Comparison of the Impacts of Topography and Urbanization on an Extreme Rainfall Event in the Hangzhou Bay Region

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Abstract The impacts of topography and urbanization on an extreme rainfall (ER) event in the Hangzhou Bay (HZB) region were investigated using the Weather Research and Forecasting model with one control simulation and three artificial scenarios of no-HZB, no-mountains on the south bank of HZB, and no-urban. Thirty members with different combinations of physical parameterizations were considered for each scenario. The control test results were evaluated and showed that the model well reproduced the ER that occurred in the HZB region, and the ensemble results were valuable and credible. The existence of HZB, mountains, and urbanization would increase the ensemble mean of accumulated precipitation by 52.07%, 37.11%, and 9.35%, and the probability of heavy rainfall by about 25%, 20%, and 15% in the main rain belt region, respectively. In addition, these factors also introduced more uncertainties in the same physical scheme combination. The impacts of these factors on the distribution, intensity, and mechanism were different. The comparison results showed that the existence of HZB played the most important role in this ER event by the remarkable influence of low-level wind field and horizontal convergence, followed by the existence of mountains, which mainly affected the distribution of rainfall caused by the airflow climbing up the hill before the mountain. Although urbanization exerted positive effects on this ER event, the impact was relatively small and locally near the urban regions compared with the other two factors.

Plain Language Summary The impacts of topography and urbanization on an extreme rainfall (ER) event in the Hangzhou Bay (HZB) region were investigated by ensemble forecast method. The control test results were evaluated and showed that the model reproduced the ER that occurred in the HZB region reasonably well, and the ensemble results were valuable and credible. The microphysics parameterization scheme exhibited the highest levels of uncertainty in this ER event, followed by the planetary boundary layer, land surface, and urban physics schemes. The comparison results showed that the existence of HZB, mountains, and urban would increase the ensemble mean of accumulated precipitation and the probability of heavy rainfall, and these factors also introduced more uncertainties in the same physical scheme combination. The existence of HZB played the most important role in this ER event by the remarkable influence of low-level wind field and horizontal convergence, followed by the existence of mountains, which mainly affected the distribution of rainfall caused by the airflow climbing up the hill before the mountain. Although urbanization exerted positive effects on this heavy rainfall, the impact was relatively small and locally near the urban regions compared with the two other factors.

1. Introduction

Extreme rainfall (ER) events always bring huge impacts and losses to human life, and their occurrence frequency has increased significantly in recent decades in East China (Jiang et al., 2020). Theoretical and observational evidence shows that global warming should be responsible for the more frequent occurrence of ER events (IPCC, 2021). The complex topography and urbanization are also important factors causing ER events by changing the dynamic and thermal effects in the land surface and planetary boundary layer processes (Chen et al., 2022; Goswami et al., 2010; Shastri et al., 2015; Wang et al., 2013; Yang et al., 2021; Yu & Liu, 2015).

Many previous studies indicated that orography and topography play important roles in forecasting heavy rainfall. Some examples include the presence of maximum vertical motion and heating rate caused by forced lifting above an upslope mountainous region play a key role in substantially increasing the total rainfall amounts (Wu et al., 2002); the slope and orientation of the local topography and the stability of approaching airflows determine where and when the ER occurs, the ER rate, and the related convective organizations (Xia & Zhang, 2019); and
the mountain-plain solenoid (MPS), alongside the sea-land breeze (SLB), leads to the diurnal variation and propagation of heavy rainfall along the coastline (Chen et al., 2016).

In addition, it is suggested that the rapid urbanization process also has a great impact on the regional environment, including the rainfall. The strong urban heat island (UHI) effect is caused by the cowarming of urban agglomerations (Wang et al., 2015). The resultant UHI circulation interacts with the SLB and MPS circulation to form a new complex circulation (Miao et al., 2015; Wan et al., 2015). The diversion effect of urban agglomeration (Yang et al., 2012) and the downstream propagation of the UHI signal can also change the distribution of precipitation (Wan et al., 2013, 2015). Both observation and model simulation indicates that rapid urbanization leads to an increase in the occurrence frequency and amount of summertime extreme hourly precipitation (Jiang et al., 2020; Zhong et al., 2017).

However, most studies focus on the individual impact of topography and urbanization on rainfall, and the comparison of relative contributions is still in the exploratory stage. Yu et al. (2018) found that the presence of cities cannot change the general state of topography-induced SLB and MPS circulations but slightly modify these local circulations. Huang et al. (2019) indicated that the synoptic weather pattern, topography, and cold pool played important roles in forming ER, while urban forcing only affected the timing and location of the rain core. Nevertheless, an opposite conclusion was reported by Yin et al. (2020); that is, although the impact was not as obvious as that of topography, the UHI effect still played an important role in forecasting ER. Considerable uncertainty remains in the study of the impacts of topography and urbanization on ER.

The Hangzhou Bay (HZB) region (29°–32°N, 119°–123°E), located in eastern China, on the south side of the Yangtze River Delta, is one of the most economically developed regions in China. Facing the East China Sea, the HZB region is frequently under the influence of the east wind system from the sea. It is affected by the complex geographical environment with the special topography of the bell mouth of HZB, plains on the north bank, and hills and mountains on the south bank of HZB. Moreover, the rapid urbanization process of the HZB region has been observed from the Defense Meteorological Satellite Program Operational Linescan System data (Yang, Hou & Chen, 2011) and resulted in a significant UHI phenomenon (Yang et al., 2015). Yang et al. (2019) emphasized that the interaction of urbanization and topography may be further amplified, and their combined effect have differed from various synoptic weather backgrounds. However, few studies have focused on the comparison of the impacts of topography and urbanization on ER forecast and its uncertainties.

Furthermore, the numerical weather prediction model is sensitive to the initial condition (Hamill & Colucci, 1997), boundary condition (Clark et al., 2011), and physical processes (Berner et al., 2011; Yu et al., 2018) because the atmosphere is a chaotic system. Some studies indicated that the sensitivity experiment result is not so reliable due to the uncertainties arising from the land use or topography changes (Fang et al., 2011; Wan et al., 2013; Yu et al., 2018). The ensemble approach is an effective way to solve this problem and analyze the uncertainties, as proved by many studies (Clark et al., 2009, 2011; Kain et al., 2013). Fang et al. (2011) found that the uncertainties in the perturbed initial state would be amplified by topography, and the forecasting of an event, such as Typhoon Morakot (2009), would benefit from probabilistic prediction. The urbanization-induced discrepancies obtained using the ensemble forecasting method passed the significance test, which improved the reliability of the results (Wan et al., 2015). Yu et al. (2018) also suggested that ensemble forecasting is valuable for investigating the impact of urbanization, and the ensemble mean analysis increased the significance of the spatial distribution of the impact of urbanization relative to an earlier case study. Benefiting from effectively filtering out some uncertain signals, the ensemble mean performs better than the individual members. Therefore, the ensemble method is used in our study to investigate the impacts of topography and urbanization on an ER in the HZB region.

The remainder of this paper is organized as follows. Section 2 gives an overview of an ER event, model configuration, and the numerical experiment design. The performance of ensemble forecast and the role of physical schemes in the result are analyzed in Section 3, with comparison of the impacts of topography and urbanization on rainfall. The paper ends with the presentation of our conclusions in Section 4.

2. Methodology

2.1. Overview of an ER Event

To investigate the influence and uncertainty of topography and urbanization in rainfall forecast, an ER event from 06:00 UTC on 18 August 2013 to 06:00 UTC on 19 August 2013 (the main precipitation period is from 13:00
UTC on 18 August 2013 to 01:00 UTC on 19 August 2013) that occurred in the HZB region was chosen for our simulations. This case was characterized by a deep easterly wave system on the south of the subtropical high, and a weak low vortex at 850 hPa got close to the eastern coast of Zhejiang Province, China, which induced a strong east wind with abundant water vapor from the East China Sea to the HZB region (Figure 1). The intense convective rainfall started around 13:00 UTC on 18 August 2013, and was organized in a mesoscale convective system (MCS) that moved westward from about 121.2°E/30.1°N to 119.7°E/30.6°N (Figure 2a). Most of the hourly heavy rain was attributed to the MCS. From 13:00 UTC on 18 August 2013 to 01:00 UTC on 19 August 2013, when the precipitation was the strongest, there were over 258 (32) stations with hourly precipitation records exceeding 30 (70) mm hr$^{-1}$ (Figure 2b). The surface rainfall amounts reached the maximum value of 117.3 mm in 1 hr and 341.3 mm in 24 hr at the Donghu Station in Shaoxing, Zhejiang Province. Figure 3 shows that the rain belt was...
mainly distributed in a northwest-to-southeast direction, and the precipitation was concentrated in Hangzhou, Shaoxing, and Shangyu. To facilitate the statistical analysis below, we defined this main rain belt as the RC region; the regions in the four directions of east, west, south, and north of RC were called RE, RW, RS, and RN regions, respectively; and the RT represented the whole region. A special line (A-B-C-D in Figure 3) is chosen for making a vertical section. Along this line, the underlying surfaces along the way are the ocean, the plain, the city, and the mountain, which is convenient for us to discuss the influence of the Hangzhou Bay, cities, and mountains on precipitation later. It is worth noting that the extreme precipitation center (>200 mm) occurred on the south bank of HZB, the northern foot of the Kuaiji Mountains, and within the urban areas of Shaoxing and Shangyu. Therefore, this case was suitable to study the impacts of topography and urbanization on extreme precipitation.

2.2. Model Configuration

The Weather Research and Forecasting (WRF; Skamarock et al., 2019) v4.0.2 (http://www2.mmm.ucar.edu/wrf/users) was applied with one-way-nested 4 and 1 km domains covering East China (with 403 × 353 grid points) and the HZB region (with 492 × 421 grid points), respectively (Figure 4a). The vertical grid contained 51 full sigma levels from the surface up to 10 hPa. About eight of these levels were below 1 km to provide a fine vertical resolution within the planetary boundary layer.

The WRF physics options fell into several categories, each containing numerous choices. Table 1 shows the model configuration and the options of the physical parameterization scheme used in our uncertainty study. No cumulus parameterization was used as recommended in the paper of Skamarock et al. (2019), given that the model can resolve the deep convective updrafts itself. The shortwave and longwave radiation schemes of the new rapid radiative transfer model (Iacono et al., 2008) were employed for the simulation. Three types of microphysics, that is, Purdue Lin (Chen & Sun, 2002), WSM6 (Hong & Lim, 2006), and Thompson (Thompson et al., 2008), three types of planetary boundary layer, that is, YSU (Hong et al., 2006), MYJ (Janjić, 1994; Mesinger, 1993), and Boulac (Bougeault & Lacarrere, 1989), two types of land surface, that is, Noah (Tewari et al., 2004) and NoahMP (Niu et al., 2011; Yang, Niu, et al., 2011), and two types of urban surface, that is, SLUCM (Chen et al., 2011) and BEP (Martilli et al., 2002) schemes were chosen for the physical parameterization perturbation study. These parameterization schemes can substantially affect the temperature and moisture profiles in the lower troposphere (Yu et al., 2018). The selected options have been confirmed by many studies to perform well on heavy rainfall simulation (e.g., Wang et al., 2013; Yang et al., 2021). Most of these physical schemes used were identical for the two nests.

The default Global Multi-resolution Terrain Elevation Data 2010 (GMTED2010, Danielson & Gesch, 2011) with a resolution of 30 arc s was chosen to generate the model terrain (Figure 4b). Meanwhile, an artificial model terrain map was derived by removing the mountainous terrain (i.e., Longmen, Kuaiji, and Siming Mountains in Figure 4b) on the south bank of HZB to investigate the effect of topography on rainfall forecast (Figure 4c). The default MODIS 20-category land use data based on the 1 km Moderate Resolution Imaging Spectroradiometer data obtained in 2004 was used in our study. In consideration of the rapid urban expansion, the updated urban land cover data at 1 km × 1 km resolution, conducted by Chen et al. (2014) was used. The urban land type was further classified into three subcategories.
based on the human settlement index and then combined with the default land use data (Figure 4d). To investigate the impacts of the urban effect and HZB on rainfall, two artificial land use maps also were designed by replacing the urban land use type with cropland (Figure 4e) and the water type in HZB with cropland (Figure 4f), respectively.

2.3. Numerical Experiment Design

Four groups of ensemble tests with 30 members in each group were conducted in our study. The 30 members were organized by different combinations of physical parameterizations in a single model. Each member was designed by selecting one option from each physical scheme group (Table 1) and named by the option numbers, for example, m2p1s2u1 represented that the Lin(2), YSU(1), Noah(2), and SLUCM(1) schemes were used in this member. The abbreviation CTL was used to represent the control ensemble test for the model evaluation and uncertainty analysis of the physical parameterization schemes on rainfall forecast. Three sensitivity tests (NoHZB, NoMT, and NoUB) were the same as the CTL test, but we replaced the water type in HZB with cropland, removed the mountainous terrain on the south bank of HZB, and replaced the urban land use type with cropland, respectively (Table 2).

All the simulations were initialized at 06 UTC on 18 August 2013, and integrated for 24 hr. The ERA5 hourly reanalysis data (Hersbach et al., 2018) with a resolution of 0.25° × 0.25° was used to provide the initial and lateral boundary conditions. No more data assimilation or nudging was performed to avoid the influence of other factors.

Observational data were obtained every 1 min from the AWS network (with 1,447 precipitation stations and 1,231 wind stations) that was operated by Zhejiang Meteorological Bureau, China Meteorological Administration. Hourly accumulated precipitation and hourly extreme maximal wind were derived from the minute-level observations, which were evaluated under extensive automated quality control. The hourly accumulated precipitation from the dense AWS network was then interpolated into the model grid by using the inverse distance weighted method. We tested eight interpolation methods, and the results were very similar (Xu et al., 2017). The insensitivity to interpolation approaches of fine-resolution data was also reported by Ikeda et al. (2010). Thus,
the gridded data were used in the quantitative evaluation of rainfall forecast, while the AWS data were used in the qualitative analysis of the weather situation.

3. Results

3.1. Evaluation of Ensemble Simulations

The CTL test has thirty members with different physical schemes, and its ensemble means of the simulated 24-hr precipitation (from 06:00 UTC 18 to 06:00 UTC 19 August 2013) was compared with the observation. Although
the rainfall magnitude was underestimated (in region RC) and a fake center was simulated on the coast line of Ningbo (in region RW), the general pattern of the northwest-to-southeast-orientated rain belt and the main rain drop near Shaoxing was captured (Figures 5a and 5b). Table 3 lists the threat scores (TS), biases (BIAS), root-mean-square errors (RMSE), and spatial correlation coefficients (SCC) of each member for different precipitation intensity levels. According to Table 3, the m2p8s4u2-run was the best member for this ER event, which had six metrics in the top five among all members, whereas the m8p2s4u1-run did the worst with the lowest scores. The best member simulated the precipitation quite well, whose rainfall center matched the observation, and the central maximum value reached 245.7 mm (Figure 5c). Although small precipitation was simulated in Shaoxing, the worst member greatly underestimated the precipitation and failed in reproducing the rain belt (Figure 5d). These results demonstrated the existence of significant uncertainties in rainfall simulation because of the different physical scheme configurations. The pattern of the accumulated precipitation spread (Figure 5e) was similar to that of the ensemble mean precipitation (Figure 5b), that is, the high value area of the spread was in the suburban area (in region RC), where the largest rainfall occurred (between the Shaoxing–Shangyu “urban line” and the Kuaiji Mountains). The heavy rainfall center (≥100 mm/24 hr) most probably occurred near Shaoxing (Figure 5f), which reflected the value and credibility of ensemble forecast (Buizza, 1997).

Table 1
Model Configurations

| Model settings | D01 | D02 |
|----------------|-----|-----|
| Model and version | WRF v4.0.2 |       |
| Horizontal grid points | 403 × 353 | 492 × 421 |
| Δx (km) | 4 | 1 |
| Vertical layers | 51 | |
| Cumulus physics | None (0)* | |
| Shortwave radiation | RRTMG (4) (Iacono et al., 2008) | |
| Longwave radiation | RRTMG (4) (Iacono et al., 2008) | |
| Microphysics | Purdue Lin (2) (Chen & Sun, 2002), WSM6 (6) (Hong & Lim, 2006), Thompson (8) (Thompson et al., 2008) | |
| PBL physics | YSU (1) (Hong et al., 2006), MYJ (2) (Janjić, 1994; Mesinger, 1993), BouLac (8) (Bougeault & Lacarrere, 1989) | |
| Land surface | Noah (2) (Tewari et al., 2004), NoahMP (4) (Niu et al., 2011; Yang, Niu, et al., 2011) | |
| Urban physics | SLUCM (1) (Chen et al., 2011), BEP (2) (Martilli et al., 2002) | |

*The numbers in parentheses represent the option number for each physical parameterization scheme.

Table 2
Summary of the Numerical Experiments

| WRF simulations | Physical parameterization options | Notes |
|-----------------|----------------------------------|-------|
| CTL             | Microphysics (Lin(2), WSM6(6), Thompson(8)) | 1. Choose one option from each physical group, and make up a member named by the option numbers, for example, m2p1s2u1 represents the Lin(2), YSU(1), Noah (2), and SLUCM(1) schemes are used in this member. |
|                 | Planetary Boundary layer (YSU(1), MYJ(2), BouLac(8)) | |
|                 | Land Surface (Noah(2), Noahmp(4)) | 2. 30 members are chosen for the numerical simulation since the YSU scheme cannot be used simultaneously with the BEP scheme. |
|                 | Urban Surface (SLUCM(1), BEP(2)) | |
| NoUB            | Same as CTL | Same as CTL, but replace the urban land use type with cropland (Figure 4e). |
| NoHZB           | Same as CTL | Same as CTL, but replace the water land use type in Hangzhou Bay with cropland (Figure 4f). |
| NoMT            | Same as CTL | Same as CTL, but remove the mountainous terrain on the south bank of Hangzhou Bay (Figure 4c). |
The observed composite reflectivity at 17:00 UTC 18 August 2013 is shown in Figure 6a. Although the serious false alarm in the coastal area (region RE) was objective existence, an ensemble probability of high composite reflectivity (≥40 dBZ) with its value greater than 70% was also found in region RC (Figure 6b), which indicated that the high composite reflectivity was successfully captured in most members, especially the best one (Figure 6c). Figure 6d shows the distribution of AWS stations with heavy rain (hourly precipitation ≥30 mm/hr) and strong wind (hourly extreme wind velocity ≥8 m/s). A small-scale vortex disturbance was observed near ground (Figure 6d), which could be found easily from the ensemble mean wind field at the lowest model level accompanied by the high value of ensemble probability of high convergence (≥10⁻³ s⁻¹) (Figure 6e). A large
value by more than $12 \times 10^{-4} \text{s}^{-1}$ of convergence was correspondingly found in that region in the best member (Figure 6f), which might be one of the most important factors causing this ER event. All these results demonstrated the reliability of the ensemble forecast.

Table 3

| CASES     | TS (≥0.1mm) | TS (≥10mm) | TS (≥25mm) | TS (≥50mm) | TS (≥100mm) | BIAS | RMSE | SCC |
|-----------|-------------|------------|------------|------------|-------------|------|------|-----|
| m2p2s2u1  | 0.86        | 0.55       | 0.37       | 0.26       | 0.14        | -7.05| 40.24| 0.45|
| m6p2s2u1  | 0.87        | 0.58       | 0.41       | 0.28       | 0.14        | -8.91| 36.72| 0.51|
| m8p2s2u1  | 0.88        | 0.49       | 0.28       | 0.12       | 0.00        | -12.93| 42.97| 0.26|
| m2p8s2u1  | 0.87        | 0.54       | 0.44       | 0.32       | 0.20        | -4.83| 35.44| 0.56|
| m6p8s2u1  | 0.88        | 0.55       | 0.44       | 0.30       | 0.21        | -7.52| 34.95| 0.58|
| m8p8s2u1  | 0.87        | 0.50       | 0.34       | 0.19       | 0.04        | -12.25| 38.28| 0.48|
| m2p1s2u1  | 0.86        | 0.56       | 0.39       | 0.30       | 0.29        | -4.65| 36.73| 0.55|
| m6p1s2u1  | 0.86        | 0.53       | 0.39       | 0.26       | 0.19        | -7.55| 37.78| 0.49|
| m8p1s2u1  | 0.87        | 0.54       | 0.33       | 0.19       | 0.02        | -11.04| 40.29| 0.40|
| m2p2s4u1  | 0.86        | 0.54       | 0.40       | 0.27       | 0.15        | -7.25| 39.08| 0.46|
| m6p2s4u1  | 0.87        | 0.54       | 0.34       | 0.18       | 0.03        | -10.24| 42.01| 0.31|
| m8p2s4u1  | 0.87        | 0.47       | 0.24       | 0.09       | 0.02        | -13.97| 44.24| 0.21|
| m2p8s4u1  | 0.87        | 0.55       | 0.44       | 0.31       | 0.13        | -6.66| 36.85| 0.51|
| m6p8s4u1  | 0.87        | 0.55       | 0.42       | 0.25       | 0.09        | -9.22| 36.48| 0.52|
| m8p8s4u1  | 0.88        | 0.51       | 0.36       | 0.19       | 0.10        | -11.93| 38.43| 0.47|
| m2p1s4u1  | 0.87        | 0.52       | 0.38       | 0.24       | 0.20        | -5.14| 40.36| 0.45|
| m6p1s4u1  | 0.86        | 0.54       | 0.37       | 0.22       | 0.14        | -7.65| 41.27| 0.40|
| m8p1s4u1  | 0.88        | 0.52       | 0.31       | 0.13       | 0.03        | -11.46| 42.74| 0.28|
| m2p2s2u2  | 0.87        | 0.56       | 0.40       | 0.29       | 0.22        | -5.88| 38.21| 0.50|
| m6p2s2u2  | 0.87        | 0.51       | 0.34       | 0.18       | 0.04        | -9.43| 42.30| 0.31|
| m8p2s2u2  | 0.89        | 0.47       | 0.29       | 0.13       | 0.01        | -12.40| 43.21| 0.27|
| m2p8s2u2  | 0.87        | 0.56       | 0.40       | 0.28       | 0.20        | -5.29| 36.30| 0.54|
| m6p8s2u2  | 0.87        | 0.55       | 0.41       | 0.30       | 0.16        | -7.57| 36.70| 0.52|
| m8p8s2u2  | 0.87        | 0.53       | 0.38       | 0.24       | 0.10        | -11.17| 36.05| 0.56|
| m2p2s4u2  | 0.88        | 0.53       | 0.40       | 0.26       | 0.19        | -7.29| 38.85| 0.48|
| m6p2s4u2  | 0.87        | 0.51       | 0.31       | 0.16       | 0.02        | -10.47| 43.67| 0.25|
| m8p2s4u2  | 0.89        | 0.49       | 0.36       | 0.14       | 0.02        | -13.36| 41.94| 0.33|
| m2p8s4u2  | 0.88        | 0.54       | 0.43       | 0.31       | 0.23        | -5.85| 35.39| 0.57|
| m6p8s4u2  | 0.86        | 0.54       | 0.44       | 0.25       | 0.13        | -9.32| 36.11| 0.54|
| m8p8s4u2  | 0.87        | 0.50       | 0.39       | 0.22       | 0.10        | -11.25| 37.04| 0.52|

*The colored grid points are the best five members, the darker the color, the higher the model performance. bTS = $\frac{N_s}{N_t}$, $N_s$ is the number of simulations that captured the observation and $N_t$ is the number of missing grids, $N_t$ is the number of total grids. cBIAS = $\frac{1}{N} \sum_{i=1}^{N} (X_i - Y_i)$, $X_i$ and $Y_i$ represents the variable in each grid from WRF model and observation, respectively. dRMSE = $\frac{1}{N} \sum_{i=1}^{N} (X_i - Y_i)^2$ eSCC = $\frac{\sum_{i=1}^{N} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{N} (X_i - \bar{X})^2} \sqrt{\sum_{i=1}^{N} (Y_i - \bar{Y})^2}}$
3.2. Impacts of Physical Schemes on Rainfall and Its Uncertainties

The choice of physical schemes can substantially affect the model performance on rainfall forecast. The 24-hr accumulated precipitation from 06:00 UTC 18 August 2013 to 06:00 UTC 19 August 2013 simulated by the 30 members and observed is listed in Figure 7. Most members reproduced the northwest-to-southeast ward of the rain belt (region RC) and overestimated the rainfall on the coast line (region RW), as also shown in the ensemble.
mean in Figure 5b. However, the differences between the individual members were obvious, especially on the south bank of HZB near Shaoxing-Shangyu, where the spread was large, as depicted in Figure 5e.

The TS, BIAS, RMSE, and SCC of each member classified following different physical schemes are drawn in the box-percentile plots (Esty & Banfield, 2003) in Figure 8. The larger scores in TS and SCC, the smaller scores in RMSE, and BIAS near zero, the better the model performance. The Lin (2) scheme/Boulac (8) scheme, which obtained the smallest BIAS and RMSE and the largest TS and SCC, achieved the best simulation effect among the three selected microphysics/PBL scheme options. The Noah (2)/SLUCM (1) scheme got similar scores compared to the Noahmp (4)/BEP (2) scheme. In general, the Lin+BouLac scheme did much better in precipitation simulation than other combinations, and the Lin + BouLac + Noahmp + BEP (m2p8s4u2-run) scheme was the best combination for this case. This result is consistent with the work of Wang et al. (2014), which suggested that the
performance of BouLac is better than that of the YSU scheme, given that the TKE-based local closure sustains the prestorm convective conditions better than the nonlocal YSU in summer.

The uncertainty of a physical scheme was evaluated by the divergence of each member’s average scores. For example, the mean value of TS (precipitation ≥0.1 mm, Figure 8c) was about 0.19, 0.12, and 0.04 for the Lin (2), WSM (6), and Thompson (8) schemes, respectively, whereas that was about 0.08, 0.14, and 0.15 for the MYJ (2), YSU (1), and Boulac (8) schemes, respectively. The variance of the mean value of TS in the microphysics group was much larger than that in the PBL group. That is, the microphysics scheme had a larger uncertainty and greater impact on this simulation than the PBL scheme in this ER event. A comparison of the differences in these scores of different options in each same physical scheme group indicated that the microphysics scheme had the highest levels of uncertainty on rainfall forecast in this ER event, followed by the PBL, land surface, and urban physics schemes.

The height of the “box” in the box-percentile plot represents the divergence of each member. The smaller the height, the less uncertainty of this physical scheme in the simulation. Thus, the uncertainty of the Lin and BouLac schemes was smaller than that of other schemes in the same physical scheme group, the Noah scheme was comparable to the Noahmp scheme, and the BEP scheme was slightly smaller than the SLUCM scheme. These physical schemes, especially the Lin and BouLac schemes, with low uncertainty were the ones that had a better performance on the precipitation simulation among each same physical scheme group. This finding demonstrated that these physical schemes were the key factors and had a greater impact on forecasting precipitation for this ER event.

Figure 8. Box-percentile plots of threat scores (TS, unitless) of different magnitudes: (a) ≥0.1 mm, (b) ≥50 mm, (c) ≥100 mm; (d) Bias (mm); (e) Root-mean-square error (RMSE, mm); (f) Spatial correlation coefficients (SCC) of the control tests for accumulated precipitation from 06:00 UTC 18 August 2013 to 06:00 UTC 19 August 2013. The black points in the middle of the irregular “box” represent the average value. The top/bottom point represents the maximum/minimum value, and the median, 25th, and 75th percentiles are marked with white line segments across the “box”. The width at any given height is proportional to the percentile of that height. The black dots beside the “box” represent each value. The detailed instructions of the box-percentile plot can be found in Esty and Banfield (2003).
In addition, the improvement of TS or BIAS brought by changing the microphysics scheme was more obvious than changing the other physical schemes, which indicated that the precipitation magnitude is more sensitive to the choice of microphysics process (or schemes) than to other processes (schemes). Meanwhile, the improvement of SCC brought by the improvement of the PBL scheme was more obvious than that of the other physical schemes, which indicated that PBL was more sensitive to the influence of the spatial distribution of precipitation.

3.3. Impacts of Topography and Urbanization on Rainfall and Its Uncertainties

The impacts of topography and urbanization on rainfall were evaluated by comparing the sensitivity tests (NoHZB, NoMT, and NoUB) with the CTL tests (Figure 9). To investigate the relative impacts of the existence of HZB, mountains, and urban on rainfall quantitatively, the difference in total precipitation in each region was calculated (Figure 10). The changes in total precipitation in the whole domain (region RT) were small in the CTL-NoMT tests (with an ensemble mean value of $-3.64 \times 10^3$ m$^3$ ($-0.18\%$)) and the CTL-NoUB tests (with an ensemble

![Figure 9](image-url)
mean value of $6.85 \times 10^3$ m$^3$ (0.34%), whereas those were increased obviously in the CTL-NoHZB tests (with an ensemble mean value of $92.79 \times 10^3$ m$^3$ (4.59%). This result indicated that the existence of HZB played a crucial role in the water vapor transport in the whole domain. The average total precipitation was increased by about $169.24 \times 10^3$ m$^3$ (52.07%), $120.62 \times 10^3$ m$^3$ (37.11%), and $30.40 \times 10^3$ m$^3$ (9.35%) in region RC, whereas that was decreased by about $5.99 \times 10^3$ m$^3$ (2.82%), $89.08 \times 10^3$ m$^3$ (41.93%), and $40.32 \times 10^3$ m$^3$ (18.98%) in region RS when HZB, mountains, and urban were considered, respectively. The absence of HZB would prevent this ER event from happening in region RC. This finding suggested that the existence of HZB played the most important role in this ER event, followed by the mountains on the south bank of HZB that affected the rainfall distribution. Although urbanization had a positive contribution to this heavy rainfall, the impact was relatively small compared with the two other factors. The box height in CTL-NoUB tests was smaller than that in the other two tests, which indicated that the urban land introduced less uncertainties than HZB and the mountains on the south bank.

3.3.1. Impacts of HZB on Rainfall

The SLB caused by differential heating between land and large water bodies is a key factor for triggering convection and causing heavy rainfall (Chen et al., 2016; Simpson et al., 2008). The model failed in simulating the precipitation of this ER event in region RC when replacing the water type in HZB with cropland (Figure 9a). Figure 9d shows that the precipitation increased by more than 30 mm at the junction of sea and land in region RC due to the existence of HZB, which helps transport substantial water vapor from the East China Sea. The spread of precipitation also increased in region RC, but its magnitude was smaller than the increment in precipitation (Figure 9g). Meanwhile, the probability of extreme precipitation increased by about 25% (Figure 9j). These results indicated that more uncertainties were introduced by the existence of HZB, but the increase in extreme precipitation could be more confirmed. An obvious increase in vertical velocity was found in Figure 11a, which was most likely caused by the thermodynamic effect of the water body of HZB. Additional cyclonic circulation increment was also found, accompanied by the increase in convergence by about $1 \times 10^{-4}$ s$^{-1}$ in Figure 11b, which was the main reason for the increase in precipitation. Figure 12a shows the vertical section of differences in precipitation, relative humidity, vertical velocity, and horizontal wind velocity along the dash black line in Figure 3. The near-surface wind velocity increased significantly due to the existence of the water surface of HZB, whose surface roughness was smaller than that of the cropland. The increased northeasterly wind converged at the junction of sea and land, which is also shown in Figure 11b, and was accompanied by increased upward movement at a low altitude of roughly 0.5–4 km. Therefore, considerable water vapors could be continuously blowing to region RC from the sea and contributing to this ER event.

3.3.2. Impacts of the Mountains on the South Bank of HZB on Rainfall

In addition to the SLB, the presence of mountains are also supportive of the occurrence of extreme precipitation (Fang et al., 2011; Huang et al., 2019). A new rainfall belt can be found in region RS and extended to the Jinqu Basin in NoMT tests compared with the CTL tests (Figure 9b). Owing to the mountains on the south bank of
HZB, the precipitation increased in the windward slope of the Kuaiji Mountains in region RC and decreased in region RS. Thus, the rain belt moved significantly northward and retreated from the Jinqu Basin (Figure 9e). More uncertainties and probabilities (increased by about 20%) of extreme precipitation could be found in the windward slope of mountains in region RC (Figures 9h and 9k), which indicated that more ER events might occur in that region. The existence of the mountains caused the airflow to climb up the hill before the mountain (Figure 12b), associated with the increasing vertical velocity and convergence in region RC (Figures 11c and 11d).

3.3.3. Impacts of Urbanization on Rainfall

The ensemble mean of 24-hr accumulated precipitation from the NoUB tests and its difference with the CTL test are shown in Figures 9c and 9f. The changes in precipitation suggested that the impact of urbanization...
The spread of precipitation increased by about 15% in this region (Figure 9i), which indicated that urbanization introduced more uncertainties in the same physical scheme combination. The rainfall event was concentrated in the urban regions near Shaoxing in region RC and led to the precipitation increase by about 18 mm. The spread of precipitation increased by about 15% in this region (Figure 9i), which indicated that urbanization introduced more uncertainties in the same physical scheme combination. The

Figure 12. Vertical section along the dash black line shown in Figure 3 of the differences in relative humidity (shaded, %), vertical velocity (blue contour, solid/dash represents positive/negative values, m/s), and horizontal wind velocity (red contour, solid/dash represents positive/negative values, m/s) between the control tests (CTL) and (a, b) NoHZB, (c, d) NoMT, and (e, f) NoUB tests. The differences in accumulated precipitation are shown below each subplot. The water/urban land use grids are indicated by the blue/yellow rectangle below the x-axis.
increased precipitation probability in region RC also indicated that urbanization would increase the likelihood of the occurrence of intense rainfall (Figure 9). The conclusion that urbanization will lead to more precipitation is consistent with the previous research findings (Huang et al., 2019; Yu et al., 2018), but the affected region was located in an urban area rather than the downwind of urban areas in other studies. The possible reason could be the different synoptic weather backgrounds, that is, a strong easterly wave in our study compared with the weak synoptic situations in other studies. The urbanization increased the vertical velocity (Figure 11e) and convergence (Figure 11f) that enhanced the low-level vortex near Shaoxing (Figures 6d and 6e) and then led to increased precipitation in region RC. Figure 12c shows that the vertical velocity and relative humidity increased above the urban and the upwind suburban area near HZB, which was likely caused by the UHI-induced circulation. The horizontal wind velocity decreased slightly due to the increase in surface roughness in the urban regions, which is consistent with previous works (He et al., 2019; Yu & Liu, 2015; Zhang et al., 2011).

4. Summary and Conclusions

In this work, the impacts of topography and urbanization on an ER event in the HZB region and its uncertainties were analyzed by a series of ensemble simulations with different physical parameterization schemes. The major results are summarized as follows.

First, results from the control simulations were evaluated using AWS observations and showed that the model reproduced the ER reasonably well, and the ensemble results were valuable and credible.

Second, the choice of physical schemes could substantially affect the model performance in rainfall forecast. In general, the Lin + BouLac scheme had significantly better performance in precipitation simulation than other combinations, and the Lin + BouLac + Noahmp + BEP (m2p8s4u2-run) scheme was the best combination for this case. The microphysics scheme had the highest levels of uncertainty on rainfall forecast in this ER event, followed by the PBL, land surface, and urban physics schemes, respectively. The microphysics was more sensitive to the influence of the magnitude of precipitation, while PBL was more sensitive to the influence of the spatial distribution of precipitation.

Third, the existence of HZB, mountains on the south bank of HZB, and urban increases the ensemble mean of accumulated precipitation in the main rain belt region by 52.07%, 37.11%, and 9.35%, and the probability of heavy rainfall by 25%, 20%, and 15%, respectively. In addition, these factors also introduced more uncertainties in the same physical scheme combination. The impact of HZB, mountains, and urbanization on this rainfall event was concentrated in the junction region of sea and land, on the windward slope of mountains, and in the urban regions near Shaoxing-Shangyu, respectively. The existence of HZB played the most important role in the ER event and total precipitation in the whole domain. The existence of mountains mainly affected the distribution of rainfall. Although urbanization had positive effects on this heavy rainfall, its impact was relatively small compared with the other two factors.

Finally, the water surface of HZB with smaller surface roughness increased the northeasterly wind. The horn mouth topography of HZB enhanced the flow convergence at the junction region of sea and land, accompanied by increased upward movement, which thus resulted in more precipitation there. The existence of mountains caused the airflow to climb up the hill before the mountains, associated with increased vertical velocity and convergence, which caused more rainfall in region RC. The urbanization introduced vertical velocity increase, accompanied by increased convergence that enhanced the low-level vortex near Shaoxing and then led to more precipitation.

These results suggested that the existence of HZB, mountains, and urban all had a nonnegligible impact on the ER event caused by easterly waves in the HZB area. In particular, the existence of the HZB and its effects on the synoptic system played a crucial role in the occurrence of heavy rainfall. In such cases, forecasters should assess the location and intensity of low-level convergence near HZB, the blocking and uplift of water vapor by the mountains on the south bank, and the impact of the UHI circulation on precipitation to predict such heavy rainfall events.

In this study, only the individual influences of HZB, mountains, and urbanization on the ER event were compared. The interaction of each factor will be further discussed in future studies. Moreover, only the uncertainty of the parameterization schemes was included in this study. Further investigations are needed to study the uncertainty of the initial conditions.
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