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Sensitivity of quasi-stationary band-shaped precipitation system to topography:
A case study for 28 August 2008 Okazaki heavy rainfall event

Yoshinori Takasaki
Graduate School of Geo-Environmental Sciences, Rissho University, Kumagaya, Japan

Masanori Yoshizaki, Asuka Suzuki-Parker, and Yasushi Watarai
Faculty of Geo-Environmental Sciences, Rissho University, Kumagaya, Japan

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1) Corresponding author: Yoshinori Takasaki, Graduate School of Geo-Environmental Sciences, Rissho University, 1700 Magechi, Kumagaya, 360-0194, JAPAN.
E-mail: 139w00001@rissho-univ.jp
Abstract

The Okazaki heavy rainfall event, which occurred at midnight on 28 August 2008 around Okazaki city in Japan, was produced by a quasi-stationary band-shaped precipitation system. This precipitation system remained quasi-stationary for approximately 5 hours over Okazaki city and the surrounding area, and produced prolonged intense precipitation. This study presents sensitivity numerical experiments to examine the impact of surrounding mountainous topography on the quasi-stationarity of the precipitation system using the Weather Research and Forecasting (WRF) model with 500 m horizontal resolution. In an experiment without the mountains to the east of Okazaki city, the quasi-stationary precipitation system was not reproduced. On the other hand, experiments including eastside mountains produced a low-level convergence in south of Okazaki city, resulting in the quasi-stationary precipitation system and prolonged precipitation as observed near Okazaki city. The convergence was formed by sustained easterlies together with northerly winds blowing in west of Okazaki city. The easterlies were maintained by westward shift of southeasterly inflow from the Pacific Ocean due to the enhanced pressure gradient on the upstream side of the eastside mountains in the low-level atmosphere with low Froude numbers (Fr < 0.5). The easterlies also steadily supplied warm and moist air to the quasi-stationary system, leading to the prolonged intense precipitation observed in the Okazaki heavy rainfall event.

Keywords: band-shaped precipitation system; mountains; Okazaki heavy rainfall event
1. Introduction

Many of the heavy rainfall events consist of band-shaped precipitation systems (Bluestein and Jain 1985, Ogura 1991, 2015). As has been indicated by past studies, topography is considered as one of the contributing factors for formation of band-shaped precipitation. In the classical work by Houze (1993), heavy rainfall events are classified according to their relationships with topography. A more recent work by Lin (2007) provides a summary on impacts of mountainous topography at various scales on precipitation around the world. In Japan, associations between heavy rainfall events and local topography have been reported in a number of case studies (Ogura et al. 1985, Kanada et al. 2000, Yoshizaki et al. 2000, Watanabe 2008, Ninomiya 2011, Morotomi et al. 2012). Numerical experiments with modified topography have shown that mountainous topography affects precipitation intensity but has little impact on spatial distribution (Suzuki et al. 2008, Kurihara et al. 2009, Tsuguti and Seino 2017, the Japan Meteorological Agency: JMA 2017). Similar finding was made for a heavy rainfall event in Texas (Nielsen et al. 2016). However, numerical experiments with modified topography are still limited in number. Furthermore, not all heavy rainfall events are affected by topography (e.g., Kato and Goda 2001). In order to develop a comprehensive understanding of precipitation-topography relationship for local heavy rainfall events, it is important to accumulate more cases with various topography and atmospheric background.

Heavy rainfall events occurred over several areas in Japan during 26–31 August 2008.
Ogura et al. (2011) showed that most of the events during this period could be classified into two types. The first type is organized band-shaped mesoscale convective systems (MCSs) along upper-level moisture fronts, and the second is back-building type systems in which MCSs successively form towards a windward direction to form an organized band-shaped precipitation system (Bluestein and Jain, 1985, Kato 1998). Among these, a heavy rainfall event reaching an hourly precipitation amount of 146.5 mm (the Okazaki heavy rainfall event), occurred at 1500 UTC and lasted until 2000 UTC on 28th around Okazaki, a city in central Japan (Fig. 1). Development of the Okazaki heavy rainfall event can be divided into two stages; in stage 1 (1300-1600 UTC), the precipitation system moved southeastward, and in stage 2 (1700 UTC and later) the precipitation system became quasi-stationary around Okazaki city (details shown in Section 2).

Shinoda et al. (2009) examined stage 1 of the Okazaki heavy rainfall event using X-band polarimetric Doppler radar observations and numerical simulations. They showed that this event was associated with a band-shaped precipitation system with a back-and side-building type structure (Seko 2001), which is maintained by mid-level winds and lower inflows blowing from different directions. However, as Shinoda et al. (2009) focused on stage 1 of the Okazaki event, potential mechanism behind the maintenance of the quasi-stationary precipitation system during stage 2 is still unknown.

Recognizing the mountainous topography around Okazaki city, the present study examines the impact of topography on the maintenance of the quasi-stationary band-
shaped precipitation system during stage 2 of the Okazaki heavy rainfall event. Section 2 of this paper presents an analysis of synoptic fields and mesoscale features of precipitation in the Okazaki heavy rainfall event. Section 3 outlines the numerical model used in this study. Section 4 describes the characteristics of the precipitation system simulated by the model. Section 5 presents sensitivity experiments to examine the impact of surrounding mountainous topography. Section 6 presents a discussion on a possible maintenance mechanism of the quasi-stationary precipitation system using a trajectory analysis and an evaluation of low-level thermodynamic environment. The paper concludes with a summary in Section 7.

2. Synoptic fields and mesoscale features of precipitation in the Okazaki heavy rainfall event

Figure 1 shows maps of the studied area. Okazaki city is located in the southeastern edge of plain areas surrounding Nagoya city (Fig. 1a). The northwestern part of this plain areas is called Nohbi plain, and the southeastern part is called Okazaki plain. Combined, these two plain areas are hereafter referred to as the Nohbi and Okazaki plain area. The Nohbi and Okazaki plain area is surrounded by mountains to the west (the Suzuka mountains), north (the Hida and Ryohaku mountains) and east (the Kiso mountains).

Figure 2 shows a time series of 10-minute precipitation at Okazaki city, observed by the Automated Meteorological Data Acquisition System of the Japan Meteorological Agency.
Heavy rainfall started at 1500 UTC and lasted until 2000 UTC. The accumulated rainfall during this period totaled 261 mm.

Figure 3 shows surface weather charts at 1200 UTC on 27, 28, and 29 August 2008, before and after the Okazaki heavy rainfall event. A nearly stationary synoptic-scale front was located on the Japan-Sea side of the Japanese archipelago. Synoptic-scale high pressure was seen far east from the Japan Islands over the Pacific Ocean, while synoptic-scale low pressure slowly moved southeastward over the ocean south of Kyushu Island. As will be shown later with model simulation results, in the Tokai area, southeasterly winds from the Pacific Ocean blew to the synoptic-scale front during this period. These winds supplied warm moist air from the ocean to the Tokai area during the Okazaki heavy rainfall event (see Fig. 5).

Figure 4 shows the distributions of observed radar reflectivity for 1300 – 2100 UTC on 28th in the Tokai area. At 1300 UTC, a line of precipitation (indicated by “S” in Fig. 4a) is located about 60 km northwest of Okazaki city. Another precipitation system (indicated by “A”) is located on the southeast side of system “S”. By 1400 UTC, while system “S” moved southeastward to approach system “A”, a new system “B” formed on the southeast side of system “A” (Fig. 4b). By 1600 UTC, systems “S”, “A” and “B” lined up in north-south direction around Okazaki city. On the south side of the lined systems, a new system formed (indicated by “C”, Fig. 4d). By 1700 UTC, system “S” merged with “A”, while system “B” merged with “C” (Fig. 4e). By 1800 UTC, system “A” dissipated but system “C” remained quasi-stationary.
around Okazaki city until around 2100 UTC (Figs. 4f-i).

The above sequence can be separated into two stages. In stage 1, system “S” moved southeastward towards system “A”. Then, together with systems “B” and “C”, these systems lined up in north-south direction around 1600 UTC. In stage 2, the system “C” remained quasi-stationary around Okazaki city. The subsequent analysis focuses on this quasi-stationary precipitation system during stage 2.

3. Outline of numerical simulation

We used the Weather Research and Forecasting (WRF) model Version 3.4.1 to investigate the quasi-stationary precipitation system around the Okazaki area. A horizontal two-way nesting was utilized with 3 model domains. Horizontal resolution of the model domain 1 was 12.5 km, with 170 (north-south direction) x 190 (west-east direction) grid points (Fig. 1b). Similarly, the model domain 2 consisted of 321 x 321 grid points at 2.5 km resolution, and the model domain 3 consisted of 351 x 421 grid points at 500 m resolution (Fig. 1a). Vertical coordinate was $\eta$ coordinate with finer resolutions at lower levels. Top of atmosphere was 100 hPa with 55 vertical layers underneath. Initial and boundary conditions for the WRF model were provided by a 3-hourly output of the Japan Meteorological Agency’s operational mesoscale model (JMA, 2013). Lower boundary condition for sea surface temperature is provided by the Merged satellite and in situ data Global Daily Sea Surface Temperatures (MGDSST) data (Kurihara et al. 2006). The model topography is based on
the United States Geological Survey Global 30 Arc-Second Elevation (USGS GTOPO30) data. The WRF model simulated for 0000 – 2100 UTC on 28 August 2008 for all 3 model domains. Thompson microphysics scheme (Thompson et al. 2004), Mlawer longwave radiation scheme (Mlawer et al. 1997), Dudhia shortwave radiation scheme (Dudhia 1989), Noah land-surface model (Chen and Dudhia 2001), and Mello-Yamada-Janjic Level 2.5 planetary boundary layer scheme (Janjic 2002) are used as physics parameterizations. Kain-Fritch convective parameterization scheme (Kain 2004) was additionally used only for Domain 1. Further details of the WRF model are in Skamarock et al. (2008).

4. Characteristics of the quasi-stationary precipitation system simulated by WRF

In Fig. 5, the simulation showed that warm moist air at 500 m above the surface, with equivalent potential temperature ($\theta_e$) greater than 355 K and mixing ratio of water vapor ($q$) greater than 18 g kg$^{-1}$, was coming ashore to the Tokai area from the southeast or east-southeast from 1200 UTC until 2100 UTC on 28 August 2008. The Okazaki rainfall event occurred at 1500 UTC during the period of background warm moist air supply.

Figure 6 shows the distributions of simulated hourly precipitation amounts and 10 m surface winds for 1300 – 2100 UTC in the model domain 3. General characteristics of the observed precipitation pattern are well captured. In stage 1, an organized precipitation system moved southeastward to form a band-shaped precipitation system near Okazaki city around 1600 UTC (Figs. 6a-d). In stage 2, the system remained quasi-stationary around
Okazaki city and produced intense prolonged precipitation for 1700 – 2100 UTC (Figs. 6e-i). The simulated precipitation amount in Okazaki city totaled about 250 mm by 2100 UTC. However, the simulated peak time of precipitation was about one hour later than the observed (Fig. 2). Throughout stage 2, easterly and east-southeasterly winds are maintained on the southeastern side of the quasi-stationary system (indicated by thick red arrows in Fig. 6). Northerly winds developed on the western side of the quasi-stationary system, and converged with the southeasterly winds to form a low-level convergence line (indicated by red dash lines in Fig. 6) on the south side of the quasi-stationary system. This convergence line is limitedly apparent from the surface to 500 m height.

5. Impact of topography on the quasi-stationary precipitation system

Okazaki city is located at the southeastern edge of the Nohbi and Okazaki plain area, surrounded by mountains to the west, east and north (Fig. 1a), as described in Section 2. Considering the above noted geography of Okazaki city, it is likely that the surrounding mountainous topography had an impact on the quasi-stationarity of Okazaki rainfall. In particular, mountains to the east of Okazaki city may have an impact in preventing eastward movement of the precipitation system leading to prolonged quasi-stationarity around Okazaki city.

With the above discussion in mind, the following sensitivity experiments were performed with ideal topography as shown in Fig. 7, namely,
• Control (CTL); with real topography (Fig. 7a),

• Case A; all mountains within ~200 km from Okazaki city are removed (Fig. 7b),

• Case B; similar to Case A, all mountains within ~200 km from Okazaki city are removed except for the southeastern quadrant (i.e., only mountains directly east of Okazaki city are remained) (Fig. 7c).

The topography modifications start at the model initial time (0000 UTC); therefore the model atmosphere is considered to be well adjusted to the modified topography prior to the formation of the quasi-stationary precipitation system. Topography in model grids between the original and the modified portions are smoothed by linearly interpolating over 5 model grid points. Topography interpolation is applied to all model domains.

Figure 8 shows spatial distributions of hourly precipitation amounts and surface winds from sensitivity experiments at 1300, 1600, and 1900 UTC. In Case A, a precipitation pattern associated with synoptic-scale front formed during stage 1 (indicated by ovals with dashed lines in Figs. 8b, e). A convergence line extended southward from this precipitation area.

MCSs successively formed and moved along the convergence line to form a band-shaped precipitation system (indicated by ovals with solid lines in Figs. 8b, e). These features of stage 1 precipitation system were similar to those in CTL. However, location of the stage 1 precipitation system was about 50 km east compared to CTL simulation (Figs. 8d, e).

Furthermore, unlike CTL, the precipitation system dissipated by 1900 UTC (Fig. 8h). In contrast, the Case B experiment reproduced the quasi-stationary precipitation from 1600
UTC to 1900 UTC around Okazaki city (Figs. 8f, i). Compared to the CTL case, spatial
distribution of precipitation was slightly different but its intensity was well captured.

We also performed additional sensitivity experiments as below (topography configurations
and horizontal distributions of hourly precipitation at 1900 UTC are shown in Supplement 1).

(1) Elevations of all mountains within ~200 km east of Okazaki city were halved
(Supplement 1a). This experiment produced a band-shaped precipitation system near
Okazaki city, but it slowly kept moving eastward (Supplement 1e).

(2) Western half of the all mountains within ~200 km of Okazaki city were removed
(Supplement 1b). Note that this experiment is similar to the Case B (Fig. 7c) except
that mountains to the northeast of Okazaki city are present. Similar to the Case B, a
quasi-stationary precipitation system was produced near Okazaki city (Supplement
1f).

(3) Eastern half of the all mountains within ~200 km of Okazaki city were removed
(Supplement 1c). No quasi-stationary precipitation system was produced near
Okazaki city in this experiment (Supplement 1g).

(4) Mountains over the Kii peninsula were removed (Supplement 1d). A quasi-stationary
precipitation was produced. However, compared to the CTL case, the intensity was
weaker and the orientation of the band-shaped precipitation system was slightly
rotated clockwise (Supplement 1h).

Therefore, mountains to the east of Okazaki city were essential for the formation and
maintenance of the quasi-stationary precipitation system during stage 2.

6. Discussion

We discuss a possible mechanism on how mountains to the east of Okazaki city contributed to the formation and maintenance of the quasi-stationary precipitation system during stage 2. Figure 9 shows distributions of winds at 500 m above the surface, and $\theta_e$ averaged from the surface to 500 m height for CTL, Case A and Case B experiments. In CTL, easterly and southeasterly winds steadily supplied high $\theta_e$ air ($\theta_e > 355K$) to Okazaki city for stages 1 and 2 (Figs. 9a, d, g). A similar pattern was observed in Case B experiment but less precipitation intensity was simulated owing to the lower $\theta_e$ (Figs. 9c, f, i). On the other hand, in Case A, easterly winds from the ocean dissipated by 1600 UTC (Figs. 9e, h). As the result, the high $\theta_e$ inflow during stage 2 was weaker compared to that in CTL and Case B. Maintenance of the quasi-stationary precipitation system during stage 2 could be associated with easterly and southeasterly winds blowing to Okazaki city, which provides steady inflow of high $\theta_e$ to the area.

Figure 10 shows time series of divergence averaged over the coastal area south of Okazaki city (indicated by black boxes in Figs. 9g, h, i). The CTL and Case B were associated with sustained low-level convergence. In contrast, for Case A, the low-level horizontal convergence did not occur. Meanwhile, latent heat flux from the ocean did not change substantially with or without mountains to the east of Okazaki city (not shown).
In order to investigate how easterly and southeasterly winds were sustained in CTL and Case B, we performed forward trajectory analysis (Stoelinga 2009). Parcels were released from the Pacific Ocean southeast of the Tokai area at the model initial time (0000 UTC on 28 August) at the height of 250 m above the surface. Figure 11 shows the representative parcel trajectories for 0000 – 1900 UTC. In CTL and Case B, the parcels traveled northwestern over the Pacific Ocean and gradually shifted westward as they approached the Tokai area (Figs. 11a, c). This westward shift was caused in the low-level atmosphere with low Froude numbers (Fr < 0.5), restricting the parcels to cross over the mountains to the east of Okazaki city. Here, Froude number (Fr = U₀ / Nh) was estimated using the averaged wind speed under the height of the mountains (U₀ ~ 8 m s⁻¹), a constant Brunt-Vaisala frequency (N ~ 1.2×10⁻² s⁻¹), and height of the mountain (top height : h ~ 2500 m) (Smolarkiewicz and Rotunno 1989).

However, in Case A, the parcels kept moving northwestern towards the Tokai area and did not reach Okazaki city (Fig. 11b). In order to qualitatively examine the westward shift of the parcels’ movements from the Lagrangian perspective, magnitudes and directions of pressure gradient and Coriolis forces were calculated along each parcel trajectory (shown as vectors in Fig. 11). With the presence of mountains to the east of Okazaki city, pressure gradient force worked on the parcels was 6.6×10⁻⁴ ~ 11×10⁻⁴ m s⁻² (in CTL and Case B), but without the mountains, pressure gradient force reduced to 3.7 ~ 5.0 x 10⁻⁴ m s⁻² (in Case A). Meanwhile, Coriolis forces worked on the parcels with and without the mountains were 5.8
~ 7.4 x 10^{-4} \text{ m s}^{-2} \text{ and } 4.0 \times 10^{-4} \sim 5.4 \times 10^{-4} \text{ m s}^{-2}, \text{ respectively. Therefore, the enhancement of pressure gradient force due to the presence of mountains to the east of Okazaki city was greater than the changes in Coriolis force.}

Figure 12 shows vertical cross-sections of $\theta_e$ and winds for 1830 UTC (a representative time for the quasi-stationary precipitation around Okazaki city). The cross-sections are taken along the white lines in Fig. 11 (denoted by A-A’). In CTL and Case B, a layer of high $\theta_e$ (>345 K) extended from the surface to 800 – 1000 m height (Figs. 12a, c). However, in Case A, the layer of high $\theta_e$ became relatively thinner in western half of the cross-section. This thinning of the high $\theta_e$ layer was caused by the eastward shift of high $\theta_e$ inflow from the ocean, as illustrated by parcel trajectory shifts shown in Fig. 11b.

The above discussion can be summarized as follows. In the low-level atmosphere with low Froude numbers (< 0.5), the enhanced pressure gradient force on the upstream side of the mountains worked on the southeasterly flow from the Pacific Ocean to shift westward, resulting in the sustained easterly inflow to Okazaki city. Together with northerly winds blowing from west of Okazaki city (c.f., Fig. 6f), the sustained easterlies formed a low-level convergence in south of Okazaki city. The sustained easterlies also provided high $\theta_e$ inflow with ~1 km depth to the convergence zone (Figs. 9, 12) and contributed to the prolonged maintenance of the quasi-stationary precipitation system. However, a question remains as to how the northerly winds in west of Okazaki city (c.f., Fig. 6f) was maintained during stage 2. This is left for future studies.
7. Summary

Most of heavy rainfall events consist of quasi-stationary precipitation systems. The Okazaki heavy rainfall event, which occurred at midnight on 28 August 2008 around Okazaki city in the central part of the Japan Islands, was caused by a quasi-stationary band-shaped precipitation system. The Okazaki heavy rainfall event started around 1500 UTC on 28th, and lasted until around 2100 UTC. This event can be divided into two stages. In stage 1 (1300 – 1600 UTC), a band-shaped precipitation system moved southeastward to reach Okazaki city. In stage 2 (1700 – 2100 UTC), the band-shaped precipitation system merged with newly formed MCSs around Okazaki city, and became quasi-stationary. The development of Stage 1 precipitation was previously described by Shinoda et al. (2009). The present study examined the quasi-stationary precipitation system in stage 2, with a focus on the impact of surrounding mountainous topography.

In order to examine the impact of mountainous topography on the quasi-stationary precipitation system, a series of numerical simulations were performed using the WRF model. The control simulation well reproduced the observed precipitation pattern of the quasi-stationary precipitation system during stage 2. Analysis of the simulated low-level equivalent potential temperature ($\theta_e$) and surface winds showed that the quasi-stationary precipitation system was sustained by low-level high $\theta_e$ inflow from the east. Next, we examined the impact of the surrounding mountainous topography to the quasi-stationary system.
precipitation system. Results showed that when all mountains within ~200 km from Okazaki city were removed, no supply of high $\theta_e$ was maintained and thus the precipitation system dissipated in stage 2. However, experiments with mountains to the east of Okazaki city produced the quasi-stationary precipitation system even when mountains to the west of Okazaki city were removed. An additional experiment with eastside mountains halved in their elevations produced weaker precipitation intensity and less stationarity. These results indicate that the key topography for the maintenance of the quasi-stationary precipitation system was the mountains to the east of Okazaki city.

Figure 13 summarizes the factors contributing to formation of the quasi-stationary precipitation system examined in this study. The results of sensitivity experiments indicated that the maintenance of quasi-stationary precipitation system was associated with the mountains east of Okazaki city in the following manner:

(1) Southeasterly winds from the ocean shifted to easterly due to enhanced pressure gradient associated with presence of the mountains to the east of Okazaki city.

(2) The sustained easterlies continuously supplied warm and moist air to Okazaki city and formed a low-level convergence to restrict the eastward movement of the precipitation system.

There remain some issues regarding the formation of the stage 1 precipitation system. In our sensitivity experiments, a mesoscale band-shaped precipitation system formed during stage 1 with or without mountains to the east of Okazaki city (Fig. 8). However, without
mountains to the east of Okazaki city, the stage 1 precipitation system formed 50 km east of the control case. The intensity was also weaker compared to the control case. These results indicate that both the location and intensity of the stage 1 precipitation system are also sensitive to topography. Previous studies showed that topography can affect precipitation intensity (Suzuki et al. 2008, Kurihara et al. 2009, Nielsen et al. 2016, Tsugut and Seino 2017, JMA 2017). Meanwhile, a case study done by Kato and Goda (2001) on a stationary band-shaped precipitation system in Niigata (the 4 August 1998 heavy rainfall case) showed little impact by the local topography. Thus, influence of local topography on heavy rainfall events vary by cases. Further investigations are necessary on why and how some heavy rainfall events are affected by local topography.

Supplement

Supplement 1. Topographical maps (panels in top row), and simulated horizontal distributions of hourly precipitation (mm hr$^{-1}$) and surface winds at 1900 UTC on 28 August 2008 (panels in bottom row) for (a) and (e) experiment with elevations of all mountains within ~200 km east of Okazaki city are halved, (b) and (f) experiment with western half of all mountains within ~200 km of Okazaki city are removed, (c) and (g) experiment with eastern half of the all mountains within ~200 km of Okazaki city are removed, (d) and (h) experiment without the mountains over the Kii peninsula. Thin solid line contours in panels in bottom row indicate topography (drawn at 200 m interval).
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Fig. 10. Time evolutions of low-level divergence (averaged from the surface to 500 m height over the area enclosed by black boxes in Fig. 9) for CTL, Case A and Case B.
Fig. 11. Results of forward trajectory analysis, and pressure level at 250 m above the surface extrapolated to the sea level for (a) CTL, (b) Case A, and (c) Case B. Pressure fields are time averages for 0000 – 1900 UTC on 28 August. Dots on the trajectories denote parcel locations for every hour. For panels (a), (b), and (c), directions and magnitudes of parcel acceleration due to pressure gradient and Coriolis are shown by black and red vectors, respectively. Grey shading indicates areas with elevation greater than 250 m.
Fig. 12. Vertical cross-sections of equivalent potential temperature and winds along the cross-section at 1830 UTC for (a) CTL, (b) Case A, and (c) Case B. The cross-sections are taken along the white lines in Fig. 11.
Fig. 13. A schematic illustration of the quasi-stationary precipitation system described in the present study.