1. Introduction

From 9 to 11 September 2015, an extremely heavy rainfall event occurred in the Tochigi prefecture, 120 km north of Tokyo, Japan, causing flooding of the Kinu River. During this event, a linear rain band (LRB) formed over the Tochigi prefecture (LRB1; Fig. 1a), in the northern part of the Kanto region (Fig. 1b). In the Tochigi prefecture, a local observation site measured total precipitation exceeding 600 mm in 48 hours. In the later stages of this event, another LRB formed in the northern part of the Tohoku region (LRB2; Figs. 1a, b) causing heavy rainfall there. Both LRBs extended hundreds of kilometers. According to the Japan Meteorological Agency (JMA), the observed precipitation of LRB1 was 59.5 mm hr$^{-1}$ at its maximum at 15UTC 9 September, and that of LRB2 peaked at 62.0

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They found that the upper-tropospheric trough advected dry air over the Kanto region, resulting in a convectively unstable condition. In addition, since a high potential vorticity disturbance was approaching, synoptic upward motion was diagnosed by Trenberth forcing (Trenberth 1978). This is an approximation to a forcing term of the quasi-geostrophic omega equation, which is calculated from horizontal advection of absolute vorticity by thermal wind. Adding to these favorable conditions for heavy rainfall, latent heat release by precipitation to the north of Etau caused negative potential vorticity advection, prohibiting eastward propagation of the trough. It also generated an upper-tropospheric ridge to the east of the trough, which intensified the low-level Okhotsk high pressure. Kitabatake et al. (2017) argued that the Okhotsk high pressure supplied moisture to the Kanto region via the associated easterly or southeasterly wind.

The typhoons Etau and Kilo are notable characteristics of the September 2015 Kanto-Tohoku heavy rainfall event. Kitabatake et al. (2017) argued that Kilo and the Okhotsk high cooperatively enhanced the meridional pressure gradient and intensified the easterly wind. Fujitani et al. (2016) showed that this low-level easterly wind brought moist air, while moisture was also advected from the south, and argued for the importance of the southeasterly wind related to the low-level ridge. In summary, it is unclear whether the easterly associated with Kilo was an essential contributor to the heavy rainfall event or only a secondary contributor. It is also unclear how Kilo affected the low-level ridge and associated southeasterly wind.

In this paper, we investigate the role of Kilo in the September 2015 Kanto-Tohoku heavy rainfall event using non-hydrostatic numerical simulations. We carry out sensitivity experiments to study the effect of Kilo on synoptic conditions, especially the low-level easterly and southeasterly winds and the low-level ridge to the east of the Kanto region.

2. Data and methodology

2.1 Model description

We used a global stretched version of the Non-hydrostatic Icosahedral Atmospheric Model (NICAM; Tomita and Satoh 2004; Satoh et al. 2008; 2014) that enhanced the horizontal resolution around a selected target location (Tomita 2008a; Uchida et al. 2016). Grid intervals were about 5.6 km at the target location (36.7°N, 139.7°E in the Kanto region) and 560 km at the opposite side of the globe. The model had 40 layers, with a top height of about 38 km. Moist processes were explicitly calculated using a six-category single-moment bulk cloud microphysics scheme.
(Tomita 2008b), without any cumulus parameterization. Unrealistic representation of clouds in the remote regions with coarse grids has minimal influence on the results near the target region in this study because of the short integration period of up to three days. More detailed characteristics of the stretched-grid NICAM simulations are described in Uchida et al. (2016). A modified Mellor-Yamada level 2 scheme (Mellor and Yamada 1982; Nakanishi and Niino 2004, 2009; Noda et al. 2010) was applied for boundary layer turbulent processes. Radiation processes were calculated with K-distribution model (MSTRNX; Sekiguchi and Nakajima 2008). The sea surface temperature was predicted using a slab ocean model with 15 m depth and was nudged toward reference data interpolated from the National Center for Environmental Prediction final analysis dataset at a relaxation time of five days. The MATSIRO scheme (Takata et al. 2003) was applied for land surface boundary conditions.

We used the Grid Point Value (GPV) dataset, which is used as initial data of JMA Global Spectrum Model (GSM); the Japanese 55-year Reanalysis dataset (JRA55) produced by JMA (Kobayashi et al. 2015); and the best track data of Kilo and Etau produced by JMA for verification. We also used Global Satellite Mapping of Precipitation (GSMaP; Kubota et al. 2007).

2.2 Experimental set-up

After examining preliminary experiments starting at various initial conditions, we defined a control experiment with an initiation date of 00UTC 9 September, hereafter referred to as CTL. CTL reproduced realistic heavy rainfall in terms of location and precipitation amount (see Section 3.1).

We conducted two sensitivity experiments. The first was identical to CTL except that it was initialized at 00UTC 8 September (hereafter referred to as EARLY). As shown in detail in Section 3.1, EARLY reproduced Kilo with lower central pressure and a westward-shifted track compared to observations but did not reproduce the rainfall over the Kanto region.

The second sensitivity experiment was a moisture-removed experiment initialized at 00UTC 8 September (hereafter referred to as RH0). In RH0, the relative humidity derived from the GPV dataset for the Kilo region, where the wind exceeds 30 kt defined by best track data of JMA, was set to 0% at all levels on the initiation date (cf. Fig. 1c). When the moisture was removed near the center of Kilo, its central pressure became higher, and its cyclonic circulation became weaker. Our intention was to investigate the effect of Kilo on the easterly or southeasterly winds and the contributions of these winds to the moisture supply to the Kanto region. We chose to initialize RH0 at 00UTC 8 September because the moisture effect of Kilo is inseparable from that of the environment after 9 September.

We defined the center of the simulated typhoon as the location of minimum sea level pressure in a 0.5° square around the previous center (one hour before).

3. Results

3.1 Simulated profiles of precipitation and typhoons

CTL reproduced a LRB between 00UTC 9 September and 00UTC 11 September over the Kanto region (Fig. 2a), and its location corresponded well to the observed LRB1 (Fig. 1a). CTL also reproduced a rain band in close proximity to the observed LRB2 but with less precipitation. By contrast, EARLY did not reproduce the rain bands (Fig. 2b). CTL reproduced characteristics of Kilo well in terms of surface pressure distribution and the track compared with the best track data provided by JMA. In EARLY, Kilo had about 5 hPa lower central pressure, and its track was shifted about 100 km to the west (Figs. 3a, b).

The moisture-removed experiment (RH0) was intended to simulate a weakened Kilo. The sea level pressure at the center of Kilo was more than 1000 hPa at 18UTC 9 September (Fig. 3b), which is weaker than the 975 hPa in CTL at the same time. Wind speeds near the center of Kilo in RH0 were much weaker than those of CTL and EARLY (details are described in later section). Kilo was located up to 200 km further west than the best track data. As for the Kanto region, a LRB was reproduced, despite the early initiation date, as in the observed LRB1 but with 5% less rain in the Kanto region than in CTL (Fig. 2c). However, over the outer band of Etau, the amount of precipitation increased by 10%. This was unexpected because previous studies (cf. Section 3 of Fujitani et al. 2016) suggested that Kilo played a role in intensifying the rain band corresponding to LRB1. Conversely, this result suggests that Kilo weakened the heavy rainfall. The rain band corresponding to LRB2 was not reproduced clearly in RH0 (Figs. 2b, c).

The simulated Etau is stronger than best track data in all three experiments, and the central pressure is about 10 hPa lower. The central pressure variability among the three experiments is within 5 hPa. Its tracks almost overlapped in the three experiments except in the later period (Figs. 3a, c).
3.2 Synoptic conditions

All three experiments simulated the evolution of the upper-tropospheric fields similarly (Fig. 4): the upper trough was over the west side of Japan and stagnated, and the upper ridge was over the northeast of Japan. This behavior is consistent with the analysis by Kita-batake et al. (2017).

The role of Kilo on synoptic scale conditions is more clearly visible by examining the low-level structure. The lower-tropospheric fields were significantly different (Fig. 5), particularly around the Kanto region and the eastern sea. The low-level ridge, represented by a 1500 m isobar around 35°N 145°E, extended more southward in CTL and RH0, and the southeast-erly wind prevailed near the Kanto region, associated with this low-level ridge. By contrast, in EARLY, the low-level ridge was not clear, and the easterly wind prevailed. Comparing the precipitating (CTL and
Fig. 2. The 48-hour integrated precipitation level (mm, shading) generated from simulations from 00UTC 9 September to 00UTC 11 September 2015. (a) CTL, (b) EARLY, and (c) RH0. The average amount in each area is noted. Area1 (black dashed box) is over the Kanto region, and Area2 (red dashed box) is over the outer band of Etau.

Fig. 3. Simulated typhoon profiles. Results from best track data (red), CTL (yellow), EARLY (green) and RH0 (blue) are shown for the period from 00UTC 08 September to 00UTC 10 September 2015. (a) The tracks of Kilo (right) and Etau (left), (b) the central pressure (hPa) of Kilo, and (c) the central pressure (hPa) of Etau.
Fig. 4. The geopotential height at the 250 hPa level averaged from 00UTC 9 September to 00UTC 11 September 2015. (a) CTL, (b) EARLY and (c) RH0 simulations. Contour lines each 50 m; arrows show horizontal wind vector.

Fig. 5. The geopotential height and horizontal wind at the 850 hPa level, and precipitable water. The images show 12UTC 09 September (left column) and 18UTC 09 September (right column), as simulated in (a), (b) CTL, (c), (d) EARLY and (e), (f) RH0. Contour lines each 10 m; arrows show horizontal wind vector (m s\(^{-1}\)); precipitation (mm) in shading.
RH0) and non-precipitating (EARLY) cases showed that southeasterly wind can be important. The time-longitudinal section of geopotential height around 35°N (Figs. 6a–d) shows that two typhoons formed this low-level ridge, which is located at 140°E to 145°E. This ridge is the relatively high pressure region between these two typhoons. In EARLY, the westward-shifted Kilo with lower pressure resulted in a lower height of the low-level ridge. By contrast, in RH0, the weakened Kilo maintained the high geopotential height region. This indicates that the low-level ridge extension was sensitive to the strength and track of Kilo. The zonal cross-section, averaged over the mature stage of the low-level ridge (Fig. 6e), shows that the zonal height gradient is positive (nearly zero) in CTL and RH0 (in EARLY). This suggests that the westward-shifted Kilo, with lower pressure, disturbed the southerly component of wind at 140°E to 145°E. Previous studies argued that the pressure gradient between Kilo and the Okhotsk high enhanced the easterly and southeasterly winds, and these winds supplied moisture. Although the three experiments described here showed the Okhotsk high with similar intensity, the simulated precipitation is different. The low-level ridge was independent of the easterly wind, which differs from the arguments made by Kitabatake et al. (2017).

### 3.3 Moisture flux variabilities

The amount of low-level moisture flux was larger in CTL than in EARLY (Fig. 7). The southeasterly wind of the low-level ridge supplied moisture more effectively around the Kanto region, resulting in a more moisture-rich condition in the lower troposphere in the Kanto region. This result shows that the southward extension of the ridge supported the moisture supply.
This is consistent with the role of the low-level ridge, which is pointed out in Section 5 of Fujitani et al. (2016).

The differences between EARLY and CTL (Figs. 8a, b) show that a stronger and westward-shifted Kilo prevented extension of the ridge and reduced the southerly component of horizontal wind significantly. Around Kilo, the moisture flux was larger due to strong wind. However, over the Kanto region, the moisture flux decreased. The differences between RH0 and CTL (Figs. 8c, d) show that the southeasterly flow was maintained, and the amount of moisture flux increased around the Kanto region. This structure was favorable for moisture supply.

Our results suggest that the southeasterly moisture advection, at the lower troposphere by the low-level ridge, was of primary importance. When only easterly winds existed, and the low-level ridge was weaker (EARLY), the low-level moisture supply to the Kanto region was underestimated, although air parcels of heavy rainfall originated near Kilo (Section 3 of Fujitani et al. 2016). To understand the role of the moisture supply to the Kanto region, it is necessary to separately evaluate the easterly wind, which is enhanced by the pressure gradient between the Okhotsk high pressure and Kilo, and the southeasterly wind, associated with the low-level ridge.

The southerly moisture-rich air along 140°E lon-
Fig. 8. Comparison between simulations at 18UTC 09 September. The left column shows differences between CTL and either EARLY or RH0 in geopotential height (m; shading) and horizontal wind (m s\(^{-1}\); vector) at the 850 hPa level. The right column shows the amount of moisture flux (g·m s\(^{-1}\); shading) and horizontal wind (m s\(^{-1}\); vector) at the 925 hPa level. Comparisons are between (a), (b) EARLY and CTL, and (c), (d) RH0 and CTL.
the Kanto region was enhanced in the sensitivity experiment, in which Kilo was weakened (RH0). Our result suggests that, in this particular event, Kilo had a suppressing effect on the low-level ridge formation, which provided the substantial southeasterly moisture flux and supported the heavy rainfall. Figure 10 schematically illustrates the relationship between Kilo, the ridge, and the rain bands. In RH0, despite the reduced easterly wind, moisture supply was plentiful due to the unsuppressed low-level ridge (yellow solid line in Fig. 10) and the associated southeasterly flow. The relative anti-cyclonic circulation of the weakened Kilo supported the low-level ridge and maintained the southeasterly wind (Fig. 9). In other words, the cyclonic circulation of Kilo disrupted the southward extension of the low-level ridge.

In this study, EARLY and RH0 did not reproduce a rain band corresponding to LRB2. The initiation date of these two experiments, 00UTC 8 September, is too early to reproduce and discuss LRB2, which peaked at 14UTC 10 September. The importance of the low-level ridge is suitable for LRB1. However, in the
period when LRB2 developed, Kilo and Ettau moved, and the low-level ridge is vanished. Thus, we need more study to discuss the role of Kilo in LRB2.

In EARLY, Kilo was reproduced slightly stronger, and its track was shifted westward (Fig. 3), resulting in a weaker ridge and reducing the moisture supply (Fig. 6). We note that accurate forecasting of typhoon track and intensity is important for predicting relatively remote heavy rainfall events.

Although this study clarifies the effect of Kilo on the ridge and the southeasterly water vapor transport between Kilo and Ettau, the simulated track of Kilo strongly depends on the lead time. A sufficiently large ensemble experiment would enable us to extract more robust information for this event.

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