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Topographic effect on heavy rainfall caused by Typhoon

Hagibis (2019) in Nagano, Japan

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Abstract

In October of 2019, Typhoon Hagibis brought abundant rainfall to eastern Japan that caused flooding of the Chikuma River in the northern region of Nagano prefecture. This study simulated the effects of changes in the elevation of the model terrain every 100 or 300 m with a regional meteorological model to understand the cause of the heavy precipitation that accompanied the typhoon in Nagano prefecture and the influence of the heights of mountains on the amount of rainfall. The model reproduced the typhoon track and spatiotemporal distribution of heavy precipitation. Mountains in the northern region of Nagano Prefecture contributed to the heavy precipitation, which increased at an approximately constant rate of 4.4 mm per 100 m increase of elevation. However, the rate of increase was especially large at elevations of 900–1200 m. The correlation of precipitation with topographic height was not as strong in the south as in the north, but the rate of variation was also anomalously high at elevations of 900–1200 m. These

elevations roughly corresponded to the level of free convection or to elevations between the level of free convection and the lifted condensation level around the typhoon track.

1. Introduction

Typhoon Hagibis caused a meteorological disaster in eastern Japan in October of 2019. A comparison by Fujibe et al. (2020) of Hagibis with previous typhoons that passed similar tracks and caused heavy precipitation has shown that Nagano prefecture was one of the regions where Hagibis caused torrential precipitation that exceeded the precipitation associated with previous typhoons. In Nagano prefecture, sixteen observation sites, including Nagano City, updated their 12-hour rainfall records, and several other observation records were also updated. The abundant and persistent rainfall caused flooding of the Chikuma River, which is a class A river that runs through the northern region of Nagano prefecture. However, the Tenryu River and the Kiso River, which are both class A rivers that run through the southern part of the prefecture, did not flood.

Takemi and Unuma (2020) have shown that the amount of precipitable water was relatively large and the absolutely unstable layer of moist air was relatively thick in the case of Hagibis versus previous strong typhoons. They have pointed out that the similarity of the altitude of the absolutely unstable layer of Hagibis to the height of nearby mountains caused topographic lifting that produced strong convection and heavy rainfall. The western side of the North Pacific was showing high temperature anomalies when Hagibis passed. The warm sea surface contributed to accelerate the Typhoon (Ito and Ichikawa, 2021) and shifted the front inland (Iizuka et al., 2021). In Kawase et al. (2021) studying effect of warming for 40 years on Hagibis precipitation, although contribution

of atmospheric warming was weaker than that of ocean, atmospheric warming enhanced precipitation. The Japan Meteorological Agency (JMA) has attributed the extreme precipitation caused by Hagibis in eastern Japan to a combination of 1) an influx of abundant water vapor, 2) formation and enhancement of a front and persistent upward motion caused by topographic effects, and 3) the direct effect of enhanced rainfall near the center of the typhoon (JMA 2019). The JMA has shown that a large temperature difference between an anticyclone over Japan and a typhoon contributes to the formation of a stationary front over the Pacific Ocean side of Japan, where warm and wet air flows in. The JMA has indicated that the terrain had small effect on the track of Hagibis and on precipitation at some stations in the upstream of the Chikuma River (Supplement 1). However, the JMA analysis did not resolve details of the impact of the terrain on the heavy precipitation because topographic effects were evaluated only with a sensitivity experiment in which all mountains in eastern Japan were removed in the numerical simulation. Additionally, the simulated precipitation was not compared with the precipitation recorded by in-situ rain gauges.

Some previous studies have analyzed the abundant precipitation that accompanies typhoons in Japan. Murata (2009) has analyzed a case of extreme precipitation that accompanied Typhoon Meari (2004), which made landfall farther west than Hagibis. They have shown that a low-level, warm and moist flow ascending mountainous slopes can cause vertical convective instability that leads to precipitation, and a cold pool and low-level inflow into the system also promotes heavy precipitation. Hara (2014) has investigated the strong rainband over Izu Oshima that was associated with Typhoon Wipha (2013), the rainband of which followed a track similar to that of Hagibis but further to the east. In their analysis, a strong temperature gradient in the coastal region induces a

coastal front that is maintained along the gradient and produces persistent precipitation. Although there have been many studies of the heavy rainfall associated with typhoons, there is still insufficient knowledge of the relationship between topographic elevation and the heavy rainfall associated with typhoons in Japan.

Lin et al. (2020) have analyzed the effects of topographic height on changes of a typhoon track and precipitation in simulations of Typhoon Fanapi (2010) by varying the elevations by 0%, 50%, and 130% of the mountainous terrain in Taiwan. They have shown that a change in terrain elevation causes a shift of the rainfall area and an asymmetric flow that changes the location of the rain band and intensity of convection. Xie and Zhang (2012) have analyzed the topographic effects on heavy rainfall in Taiwan associated with Typhoon Morakot (2009) by varying the topographic elevations between 0%, 50%, and 100%. Over Taiwan, the precipitation when the terrain elevation was halved decreased by about 30% compared to the normal case, but it was only about 3–30% larger than the precipitation when all the terrain was removed. These previous studies have evaluated the impact of changes of topographic elevation on rainfall, but they have not had sufficient vertical resolution to simulate changes of the elevations of mountains.

It is important to study the influence of mountains in Nagano Prefecture, where the surrounding high mountains are considered to have a strong influence on precipitation (Suzuki, 2008). In this study, we quantitatively evaluated the relationship between rainfall and changes in topographic elevations during passage of a typhoon by varying the elevation of mountains at a high vertical resolution (300-m intervals) and dividing Nagano prefecture into a northern sector where the Hida Mountains rise to elevations that exceed 3000 m and a southern region where the Akashi Mountains also exceed 3000 m in height.

2. Data and methods

2.1 Weather stations and observation data

Forty-five JMA meteorological observation sites, including five weather stations and 40 Automated Meteorological Data Acquisition Systems (AMeDASs), record precipitation in Nagano prefecture with tipping-bucket rain gauges. Kuribayashi et al. (2019) provide details about the location of each observatory. Weather station Nagano (36.662°N, 138.192°E, 418 m above sea level: a.s.l.) recorded record-breaking daily precipitation of 132.0 mm on 12 October 2019. The Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLITT) records precipitation with tipping-bucket rain gauges located along rivers and gorges in mountainous areas. The elevations of some sites, such as Kitazawa (35.744°N, 138.212°E, 2064 m a.s.l.), exceed 2000 m. The JMA has calculated mesh precipitation rates based on Doppler weather surveillance radar and in-situ observation data. The temporal and spatial resolutions are 30 minutes and 1 km, respectively.

To compare the lifting condensation level (LCL) and the level of free convection (LFC) of the simulations, we used the Tateno station (36.057°N, 140.125°E, 25 m a.s.l.), which is the upper-air observation station closest to the typhoon's track, as the observation site for comparison. At Tateno, radiosonde observations are made twice a day at 00 and 12 UTC.

2.2 Numerical experiment

To analyze the relationship between the heavy precipitation caused by Hagibis and topography, we conducted a control simulation (CTRL) with the Weather Research and Forecasting model (WRF) version 3.6 (Skamarock et al. 2008), which is a non-hydrostatic

mesoscale meteorological model. Table 1 provides details of the numerical settings, and Figure 1a shows the domains calculated for this study. LCL and LFC were calculated over Nagano prefecture. To evaluate the contributions of mountains to the heavy rain, we carried out sensitivity simulations in which the elevations of the mountains were limited to one of seven elevations from 1 m (LM1) to 1800 m (LM1800) approximately every 300 m. In addition, at elevations of 1200 m and 900 m, elevation limits of 100 m above and below these limits (LM800-LM1300) were also considered as alternatives. Mountains higher than these thresholds were represented by flat plains at the threshold elevations.

3. Results and discussion

3.1 Model validation

Typhoon Hagibis formed on 6 October 2019. It made landfall on the Izu Peninsula at 10 UTC on 12 October, passed the Kanto Plain east of Nagano, and moved northeastward with a central pressure around 955 hPa shortly thereafter (Fig. 1a). Hagibis then continued moving northeastward and weakened into an extratropical cyclone above the Northwest Pacific Ocean. Figure 1b shows the terrain of the WRF simulation in domain 03. Supplement 2 illustrates the observed terrain in the same region as domain 03 based on the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) version 2 with a horizontal grid spacing of 30 m retrieved from the satellite-borne sensor ASTER (Tachikawa et al. 2011).

Figures 2a-d show typhoon tracks, translational speeds, central pressures, and maximum wind speeds of JMA best track and model simulation during 11–13 October. The CTRL simulation reproduced the typhoon track, translational speed, central pressure, and maximum wind speed well, but it underestimated the translational speed during 12–

21 UTC on 12 October after the peak of precipitation had already passed.

Figures 2e-f show time series of the precipitations at Nagano (relatively lowland) and Kitazawa (highland). At Nagano, weak precipitation started at 12 UTC on 11 October and continued until around 00 UTC on 12 October, when the rain began to strengthen. From 05 UTC, precipitation increased to over 10 mm per hour. The rain slackened at 10 UTC and almost stopped at 18 UTC. The observed cumulative precipitation in Nagano during this heavy rainfall was approximately 140 mm, which is equivalent to 170% of the mean precipitation in October at Nagano (~83 mm). The rainfall in Kitazawa preceded the rainfall in Nagano by a few hours, but the patterns of the time series were similar. The observed cumulative precipitation in Kitazawa was ~640 mm, which corresponds to 2.1 times the mean precipitation in October (approximately 308 mm).

In the CTRL, though the maximum precipitation tended to lag behind the observed peak at both observatories, the difference between the calculated and observed cumulative precipitation was very small at Nagano. At Kitazawa, the calculated cumulative precipitation exceeded the observed precipitation by 86.1 mm (13%). The difference between the calculated and observed hourly precipitation was especially large during 05–09 UTC on 12 October. There are at least two possible reasons for this overestimation. First, because the horizontal resolution of the model (3.3 km) was insufficient to represent steep mountains, water vapor that did not precipitate on the windward side of the mountains could reach the Akaishi Mountains because of the underestimation of topographic height (Wu et al. 2002). In comparison of terrain heights between domain 03 of the WRF and GDEM, the differences of 95% is smaller than 55 m. Second, wind, funnel wetting, evaporation, and receiver fault cause a tipping-bucket rain gauge to tend to underestimate precipitation (Devine and Mekis 2008). Because the error depends on

the intensity and timescale of the local rainfall (Ciach 2003), the rain gauges may have underestimated precipitation.

Figures 3a and 3b show the observed and calculated cumulative precipitation, respectively, from 00 UTC on 11th to 13th. The principal rain clouds around the typhoon passed over the Kanto Plain, and the rain clouds approached from approximately southeast because the winds blew from the direction (Fig. 3e). For the precipitation period, the Froude number (F_r) of the surface wind over the windward region are approximately 1.76 and 0.47 for 1 km and 2 km obstacles, respectively. Thus, the air flow has enough speed to pass through low mountains, but was deflected by high mountains except during high winds. Both observations and the CTRL simulation showed total cumulative precipitation for two days that exceeded 540 mm around the landfall area, in the southeastern boundary of Nagano prefecture, and on the Pacific side of northeastern Japan.

Figure 4 compares the LCL and LFC from the surface calculated over Nagano prefecture and observed over Tateno. The calculated LCL was 600–700 m until 12 UTC on 12 October. It was lowest around 16 UTC on 11 October, gradually increased for the next 20 hours, and then rose sharply at around 12 UTC on 12 October when precipitation around Nagano weakened. The LCL was also very low at Tateno, but because the LCL was almost at ground level, the simulation could not reproduce it satisfactorily. The simulation could reproduce the higher LCL values around 12 UTC on 12 October. The calculated LFC value was high before 15 UTC on 11 October, but after that time it was low (1100–2000 m) until 11 UTC on 12 October, when it could no longer be detected. The observations at Tateno also revealed a very high value at 12 UTC on 11 October, although not as high as the calculated value, and a lower value at 00 UTC on 12 October.

3.2 Effect of mountains

Although the elevations of some mountains in the Chubu region exceed 3000 m, the typhoon tracks in the sensitivity simulations with limited mountainous terrains were almost the same as the CTRL tracks (Fig. 2a). Figures 3c and 3d show the spatial distribution of precipitation in the LM1 simulation and the difference between that simulated precipitation and the CTRL precipitation, respectively. In the LM1, the removal of topographic effects led to a decrease in precipitation, especially in the areas of heavy rainfall, and a general increase in other areas.

Limiting the mountain elevations changed the spatial distribution of precipitation because of orographic effects. Figure 5 compares the cumulative precipitation in the northern and southern regions in the CTRL and 11 LM simulations. In the CTRL simulation, the spatial mean cumulative precipitation in the northern and southern regions of Nagano prefecture during the heavy rainfall were 245.5 and 187.2 mm, respectively, from 00 UTC on 11th to 13th. The mean cumulative precipitation in the northern region changed by -78.6 mm (-32.0%) in the LM1 versus the CTRL. The differences from the CTRL decreased as the height limitation was relaxed. The mountains had a strong influence on precipitation in the northern region of Nagano prefecture during the heavy precipitation associated with Hagibis, and the total precipitation was approximately proportional to the elevation of the land.

When the height of the mountains was reduced by 300 m, the decrease in precipitation by limiting the elevation of the mountains averaged 4.4 mm per 100 m for the 7 LMs in the northern region based on an approximately linear relationship between elevation and rainfall. However, the sensitivity was larger in the elevation range 900–1200 m and especially in the range 1000–1100 m, wherein precipitation in the northern region

changed significantly. The limiting elevation for large variations was roughly equivalent to the LFC or the elevation between the LCL and LFC. The LCL and LFC in LMs are almost similar to CTRL but from 00 to 12 UTC on the 12th. The difference is due to the results that the target area had been affected by warmer and more humid air.

In contrast to the northern region, the simulated precipitation in LM1 decreased in the eastern part of the southern region, while it increased in the western part. The difference of the precipitation between the LM1 and CTRL simulations in the southern region was only 14.6 mm (+7.8%) and the change of precipitation in response to the change in elevation was not constant. There were minima and maxima of precipitation in the LM1200 and LM900 simulations, respectively, and the large change of precipitation between 900–1200 m was very similar to the analogous change in the northern region.

Decreasing terrain elevation redistributed topographic precipitation in both the northern and southern regions (Fig.3d). In the southern region, where high mountains (Akaishi) are located in the eastern part of the region, precipitation was redistributed leeward of the mountains and was then more-or-less constant throughout the southern region. In contrast, in the northern region, there is a high mountain (Hida) to the west of the region, and precipitation was redistributed both leeward of the high mountain and further west. In both regions, the sensitivity of precipitation change to topographic elevation change was high around the LFC or at elevations between the LCL and LFC. Wang and Chang (2012) have shown that precipitation tended to change with elevation around the LCL similarly but in a monsoon case (no typhoon).

4. Conclusions and future work

Typhoon Hagibis brought heavy rainfall to eastern Japan in October 2019. The present

study of precipitation in and around the Chubu region showed that variations of rainfall were related to topographic elevation. In the northern region, rates of precipitation change as a function of elevation were generally constant; precipitation decreased by about 4.4 mm for every 100-m reduction of elevation. Thus, the implication is that the mountains may have enhanced precipitation in the northern region. In contrast, that in the southern region was not constant, but the high mountains on the east side of the region cancel out the decrease in the east and the increase in the west and precipitation increased slightly with the removal of mountains.

In both the northern and southern regions, the sensitivity of precipitation to elevation was particularly high at elevations of 900–1200 m. The highest sensitivity of precipitation to elevation was associated with elevations comparable to the LFC or elevations between the LCL and LFC. In this study, LCLs and LFCs were calculated using a large area inside a computational model, and there were not enough observations to compare observed and simulated LCLs and LFCs. More detailed analysis is needed to study the relationship during typhoons between rainfall and topography, including the LCL and LFC.

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List of Figure Captions

Fig. 1. (a) Domains for calculations in the present paper. Orange line is the observed typhoon track (JMA best track). (b) Chubu region (containing Nagano and adjacent prefectures) in domain 03. Orange diamonds indicate the Nagano weather station and Kitazawa precipitation observation site. Orange triangle indicates the JMA station at Tateno. Red quadrangles indicate the regions targeted to estimation of precipitation in the northern and southern regions, which correspond roughly to the prefecture border. In the limited mountain height (LM) sensitivity test, terrain height inside the purple line was controlled.

Fig. 2. Comparisons between JMA best track for typhoon or precipitation recorded by rain gauges by the JMA and MLITT (blue) and calculations (CTRL; orange, seven LMs for a; red) in domain 01 (a–d) and 03 (e–f). Typhoon track (a), translational speed (b), central pressure (c), and maximum wind speed (d), time series of precipitations and cumulative precipitation at Nagano (e) and Kitazawa (f). The calculated precipitations at Nagano and Kitazawa are average of 9 grids at and around the site.

Fig. 3. Spatial distributions of cumulative precipitation and horizontal wind speed in domain 02 from 00 UTC on 11th to 00 UTC on 13th October, UTC. Panels (a–c) show cumulative precipitation (mm) of weather surveillance radar analysis (a), simulated with the CTRL (b), and LM1 (c). Panel (d) shows the difference of cumulative precipitation, LM1 – CTRL, within domain 03. Green lines indicate surface altitude of 1800m. Panel (e) shows the mean horizontal wind speed simulated at 850 hPa with the CTRL.

Fig 4. Lifted condensation level (LCL; orange) and the level of free convection (LFC; blue) based on calculations around the typhoon track in domain 03 (lines) and observations at Tateno (square).

Fig. 5. (a) Scatter plot of spatial mean cumulative precipitation of the CTRL simulation and 11 LMs during the heavy rainfall event in the northern region and southern regions of Nagano prefecture. The error bars indicate the amounts of changes when areas of the regions are magnified by factors of 0.9 and 1.1. (b) Relationship between ratio of elevation-limited area and mean cumulative precipitation in the northern (square) and southern (triangle) regions. The error bars have the same meaning as in panel (a).

List of Table Legends

Table 1. Computational conditions for WRF calculations. The computational areas of domains 01, 02, and 03 are shown in Fig. 1.

List of Supplements

Supplement 1. Cumulative precipitation distribution (mm) for 51-hours from 00 UTC on October 11 to 03 UTC on October 13, based on the results of numerical simulations. The left panel shows the case with the terrain of Honshu, and the center panel shows the case without the terrain. The right panel shows the difference of the center from the left. The dotted line indicates the track of the typhoon center. Based on Figure 3 on JMA (2019).

371 Supplement 2. Terrain height based on observation data with 30 m of spatial resolution
372 from the Advanced Spaceborne Thermal Emission and Reflection Radiometer
373 Global Digital Elevation Model version 2 in the same region as Fig1b. Some place
374 names are indicated. Blue lines indicate representative class A rivers. The names of
375 representative mountains in the Chubu region are indicated.

376

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Domain	1	2	3	References
Initial and boundary conditions	The National Centers for Environmental Prediction (NCEP) Final Analysis (GFS-FNL) global tropospheric analyses			
Number of grids (X x Y)	100 x 100			
Spatial resolution	30 km	10 km	3.3 km	
Vertical resolution	60.8m at the lowest level			
Period	2019-10-08 to 15			
Time step	90 s			
Top level	19 km			
Vertical levels	61 eta levels			
Microphysics	WSM 6-class graupel scheme			Hong and Lim 2006
Radiation	RRTMG both for longwave and shortwave			Iacono et al. 2008
Surface layer	Monin-Obukhov (Janjic Eta) Similarity scheme			Janić 2001
Land surface	Noah Land-Surface Model			Ek et al. 2003
Boundary layer	Bougeault and Lacarrere PBL			Bougeault & Lacarrere 1989
Cumulus convective parameterization	New Tiedtke Scheme		Off	Zhang and Wang 2017
Vertical velocity damping	Not applied			
Nudging	Not applied			

Note: WSM6 = WRF Single Moment 6 Class; RRTMG = Rapid Radiative Transfer Model – Global; PBL = Planetary Boundary Layer

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