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Short Communication

Complex terrain causes global model prediction biases of 21.7 Zhengzhou extreme precipitation

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Extreme precipitation is one of the most severe weather of high socio-economic impact. In the warming climate, extreme precipitation has been shown to increase in both intensity and frequency over China and over the world [1–3]. On 20 July 2021, an extreme precipitation event hit Zhengzhou, a highly urbanized megacity with a dense population of 12.8 million in North China. The hourly rainfall rate was up to 201.9 mm, which broke the hourly record in mainland China. This unprecedented rainfall event caused severe flooding in Zhengzhou, resulting in 380 casualties and huge economic losses of over 100 billion RMB [4]. While many advances have been made in the understanding and numerical prediction of extreme precipitation in recent decades, accurately predicting the location and intensity of extreme precipitation events remains challenging [5]. Understanding the reasons for poor predictive skills of such events is critical for improving numerical weather prediction (NWP) models and quantitative precipitation forecasting (QPFs) [6].

Leading global NWP models significantly underpredicted the extreme precipitation near Zhengzhou. The models of the European Centre for Medium-Range Weather Forecasts (ECMWF) and of the USA predicted the maximum 12 h precipitation as 120 and 110 mm, respectively, versus the observed 548 mm (Fig. 1a–c). More importantly, the models wrongly predicted the rainfall center to occur over the Taihang Mountains rather than in Zhengzhou, which hindered the disaster risk assessment and management of the government. Our earlier study [7] found that the mountain-blocking effects on the air flows played important roles in this extreme precipitation event. Inadequate treatment of the orography and its effects, including those of the orographically-forced gravity waves, could be an important reason for such forecast biases in global NWP models. We show in this study that the parameterized orographic gravity wave drag (OGWD) due to unresolved complex terrain [8] played an important role in forecasting the location and intensity of the extreme precipitation in Zhengzhou, China.

We produce three forecasts using the Model for Prediction Across Scales (MPAS) [9] covering the globe, with a horizontal resolution of 15 km, which is typical of mainstream global operational NWP models. The OGWD parameterization is turned off in the OGWD_OFF experiment but switched on in OGWD_ON. The third experiment OGWD_HALF is similar to OGWD_ON but with the magnitude of parameterized OGWD halved. This is to account for the uncertainties in the parameterization of OGWD [8,10]. Other model configurations can be found in Supplementary material (Text S1 online).

The MPAS model can well reproduce the amount of the 12-h rainfall (i.e., 604.8 mm) from 0000 UTC to 1200 UTC of 20 July 2021 in the OGWD_ON experiment (Fig. 1d), which is in good agreement with observation (548.1 mm). This 12-h rainfall is of particular interest because it accounts for approximately 88% of the 24-h rainfall. The location of the rainfall center is also captured which is located to the west of Zhengzhou City by ~80 km. In OGWD_HALF (Fig. 1e), the intensity of the extreme precipitation decreases to 368.4 mm, significantly less than the observation. Furthermore, the rainfall area tends to shift northwestward. The 50-mm rainband is oriented in the southeast-northwest direction, i.e., normal to the Taihang Mountains, which is also the case of

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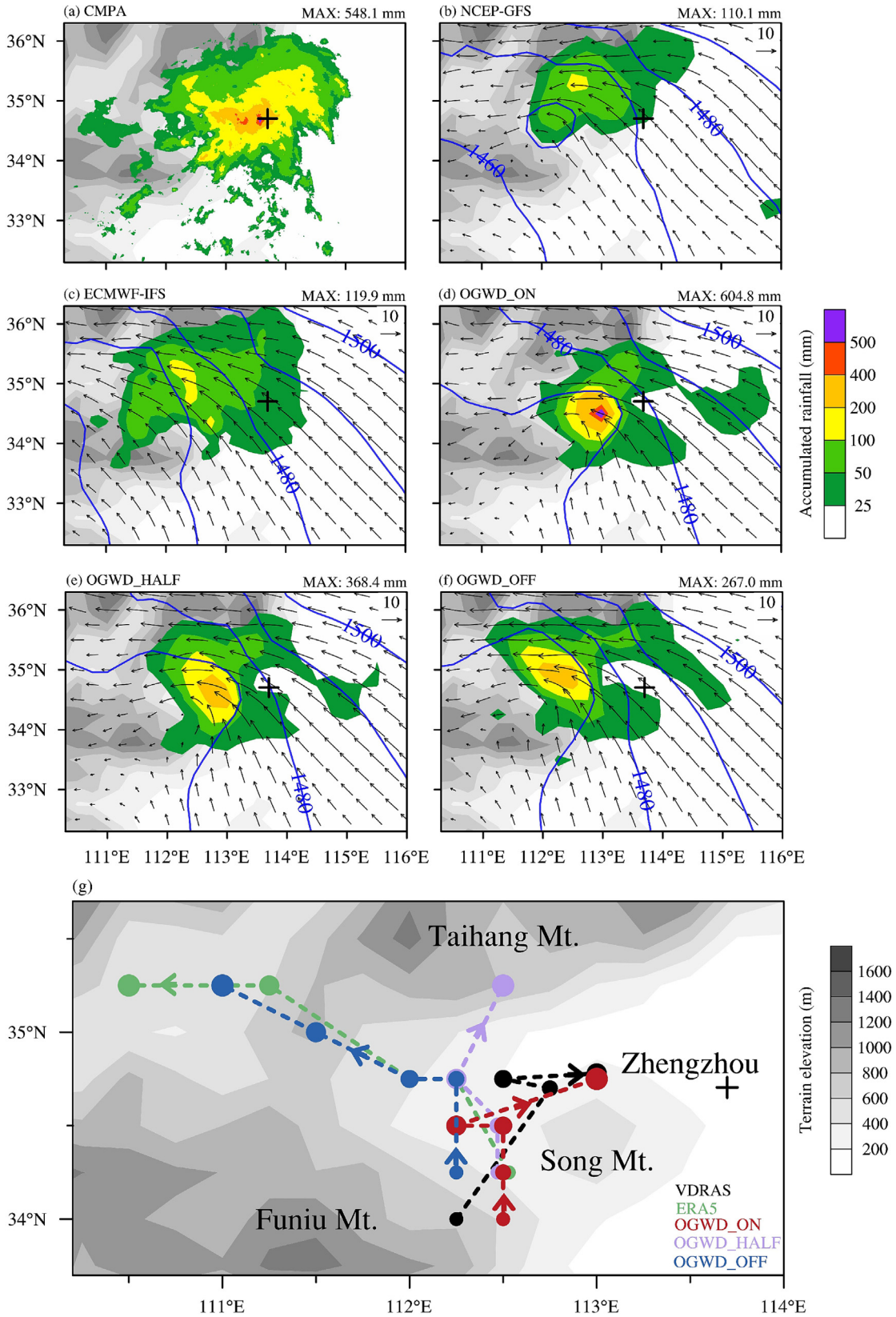

Fig. 1. Accumulated rainfall (color shading; unit: mm) from 0000 UTC to 1200 UTC on 20 July 2021 for (a) CMPA, (b) NCEP, (c) ECMWF, (d) OGWD_ON, (e) OGWD_HALF, (f) OGWD_OFF. Horizontal wind (vectors, units: m s^{-1}) and geopotential height (blue lines, unit: gpm) at 850 hPa are also shown in (b–f). (g) Track of low-level mesoscale vortex center during 0000–1200 UTC on 20 July 2021 in ERA5 reanalysis (green line), OGWD_ON (red line), OGWD_HALF (purple line), and OGWD_OFF (blue line). The vortex center is denoted by local maxima of 850-hPa relative vorticity. Also shown is the vortex track obtained from VDRAS analysis (black line) during 0000–0900 UTC on 20 July 2021, which is considered an observation. The VDRAS vortex center is denoted by the local maxima of relative vorticity at 3 km. The geographical location of Zhengzhou City is indicated by the cross, with the terrain height shaded in gray (unit: m).

the ECMWF forecast (Fig. 1c). Conversely, in OGWD_ON, the 50-mm rainband is parallel to the Taihang Mountains (Fig. 1d) as in observation. When the parameterization of OGWD is turned off (Fig. 1f), the extreme precipitation is more notably underestimated (with a maximum value of only 267.0 mm) and propagates further northwestward. These results suggest that both the intensity and location of the Zhengzhou extreme precipitation are significantly affected by the parameterized OGWD. The weakening of the OGWD leads to a decrease in the rainfall intensity and northwestward shift of the rainfall center, which resembles the forecast biases in operational global NWP models. This influence of OGWD is robust, confirmed by a series of sensitivity experiments with different configurations of model physics (Text S1, Table S1, and Figs. S1 and S2 online). Moreover, the OGWD parameterization scheme includes both the effects of gravity wave drag (GWD) and flow blocking drag (FBD). Additional sensitivity experiments of GWD_only and FBD_only reveal that the GWD is much stronger than the FBD, thereby playing a more important role in affecting the extreme rainfall event (Text S1a and Fig. S3 online).

The development of the Zhengzhou extreme precipitation has been found to be intimately related to a low-level mesoscale vortex and the associated moisture convergence [7,11,12]. Herein, the parameterized OGWD significantly affects the track of the simulated mesoscale vortex. According to the three-dimensional wind analysis obtained from the four-dimensional Variational Doppler Radar Analysis System (VDRAS) through assimilation of radar and surface observations [4,13], which is thus considered as ground truth, the vortex center was located at the eastern tip of the Funiu Mountains (southwest of Zhengzhou) at 0000 UTC of 20 July 2021 (Fig. 1g). The vortex, generally moved northeastward between the Funiu and Song Mountains, reaching the due west of Zhengzhou at 0900 UTC of 20 July 2021. The vortex center remained stationary between 0700 UTC and 0900 UTC of 20 July 2021, helping produce the record-breaking hourly rainfall of 201.9 mm [7]. In OGWD_ON, the MPAS model well captures the northeastward movement of the low-level mesoscale vortex, with its location being maintained to the east of the Taihang Mountains. In OGWD_OFF, the vortex firstly moves northward as in OGWD_ON, but shifts westward from about 0400 UTC and finally climbs over the Taihang Mountains. At 1200 UTC of 20 July 2021, the vortex center is more than 200 km away from Zhengzhou City. This northwestward track is similar to that in ERA5. The simulated vortex track in OGWD_HALF is between those simulated in OGWD_ON and OGWD_OFF, which firstly moves northwestward until encountering the Taihang Mountains at 0900 UTC, then turns to move northeastward, i.e., parallel to the terrain.

The differences in the low-level mesoscale vortex tracks can be attributed to the differences in the horizontal wind speeds. The mean horizontal winds at 850 hPa averaged between 0000 and 0600 UTC on 20 July 2021 in OGWD_ON and OGWD_OFF are shown in Fig. 2. This period is chosen because the simulated low-level vortex in OGWD_OFF is about to climb over the Taihang Mountains around 0600 UTC (Fig. 1g). In both the experiments, high winds are found to wrap cyclonically on the northern and northeastern flanks of the vortex. The largest wind speed is 18.1 m s^{-1} in OGWD_ON, which is 2.1 m s^{-1} weaker than in OGWD_OFF. Move evidently, the horizontal winds are decelerated by more than 9 m s^{-1} over the Taihang Mountains, where the terrain is much complex with remarkable OGWD (Fig. S4 online). [Indeed, in the 4-km-resolution WRF simulation conducted in our earlier study [7], there are also obvious gravity wave activities over the Taihang Mountains, accompanied by remarkable wave breaking (inferred from the turbulent kinetic energy, TKE) in the lower troposphere of this region (Fig. S5 online)]. The horizontal wind speed in OGWD_HALF is between those in the above two experiments (not shown). The faster low-level easterly flow in OGWD_OFF is able to move over the Taihang Mountains, rather than being blocked by it. Therefore, the heavy rainfall-producing vortex exhibits a westward-moving track, and the rainfall distribution shows a southeast-northwest pattern with the maximum located over the Taihang Mountains (Fig. 1e). Conversely, the decelerated flow in OGWD_ON cannot overrun the Taihang Mountains and is thus blocked. The blocking of the low-level flow is readily inferred from the non-dimensional Froude number of lower than unity [14] on the windward (i.e., eastern) slope of the Taihang Mountains (Text S2, Fig. S6 online). Consequently, the low-level mesoscale vortex moves slowly and remains east of the Taihang Mountains. According to the above analyses, the OGWD due to the small-scale complex terrain of the Taihang Mountains decelerates the low-level easterly flow, which subsequently enhances the blocking by the large terrain of the Taihang Mountains. Therefore, the synergy of multi-scale orography prevents the northwestward movement of the low-level mesoscale vortex in OGWD_ON. As OGWD is a subgrid-scale process that needs to be parameterized and flow blocking is explicitly resolved by the model, this reflects an important interaction between the model physics and dynamics.

Compared to the westward-travelling vortex in OGWD_OFF, the slowly-moving vortex in OGWD_ON is more efficient in focusing the low-level moisture within a local area, resulting in extreme precipitation. Indeed, the record-breaking hourly rainfall of 201.9 mm just occurred between 0800 and 0900 UTC on 20 July 2021 when the vortex is quasi-stationary. In OGWD_ON (Fig. 2c), large water vapor fluxes (WVFs) wrap cyclonically around the eastern and northern sides of the rainfall center which are confined to the east of the Taihang Mountains. In OGWD_OFF (Fig. 2d), large WVFs extend well northwestward to the Taihang Mountains, along with a larger magnitude owing to the faster horizontal winds (Fig. 2b). Nevertheless, the convergence of the WVFs is weaker than that in OGWD_ON, as revealed by the quantitative budget analysis (Text S3 online) of the WVF within a box encompassing the rainfall region.

The WVF mainly comes from the eastern boundary of the budget domain, which is about twice that from the southern boundary (Fig. 2e and f). In OGWD_ON, most of the moisture influx is retained in the rainfall area, with only about 28% exiting the western boundary. There is little moisture extrusion from the northern boundary, given the predominantly westward winds there, i.e., parallel to the northern boundary (Fig. 2a). In OGWD_OFF (Fig. 2f), there is a greater moisture influx through the eastern boundary, despite a slightly weaker influx through the southern one. However, the larger moisture influx is completely offset by the greater moisture extrusion through the western boundary, due to the stronger horizontal winds over the Taihang Mountains (Fig. 2b). In consequence, there is a reduction in the net moisture influx in the rainfall area. It explains why the extreme precipitation in OGWD_OFF is much weaker than that in OGWD_ON.

This study demonstrates that the parameterized OGWD due to fine-scale complex terrain can have very significant impacts on both the location and intensity of the simulated Zhengzhou extreme precipitation in global NWP models. The orographic drag acts to slow down the easterly winds over the Taihang Mountains and thus prevents the westward movement of the low-level mesoscale vortex, which enhances the moisture convergence and associated rainfall to the east of the Taihang Mountains. Similar orographic effects are also found for the well-known “75.8” Henan heavy rainfall event, i.e., the extreme rainfall that occurred in Zhumadian City, Henan during 5–7 August 1975 (not shown). It suggests a universal role of parameterized OGWD for the occurrence of heavy rainfall events in this region. However, accurate representation of OGWD and its interaction with the model dynamics is challenging and remains a large source of model uncertainties

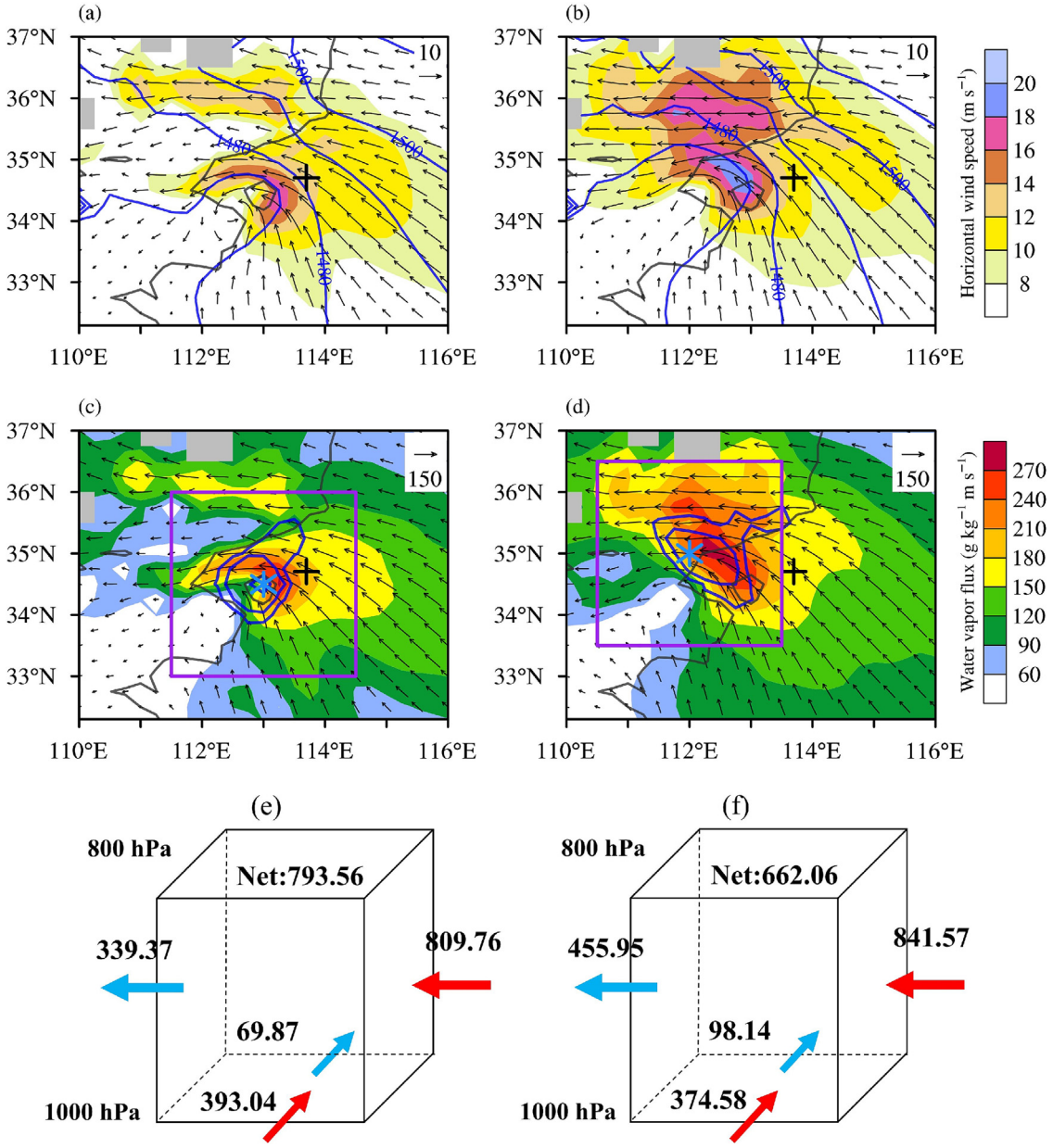

Fig. 2. Horizontal wind (vectors, units: m s^{-1}) and speed (shading, unit: m s^{-1}) and geopotential height (blue lines, units: gpm) at 850 hPa averaged between 0000 UTC and 0600 UTC on 20 July 2021 in (a) OGWD_ON and (b) OGWD_OFF. Gray line indicates the terrain elevation of 400 m, whereas the geographical location of Zhengzhou City is indicated by the black cross. Water vapor flux (vector, unit: g kg^{-1} m s^{-1}) and its magnitude (shading, unit: g kg^{-1} m s^{-1}) at 850 hPa averaged between 0000 UTC and 1200 UTC on 20 July 2021 in (c) OGWD_ON and (d) OGWD_OFF. Also shown is the accumulated precipitation contoured at 50, 100, and 400 mm, with the rainfall center denoted by blue asterisks. Budget of water vapor flux below 800 hPa (units: 10^5 kg s^{-1}) within a 3° × 3° box (purple box in (c) and (d)) centered at the maximum precipitation between 0000 UTC and 1200 UTC on 20 July 2021 in (e) OGWD_ON and (f) OGWD OFF.

[10]. To improve the forecasting skills of extreme precipitation in the warming climate, especially in complex terrain regions, a deeper understanding of the OGWD dynamics, more observations to constrain the parameterized OGWD in numerical models, and possible new technologies like machine learning to combine the two together are in high demand.

Conflict of interest

The authors declare that they have no conflict of interest.

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Author contributions

Peng Wei conceived the work, completed the data analysis, and wrote the draft. Xin Xu developed the concept of the study and revised and edited the draft. Qinghong Zhang provided the VDRAS analysis. Ming Xue, Jian Li, and Kun Zhao gave valuable comments and suggestions on the analyses and proofread the manuscript.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scib.2025.09.015.

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