^{-3}\) − 35.22 kg m\(^{-3}\)) / 60.69 kg m\(^{-3}\).

Based on five TC datasets, Park et al (2014) revealed that the threat of intense TCs to East Asian coasts increased during 1977–2010. With extended time series over the world, Wang and Touni (2021) demonstrated that the distance of TC maximum intensity to coasts has decreased by approximately 30 km per decade. These results suggest that the frequency of TRPE is expected to increase over East Asia, and the contribution of TCs to TRPE may be strengthened.

4. Summary

This study has investigated the remote effects of TIF on the torrential rainfall extremes over Henan during 18–22 July 2021 and further quantified the TIF’s contribution to the record-breaking ‘21/7’ precipitation by utilizing the cloud-resolving WRF-ROMS coupled model with ten-member ensembles.

The CTRL reasonably captures the space-time characteristics of the strengthened rainfall over Henan and major atmospheric circulation features associated with the TIF and WPSH. For example, TIF is blocked by the WPSH when it carries a lot of moisture fluxes and moves northwestward after its formation on 18 July over the WNP. The water vapor is transported southeasterly by the combined actions of TIF and WPSH along their confluence front near 30°N. Thus, more water vapor accumulates over Henan with the persistent water vapor transport induced by TIF from WNP, providing a conducive condition for the occurrence of precipitation extremes in Henan. Without the TIF effects (NoTC), the southeasterly moisture transport path is turned northward and advect water vapor to the Korean Peninsula, where severe rainfall occurs along the frontier of WPSH, instead of precipitating in Henan.

The water vapor budget shows that the proportion of extraneous moisture fluxes (\( Q_{v,DIA} \)) over Henan is much larger (approximately 96%) than the local evapotranspiration (about 5%) in CTRL. With the abundant moisture fluxes accumulating over Henan after 19 July, the water vapor immediately transforms to cloud, furthermore, about 58% of \( Q_{v,DIA} \) transforms to rainfall over Henan. Therefore, the persistent transportation of water vapor by TIF from WNP results in the occurrence of torrential rainfall. Particularly, NoTC does not have sufficient water vapor to cause precipitation extremes over Henan, even though the amount of water vapor transported into Henan (53.57 ± 20.56 kg m\(^{-3}\)) is comparable with \( Q_{v,PBL} \) (6.61 ± 0.47 kg m\(^{-3}\)) and \( Q_{v,Ten} \) (1.25 ± 5.73 kg m\(^{-3}\)). Simulated results indicate that the record-breaking ‘21/7’ rainfall during 19–21 July is mainly attributable to the excessive water vapor advected by TIF, together with the obstruction of the WPSH near 30°N. For the first time, we have quantified a contribution of ~42% from TIF to the catastrophic ‘21/7’ rainfall event and this contribution might be underestimated based on the conventional diagnostic analysis of the atmospheric circulations.

While WRF-ROMS coupled model reproduces the total rainfall caused by TIF reasonably well, it should be noted that there is still bias in the precipitation extremes partly related to the poleward shift of TIF’s track in the CTRL experiment after 1200 UTC 20 July (figures 1(b) and (g)), since the emergence of TCs can result in multiple magnitudes of precipitation intensity along the TC paths (Peduzzi et al 2012, Khouakhi et al 2017).

This study primarily focuses on TIF’s remote contribution to the extreme precipitation events in Henan, we also examined the impacts of the WPSH on the water vapor transport to Henan, the related atmospheric circulations such as short-wave trough and vorticity as well as their interactions with topography (Ran et al 2021, Yin et al 2022) and urbanization (Zhang et al 2018b), which is beyond the scope of this study and will be conducted in our parallel works. Given the massive joint influences of
the TIF and WPSH on TRPEs over Henan in 2021, plenty of regional TRPEs over East Asia occurred in the context of different non-landfalling TC-WPSH setups during past decades (Wang et al 2009, Ding et al 2017). Thus, longer-lead time and more accurate forecasts of regional TRPEs associated with specific non-landfalling TC-WPSH setup, as well as the development of proactive disaster-preparedness measures, are urgently needed. Our results provide not only insights into understanding the TRPEs, but also an analysis and modeling framework for similar analyses of TRPEs. Examining all non-landfalling typhoon-WPSH setups that led to regional precipitation extremes in historical data is beyond the scope of this work, which will included in our forthcoming studies.

Data availability statements

The WRF model is available at www2.mmm.ucar.edu/wrf/users/, and the ROMS model is avail at www.myroms.org/. Several data sources were used in this study: GDAS data from https://rda.ucar.edu/datasets/ds083.3/; IBTrACS best track data from www.ncdc.noaa.gov/ibtracs/; the CMA best track data from https://tdata.typhoon.org.cn/zj/lsjz_zljq.html; the ERA5 reanalysis data from www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5; and the GMP IMERG data from https://gpm.nasa.gov/data/imerg.

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