Possible hydrological effect of rainfall duration bias in dynamical downscaling

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Abstract:
Motivated by the problem of rainfall duration bias typically found in dynamical downscaling, its possible effect on hydrology was evaluated for heavy rainfall events over Kyushu, Japan, during summer. Heavy rainfall in western Kyushu is often related to a persistent Baiu rainband across Kyushu, while in eastern Kyushu it is related to the passage of typhoons near Kyushu. For typical heavy-rainfall periods, we ran a tank model for several target rivers to analyze runoff and water-depth sensitivity to the hyetograph by artificially extending the rainfall duration to 8 hours while maintaining the same total rainfall. This showed that a spike in peak runoff was suppressed by prolonged weak rainfall as typically found in downscaling outputs. The timing of rising runoff and water depth in the tank model was shifted earlier.

KEYWORDS rainfall duration bias; runoff; heavy rainfall events; weather pattern; dynamical downscaling

INTRODUCTION

Dynamical downscaling (DDS; Giorgi 1990), a powerful method to provide high-resolution meteorological data from coarse-resolution data with a regional atmospheric model (RAM), generally suffers from bias, especially in precipitation owing to smoothed surface height and incomplete physical parameterizations of clouds, convection, and turbulence (Ehret et al., 2012; Wang et al., 2004). The bias in precipitation can be classified into an amount and a duration. Quantile mapping (Piani et al., 2010a, b), often used in climate change adaptation research, can correct the probability distribution of rainfall intensity. However, it cannot correct a duration bias. Recently, Tamaki et al. (2018) suggested that the DDS tended to prolong heavy rainfall events in Kyushu, and the extent of this duration bias was closely related to synoptic weather patterns such as a persistent Baiu rainband across the island and the passage of a typhoon along the island.

If a hyetograph with a prolonged bias in rainfall duration were inputed into a hydrological model, the peaks in surface runoff and river-flow amount would be substantially underestimated. This is because the hydrological response strongly depends on the temporal variation of the precipitation over the river catchment area, mostly attributed to mesoscale phenomena such as storm movement (Kim and Seo, 2013; Sigaroodi and Chen, 2016) and sporadic convective cores (Syed et al., 2003). For example, when the intense convective line moves parallel to the direction of the convective line itself (Doswell et al., 1996) under a back-building type convective system (Schumacher and Johnson, 2005), an extreme flash flood is likely to occur due to torrential rainfall over a short period. Hence the hydrological response to a hyetograph with rainfall duration bias should be evaluated, and a caveat should be provided in hydrological estimations based on DDS data, particularly when assessing climate change problems. However, few studies have focused on this problem, despite the fact that the rainfall duration bias probably influences the risk evaluation of flash floods.

The purpose of this study is to evaluate a possible hydrological effect of rainfall duration bias as shown in Tamaki et al. (2018). Since the bias extent depends on synoptic weather patterns, we selected two typical heavy rainfall periods over Kyushu, Japan, in the summertime. One was the period 11–15 July 2012 when a persistent Baiu rainband occurred The other 12–16 July 2007 when strong cyclonic circulation occurred due to a typhoon over the East China Sea. These two periods are quite typical of heavy rainfall events in Kyushu that are closely related to synoptic weather patterns (See Fig. 5 of Tamaki et al. 2018). To clarify the effect of rainfall duration bias to runoff, we developed a new method to artificially extend rainfall duration while maintaining total rainfall. According to Tamaki et al. (2018), the ratio of average rainfall duration between dynamical downscaling data and observed data was 1.41 at the Shimouke dam site (site a in Fig. 1) under strong monsoon patterns, and 1.28 at Iwase dam site (site f in Fig. 1) under typhoon patterns (Fig. S1). In this study, the ratio of average rainfall duration between data with 8-hour extension runs and observed data was 1.53 at the Shimouke dam, and 1.29 at the Iwase dam (Fig. S1); these two values are...
thus almost the same as the average rainfall duration bias in Tamaki et al. (2018). Sensitivity experiments were then conducted with a tank model forced by hyetographs with 8-hour extensions.

DATA AND METHODS

We used the site-observed hourly rainfall (mm h$^{-1}$) with a rain gauge and the runoff (m$^3$ s$^{-1}$) data from eight dams over Kyushu (Fig. 1) that do not have any more dams upstream. The dam data at Ryumon, Yabakei and Kyuragi were downloaded from Water Information System (http://www1.river.go.jp) operated by Ministry of Land, Infrastructure, Transport, and Tourism (MLIT). The dam data at Shimouke, Houri, Iwase, Ayaminami and Tashirobe were provided by Prefectural Land Development Department, Miyazaki Prefectural Government. The river catchment area around each dam ranged from 26.5 to 354.0 km$^2$ (Fig. 1). We will focus on the results at Shimouke and Iwase dams for simplicity. We also used 6-hourly JRA-55 reanalysis data (Kobayashi et al., 2015) for a synoptic field analysis, and the Radar/Rain Gauge-Analyzed Precipitation (RA; Nagata 2011) for a precipitation field analysis.

Figure 2 illustrates the procedure to artificially extend the rainfall duration using any timeseries of hourly rainfall at a site. Here we define rainfall events as the period during which hourly rainfall continuously exceeds 0.1 mm h$^{-1}$, the minimum unit for the rain gauge. A heavy rainfall event is defined as a rainfall event in which the total rainfall amount exceeds 10 mm. We focus exclusively on heavy rainfall events. First, in an x-hour extension, a time stamp of rainfall data after the peak is offset by $+x/2$ hours and a time stamp before the peak is offset by $-x/2$ hours. Note that if an event overlaps another one in this extension process, the rainfall data in the overlapped period are replaced with an addition of shifted data from both events. Second, the rainfall data around the peak are compensated with a linear interpolation from peak to the shifted data. Finally, an artificial hyetograph ($R_p$ in Fig. 2) is obtained by uniformly scaling the processed data so as to maintain the total rainfall amount during the event.

We used the four stage-tank model (Sugawara, 1972, 1995) to estimate runoff (Fig. S2). The tanks were designated as tank0, tank1, tank2, and tank3 from top to bottom. Tank0 had two runoff holes and tank3 did not have an infiltration hole. The runoff component of tank0, ..., tank3 was physically regarded as surface/subsurface runoff, fast intermediate runoff, slow intermediate runoff, and base flow.

Figure 1. Geographic distribution of dam sites on Kyushu, zooming into the red solid box shown in the Japanese map in the inset. The catchment areas (km$^2$) and river systems are shown in the right.

| Name       | Area (km$^2$) | River system |
|------------|--------------|--------------|
| Shimouke dam | 185.0        | Chikugo      |
| Ryumon dam   | 26.5         | Kikuchi      |
| Yabakei dam  | 89.0         | Yamakuni     |
| Kyuragi dam  | 33.7         | Matsuichi    |
| Houri dam    | 45.2         | Gokase       |
| Iwase dam    | 354.0        | Oyodo        |
| Ayaminami dam| 87.0         | Oyodo        |
| Tashirobe dam| 131.5        | Oyodo        |

Figure 2. Illustration of the procedure to artificially extend rainfall duration. $R_o$ denotes the original rainfall intensity (mm h$^{-1}$) at a site, and $R'$ and $R_p$ respectively denote the intermediate and resultant data. Note that green and blue bars in $R_o$ is same as for those in $R'$.
respectively. This tank model had 4 parameters relating to initial water depths, 5 to runoff, 4 to outlet-hole heights, and 3 to infiltration. They were optimized with the L-BFGS-B algorithm (Byrd et al., 1995) for each site during a heavy rainfall case (Table SI). We have checked that the results shown below do not change with different parameter sets considered realistical (Figure S3 and Table SII). The tank model was forced by the observed control (CTR) hyetograph and the hyetograph in which the rainfall duration was extended by 8 hours (D8 hyetograph).

RESULTS

Event with a Baiu rainband and hydrology at Shimouke dam

During 11–15 July 2012 a persistent Baiu rainband, characterized by a strong meridional gradient of equivalent potential temperature in the East China Sea along with a low-level jet and warm and humid air, intruded into Kyushu with cumulative rainfall exceeding 450 mm in western Kyushu (Figs. 3a, b). The total rainfall during 11–15 July 2012 accompanied with the Baiu rainband across Kyushu was 530 mm at Shimouke dam (Figs. 3a, b). Figure 3c displays the observed runoff and the runoff simulated with the tank model forced by the CTR hyetograph at Shimouke dam during 11–15 July 2012. The CTR hyetograph showed three major peaks around \( t = 30 \), 60 and 80 and its hydrograph represents a rapid response with peaks of 250 m\(^3\) s\(^{-1}\) around \( t = 30 \), 500 m\(^3\) s\(^{-1}\) around \( t = 60 \), and 1,000 m\(^3\) s\(^{-1}\) around \( t = 80 \) (Fig. 3c). The tank model forced by this CTR hyetograph reproduced the observed hydrograph; the correlation coefficient between observation and simulation was 0.95. Similar to the CTR hydrograph response, the water depth response had three major peaks of 150 mm around \( t = 30 \), 200 mm around \( t = 60 \), and 300 mm around \( t = 80 \) (Fig. 3d).

The D8 hyetograph, given the typical DDS bias in Baiu rainband, shows that its sharp peaks are smoothed and the second and third rainfall event are connected due to rainfall duration bias (blue bars in Fig. 4c). The maximum rainfall intensity was reduced to about a half compared with the CTR hyetograph around \( t = 80 \) (Figs. 4b, c). The tank model forced by the D8 hyetograph also shows three runoff peaks around \( t = 30 \), 60 and 80 (Fig. 4a). The peak runoff was reduced to about 2/3 compared with the CTR runoff (Fig. 4a). The runoff amount just after the third major peak around \( t = 80 \) increased following the rainfall duration extending in D8 hyetograph (Fig. 4a). Moreover, a valley between the second and third runoff peaks around \( t = 70 \) found in the CTR runoff becomes obscure in the D8 runoff (Fig. 4a). The surface/subsurface runoff contribution decreased considerably and the runoff from tank0 and tank1 varied less with time (Figs. 4b, c). Since, in the D8 run, the second and third heavy rainfall events of the CTR hyetograph overlapped around \( t = 70 \) for an artificial extension (blue bars in Fig. 4b, c), the runoff of tank1 slowly ended around \( t = 65–70 \) and slowly restarted around \( t = 75–80 \) (Fig. 4c). The water depth response to the D8 hyetograph (Fig. 4d) also reduced the peak-to-peak difference of runoff around \( t = 50 \) and 70. The timing of the water level rise was earlier, owing to the smoothing of the CTR hyetograph (blue bars in Figs. 4e, f). It is noted that the tank model results at Ryumon, Yabakei, and Kyuragi dams, where heavy rainfall events were also observed accompanied with the Baiu rainband, were similar to the result at Shimouke dam shown here (Fig. S4).
Event with the typhoon approach and hydrology at Iwase dam

In the typhoon period, the cumulative rainfall exceeded 300 mm in eastern Kyushu with strong cyclonic circulation over the East China Sea (Figs. 5a, b). The total rainfall during 12–16 July 2007 accompanied with the typhoon approaching Kyushu was 352 mm at Iwase dam (Figs. 5a, b). Figure 5c displays the observed runoff and the runoff simulated with the tank model forced by the CTR hyetograph at Iwase dam during 12–16 July 2007. The CTR hyetograph shows a large rainfall event during $t = 40$ and $t = 70$ with major peaks around $t = 55$ (Fig. 5c) and a hydrograph with one peak spike exceeding 700 m$^3$s$^{-1}$ around $t = 60$ (Fig. 5c). The tank model forced by this CTR hyetograph sufficiently reproduced the observed hydrograph with a correlation coefficient of 0.89, though the peak of CTR hydrograph was slightly shifted earlier than the observed hydrograph (Fig. 5c). Similar to the CTR hydrograph response, the water depth in response to the CTR hyetograph had one major peak exceeding 250 mm around $t = 60$ (Fig. 5d).

The D8 hyetograph, given the typical DDS bias in typhoon, represents sharp smoothing of peaks due to the rainfall duration bias (blue bar in Fig. 6c). The major peaks in rainfall intensity in the D8 hyetograph were reduced to about 2/3 around $t = 55$ (blue bars in Figs. 6b, c), compared with the CTR hyetograph. The tank model forced by the D8 hyetograph shows a major runoff peak around $t = 64$ (Fig. 6a). The D8 peak runoff was limited to 73% of CTR runoff during major peaks (Fig. 6a). The timing of rising peaks was earlier and runoff increased with the D8 hyetographs (Fig. 6a), owing to the smoothing of the hyetograph (blue bars in Figs. 6b, c). The surface/subsurface runoff contribution considerably decreased and the runoff from tank0, and both tank0 and tank1 varied less with time (Figs. 6b, c). In terms of the response of water depth, the timing rising water was just before the major peaks around $t = 60$, i.e., earlier in the D8 run. This early water level rise also accounted for the smoothing of the CTR hyetograph (Figs. 6e, f). It is noted that the tank model results at Houri, Tashirobae, and Ayaminami dams, where heavy rainfall events were also observed accompanied with the typhoon approaching, were similar to the result at Iwase dam shown here (Fig. S5).

DISCUSSION

Effect of antecedent rainfall

Here we checked the effect of antecedent rainfall on runoff response. CTR and D8 runs were extended back to 2 July 2007 at Iwase dam with the same parameter set (Fig. S6). The major runoff peak in the CTR run was larger
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(Figs. S6a, 5c) because the runoff responded to the rainfall more quickly for the higher water depth due to the antecedent rainfall. On the other hand, the early start of the main peak did not substantially change (Figs. S6b, 6a). In terms of the response in water depth, the timing of the rise just before the major peak around \( t = 290 \) was slightly earlier, consistent with the original run (Fig. S6b). Therefore, the antecedent rainfall affected the runoff amount at the major peak but did not affect the timing of rising runoff and water depth.

Caveat in hydrological estimation

Our results shown here provide a caveat applicable to when one applies the DDS result for studies on climate change adaptation. Nakakita and Osakada (2018) and Osakada and Nakakita (2018) showed that the frequency of occurrence of heavy rainfall related to Baiu rainbands around Kyushu will significantly increase under future climates, on the basis of the DDS data with 5-km mesh and a large ensemble climate prediction dataset (d4PDF; Mizuta et al., 2017). In addition, heavy rainfall related to Baiu rainband is spatio-temporally localized under future climates (Nakakita and Osakada, 2018). This concentration trend for heavy rainfall events has also been found for northern Japan (Hoshino et al., 2018; Yamada et al., 2018). Therefore, rainfall duration bias, in addition to rainfall amount bias, must be considered for accurate evaluation of runoff and flood risk in the future. As raised in the Introduction, however, quantile mapping does not correct for rainfall duration bias. Our original method for making pseudo-hyetographs could be applied to the bias correction for rainfall duration. However, while our method for correction of rainfall duration can correct the average rainfall duration bias, it cannot perfectly reproduce the shape of the hyetograph itself.

Application to runoff forecast considering rainfall duration bias

In terms of disaster prevention, the methods highlighted in this study can be used towards runoff forecasting. Figure S7 shows the flowchart of forecasted runoff using a correction for rainfall duration bias. We first identify the synoptic pattern in the forecast period and correct the rainfall duration in the forecasted rainfall time series using mean rainfall duration bias maps derived by Tamaki et al. (2018). Next, using the corrected rainfall data, the runoff response is predicted using the tank model.

CONCLUSIONS

We have investigated the response of runoff and water depth to rainfall duration bias found in dynamical downscaling over Kyushu, Japan. We selected two heavy rainfall periods related to typical synoptic patterns, Baiu rainbands and typhoons. The results showed that a spike in the peak runoff was suppressed by prolonged weak rainfall as typically found in downscaling outputs. The timing of increasing runoff and water depth in the tank model was shifted earlier in response to a smoothed hyetograph. Our results suggest that the rainfall duration bias of DDS is a non-negligible factor for predicting river runoff and flood risk as part of climate change adaptation.

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SUPPLEMENTS

Figure S1. (a, b) The ratio of average rainfall duration between the dynamical downscaling data and observed data under both (a) strong monsoon and (b) typhoon patterns. The bottom table shows the ratio of average rainfall duration bias at eight dam sites (DDS/RA-S). The table also shows the rainfall duration bias of D8/CTR during 11–15 July 2012 with Baiu rainband case and 12–16 July 2007 with typhoon cases on 8 dam sites

Figure S2. Schematic diagram of four cascade tank model

Figure S3. (a, b) Same as Figs. 4a, 6a, but results with eleven different parameter sets shown in Table SII. (c, d) Same as Figs. 4d, 6d, but results with eleven different parameter sets shown in Table SII

Figure S4. (a–c) Runoff response (m$^3$ s$^{-1}$) to (red) CTR and (blue) D8 hyetographs at (a) Ryumon (b) Yabakei and (c) Kyuragi during 11–15 July 2012, (d–f) Same as (a–c), but for water-depth response (mm)

Figure S5. (a–c) Runoff response (m$^3$ s$^{-1}$) to (red) CTR and (blue) D8 hyetographs at (a) Houri (b) Tashirobae and (c) Ayaminami during 12–16 July 2007. (d–f) Same as (a–c), but for water-depth response (mm)

Figure S6. (a) Runoff response (m$^3$ s$^{-1}$) and (b) The water-depth response (mm) to (red) CTR and (blue) D8 hyetographs at Iwase dam during 2–16 July 2007

Figure S7. Flowchart for runoff forecasting using the bias correction of rainfall duration

Table SII. Eleven set of optimized parameters used in sensitivity test of parameters both Shimouke and Iwase-dam

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