Dynamical role of the Changbai Mountains and the Korean Peninsula in the wintertime quasi-stationary convergence zone over the Sea of Japan

Yuta Shinoda1 | Ryuichi Kawamura1 | Tetsuya Kawano1 | Hiroyuki Shimizu2

1Department of Earth and Planetary Sciences, Faculty of Science, Kyushu University, Fukuoka, Japan
2Japan Meteorological Agency, Tokyo, Japan

Abstract
This study focused on a quasi-stationary convergence zone over the Sea of Japan (Japan Sea polar airmass convergence zone, JPCZ) in early winter and examined how the Changbai Mountains and the Korean Peninsula play an influential role in the formation and maintenance of the JPCZ and associated precipitation amounts in the coastal regions of central and western Japan. We performed numerical simulations with and without modified topography of the Changbai Mountains and the Korean Peninsula using a regional atmospheric model. The results show that the presence of the mountains is largely responsible for the JPCZ formation and usually contributes to the reduction of precipitation in the coastal regions. If specific conditions are satisfied, however, it can trigger heavy precipitation. One condition is the rapid growth of mesoscale eddies off the Sea of Japan coast under strong low-level wind convergence. The precipitation band involved in the enhanced eddies slowly migrates southward and reaches the coastal regions, causing heavy snowfall. Another condition is the change in background monsoonal flows associated with synoptic-scale cyclone development due to the orographic effect. The resultant background flows may help sustain a significant amount of precipitation in the coastal regions. Under the prevailing JPCZ, the mountains play two contradictory roles in modulating precipitation amounts in the coastal regions.

KEYWORDS
convergence zone, heavy snowfall, mesoscale disturbances

1 | INTRODUCTION

The Sea of Japan coastal region of mainland Japan receives extremely heavy snowfall when the East Asian winter monsoon dominates. It has long been known that such heavy snowfall events are often involved in a quasi-stationary convergence zone over the Sea of Japan. Asai (1988) named it the Japan Sea polar airmass convergence zone (JPCZ) and reviewed its association with mesoscale disturbances developing over the Sea of Japan. Using a primitive model, Nagata et al. (1986) and Nagata (1987, 1991) investigated the formation mechanism of the JPCZ and emphasized that three major factors are indispensable for JPCZ formation: the presence
of the mountains north of the Korean Peninsula (the Changbai Range and the Hamgyong Range), thermal contrast between the Sea of Japan and the peninsula, and a subpolar oceanic front in the central Sea of Japan, although their studies highlighted a particular JPCZ event. The relationships between mesoscale disturbances and the JPCZ have also been examined by Nagata (1993), Tsuboki and Asai (2004), Watanabe et al. (2018), and others.

More recently, Shimizu et al. (2017; hereafter S17) examined the dynamical impact of the Changbai Mountains on synoptic-scale cyclone activity over the Sea of Japan, especially in early winter, using a regional atmospheric model, and clarified that the Changbai Mountains influence the wintertime surface cyclogenesis over the Sea of Japan in spite of the comparatively small scale of the mountains. They also indicated that, in climate terms, the amount of precipitation increases on the Sea of Japan side of central and western Japan in the modified topography experiment without the Changbai Mountains. According to their discussion, this may be because the weakened and less organized JPCZ facilitates increased moisture transport toward the coastal regions of central and western Japan, leading to enhanced precipitation in those regions. It appears, however, that this result is not consistent with the previous knowledge that the JPCZ triggers heavy snowfall events in the Sea of Japan coastal region (e.g., Nagata et al., 1986).

To resolve this contradiction, our main objective in this study is to inspect the dynamical role of the Changbai Mountains and the Korean Peninsula in the formation of the JPCZ and associated precipitation amounts in the coastal regions during periods when individual JPCZ events are prominent. Many JPCZ events are examined in this study, which is distinguished from the previous studies (e.g., Nagata, 1993; Tsuboki and Asai, 2004) that focused mainly on a particular event. We first extract significant JPCZ events based on the long-term simulation of a regional atmospheric model and reconfirm the influence of the JPCZ on wintertime precipitation in the Sea of Japan coastal region. Second, we perform sensitivity experiments that modify the topography of the Changbai Mountains and the Korean Peninsula and clarify how the mountains dynamically modulate the JPCZ and associated precipitation amounts in the coastal regions.

The rest of the paper is organized as follows: Section 2 gives a brief description of the model used and the experimental design. Section 3 documents the extraction and classification of JPCZ events and presents the overall features of precipitation distributions and the associated synoptic environment with respect to each type of JPCZ. Sections 4 and 5 compare the experiments with and without modified topography and evaluate the orographic effect of the Changbai Mountains and the Korean Peninsula. Conclusions are presented in Section 6.

2 | MODEL CONFIGURATIONS AND EXPERIMENTAL DESIGN

In this study, the model used and the experimental design are the same as those in S17. We used the Weather Research and Forecasting (WRF)-ARW model, version 3.5.1, which was developed by the National Center for Atmospheric Research (NCAR) (Skamarock et al., 2008). The model domain is East Asia and the western North Pacific sector, which is divided into a 346 \times 291 grid with a horizontal resolution of 10 km (Figure 1). The vertical coordinate is a terrain-following coordinate, and 35 vertical layers are included, with the top level at 50 hPa. The physical parameterization schemes used in this study include the Rapid Radiative Transfer Model (RRTM) longwave radiation (Mlawer et al., 1997) and Dudhia shortwave radiation (Dudhia, 1989) schemes, the Noah scheme for surface processes (Chen et al., 2001), the Kain–Fritsch scheme (Kain, 2004) for cumulus convection, the WRF single-moment 6-class scheme (WSM6) (Hong and Lim, 2006) for cloud microphysics, and the Yonsei University scheme for the planetary boundary layer. The initial and lateral boundary conditions for WRF are derived from the National Centers for Environmental Predictions—Final (NCEP FNL) operational
model global tropospheric analyses with a time resolution of 6 hr and a spatial resolution of 1° longitude by 1° latitude. We utilized the daily optimal interpolation sea surface temperature (OISST) data based only on the Pathfinder Advanced Very High Resolution Radiometer (AVHRR) (Reynolds et al., 2007) with a spatial grid resolution of 0.25° as a surface boundary condition of the WRF.

S17 conducted a long-term simulation over 15 winter months (December only) for the period 2000–2014 because synoptic-scale cyclone activity over the Sea of Japan is most dominant in December (e.g., Yoshiike and Kawamura, 2009; Hayasaki and Kawamura, 2012). Intense JPCZ events also often occur in December. Thus, we extended their simulations until 2018, following the same experimental design. Consequently, 19 months for the period 2000–2018 are available to extract significant JPCZ events. The initial time of the simulations is 0000 UTC on November 23 each year. To aid in proper understanding of mesoscale disturbances embedded in the JPCZ, we also carried out independent higher-resolution simulations of individual JPCZ events, as will be mentioned in Section 5.

Figure 1 indicates the geographical map and topography in East Asia and the western North Pacific sector, which corresponds to the model domain (labelled D1). To evaluate the dynamical impact of the Changbai Mountains and the Korean Peninsula on the JPCZ, we artificially modified the mountain elevation to 0 m within the Changbai Mountains and the Korean Peninsula (red rectangle in the figure) but made no changes in the land use, which is hereafter called the MOD run. In contrast, the experiment without modified topography is called the control (CTL) run. In this study the Changbai Mountains and the Korean Peninsula are hereafter referred to simply as Changbai Mountains for convenience.

3 | EXTRACTION AND CLASSIFICATION OF JPCZ EVENTS IN THE CTL RUN

Figure 2 shows the climatological mean December 925 hPa horizontal wind divergence over the Sea of Japan for the CTL run based on the 19-year period from 2000 to 2018. A distinctive convergence zone that expands from the northwest to the southeast can be seen to the east of the Korean Peninsula, indicating a JPCZ signature. We defined the 925 hPa wind divergence averaged over the area enclosed by a black solid line in the figure as an appropriate measure of the JPCZ. Since we would like to focus specifically on salient and prolonged JPCZ events, we calculated 12-hr mean values ($\bar{D}$) of the area-averaged wind divergence over the whole period and their standard deviation ($\sigma$) and subsequently picked up extremely anomalous cases with less than a threshold value of $\bar{D} - 2\sigma$. Note that the wind divergence was calculated every 1 hr. If this criterion was satisfied at consecutive time steps, we regarded the period when the anomaly reached its peak as a JPCZ event. As a consequence, we extracted 35 cases as major JPCZ events. Their frequency is approximately 1.84 events per month.

As a next step, we tried to classify those events into several categories, since synoptic environmental conditions are expected to differ between each event. Since the JPCZ tends to appear when northwesterly monsoonal flows prevail over the Sea of Japan, we defined the difference in the 12-hr mean sea level pressure (SLP) between Seoul in Korea and Sapporo in Japan (former minus latter) as a winter monsoon intensity index and classified all events into two major categories that are stronger and weaker than the normal monsoon intensity, which are hereafter designated type 1 (22 cases) and type 2 (13 cases), respectively. It is noteworthy that the index used in this study is different from other winter monsoon indices (e.g., Hanawa et al., 1988; Chen et al., 2000; Yang et al., 2002; Jhun and Lee, 2004; Li and Yang, 2010) because we focus specifically on the strength of low-level northwesterlies over the Sea of Japan. As shown later, we also considered the curvature of the JPCZ in relation to the low-level cyclonic circulation field and defined the 12-hr...
mean 925 hPa relative vorticity (ζ) averaged over the rectangle (drawn with a dashed line in Figure 2) as an another index. We further classified type 1 into two minor categories that are less and greater than a threshold value of $\zeta + \sigma$, based on the standard deviation ($\sigma$) of the index values, which are hereafter called type 1A (15 cases) and type 1B (7 cases), respectively.

Figure 3 shows the composite features of the 12-hr mean SLP and 925 hPa horizontal wind divergence for types 1A, 1B, and 2. Types 1A and 1B are both characterized by a noticeable zonal pressure gradient over the Sea of Japan, which implies the dominance of northwesterly monsoonal flows. A remarkable trough line along the JPCZ is also seen in both types. On average, the center of synoptic-scale cyclones is located to the northeast of Hokkaido, the northernmost island of Japan, in type 1A, while it shifts toward the island in type 1B. Both the zonal pressure gradient and the convergence related to the JPCZ are more pronounced in type 1B than in type 1A. As for the configuration of the JPCZ, type 1B has more curvature than type 1A. In contrast, a low-pressure area around the JPCZ and a weak pressure gradient characterize type 2, which is quite different from the synoptic environment of types 1A and 1B.

In a similar fashion, Figure 4 shows the composite patterns of 12-hr accumulated precipitation amounts for types 1A, 1B, and 2. A common feature of types 1A and 1B is the presence of a sharp zone over the sea and significant amounts of precipitation in the coastal regions of central and western Japan, whereas minor differences between the two are the configuration of the precipitation pattern and precipitation amount. Again, the precipitation pattern of type 2 is considerably different from that of other types. The pattern is less clear. The maximum area of precipitation is observed over the sea, and the coastal regions of central Japan receive less precipitation. As inferred from Figure 3c, the precipitation area coincides well with the low-pressure one, reflecting a substantial fraction of a mesoscale cyclone or the early developing stage of a synoptic-scale cyclone system. Since we highlight the JPCZ formation and associated precipitation amounts in the coastal regions in this study, as stated earlier, type 2, which is an irregular type of JPCZ, is not considered for our examination in later sections.

4 | RESULTS OF THE MODIFIED TOPOGRAPHY (MOD) RUN

Figure 5a,b shows composite maps of the 12-hr mean 925 hPa horizontal wind and its divergence for type 1 (22 cases) in the CTL and MOD runs, respectively. We see that in the CTL run, the JPCZ is formed by a convergence of northerlies to its north and northwesterlies to its south. As expected, the MOD run can hardly simulate strong JPCZ events such as those in the CTL run. The directions of the monsoonal winds are similar over the entire sea. The composite difference in 12-hr accumulated precipitation between the CTL and MOD runs (latter minus former) for the same type is shown in Figure 5c. In a similar way, the differences in the 12-hr mean vertically integrated moisture flux and its flux divergence between the two runs are shown in Figure 5d. A notable feature in the MOD run is the appreciable reduction in precipitation along the JPCZ, accompanied by less moisture flux convergence, whereas precipitation increases in the coastal regions (enclosed by a green line in Figure 5c) with enhanced moisture flux into the inland from the sea. Note here that we call the domain enclosed by the green line the coastal regions for convenience, although it includes plain areas near the coast and part of mountain areas.

**FIGURE 3** Composite patterns of the 12-hr mean SLP (contours) and 925 hPa horizontal wind divergence (shaded) for types 1A, 1B, and 2. The contour interval is 2 hPa. The shading interval is $1 \times 10^{-5}$ s$^{-1}$. Values of greater than $-3 \times 10^{-5}$ s$^{-1}$ are not drawn.
Another important view is a marked change in moisture flux north of the JPCZ due to the absence of the Changbai Mountains, leading to decreased precipitation within the JPCZ. Since small mountains (mostly less than a height of 1,500 m) in the Korean Peninsula are located to the south of the JPCZ, moisture import into the JPCZ from its south is also expected to change if their blocking effect for the monsoonal flows is large, but no significant changes in moisture flux are seen to the south of the JPCZ. Although the topography of the Korean Peninsula is also modified in the MOD run, its modification may play only a minor role in the change in the moisture flux as suggested from Figure 5d.

Comparing the surface latent heat flux over the Sea of Japan between the two runs, furthermore, the evaporation from the ocean surface within the corresponding JPCZ region is enhanced in the MOD run (not shown). Larger amounts of water vapour can be imported into the coastal regions with less consumption due to condensation along the JPCZ. We also made comparisons between the two runs for types 1A and 1B, and similar features were obtained in both types. These results may be consistent with the research of S17, which suggested that decreased precipitation in the coastal regions of central and western Japan is attributable mainly to the Changbai Mountains.
Next, because the contradiction mentioned in Section 1 is unresolved, we examine the time evolution of the precipitation amount in the coastal regions in detail. Figure 6a,b displays the time evolution of 3-hr accumulated precipitation averaged over the coastal regions (enclosed by a green line in Figure 5c) in the CTL and MOD runs for types 1A and 1B, respectively. Recall here that the JPCZ is defined based on the 12-hr mean 925 hPa horizontal wind divergence. It turns out that the precipitation amount in the MOD run is greater than that in the CTL run during the JPCZ period for both types. On average, the increase rates relative to the CTL run are approximately 10.9 and 16.2% for types 1A and 1B, respectively. However, a conspicuous feature is that, as for type 1B, the CTL precipitation tends to be great over approximately 12 hr after the JPCZ period, as compared to the MOD run. Since such a reversal cannot be seen for type 1A, it is unclear why the reversal occurs after the JPCZ period only in type 1B.

Figure 7 shows the composite differences in 12-hr mean SLP between the CTL and MOD runs (latter minus former) for types 1A and 1B. In type 1A, the SLP difference with the magnitude of 2 hPa is almost confined within the JPCZ, whereas in type 1B, its difference expands into the mainland of Japan and further into the Pacific Ocean. One might wonder why the modified topography in the Korean Peninsula can remotely influence the SLP field over those regions only in type 1B. It is likely that this question is closely related to the aforementioned reversal with respect to precipitation amount. Thus it is necessary to inspect the behavior of individual type 1B events in detail.

5 | INDIVIDUAL JPCZ TYPE 1B EVENTS

5.1 | Higher-resolution simulations

In this section, we present the primary results of the CTL and MOD runs for seven type 1B events. To better capture mesoscale disturbances in conjunction with the JPCZ, we adopted three domains with two-way nesting and conducted higher-resolution simulations of each event. The horizontal resolutions of domain 1 (D1), domain 2 (D2), and domain 3 (D3) are 10, 5, and 2.5 km, respectively. D1 coincides with the model domain explained in Section 2. D2 and D3 are illustrated in Figure 1. The Kain–Fritsch cumulus parameterization scheme is not adopted for D3. Other experimental designs are unchanged, except that we adjusted the initial time and integration time for each event. The 5 km- and 2.5 km-resolution simulations started 2 days and 1 day before the beginning of the JPCZ period, respectively. Both simulations continued until 1 day after the termination of that period.

We checked the results of Figure 6 based on the precipitation simulated in D3. The high-resolution simulations revealed that the increase rates relative to the CTL run are approximately 14.3 and 21.3% for types 1A and 1B, respectively. The differences between the two runs are more evident in the high-resolution simulations. Although we also examined the maximum precipitation within the corresponding area, there are no significant differences between the two runs in terms of the maximum value and location.

Figure 8 shows the time evolution of hourly precipitation averaged over the coastal regions (enclosed by a green line in Figure 5c) in the CTL and MOD runs for all type 1B events. The precipitation simulated in D3 is used in this figure. We used 87 in situ observation stations provided by the Japan Meteorological Agency and validated the simulated precipitation in the coastal regions. The time evolution of CTL precipitation is well correlated with that of observations, but the model tends to underestimate or overestimate the precipitation amount in each JPCZ event. Note here that time 0 hr is the peak time of the JPCZ on the basis of 11-hr running averaged 925 hPa horizontal wind divergence. We see that the CTL precipitation tends to be greater than the MOD precipitation after the JPCZ period in many cases, which is consistent with the result shown in Figure 6b.
Particularly, a predominant peak in the precipitation amount within 12 hr after the JPCZ period appears in Figure 8a,b, suggesting the occurrence of heavy snowfall in the corresponding region. We consider these two type 1B events as typical cases and examine them in more detail.

5.2 | Case studies of typical type 1B events

Figure 9 shows the spatial distributions of the precipitation intensity and SLP in the CTL and MOD runs at 0100 UTC, 0700 UTC, and 1300 UTC on December 12, 2005,
as the first typical case. The peak time of the CTL precipitation seen in Figure 8a is 1300 UTC on December 12 (Figure 9c) 10 hr after the time 0 hr. In the CTL run, a salient precipitation band accompanied by a surface pressure trough is formed over the sea and subsequently reaches the coastal regions. Another intriguing feature is that mesoscale eddies are growing around the precipitation band at 0700 UTC on December 12 (Figure 9b). Conversely, we can see no systematic precipitation bands or surface troughs in the MOD run. The coastal regions experience continuous precipitation due to the pronounced northwesterly monsoonal flows.

Figure 10 is the same as Figure 9 but for the second typical case. The peak time of the CTL precipitation seen in Figure 8b is 1400 UTC on December 17, 2005 (Figure 10c), 11 hr after the time 0 hr. In the CTL run, a zonally elongated precipitation band and mesoscale eddies appear over the sea at 0200 UTC on December 17 (Figure 10a). This line-shaped precipitation system develops and migrates southward, subsequently reaching the coastal regions. As a consequence, heavy precipitation occurs over the entire coastal region (Figure 10c). In contrast, the above features cannot be seen in the MOD run. Significant amounts of precipitation are continuously confined in the coastal regions, which is similar to the MOD run of the first typical case.

A common feature in these typical cases is the formation and southward migration of a systematic precipitation band, together with mesoscale eddies over the sea, in the CTL run. Since it takes time for this system to reach the coastal regions, the heavy precipitation reaches its maximum in those regions after the JPCZ period. In contrast, the MOD run is characterized by continuous precipitation in the coastal regions due to the northwesterly monsoonal flows, as predicted in Figure 5.

To further explore why mesoscale eddies grow around the JPCZ in the CTL run, we made a vorticity budget analysis at the 925 hPa level. The vorticity tendency equation is given as follows:

$$\frac{\partial \zeta}{\partial t} = -\mathbf{V} \cdot \nabla (\zeta + f) - \omega \frac{\partial \zeta}{\partial p} - (\zeta + f) \nabla \cdot \mathbf{V} + \mathbf{k} \cdot \left( \frac{\partial \mathbf{V}}{\partial p} \times \nabla \omega \right),$$

(1)
where $\zeta$ is the vertical component of relative vorticity, $f$ is the planetary vorticity, $\mathbf{V}$ is the horizontal wind vector, and $\omega$ is the vertical $p$-velocity. Figure 11 shows the vorticity tendency, each budget term, and the sum of all terms on the right side of the equation in the CTL run for the first typical case. The time is 0700 UTC on December 12, 2005, when mesoscale eddies are developing rapidly near the precipitation band over the sea (Figure 9b). The tendency is basically explained by the sum of all terms. As for each term, the horizontal advection term is relatively large, but this merely indicates that the mesoscale system migrates horizontally with time. An important indication is that the vortex stretching term, which induces the vorticity, is significantly positive in the vicinity of the mesoscale eddies, suggesting the intensification of cyclonic vorticities within the JPCZ through enhanced low-level wind convergence.

Figure 12 is the same as Figure 11 but for the second typical case. To save space, we demonstrate only the features at 0800 UTC on December 17, 2005, when mesoscale eddies embedded in the precipitation band are growing over the sea (Figure 10b). Since many eddies are present, the results of the vorticity budget are complicated, but it seems that the stretching term is still important for enhanced cyclonic vorticities, although in this case, the vertical advection term is also large. For instance, Watanabe and Niino (2014) examined a polar mesocyclone observed over the Sea of Japan on December 30, 2010, as a case study and showed that during its early development stage, a number of small vorticities appeared along a JPCZ. They postulated that the vorticities increase as a result of strong updrafts within cumulus convection, which may support our vorticity budget analysis.

From these analyses, we thus anticipate that once mesoscale eddies grow rapidly off the Sea of Japan coast under strong low-level wind convergence, their associated precipitation band also becomes more pronounced and slowly approaches the coastal regions. This results in heavy snowfall when such an active precipitation band reaches those regions.

### 5.3 Other type 1B events

Three of the remaining five type 1B events (Figure 8c,d,f) have features similar to the above two typical cases in
FIGURE 11  Results of the vorticity budget analysis in the CTL run for the case of Figure 8a. The selected time is 0700 UTC on December 12, 2005. The shading denotes the spatial distributions of vorticity tendency, each budget term, and the sum of the budget terms. The SLP distribution (contours) at the same time is also shown. The contour interval is 2 hPa.

FIGURE 12  As in Figure 11 but for the case of Figure 8b. The selected time is 0800 UTC on December 17, 2005.
terms of the development of mesoscale eddies, although their features are less clear. On the other hand, the remaining two events (Figure 8e,g) have additional intriguing features, in contrast to the other type 1B events. Figure 13 shows the spatial distributions of SLP in each run and the difference between the two at 0700 UTC, 1300 UTC, and 1900 UTC on December 30, 2009, for the case of Figure 8e. The shading interval is 4 hPa. Lower panels show the SLP differences between the CTL and MOD runs (latter minus former). The shading interval is 2 hPa.

Figure 14 is the same as Figure 13 but for the case shown in Figure 8g. In this case, the time 0 hr (JPCZ peak time) is 1900 UTC on December 30, 2009 (right panels). We see a twin synoptic-scale cyclone feature, which is composed of one cyclone over the Sea of Japan and another over the Kuroshio Current off the Pacific coast of Japan. Interestingly, the rapid development of the synoptic cyclone over the Kuroshio is significantly different between the two runs. Focusing on the temporal change in the central pressure of the cyclone, the deepening rate of SLP is 29.4 (25.3) hPa per 12 hr in the CTL (MOD) run. This implies that the Changbai Mountains have the potential to

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**FIGURE 13** Spatial distributions of SLP in the CTL run (upper panels) and the MOD run (middle panels) at 0700 UTC, 1300 UTC, and 1900 UTC on December 30, 2009, for the case of Figure 8e. The shading interval is 4 hPa. Lower panels show the SLP differences between the CTL and MOD runs (latter minus former). The shading interval is 2 hPa.
remotely modulate the SLP field over the Pacific Ocean in the vicinity of Japan through synoptic-scale cyclone development. Thus, both cases demonstrate that even the synoptic environment, which is the background for the development and persistence of the JPCZ, can be changed by the orographic effect of the Changbai Mountains. A signature of such a change may be seen in Figure 7b.

Once a synoptic environment changes greatly, it is quite possible for a significant amount of precipitation to persist in the coastal regions, as in the case of Figure 8g, because the background monsoonal flows are forced to change over the Sea of Japan. Actually, when the precipitation amount in the CTL run is greater than that in the MOD run after the JPCZ period in the case of Figure 8g, active precipitation bands are located around the coastal regions. A quasi-stationary feature of the intense precipitation bands is in conjunction with the change in SLP gradient over the sea off the coast. S17 pointed out that the presence of the Changbai Mountains not only induces the structural change in the vicinity of the cyclone’s center but also triggers the cyclogenesis over the Sea of Japan. They called it the dynamical modulation of synoptic-scale cyclone activity due to the Changbai Mountains. We infer that such modulation is one of the major reasons the CTL precipitation tends to be greater than the MOD precipitation after the JPCZ period in the type 1B events.

6 SUMMARY

To examine the dynamical role of the Changbai Mountains and the Korean Peninsula (hereafter referred to simply as Changbai Mountains) in the formation and
development of a quasi-stationary convergence zone over the Sea of Japan and associated precipitation amounts in the coastal regions of central and western Japan in early winter, we conducted numerical simulations with and without modified topography of the Changbai Mountains (the MOD and CTL runs, respectively) using a regional atmospheric model. We extracted significant JPCZ events in the CTL run and classified those events into two major categories (types 1 and 2) and two minor categories (types 1A and 1B) on the basis of three criteria (i.e., 925 hPa horizontal wind divergence, relative vorticity, and a winter monsoon intensity index). Comparisons between the two runs were made over 19 months (December only) for the period 2000–2018. In addition, we adopted three domains with two-way nesting and performed higher-resolution simulations of individual type 1B events to better capture mesoscale eddies in conjunction with the JPCZ. The major findings in this study are briefly summarized below:

- Type 1 appears under the dominance of northwesterly monsoonal flows through a strong zonal pressure gradient over the Sea of Japan and causes a significant amount of precipitation in the coastal regions of central and western Japan. In contrast, type 2 appears in the vicinity of a synoptic-scale cyclone's center, which is an irregular type not involved in heavy snowfall in the coastal regions.
- It is reconfirmed that the presence of the Changbai Mountains are largely responsible for the formation and development of the JPCZ (type 1). Composite analyses for type 1 show less precipitation in the coastal regions of central and western Japan in the CTL run than in the MOD one during the period when the JPCZ was defined. In the MOD run, the weakened and less organized JPCZ facilitates increased moisture import into the inland from the sea, leading to much precipitation in the coastal regions. The Changbai Mountains contribute to the reduction of precipitation in those regions for many JPCZ events.
- We also find that the CTL precipitation tends to be greater than the MOD precipitation, which is delayed after the JPCZ period, as for type 1B. Two primary reasons are proposed from the results of our higher-resolution simulations of individual type 1B events. One reason is the rapid growth of mesoscale eddies off the Sea of Japan coast under strong low-level wind convergence. The precipitation band involved in the enhanced eddies slowly migrates southward and reaches the coastal regions, causing heavy snowfall.
- Another reason is the change in the background field for the development and persistence of the JPCZ due to the orographic effect of the Changbai Mountains.

This mountain range has the potential to remotely modulate synoptic-scale cyclones that develop in the vicinity of Japan. Once the background monsoonal flows relevant to synoptic-scale cyclone development are forced to change over the Sea of Japan, it is possible for a significant amount of precipitation to persist in the coastal regions in some cases.

We successfully resolved the inconsistency mentioned in Section 1. As usual, the Changbai Mountains play an influential role in decreasing precipitation in the Sea of Japan coastal region of mainland Japan, even while the JPCZ predominates. Conversely, however, it can trigger heavy precipitation if specific conditions are satisfied, as stated earlier. Thus, the Changbai Mountains play two contrary roles in modulating precipitation amounts in the coastal regions under a prominent JPCZ. To increase the reliability and validity of our conclusion, we carried out higher-resolution simulations of 15 type 1A events and confirmed that, in most cases, the CTL precipitation amount in the coastal regions of central and western Japan tends to be small compared to that in the MOD run, which is consistent with Figures 5 and 6a. New findings obtained in this study indicate that more precise forecasting, both of the rapid growth of mesoscale eddies off the Sea of Japan coast and of synoptic-scale cyclone development around Japan, is necessary to better predict extremely heavy snowfall in the coastal regions related to the JPCZ. We estimated the results of the 2.5-km resolution simulation in this study, but higher-resolution simulations are further required (e.g., Kawase et al., 2019). Another concern is a possible change in the frequency and intensity of heavy precipitation events associated with the JPCZ due to global warming. The present study suggests that high-resolution models with detailed topography of the Changbai Mountains should be applied to quantitatively evaluate such a change.

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ORCID
Ryuichi Kawamura https://orcid.org/0000-0002-6783-1496

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