Regional Snowfall Distributions in a Japan-Sea Side Area of Japan Associated with Jet Variability and Blocking

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Abstract

This study found that regional snowfall distributions in a Japan-Sea side area of Japan are controlled by intra-seasonal jet variability, particularly the 10-day-timescale quasi-stationary Rossby waves across the Eurasian continent and the atmospheric blocking over the East Asian region. This study was mainly focused on the Niigata area, which is representative of heavy snowfall areas in Japan. Based on previous studies, three types of dominant snowfall distributions were defined: (1) the plain (P) type, which is characterized by heavy snowfall events predominant in coastal regions of the Niigata area; (2) the mountain (M) type, which occurs in the mountainous regions; and (3) the PM type, which occurs across the whole Niigata area.

Our results revealed that all distribution types were related to the southward shift of the westerly jet over Japan associated with an intensified trough, i.e., cyclonic anomalies, originating from quasi-stationary Rossby waves along westerly jets over Eurasia (Eurasian jets). The cyclonic anomalies were found to be also related to blocking cyclones because the frequency of blocking events considerably increased in the East Siberian region. The mechanisms leading to trough intensification were different among the events of the three snowfall types. The formation of Siberian blocking with relatively different positions and different paths of quasi-stationary Rossby wave packet propagation along Eurasian jets was evident in the distribution types. Therefore, local-scale snowfall distributions in the Japan-Sea side area are determined by anomalous large-scale circulations, which can be evidently distinguished in the global reanalysis data.

Keywords  regional snowfall distributions; 10-day timescale; winter East Asian monsoon; subpolar and subtropical jets; atmospheric blocking

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1. Introduction

The Japan-Sea side areas of northern and central Japan experience some of the heaviest snowfall in the world (e.g., Honda and Kusunoki 2007; Kawase et al. 2016), even though they are located at relatively low latitudes in the extratropics. During winter, monsoonal cold northwesterly air flows from the Eurasian continent and over the Sea of Japan, where it acquires turbulent heat leading to convective systems that lead to snowfall (e.g., Yoshizaki and Kato 2007). The mechanism that determines how such snowfall occurs has been investigated in a number of previous studies in terms of both mesoscale (e.g., Tsuboki and Asai 2004; Yoshizaki et al. 2004; Eito et al. 2005) and synoptic–large-scale (e.g., Hori et al. 2011; Yamashita et al. 2012; Ueda et al. 2015) atmospheric circulations.

It is empirically and statistically known that there is variability in snowfall distributions in the Japan-Sea side areas, for which the predominant snowfall occurs in the mountainous areas, referred to as mountain-(M-) type snowfall; the other predominant one occurs in the plains, referred to as plain-(P-) type snowfall (Akiyama 1981a, b; Tachibana 1995; Iwamoto et al. 2008; Ueda et al. 2015). The P- and M-type snowfalls occurring in the Niigata area, one of the heaviest snowfall areas at the Japan-Sea side, have been studied (e.g., Fukaiishi 1961; Akiyama 1981a, b; Iwamoto et al. 2008). There are three dominant snowfall distributions: the P type, the M type, and a positive/negative snowfall anomaly in both the plain and the mountainous areas, referred to as the PM type. Akiyama (1981a) performed a statistical analysis on daily precipitation data from the Niigata area using the empirical orthogonal function (EOF) and found the three snowfall distribution types: the P type, the M type, and a positive/negative snowfall anomaly in both the plain and the mountainous areas, referred to as the PM type. Akiyama (1981a) named the first mode “normal snowfall type”, but here, we referred to it as the PM type.

Akiyama (1981b) investigated the characteristics of synoptic fields in each type. She found that all snowfall distribution types commonly accompany cold air in the upper troposphere (trough or a cold vortex) over the Niigata area and conditionally unstable stratification in the lower troposphere. A difference in the synoptic fields between the P type and the M type was also noted, particularly in the sea-level pressure (SLP) field. In the M-type climatological winter monsoon pattern, the high pressure in the west of Japan and the low pressure in the east are temporally enhanced and lead to northerly–northwesterly winds from the Eurasian continent, whereas in the P-type snowfall distribution, the pattern rather temporally weakens due to a weak and/or slow depression over the Sea of Japan. Iwamoto et al. (2008) found different local surface wind directions/strengths between the P-type and the M-type snowfalls in the Niigata area. Strong M-type local winds occur in the southward–southeastward direction, whereas weak P-type local winds are directed eastward.

It is important to predict the occurrence of a snowfall and the resulting snow accumulation; however, such prediction is generally difficult even in the state-of-the-art regional models because snowfalls are caused by convective activities at the ~ 10-km scale. To address this issue, we would like to propose to forecast the large-scale fields that potentially lead to snowfall events rather than to directly forecast the snowfall occurring at the mesoscale. This approach could be useful because large-scale (general circulation) fields generally have longer timescales and thus longer inherent predictability than mesoscale fields (cf. Inaba and Kodera 2010; Yamazaki et al. 2015). The results of the general circulation forecasts could be used to predict local snowfall events.

In this study, the characteristics of large-scale variabilities related to the P-, M-, and PM-type snowfalls will be evaluated. Similar studies on large-scale variabilities and local precipitation events have been conducted (Yamashita et al. 2012; Yamazaki et al. 2015; Ueda et al. 2015); however, to the best of our knowledge, previous studies have not classified the large-scale \((10^3 \sim 10^5 \text{ km})\) characteristics that determine local snowfall distributions \((10 \sim 10^2 \text{ km})\). Our results will describe a dynamical connection between the global atmospheric variability and local precipitation, where the scale gap is ~ \(10 \sim 10^2 \text{ km}\).

The relationship between an intraseasonal variability with a seasonal timescale of ~ 3 months and snowfall in the Japan-Sea side areas was explored by Ueda et al. (2015). They evaluated the characteristics of large-scale circulations occurring in winter (December–February), which is associated with the interannual variability of snowfall amounts in coastal
areas. The large-scale circulations exhibited a cyclonic anomaly (trough) in the upper troposphere over the East Asian region, which is similar to the characteristics found in previous studies (Akiyama 1981b; Iwamoto et al. 2008) but at substantially different timescales. Moreover, their results showed that the tropical convective activity near the Philippines Sea had a large impact on the formation of the cyclonic anomaly.

This study focuses on a relatively shorter timescale, particularly a timescale of a bi-pentad, that is, one-third of a month (’jun’ in Japanese), and ≈ 10 days, allowing us to focus on extreme (hourly-to-daily) snowfall events modulated by mid-latitude, low-frequency variabilities (Blackmon 1976; Itoh and Kimoto 1999), which have a timescale of 10 days rather than a timescale of one month (Feldstein 2000, 2003). In addition, analyzing the bi-pentad period would be advantageous for the following reasons: (1) The period represents the minimum timescale over which meso–synoptic scale disturbances from low-frequency variabilities can be filtered out. (2) One-third of a month is a recognizable period within a calendar month and is thus of relevance to our social lives.

Atmospheric blocking, a low-frequency variability, is a special focus herein. Blocking is typically an event that extends beyond the synoptic timescale (e.g., Barriopedro et al. 2006, 2010) and leads to substantial impacts on various mid-latitude unusual/extreme weather conditions. Blocking over Siberia can interact with and enhance the Siberian High (Takaya and Nakamura 2005a, 2005b; Mori et al. 2014). The enhanced Siberian High can then promote the winter East Asian monsoon. Takeuchi et al. (2008) reported that the stronger winter East Asian monsoon is related to a larger precipitation anomaly in the heavy snowfall areas of Niigata. Another reason to focus on blocking is that it probably appears as the most visible low-frequency, extratropical variability in the global weather. Therefore, it is advantageous to use blocking as an indicator for evaluating the potential of a local snowfall event in the results of reanalyses and weather forecasts or seasonal predictions.

2. Strategy and data

2.1 Local snowfall data

In this study, our aim is to determine the large-scale features associated with local snowfall distributions obtained at the observation points of the Japan Meteorological Agency (JMA, Fig. 1). Moreover, we make the timescale of a local snowfall event correspond with that of a large-scale circulation: separating the spatial scales but synchronizing the timescales between them (cf. Minobe et al. 2016). Based on these strategies, we used the 10-day accumulated (bi-pentad) local observation data of the amount of snowfall. The period of data used was the winters (December–February, DJF) of 1980/1981–2016/2017 for a total of 333 bi-pentads (nine bi-pentads for each winter).

The P-, M-, and PM-type snowfall events were defined using observation data. Snowfall amounts at the five (six) observation points of Niigata, Niitsu, Nagasaki, Shimozeki, and Tsugawa (Yuzawa, Sekiyama, Tsunan, Tohkamachi, Koido, and Sumon, which was originally Irihiro) were gathered as P-type (M-type) regional snowfall (Fig. 1). The P- and M-type regional snowfall amounts were averaged across all available observations for each bi-pentad. Note that these points were selected based on correlation analysis performed by Iwamoto et al. (2008). Because they calculated correlations in the daily data, we focused on the 10-day accumulated data concerning the mutual correlation coefficients of all P- and M-region points (Table 1). Table 1 summarizes high correlations even between P- and M-region points and a moderate gap in the coefficients between the M and P regions, indicating that the characteristics of snowfall variation in the M and P regions are to some extent independent of each other. In addition, it is worth mentioning that, at most, the P and M regions are 10–100 km apart, which is much smaller than the spatial scale of low-frequency variabilities. The gap found in the correlation despite such small differences in the spatial scale implies that the P- and M-type snowfalls can occur even within the timescale of low-frequency variabilities as well as those in synoptic disturbances.

A high correlation between snowfall amounts in the P and M regions was found over different timescales, which correspond to the PM-type snowfall variations. Snowfall amounts in both regions were found to be positively correlated with coefficients of 0.69, 0.79, and 0.82 for the daily, 5-day, and 10-day timescales, respectively (Supplement 1). Independent P- or M-type snowfall events could be more frequent over the shorter timescales. This implies that local snowfalls in each region tend to be directly triggered by meso–synoptic scale disturbances. However, we here focus on the P- and M-type snowfall events that sometimes occur in the 10-day timescale (see Supplement 1 or Fig. 3 below), because these events have the
Fig. 1. Observation points in the plain-type (P-type) region (circles) and mountain-type (M) region (squares) and maps enclosing the points with topography (shaded area, m). The panels show the maps of the Northern Hemisphere (upper); the enlarged East Asian region, including Japan (left bottom); and the enlarged Niigata area (right bottom). Light, medium, and heavy, gray-shaded areas in the upper panel with contours indicate 1000-, 3000-, and 5000-m altitudes, respectively.

Table 1. The correlation coefficient matrix for all the six M-region points (Yz: Yuzawa, Sk: Sekiyama, Tn: Tsunan, Tk: Tohkamachi, Kd: Koide, and Sm: Sumon) and five P-region points (Ng: Niigata, Nt: Niitsu, Nk: Nagaoka, Ss: Shimoskeki, and Tg: Tsugawa). Correlation coefficients are calculated from 333 bi-pentads (37 winters), except where data were lacking. The altitude [m] of each observation point is denoted in each parenthesis in the first column. The names of the M regions are displayed in bold, and borderlines of rows and columns between the M and P regions are drawn for readers. Diagonal components and autocorrelation are not shown for brevity. The lower triangular components are also omitted here.
same timescale as low-frequency variabilities that can modulate the frequency and/or strength of such meso–synoptic scale disturbances.

The P and M region’s snowfall climatology and the deviation of each bi-pentad were defined as the average of bi-pentad snowfall amounts for the 37 winters and the difference from the climatology, respectively. The standard deviations were also defined for each bi-pentad. Figure 2 shows time evolutions (seasonal marches) of snowfall climatologies and standard deviations during November–March (15 bi-pentads per winter). We found that heavy snow bi-pentads occur from December to February. Thus, we analyzed the 10-day timescale data during December–February. Local snowfall indices $I_P$ and $I_M$ were then defined as snowfall deviations normalized by the standard deviation for each bi-pentad in the P and M regions, respectively (Fig. 3).

Fig. 2. Snowfall climatologies (cm) with standard deviations (boxes) and maximum and minimum values (whiskers) for each bi-pentad for the P region (a) and M region (b) during November–March of 1980/1981–2016/2017. The horizontal axis indicates the time sequence of bi-pentads from November (N) to March (M).

Fig. 3. Scatter diagram for the normalized snowfall deviations in the P region ($I_P$, horizontal axis) and M region ($I_M$, vertical axis) for all the bi-pentads (crosses). The circles, squares, and triangles indicate the top 15 bi-pentads for the P, M, and PM types, respectively. For the readers, thin and thick lines are drawn at the 0.0 and ±1.0 normalized snowfall deviations, respectively.
The P-, M-, and PM-type snowfall events were defined as the top 15 bi-pentads with the largest $I_P$ and/or $I_M$. Here, the P-type (M-type) events represent the top 15 bi-pentads with the largest $I_P$ ($I_M$), with $I_M$ ($I_P$) being less than a standard deviation of $+1.0$ (Fig. 3). The PM-type events were defined as the top 15 bi-pentads with the largest normalized deviations in both the P and the M regions (the whole Niigata area), which correspond to normal-type events belonging to the most dominant EOF mode found in the research conducted by Akiyama (1981a, b). Figure 3 shows that a strong covariability exists between the snowfalls within the P and the M regions, as summarized in Table 1, which corresponds to the most dominant snowfall variability in the 10-day timescale. This characteristic is similar to that found in the daily and 5-day timescales (cf. Akiyama 1981a). Moreover, we found that, sometimes, a large amount of snowfall only occurs in the P or M region during several bi-pentads. Thus, Table 1 and Fig. 3 show that the P-, M-, and PM-type snowfalls also exist in a 10-day timescale. The top 15 bi-pentads of the P-, M-, and PM-type snowfalls selected in this study are listed in Table 2.

### Table 2. Selected top 15 snowfall bi-pentads for the P, M, and PM types. The columns list the top 15 bi-pentads for the (left) P, (middle) M, and (right) PM types. Ranks of the normalized snowfall deviations in the top 15 bi-pentads are displayed in parentheses. The early (1st to the 10th day of a month), middle (11th to the 20th day of a month), and late (21st to the last day of a month) bi-pentads are written as “Early”, “Mid”, and “Last”, respectively.

| Selected top 15 bi-pentad periods | P-type                  | M-type                  | PM-type                  |
|----------------------------------|-------------------------|-------------------------|-------------------------|
| Mid January 1982 (11)            | Mid Jan 1981 (3)        | Mid Jan 1981 (11)       |
| Early February 1983 (13)         | Last Feb 1983 (10)      | Last December 1984 (1)  |
| Mid Feb 1983 (1)                 | Early Jan 1987 (12)     | Mid Dec 1985 (5)        |
| Early Jan 1984 (9)               | Early Feb 1991 (11)     | Early Jan 1986 (3)      |
| Last Jan 1984 (7)                | Last Feb 1992 (13)      | Last Jan 1986 (14)      |
| Early Jan 1985 (10)              | Last Jan 1997 (5)       | Early Dec 1987 (2)      |
| Last Jan 1988 (5)                | Mid Feb 1997 (9)        | Mid Feb 1988 (8)        |
| Mid Dec 1988 (14)                | Early Jan 1999 (6)      | Mid Jan 1995 (10)       |
| Last Feb 1991 (2)                | Mid Feb 2000 (2)        | Last Feb 2000 (12)      |
| Mid Dec 1994 (6)                 | Mid Feb 2002 (8)        | Mid Jan 2001 (9)        |
| Mid Feb 2001 (12)                | Early Jan 2006 (14)     | Mid Dec 2005 (7)        |
| Last Feb 2005 (4)                | Mid Feb 2008 (1)        | Last Dec 2005 (15)      |
| Mid Dec 2009 (8)                 | Last Dec 2011 (7)       | Early Dec 2012 (4)      |
| Early Feb 2012 (3)               | Last Jan 2012 (15)      | Early Dec 2014 (6)      |
| Mid Feb 2012 (15)                | Mid Feb 2013 (4)        | Mid Dec 2014 (13)       |

2.2 Interannual variability

The interannual variabilities of the PM-, P-, and M-type snowfall events were examined. Here, the P-type (M-type) snowfall event is defined as a normalized snowfall deviation with more than $+1.0$ in the P region (M region) and a normalized snowfall deviation with less than $+1.0$ in the M region (P region) during a bi-pentad. Conversely, the PM-type snowfall event is defined as deviations with more than $+1.0$ in both the P and the M regions. The snowfall events in the P, M, and PM types were 20, 21, and 32, respectively (Table 3). Figure 4 shows the interannual
variability during 1980/1981–2016/2017. Findings from this figure are summarized as follows:

- PM-type snowfall events were more frequent than the P- and M-type snowfall events. This can be found in Fig. 3 as the most dominant covariability (high correlation) between the P and M regions’ snowfall deviations.
- One type of the snowfall events at most occurred 2–3 times during one winter, except for the PM type during the winter of 1985/86, for which the snowfall event occurred six times. This implies that each type of snowfall event occurs intermittently rather than continuously during one winter, which is similar to the nature of low-frequency variability, including blocking (Itoh and Kimoto 1999).
- Snowfall event frequencies in all types appear modulated in several-year–decadal timescales, e.g., snowfall events were more frequent in the early 1980s but less in early 2000, implying that the snowfall occurrence frequencies would be modulated by climate variability on decadal timescales. Note that such decadal, local snowfall variations were found for the Toyama area (Yamashita et al. 2012).

The seasonal marches during the winter of each snowfall-type event are also summarized in Table 3. The table summarizes that the PM-type snowfall can occur throughout winter, whereas the P- and M-type snowfalls tend to occur in mid-winter rather than in early winter.

3. Composite maps

Large-scale circulations were examined using the JRA-55 long-term global reanalysis dataset (Kobayashi et al. 2015). In the reanalysis data, 37 winters (DJF) between 1980/1981 and 2016/2017 were used. The horizontal resolution was $1.25^\circ \times 1.25^\circ$, and daily fields averaged from 6-h fields were analyzed. The climatologies and anomalies were defined as 37 winter averages at calendar days and deviations from these averages, respectively. Then, 10-day averaging was conducted on both the climatologies and the anomalies.

The large-scale features for the selected P-, M-, and PM-type snowfall events (Table 2) were determined. For the top 15 snowfall bi-pentad periods, 10-day averaged anomalies were composited.

Before discussing anomaly fields, we describe the climatological features related to wintertime in East Asian regions. Figure 5 shows the climatology averaged over 37 winters. In the lower troposphere (Figs. 5a, b), the East Asian region, including Japan, is relatively colder than that in the mid-latitudes because of the northerly–northwesterly winds occurring between the Siberian High and the Aleutian Low, indicating that the region is frequently influenced by cold air masses (CAMs) originating from Arctic regions (e.g., Iwasaki et al. 2014). In the upper troposphere (Fig. 5c), the region is located below the large-scale trough extending from the polar vortex, or the polar cold air mass in the upper troposphere, at the westerly jets flowing circumglobal in mid-latitudes. The jet over Japan originates from two branches of strong westerlies over the Eurasian continent. We call these branches Eurasian jets. The Eurasian jets are composed of subtropical and subpolar jets. The subtropical jet extends from North Africa to South China (Fig. 5c). Along the jet, there is a Rossby waveguide visualized as a great gradient of potential vorticity (PV) in the upper troposphere (Fig. 5d). The subpolar jet is weaker, but it intermittently appears as the secondary jet axis from Northern Europe to North China via Russia and is evident as a moderate waveguide region (Figs. 5c, d). Thus, quasi-stationary Rossby waves can propagate along the two jets toward the climatological trough over Japan.

3.1 Conditions in the lower troposphere

Composite maps for the SLP field in the PM, P, and M types are shown in Fig. 6. The anomaly fields show patterns of intensification of the Siberian High and/or the Aleutian Low across all types, indicating the enhancement of the winter East Asian monsoon (e.g., Takaya and Nakamura 2005a; Sakai and Kawamura 2009; Yamashita et al. 2012; Shoji et al. 2014). Interestingly, the patterns show differences among the three types; both the Siberian High and the Aleutian Low are intensified in the PM type, whereas only the Siberian High is intensified in the P type and only the Aleutian Low is intensified in the M type. These results support the idea that large-scale variabilities are tied to the local snowfall distributions.

A factor that promotes snowfall occurrence is possi-
Fig. 5. Winter climatology in (a) sea-level pressure (SLP, hPa), (b) temperature (contour, °C) and wind (arrows, m s\(^{-1}\)) at 850 hPa, (c) geopotential height (Z250, contour, m) and the wind magnitude (shade) at 250 hPa, and (d) potential vorticity (PV, contour, PVU) and magnitude of the horizontal PV gradient (the effective \(\beta\), shade, 10\(^6\) PVU m\(^{-1}\)) at 320 K. The dataset is from JRA-55.

Fig. 6. Composite anomalies of SLP (contours, hPa) in the (a) PM, (b) P, and (c) M types. Shades indicate significance at the 95 % level in the \(t\)-test. Contour intervals are 1 hPa (zero contours are omitted). Dashed (solid) lines are for negative (positive) values.
ably a lower temperature condition in the lower troposphere compared with that usually experienced during winter. We drew composite maps of temperature anomalies at 850 hPa and flow streams of cold air (Fig. 7) and found that negative temperature anomalies prevailed over Japan in all types (black dashed contours), which is consistent with the intensification/extension of the Siberian High and/or the Aleutian Low during the snowfall period (Fig. 6). With the exception of different timescales, this finding is also consistent with that of a study conducted by Takeuchi et al. (2008).

The origins of the CAMs that cause negative temperature anomalies in each type were explored using the CAM flux proposed by Iwasaki et al. (2014). The CAM flux $F$ is defined as the flux of the sum of the mass (i.e., CAM) below a threshold isentropic surface in the lower troposphere:

$$ F = \int_{p(\theta)}^{p_s} v \, dp, $$

where $p_s$ and $p(\theta_T)$ are the ground surface pressure and the pressure on the threshold isentropic surface $\theta_T$, respectively, and $v$ is the horizontal wind field vector. Since the CAM flux is based on the conservative laws of air mass and thermodynamics, it can quantify the strength and directions of CAM movements related to the extratropical meridional circulation (Iwasaki and Mochizuki 2012; Iwasaki et al. 2014; Kanno et al. 2015a). The CAM flux can thus capture cold air outbreaks from the polar regions, where the polar CAM accumulates during winter, in the synoptic and longer timescales (e.g., Shoji et al. 2014; Kanno et al. 2015b; Abdillah et al. 2017, 2018). $\theta_T$ is defined as 280 K (Iwasaki et al. 2014).

The climatological features of the CAM flux are shown in Fig. 7a. It can be clearly discerned that much of the polar CAM intrudes toward Japan across the large-scale topographies in East Asia and Siberia.

The 10-day averaged CAM flux anomalies in the PM, P, and M types (Figs. 7b–d) show different stream anomalies between the PM or P type and the M type. In the PM and P types, polar CAM anoma-
lies run from the north of eastern Siberia toward the northeast of the large mountainous area in central Eurasia (around 120°E) through the south of eastern Siberia and the Sea of Okhotsk, and then are directed southeastward to the Far East, including Japan. In the M type, polar CAM anomalies over the Arctic Ocean anticyclonically move through the Bering Strait toward the south of the Sea of Okhotsk and shift southward over the Far East (around 140°E), where they rotate cyclonically. Despite the different paths of polar CAM anomalies between the snowfall event types, they all enhance the climatological south-eastward/southward CAM flux toward Japan through the Sea of Japan. Thus, cold temperature anomalies prevail around Japan in all types. Interestingly, the CAM flux anomalies in eastern Siberia and the Far East showed that Siberian blocking in the upper troposphere can regulate the CAM streams over the East Asian regions and therefore enhance cold air outbreaks toward Japan (see Section 5).

The enhanced cold air outbreaks promote active turbulent heat fluxes from the Sea of Japan and can cause convective instability, resulting in a considerable amount of snowfall over the Niigata area. Here, the convective instability was measured as the vertical inverse of the equivalent potential temperature $\theta_e$ (Yoshizaki and Kato 2007). We simply counted the number of layers $\sum(\theta_e)_{rev}$ that had $\theta_e$ greater than one of the upper layers below 750 hPa in JRA-55\(^3\), where $0 \leq \sum(\theta_e)_{rev} \leq 11$. Larger $\sum(\theta_e)_{rev}$ indicates more potential convection. We calculated the winter climatology of $\sum(\theta_e)_{rev}$ averaged during the DJF of 1980/1981–2016/2017 and the composite of each of the top 15 bi-pentads in each type deviated from the climatology.

Figure 8a shows the climatology of $\sum(\theta_e)_{rev}$ and wind streamlines at 925 hPa. The climatological map shows a large convective instability over the Sea of Japan, particularly over the offshore side of Japan, and southeastward wind directions. Figures 8b–d show the 10-day averaged anomalies (deviations) in the PM, P, and M types. The instability was found to be significantly greater over the Sea of Japan in all snowfall event types compared with the climatological one, indicating that the potential of convections is higher during the snowfall event. Furthermore, the patterns of the more actively unstable areas are different among the types. In the PM type, the streamlines over the Sea of Japan are southeastward, and positive instability anomalies mostly cover the Sea of Japan. The climatological winter East Asian monsoon seems to be enhanced in this type. In the P type, the streamlines are rather eastward, and the positive anomalies are located offshore of northern Japan and to the west of the Niigata area. In the M type, dominant northerlies prevail over the north of Japan, and the convective instability is active nearshore of Tohoku and in central areas of Japan. The wind directions for these types are similar to those found in the daily timescale (Iwamoto et al. 2008). Therefore, the convective instability and wind streamlines over the Sea of Japan have considerably different patterns among the types, even though they are relatively smaller spatial scales (just over the Sea of Japan) compared with other large-scale fields.

In addition, it should be discussed how the lower-tropospheric conditions could support synoptic conditions that lead to local snowfall. Figure 9 shows composite maps in SLP and temperature at 850 hPa for each type of snowfall event but close to Japan. The SLP fields show that the P type is different from the PM and M types. The SLP anomaly in the P type implies that monsoonal northwesterlies become weaker locally around Japan, and vice versa in the PM and M types. In the P type, a negative SLP anomaly was also found prevailing over the Sea of Japan. These are consistent with the rather weak and strong monsoonal situations in the traditional P and M types, respectively, similar to the synoptic scale study (cf. Akiyama 1981b; Yoshizaki and Kato 2007). The 850-hPa temperature field in the M type is not relatively colder than those in the PM and P types, even though they all were significantly cold against the climatology (see Fig. 7). This may indicate that colder air temperature in the lower troposphere contributes to much snowfall in the P region, which is also found in the synoptic field (Yoshizaki and Kato 2007). Thus, the near-surface and lower-tropospheric fields in the PM, P, and M types can support the different synoptic conditions, implying different roles of large-scale circulation anomalies in the upper troposphere and the CAM stream field on meso–synoptic scale disturbances.

3.2 Conditions in the upper troposphere

The upper-level circulation anomalies (geopotential height at 250 hPa, Z250) and quasi-stationary Rossby wave packets related to the subpolar and subtropical jets in the types are shown in Fig. 10. The negative Z250 anomalies (cyclones), i.e., intensified trough, commonly appear over Japan in all types. These characteristics are consistent with the circulation patterns in the P and M types found in synoptic times-
When the anomalies in between the types were compared, the PM type was found to be the strongest and the anomaly in the P (M) type was located slightly toward the Sea of Japan (Pacific Ocean) relative to Japan. Additionally, positive Z250 anomalies (anticyclones) can be found over the Siberian region in the PM and P types and over the south of China in the PM and M types. The former occurs along the subpolar jet, whereas the latter occurs along the subtropical jet.

The Rossby wave packets along the subtropical and subpolar jets can be seen as sequential positive-negative patterns of anomalies or lines of the wave activity flux (Takaya and Nakamura 2001). The subtropical wave packet can be found in the M and PM types but not in the P type. This wave packet can be clearly distinguished using the 250-hPa meridional wind (V250) anomaly fields in Fig. 11, as per the research conducted by Branstator (2002) and Watanabe (2004). The subtropical wave packet in the P type is interrupted over the south of China, where the anticyclonic anomalies can be found (Fig. 10). The subpolar wave packet is also found in the PM and P types, although it does not appear in the M type.

In summary, we found that the occurrence of the PM-, P-, and M-type snowfall events was commonly associated with the enhanced upper-level trough identical to the cyclonic anomalies over Japan, although

Fig. 8. Same as Fig. 7 but for the index of the convective instability $\sum(\theta_e)_c$ in the lower troposphere. Shades are shown for only areas with 95% significance level. Streamlines indicate winds at 925 hPa for (a) the climatology and (b–d) 10-day averaged raw values of the composites.
the anomaly in the P (M) type was located relatively westward (eastward) and that in the PM type was zonally broad. However, the causes of the cyclonic anomalies differed between the types; Rossby wave packets along the subpolar and subtropical jets contributed to the anticyclonic anomalies over Siberia and the south of China, respectively, and both enhanced the trough in the PM type, whereas the wave packet along the subtropical (subpolar) jet was hampered over the south of China during the P-type (M-type) snowfall. Note that the upper-level circulation field in the PM type appeared to be consistent with that of Inaba and Kodera (2010), who found that quasi-stationary Rossby wave propagation along these jets led to cold temperatures in Japan in December 2005: Two bi-pentads belonging to this month were
among the top 15 bi-pentads of the PM type (Table 2). Because the anticyclonic anomalies in the PM and M types located upstream of the trough along the subtropical jet are significant, they may also result from tropical forcing. The anticyclonic anomalies in the PM and P types upstream along the subpolar jet can interact with the Siberian High and enhance each other (Takaya and Nakamura 2005a), as shown in Fig. 6. It is noteworthy that although the spatial scale used to classify the snowfall types is less than 10^2 km, circulation anomalies are different even at a large scale. It could be concluded that local snowfall distributions over the whole Japan-Sea side areas would change with small but distinguishable differences in the large-scale circulations associated with the PM, P, and M types, despite the fact that classification was based on only the Niigata area.

4. Dominant jet variability over Eurasia

In this section, we discuss why the PM-type snowfall events are more frequent than the P- and M-type snowfall events (Table 3, Figs. 3, 4), and we try to separate the roles of the Rossby wave packets along the subtropical and subpolar jets.

The results presented in Section 3 showed that the P- and M-type snowfalls have signals along the subpolar and subtropical jets, respectively, and the PM-type snowfall has signals along both of the jets. It is interesting that if the signals along the subtropical and subpolar jets are independent of or negatively correlated with each other, the frequency of the PM-type snowfall might be equal to or less than those of the P- and M-type snowfalls because these signals can appear simultaneously by chance. It is important to understand the reason why the signals in both of the jets can coexist.

Figures 12a and 12b show the first and second dominant EOF modes (EOF1 and EOF2, respectively) in V250 over the Eurasian domain (0–140°E, 10–90°N) against 333 bi-pentad periods during winter. EOF1 and EOF2 are characterized by signals along the subtropical jet, which can be clearly found in the mid-latitudes from Europe to Japan. The proportions of EOF1 and EOF2 account for 21.0 % and 13.6 % of the total variance, respectively. EOF1 exhibits a pattern similar to that of the PM-type snowfall (Fig. 11a), and EOF2 is dominant along the subpolar jet. Thus, in the 10-day timescale, a Rossby wave packet is predominant along the subtropical jet, as found in the PM- or M-type snowfall. Such variations or signals would correspond to the circumglobal teleconnection pattern (Branstator 2002; Watanabe 2004).

In order to find covarying signals along the subpolar jet, regression with the principal components of EOF1 and EOF2 (PC1 and PC2) onto bi-pentad averaged Z250 fields was calculated (Figs. 12c, d). The regressed Z250 field onto PC1 exhibits a significant anticyclonic anomaly over northern Eurasia along with the subpolar jet accompanying the cyclonic anomaly over Japan, and regression onto PC2 exhibits an anticyclonic anomaly to the north of central Russia. These results support the notion that signals (wave packets) in the 10-day timescale along the subtropical and subpolar jets can covary with each other and can appear simultaneously. Therefore, it can be said that P-type (M-type) snowfall events occur in less dominant situations than PM-type events, thereby hampering a signal along the subtropical (subpolar) jet.

We attempted to create subpolar and subtropical jet indices associated with the signals along these jets.
that cause the local snowfall events. We selected the following centers of action on the basis of the anomaly patterns in Figs. 10 and 11, and we identified the bi-pentad subpolar and subtropical jet indices, i.e., $I_{SP}$ and $I_{ST}$, respectively, in the same manner as Yamashita et al. (2012) did:

$$I_{SP} \equiv -Z^*(20^\circ E, 45^\circ N) + Z^*(120^\circ E, 70^\circ N),$$

and

$$I_{ST} \equiv V^*(90^\circ E, 25^\circ N) - V^*(125^\circ E, 40^\circ N),$$

where $Z^*$ and $V^*$ indicate the bi-pentad averaged $Z_{250}$ and $V_{250}$ anomalies from the bi-pentad climatology at the geographical points, respectively. Note that the selection of these centers was reasonable based on regressed patterns of the $Z_{250}$ and $V_{250}$ fields onto the 10-day averaged local snowfall indices (Supplement 2). Using the bi-pentad $I_{SP}$ and $I_{ST}$, signals along the subpolar and subtropical jets were reproduced, as illustrated in Fig. 13. The signals clearly capture the separate Rossby wave packets along the subpolar and subtropical jets. The subpolar and subtropical signals have their wave sources near the north of the Mediterranean Sea and antinodes over Japan in close geographical proximity. The subpolar and subtropical jet signals were found to have similar
patterns from the 10-day to the 30-day averaged fields (Supplement 2), which implies that dominant low-frequency jet variabilities along these jets could be resolved, even in the 10-day averaged fields.

The relationship between \(I_{SP}\) and \(I_{ST}\) suggested that these signals could coexist, especially when the Rossby wave packets were active; the correlation coefficient between these indices was positive (0.29), and the ratios of bi-pentads when \(I_{SP}\) and \(I_{ST}\) have the same polarity to all the bi-pentads became greater as the amplitudes of \(I_{SP}\) or \(I_{ST}\) became larger (Supplement 3). The covariability of the subpolar and subtropical signals has been discovered by Sakai and Kawamura (2009) who applied an EOF analysis to the wintertime monthly mean 200-hPa stream function anomalies within a specific Eurasian region. Our results are consistent with their findings, except regarding the difference of timescales; we found covariability even on timescales shorter than a month (10 days).

Note that some previous studies have already focused on the Rossby wave packets along the subpolar and subtropical jets that can cause heavy snowfall in Japan. For example, Barnston and Livezey (1987) found teleconnection patterns across Eurasia through an EOF analysis. Yamashita et al. (2012) successfully separated those packets and quantified the subpolar and subtropical jet indices on the synoptic timescale. The subpolar pattern of the signals seems to be similar to that in Fig. 13b, whereas the subpolar pattern appears further southward and westward than that in Fig. 13a. Tachibana et al. (2007) obtained subpolar signals associated with the Eurasian (EU) pattern related to snowfall events over a Pacific-side area of Japan on the monthly timescale; however, the pattern that they found is shifted westward compared with the subpolar signals in the present study. The shifts of subpolar signals might be related to different timescales or to snowfall events in different regions. Similar subpolar patterns were found by Sakai and Kawamura (2009) and Inaba and Kodera (2010) for DJF-averaged fields and the case of December 2005, respectively, similar to the subpolar signals identified in this study. They also mentioned that stronger subpolar and subtropical signals contribute to colder and more heavily snowed winters in Japan.

As will be found in Section 6, blocking over the Siberian region was another contributor to more frequent PM-type snowfall than the P- or M-type one.

5. Relationship with Siberian blocking

As another factor of the Rossby wave packets along the Eurasian jets, Siberian blocking occurring close to Japan can affect local snowfall because the cyclonic anomalies over Japan are quasi-stationary and can compose meridional dipole structures with quasi-stationary or instantaneous anticyclones northward over the Siberian region. As such, we speculated that the quasi-stationary anomalies correspond to atmospheric blocking characterized by the meridional reversal of a geopotential gradient, namely, a temporal large-scale easterly in the mid-latitudes (e.g., Pelly and Hoskins 2003). To determine this correspondence, we examined whether blocking events significantly occur during the snowfall events.

Blocking events were detected based on a two-dimensional index presented in a study by Masato et al. (2013b). A large-scale meridional reversal in the daily geopotential height field at 500 hPa was detected using the following equation:

\[
B(\lambda_0, \phi_0) = \frac{2}{\Delta \phi} \left[ \int_{\phi_0 - \Delta \phi/2}^{\phi_0 + \Delta \phi/2} Z(\lambda_0, \phi) d\phi - \int_{\phi_0 - \Delta \phi/2}^{\phi_0 + \Delta \phi/2} Z(\lambda_0, \phi) d\phi \right],
\]

where \((\lambda_0, \phi_0)\) are the central longitude and latitude of blocking, respectively, \(\Delta \phi = 30^\circ\), and \(Z\) is the geopotential height. The blocking index \(B\) is expressed as follows:

\[
B(\lambda_0, \phi_0) = \begin{cases} 
1 & \text{where } B > 0 \\
0 & \text{where } B \leq 0.
\end{cases}
\]

On any day, blocking occurs when \(B = 1\) and does not when \(B = 0\). Since the distributions of the blocking index can be obtained for each day, we evaluated the blocking frequency as a 10-day averaged blocking index, which represents the probability of blocking occurrence during a 10-day period. Using the blocking index, blocking frequencies in the Siberian region were quantified. Figure 14a shows the climatology of the blocking frequency distribution. We found that East Siberia, namely, the north of the Far East, is the most frequent region of blocking.

Figures 14b–d show 10-day averaged deviations of the blocking index from the climatology during the PM-, P-, and M-type snowfall events. The blocking frequencies increased in all types, suggesting that the persistent cyclonic anomalies over Japan with anticyclonic anomalies northward (Fig. 10) were significantly equivalent to atmospheric blocking over East Siberia. Additionally, the blocking positions were located to the northwest (northeast) of Japan in the PM and P types (M type) according to the central blocking posi-
tions in the types denoted by maxima in the frequency deviations (cross signs in Figs. 14b–d). Therefore, the PM-, P-, and M-type blocks have different central positions. This would reflect the difference in relative positions and shapes of the cyclonic and anticyclonic anomalies apparent in Fig. 10.

We will next investigate the relationship between Siberian blocking and the CAM streams over East Asian regions. Regression and correlation analyses were conducted by determining bi-pentad indices of the Siberian blocking frequency, defined as follows:

\[ I_{WB} \equiv \overline{B}(100^\circ - 135^\circ E, 50^\circ - 60^\circ N), \]
\[ I_{CB} \equiv \overline{B}(117.5^\circ - 152.5^\circ E, 50^\circ - 60^\circ N), \]
\[ I_{EH} \equiv \overline{B}(135^\circ - 170^\circ E, 50^\circ - 60^\circ N), \]

where \( \overline{B} \) indicates the area-averaged blocking index Eq. (5) within the regions denoted in the brackets. The area-averaged regions were defined on the basis of the anomaly patterns in Figs. 14b–d.

Figure 15 shows a regression map of Z250 and CAM flux fields on the Siberian blocking index \( I_{CB} \). In Z250, we can find the blocking anticyclone over East Siberian regions and the blocking cyclone over Japan. As inferred from Fig. 7, the CAM stream was significantly modulated by the blocking: The regressed CAM flux anomalies were found along the fringe of the blocking anticyclone, and the southwestward/southward movements of the CAM stream toward Japan through the Sea of Japan were significantly promoted. Note that the geographical positions of the promoted movements were fixed irrespective of the slight shifts of Siberian blocking, that is, choice of \( I_{CB} \), \( I_{WB} \), or \( I_{EH} \) (not shown). Therefore, Siberian blocking in the upper troposphere supports colder conditions in the lower troposphere, which are advantageous for the occurrence of snowfall.
In summary, the increased probability of the Siberian blocking frequency during the snowfall events, and the differences in the relative Siberian blocking positions between the PM-, P-, and M-types were found. These results are beneficial in proactively detecting circulation anomalies in the large-scale circulations that cause the local snowfall events. This is because blocking is easily detected in global reanalyses or models, and the timescale of blocking predictability is generally longer than that of snowfall predictability in a local region.

6. Relative contributions of Eurasian jet signals and Siberian blocking on local snowfall variations

Hereafter, we try to quantify the relative contributions of the Rossby wave signals along the subpolar and subtropical jets and Siberian blocking to local snowfall events. Here, we used the jet and blocking indices of Eqs. (2)–(3) and (6)–(8) as global indices. In this section, we redefined these indices as daily-based 10-day running means but not as bi-pentad ones. Local snowfall indices for the P and M regions, i.e., \( I_p \) and \( I_m \), respectively, were also redefined as 10-day running averages of daily snowfall amounts in the P and M regions. These daily snowfall indices were normalized by the daily standard deviation from the 10-day running averaged climatology for 1980/1981–2016/2017 at each calendar date. The indices during DJF of 1980/1981–2016/2017 were used, as with all the bi-pentad periods.

Table 4 presents the mutual correlation coefficients between the local snowfall indices and the global indices. These coefficients indicate that both of the Eurasian jet signals can contribute to the local snowfalls in both regions. Comparing their relative contributions, the subpolar (subtropical) signals contribute more than the subtropical (subpolar) signals to the P-region (M-region) snowfall, which is consistent with the discussion in Sections 3 and 4. Siberian blocking also contributes to both P- and M-region snowfalls. The contribution (correlation) of \( I_{CB} \) was the largest among Eqs. (6)–(8).

The relationship between the jet signals and Siberian blocking is found in Table 5. It is found that the jet signals and the blocking do not suppress each other. The subpolar jet signals are highly correlated with Siberian blocking frequency, indicating that Siberian blocking tends to occur simultaneously during the subpolar signals. The correlation between the subtropical jet index and blocking frequency was positive but small: The subtropical jet signals appear to be more independent of Siberian blocking. It can also be found that the subpolar (subtropical) signals are related more to western (eastern) Siberian blocking than at the other longitudes.

The global indices were found to be capable of explaining local snowfall variations. Thus, the practical use of the indices with forecast or reanalysis datasets would be valuable for examining the predictability of regional snowfall events over the Niigata area.

7. Discussion: Tropical forcing

In this section, we discuss other characteristics of the large-scale circulations beyond the extratropics;
large-scale convective activities far in the tropics.

It would be interesting to examine the tropical circulations in outgoing longwave radiation (OLR) related to the snowfall events. The climatology exhibits active convective regions in the Maritime Continents (around 120°E) extending near the equator and to the south (~ 5°S) and relatively inactive regions over the northern hemispheric subtropics from the northern Indian Ocean to the Philippine Sea (Fig. 16a).

In the OLR anomaly fields during the PM-, P-, and M-type events (Figs. 16b–d), we found some signals of active convections over the Indian Ocean and the Maritime Continents. In the PM and M types, large-scale convections are more active over the climatologically active convective regions, although their relative active positions are different. The more active position in the PM type is relatively northward and that in the M type is located in the Southern Hemisphere (~ 10°S). Conversely, in the P-type snowfall, no significant convective signals are found in the active regions. Active convective anomalies over the Maritime Continents, found in the PM and M types (Figs. 16b, d), could be supported by tropical forcing such as the El Niño–Southern Oscillation and extratropical internal variability. Such convective anomalies can enhance the trough over Japan and the Siberian blocking frequency via a local Hadley circulation and stationary Rossby wave emission (e.g., Simmons et al. 1983; Chen 2002; Ueda et al. 2015). Chen (2002) proposed that higher-than-normal sea-surface temperatures in the western equatorial Pacific accompanied by La Niña events can emit energy fluxes of stationary Rossby waves from southern China to the North Pacific via the upper troposphere around Japan. The convective anomalies may support the local snowfall in a 10-day period along with subtropical jet variability, as found in the snowfall along the Japan-Sea side coastal areas of Japan at the seasonal timescale (Ueda et al. 2015).

8. Concluding remarks

In this study, we investigated the relationship between the dominant local snowfall patterns in a heavy snowfall area in the Japan-Sea side areas and the associated large-scale circulation anomalies. Along with the observations of the amount of snowfall in the Niigata area for every bi-pentad period, dominant local snowfall distributions in the 10-day timescale were classified as three well-known types: P, M, and PM types. Based on the three classifications of the bi-pentads, the associated large-scale circulation fields were composited and analyzed.

In the large-scale circulation fields in the three types, the intensification of the Siberian High and/or the Aleutian Low was found, commonly indicating enhanced winter East Asian monsoon that leads to cold weather conditions over Japan. In addition, intensified trough or cyclonic anomalies in the upper troposphere appeared over Japan. These cyclonic anomalies originated from a quasi-stationary Rossby wave packet along the subpolar jet over the northern part of Eur-
Asia in the P type, from that along the subtropical jet over the southern part in the M type, and from both wave packets along the jets in the PM type. Schematic pictures are shown in Fig. 17.

The cyclonic anomalies (cyclones) over Japan were found to be also associated with blocking over the East Siberian region in all types (Figs. 17b –d). The primary difference found in the Siberian blocks between the snowfall event types was their relative positions; blocking in the P type (M type) was distributed in the northwest (northeast) of Japan, whereas that in the PM type was located anywhere in eastern Siberia (the blocking frequency was zonally distributed). Furthermore, we found that these Siberian blocks promoted cold air intrusions in the lower troposphere from the polar regions toward the Far East, including Japan, which is favorable for heavy snowfall in the Japan-Sea side areas of Japan.

Year-to-year occurrence of each snowfall event type seemed to be modulated in several-year–decadal timescales. We also found that PM-type snowfall was the most frequent, because it was accompanied by both dominant subpolar and subtropical jet signals, which tend to coexist (e.g., Sakai and Kawamura 2009), and Siberian blocking. During the P-type (M-type) snowfall, the signals along the subpolar (subtropical) jet were temporally hampered.

We would thus conclude that these snowfall types were tied to extratropical internal variability rather than to other external forcing, although the tropical active convective anomalies in OLR that might be related to tropical oceanic variability can support or suppress the extratropical variability.

The following are strategies stemming from this study for clarifying the relation between the local-/regional-scale and global-/large-scale phenomena:

- We focused on 10-day timescales rather than daily ones. This strategy might enable the efficient extraction of the impact of low-frequency variabilities dominant in the global scale on the regional weather/climate, because the timescales can filter out the direct effects of meso-synoptic scale disturbances.
The choice of 10 days rather than a month would be efficient to determine the impacts of blocking.

- The large-scale circulation characteristics in the reanalysis were “restored” based on the index defined in the local observations, which is the same method as that used by Iwamoto et al. (2008), Yamashita et al. (2012), and Ueda et al. (2015). Such a method makes it easy for the relationships between the general circulation and regional weather events to be found.

Further questions to be investigated are listed as follows:

1. A detailed process connecting the large-scale circulation anomalies to individual snowfall events accompanied by a convective system: Here, we could not investigate the mesoscale fields associated with the large-scale circulations, since it was difficult to sufficiently investigate such small and short scale processes in the global reanalysis. Using radar and mesoscale analysis data and dynamical downscaling approaches using convection-permitting models may be promising (e.g., Nakai et al. 2005; Kawase et al. 2015; Kayaba et al. 2016; Fukui et al. 2018).

2. Formation and maintenance mechanisms of the Siberian blocking: The Siberian blocking discussed herein is a high-latitude blocking rather than a mid-latitude one. One can discuss how mid-latitude blocking is formed and/or maintained by major storm tracks or tropical forcing; however, blocks in the high latitudes are located far from the storm tracks or the tropics.

3. Predictability of the occurrences of snowfall event types: Although we could determine the characteristics in the large-scale circulations that can cause regional snowfall events, we could not investigate their predictabilities. Related to such predictability, Matsueda and Kyouda (2016) studied the predictabilities of dominant winntertime synoptic–large-scale weather patterns in East Asia. Interestingly, some patterns were found to accompany P- or M-type precipitation patterns in the Niigata area (Matsueda, personal communication). Their results may be helpful for elucidating the predictability of the snowfall event types.

Supplements

Supplement 1 shows scatter diagrams of snowfall amounts in the P and M regions summed up for daily, 5-day running, and 10-day running periods. Supplement 2 shows regression maps of the Z250 and V250 fields onto 10-day, 20-day, and 30-day running averaged daily local snowfall indices. Supplement 3 shows the scatter diagram between the bi-pentad subpolar and subtropical jet indices ($I_{SP}$ and $I_{ST}$).

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