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Snowfall variations in Japan and its linkage with tropical forcing

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ABSTRACT: In this study, the causes of inter-annual variability of wintertime snowfall in the coastal plain facing the Sea of Japan over the past 33 years (1980–2012) are investigated. The observational evidence showed that intensified cold air intrusion from the Eurasian continent towards Japan in combination with anomalous cyclonic circulation favours *in situ* heavy snowfall. The composite analysis of the tropical convection during the heavy snow winters indicates that enhancement of convection in the vicinity of the Philippines, including the eastern Indian Ocean, is responsible for the emergence of anti-cyclonic circulation over the Asian continent and subsequent anomalous cyclonic circulation around Japan. Idealized experiments by use of the linear baroclinic model (LBM) were conducted to elucidate the origin of the teleconnection. We put idealized diabatic heating in the LBM under the wintertime atmospheric circulation and examined the heat-induced response. The experimental results clearly indicated that the intensified convection over the maritime continents and the neighbouring oceans is primarily responsible for the pair of the anti-cyclonic and cyclonic circulation. Thus, a study of the predictability of the tropical forcing may shed light on the predictable dynamics of snowy winters in Japan.

KEY WORDS heavy snow; East Asia; La Niña

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1. Introduction

Wintertime snowfall represents a major water source in the northern part of Japan. In particular, the Sea of Japan side is known as one of a heavy snow area in the world (Manabe, 1957). Therefore, understanding the inter-annual variations of snowfall is a prerequisite to improve the accuracy of the seasonal prediction. The climatological view of the snowfall process is directly linked with the northwesterly monsoon flow, which is associated with the development of both the Siberian high and the Aleutian low (Matsumoto, 1992). The boundary layer northwesterlies originated from the Siberian high exhibit a dry and cold air mass over the Asian continent; however, this mass becomes an unstable stratification by absorbing a large amount of moisture from the Sea of Japan (Manabe, 1958; Ninomiya, 1968; Matsumura and Xie, 1998). This modified air mass brings heavy snow over the backbone range of the Japan Islands aided by orographic lifting.

There are two schools of thought regarding the anomalous snowfall events in Japan (Fukaishi, 1961; Fujita, 1966; Tachibana, 1995). The first is the mountain-centered distribution of snowfall (hereafter referred to as M-type), which is characterized by an enhanced wintertime pressure gradient across Japan, namely, high pressure to the west and low pressure to the east, in conjunction with intensified cold air outbreaks. According to the second, deep pressure trough over the Sea of Japan sometimes lasts for a few days, during which cyclogenesis near the surface is enhanced due to the embedded cold vortex. The developed cyclone gives rise to intrusion of cold air into the mid-troposphere, causing unstable stratification and ensuing deep cumulous convection. These processes, associated with atmospheric blocking such as the cut-off low, also bring heavy snowfall over the coastal plains facing the Sea of Japan. With such a background, the snowfall-related synoptic disturbance is referred to as the plain-centered distribution of snowfall (henceforth referred to as the P-type).

The East Asian winter monsoon (EAWM) is one of the prominent circulations over the Eurasian continent that is characterized by cold air outbreaks originated from the Siberian high, having strong impact on local weather conditions over the broad East Asian regions (Wang *et al.*, 2000; Wang *et al.*, 2010). Thus the physical processes involved in modulation of the EAWM have received lots of attention in view of cold air outbreaks towards the subtropics as well as tropics (Chang *et al.*, 1980). The EAWM itself has the potential to be influenced by Arctic Oscillation (AO) as well as El Niño-Southern Oscillation (ENSO). However, the observational evidence showed that the AO and EAWM are almost independent of each other (Wu and Wang, 2002; Kawamura and Ogasawara, 2007; Nan and Zhao, 2012).

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As for the influence of ENSO on the EAWM, Hong and Li (2009) revealed that La-Niña related enhanced convection over the Asian Maritime Continent induces anomalous anti-cyclonic (cyclonic) circulation to the east (west) of 120°E, generating cold-air intrusion towards the subtropics. Sakai and Kawamura (2009) showed that intensified wintertime tropical convection over the western Pacific induces the anomalous cyclonic circulation accompanied by cold-air intrusion over and around Japan that is crucial factor for the anomalous snowfall in Japan. Recently, Nan and Zhao (2012) revealed that extreme snow event occurred over the central-eastern China in January 2008 is closely associated with confluence of the Asian atmospheric cold source at the surface and low-level southerly wind anomalies from the South Asia.

Despite these facts, our understanding of the fundamental controlling mechanisms for extreme snowfall as well as modulation of the EAWM caused by the AO or ENSO remained deficient especially for Japan. The aforementioned cyclonic circulation anomaly (Sakai and Kawamura, 2009) emerging over Japan bears resemblance with the typical atmospheric pattern relevant to the P-type. However, to our knowledge, a direct analysis between the heavy snowfall in the coastal region of the Sea of Japan side and atmospheric teleconnection patterns has not been performed until now. Therefore, we first identify the dominant circulation pattern explaining the heavy snowfall in the Sea of Japan side and then detect the source region of the teleconnection.

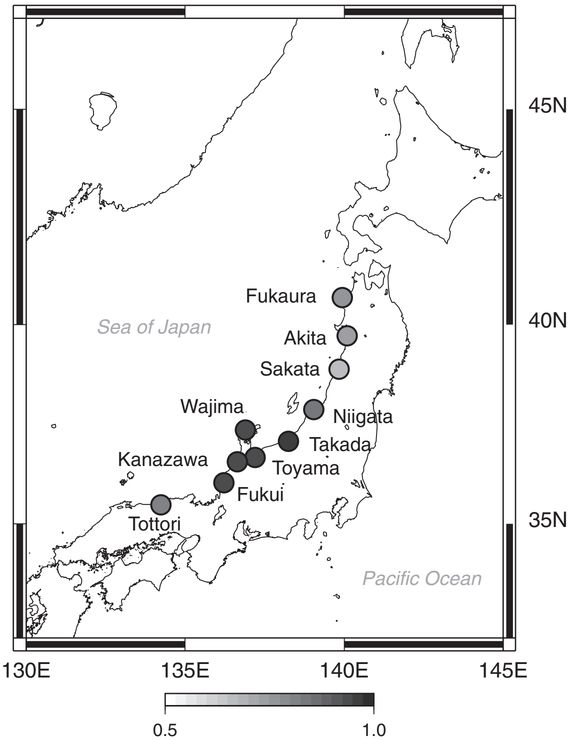

Figure 1. Spatial distributions of 10 meteorological observation stations. Shading denotes correlation coefficients between wintertime (DJF) snowfall depths at the each station and those averaged over 10 stations.

2. Data and model

We used the wintertime 3-month (DJF) average of snow depth data provided by the Japan Meteorological Agency (JMA) for the period between 1979/1980 and 2011/2012. The scope of this study is to shed light on the background climatological conditions relevant to ENSO anomalies, therefore we utilize DJF mean snow depth. To examine the P-type snowfall, 10 meteorological observation stations were utilized (Figure 1), which are located in the coastal plains facing the Sea of Japan. Snow depth is defined as accumulated increments of hourly snow depths. Shading in Figure 1 shows the correlation coefficients between the snow depths at each station against those averaged over 10 stations. The correlations are positive (>0.7) without exception, suggesting that the mean value is a suitable index for the P-type snowfall.

We also used the daily National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay *et al.*, 1996) with a spatial resolution of 2.5° longitude × 2.5° latitude for the period of 1979–2012. The arctic oscillation index (AOI) is computed at the Climate Prediction Center of the National Weather Service by applying the methodology of Thompson and Wallace (1998). The AOI is defined as the first leading mode from the EOF analysis of monthly mean height anomalies at 1000 hPa. Details are found on the CPC website (http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/ao_index.html). To examine the circulation in low latitudes, outgoing long wave radiation (OLR; Liebmann and Smith, 1996) was utilized in this study. To diagnose the atmospheric response to specified heating, we used a spectral baroclinic model based on primitive equations linearized about the observed boreal winter (DJF) climatology derived from NCEP/NCAR reanalysis. The linear baroclinic model (LBM) is described by Watanabe and Kimoto (2000). It has 20 sigma levels with horizontal resolution of T42. The model employs Del-forth horizontal diffusion, Raleigh friction, and Newtonian thermal damping with an e-folding scale at 1 day in the lower boundary layer and the uppermost two levels and at 30 days elsewhere. The LBM is forced with externally imposed heating and integrated towards a steady state. We prescribe deep diabatic heating with horizontal distributions based on observed precipitation.

3. Large-scale circulation in heavy and light snow years

The year-to-year variation of snowfall averaged over the 10 observation stations is shown in Figure 2, exhibiting a salient decrease in the snow depth during the latter half of the 1980s, which is consistent with previous studies (Suzuki, 2006). Nakamura and Abe (1998) attribute the physical reasons to recent global warming, especially the increase in the wintertime air temperature. Nakamura *et al.* (2002) showed that decadal weakening of the Aleutian Low emerged in the latter half of the 1980s, which explains

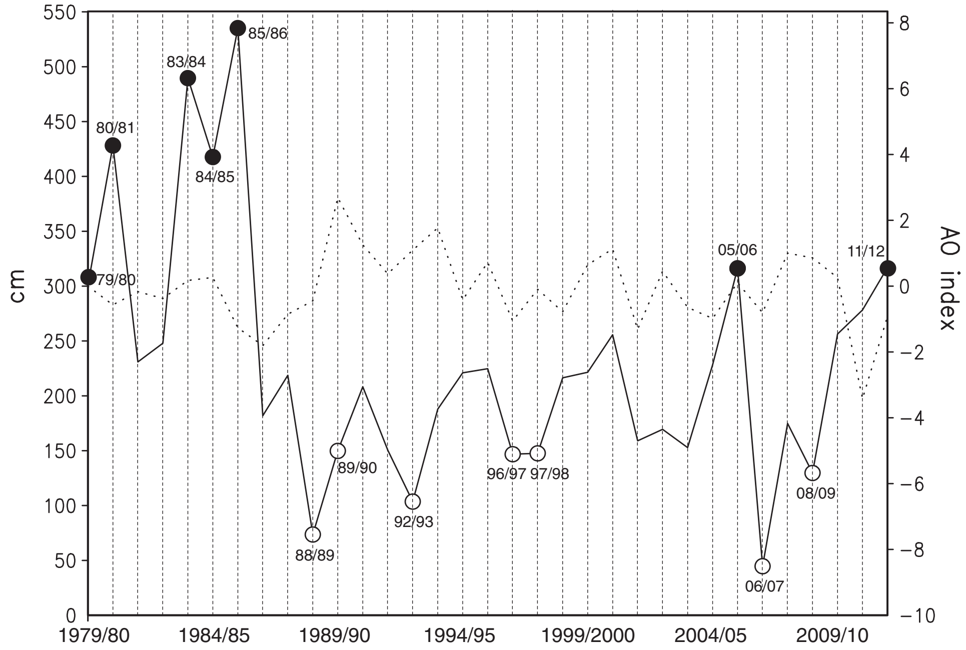

Figure 2. Time series of year-to-year variations of wintertime (DJF) snow depths (plain line) averaged over 10 observation stations and AOI (dashed line). Filled (open) circles denote heavy (light) snow years. Negative AOI shows discharge of cold air mass from polar regions.

the reason for the decreased snowfall through the attenuated wintertime northwesterlies across Japan.

Here, we should note caveat that the inter-annual variations include low-frequency component. In terms of the decadal variation, Yasunaka and Hanawa (2003) showed that regime shifts in Northern Hemisphere SST fields occurred 1976/1977 and 1988/1989. The 1976/1977 transition has been extensively studied in view of the Pacific decadal oscillation (PDO) (Trenberth, 1990; Graham, 1994). As for the 1988/1989 shift, Watanabe and Nitta (1999) indicated that snow cover extent over the eastern part of the Eurasian continent play a role as an amplifier of the circulation changes. Despite these facts, our comprehension of the fundamental controlling physical mechanisms involved in the PDO and its linkage with the modulation of EAWM remain deficient.

As for influence of large-scale circulations, relationship between the AOI and the snowfall variations should be taken into account. In this study, we use the AOI defined by Thompson and Wallace (1998). Negative AOI indicate discharge of cold air from the polar regions. At glance of Figure 2, it is obvious that the AOI and snowfall variations do not change in a coherent manner. Indeed the correlation coefficient is −0.43, which is significant at 90% confidence level. However, it also implicates that factors other than the discharge of cold air mass from higher latitudes presumably contribute to the anomalous snowfall.

It has been widely recognized that the El Niño-Southern Oscillation (ENSO), varying year-to-year, directly affects the climatic conditions around the neighbouring regions to the western Pacific Ocean (Wang *et al.*, 2000) and subsequent snowfall variations in Japan. The examinations of those processes are expected to provide primarily important knowledge for the snowfall variations. Therefore, we first investigate the difference of large-scale circulation fields between excessive snow years and light snow years. In our analysis, we chose 7 years from the top (bottom) as heavy (light) snow years among 33 wintertime snow depths. On the basis of these criteria, the years of 1979/1980, 1980/1981, 1983/1984, 1984/1985, 1985/1986, 2005/2006, and 2011/2012 are defined as heavy snow years. The years of 1988/1989, 1989/1990, 1992/1993, 1996/1997, 1997/1998, 2006/2007, and 2008/2009 are classified as light snow years.

The spatial distributions of anomalous atmospheric circulations during heavy and light snowfall winters were analysed. Figure 3(a) and (b) shows the composites for the air temperature, horizontal winds, and stream function at 850 hPa; they were derived from the anomalies of (a) 7 heavy snow years and (b) 7 light snow years from the 33-year mean. The years of heavy snowfall are characterized by enhancement of cold air intrusion from the Northeast China towards Japan, which is accompanied by acceleration of climatological northwesterlies appearing over the western part of Japan. Negative anomalies of stream function emerge over the western North Pacific to the east of Japan, which is consistent with the intensification of monsoonal northwesterlies. However, the years of light snowfall are almost a mirror image of the heavy snowfall years, suggesting that the regulation of snowfall in the coastal region of the Sea of Japan side is closely connected with the variations of cold air intrusion from the Eurasian continent embedded in the fluctuation of the Asian winter monsoon.

It should be mentioned here that Sakai and Kawamura (2009) derived the similar circulation patterns to Figure 3, however, their obtained result is reflection of the large-scale wintertime Asian monsoon activity.

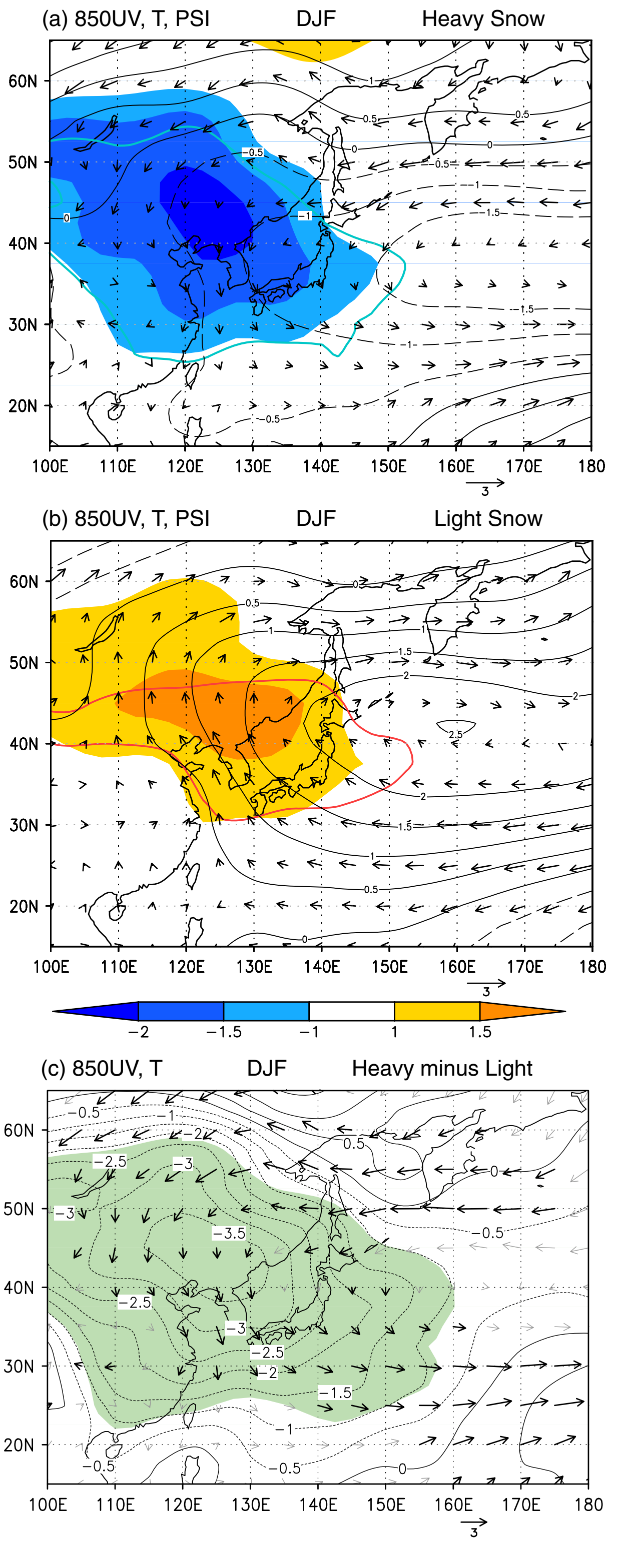

Figure 3. Composite anomalies of wintertime (DJF) air temperature (shading) and stream function (contours, 1.0×10^6 m^2 s^{-1}) at 850 hPa wind vectors (m s^{-1}) for (a) heavy snow years and (b) light snow years. Bold lines denote significant at 95% confidence level for the air temperature. (c) Composite difference of 850 hPa winds and temperature (contour, K) between heavy and light snow years. Black (Grey) vectors denote that the difference of zonal and/or meridional wind component is (not) significant at 95% confidence level. Shading indicates that the temperature difference is significant at 95% confidence level.

As mentioned in the Introduction, snowfall variations are regulated by the mountain-type snowfall relevant to the large-scale wintertime Asian monsoon activity and the plain-type snowfall pattern caused by local synoptic disturbances. The separation of the mountain-type and plain-type snowfall is beyond scope of this study, however, the closer resemblance with Sakai and Kawamura (2009) and our results suggest that the snowfall variations are regulated largely by the large-scale circulation patterns in which the local synoptic disturbance also contribute to the anomalous snowfall. The lowest panel of Figure 3 shows composite difference of temperature and winds between heavy and light snow years with statistical significance at 95% confidential level (shading). The result clearly shows that anomalous cyclonic circulation together with cold air intrusion caused by enhance northwesterly monsoon relevant to the EAWM is robust pattern for the snowy conditions in Japan.

The DJF composite anomalies of OLR and stream function in the upper troposphere show some interesting distinctions between heavy and light snow years (Figure 4). As for the heavy snow years, cyclonic circulation anomalies can be seen in the vicinity of Japan. In contrast to the stream function in the lower troposphere (Figure 3(a)), the vertical stratification exhibits a barotropic structure, which is indicative of the stationary Rossby wave. The most notable indication in Figure 4(a) is that enhancement of convection takes places over the tropical western Pacific through the maritime continent together with the appearance of anomalous anti-cyclonic circulation emerging over the southern part of China. As discussed by Kawamura (1998), the anti-cyclonic circulation over the Asian continent can be understood as a consequence of the enhanced convection in the vicinity of the maritime continent and the resultant heat-induced atmospheric response (Matsuno, 1966; Gill, 1980). The anomalous anti-cyclonic circulation may be an important player in the generation of cyclonic circulation seen over Japan as a vorticity source for the emanation of northeastward propagating stationary waves. The feature of the circulation anomaly regarding the light snow years is not simply the opposite of heavy snow years (Figure 4(b)). The anomalous anti-cyclonic circulation over Japan is consistent with the decreased snowfall and warmer air temperature (Figure 3(b)), while convective activity does not exhibit a salient anomaly in the tropics.

A number of observational studies (Yeh and Gao, 1979; Nitta, 1983; Yanai and Li, 1994; Ueda *et al.*, 2003) have recognized that the Tibetan Plateau plays an important role in the establishment and maintenance of the Asian summer monsoon as an elevated heat source. Those heat sources have large impact on the Northern Hemispheric climate through the emanation of stationary Rossby waves (Zhou *et al.*, 2009). During the anomalous snow event occurred in January 2008 in the central-eastern China, Nan and Zhao (2012) pointed out that positive diabatic heating $<Q_1>$ appears the most of the Asian hinterland, which might have a role as the heat source for the emergence of cyclonic circulation and ensuing southerly wind anomaly

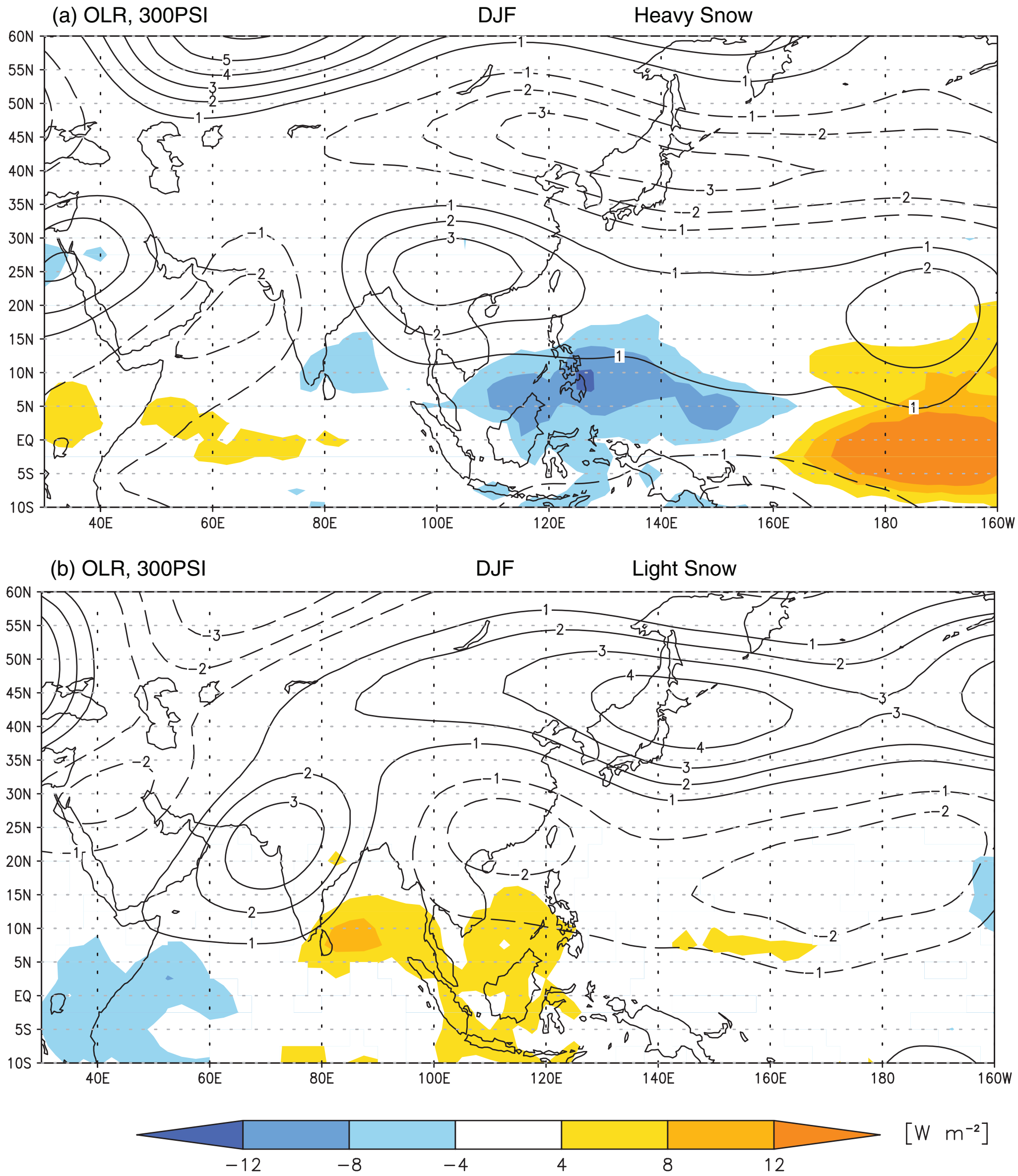

Figure 4. Composite anomalies of wintertime (DJF) OLR (shading with thin contours) and stream function (bold contours) at 300 hPa for (a) heavy snow years and (b) light snow years.

towards the snow disaster regions. The anomalous wintertime $<Q_1>$ is consistent with large inter-annual variability over the Tibetan Plateau (Zhao and Chen, 2001), therefore, we examine the heating field during heavy and light snow years in Japan.

To examine more quantitatively the heating field relevant to the heavy and light snow years in Japan, we computed atmospheric heat budgets by use of the thermodynamic equations (Yanai *et al.*, 1973):

$$\frac{\partial T}{\partial t} = -\boldsymbol{v} \cdot \nabla T + \omega \left(\frac{RT}{c_p p} - \frac{\partial T}{\partial p} \right) + \frac{Q_1}{c_p} \tag{1}$$

where T is temperature; $\boldsymbol{v}$, the horizontal wind; ω, the vertical p-velocity; R, the gas constant; c_p the specific heat for the dry air; and p, the pressure. Q_1 is called apparent heat source. As shown by Yanai *et al.* (1973), vertically integrating Eq. (1) from tropopause pressure P_T to the surface pressure P_s, we obtain

$$\langle Q_1 \rangle = \langle Q_R \rangle + L_c P + S \tag{2}$$

where

$$\langle\rangle = \frac{1}{g} \int_{P_T}^{P_s} ()\, dp, \tag{3}$$

L_c, P, S, Q_R, and g are respectively the latent heat of condensation, the precipitation rate, the sensible heat flux, radiative heating rate, and the acceleration of gravity.

Figure 5 shows the composite anomalies of vertically integrated Q_1 during heavy and light snow years. At glance of this figure, one may notice that overall patterns have considerable resemblance with the OLR anomalies (Figure 4), implicating that enhanced convection in the vicinity of the Philippines during the heavy snow years are primarily important in the heating fields. The reverse is true for the light years that convective activity is much

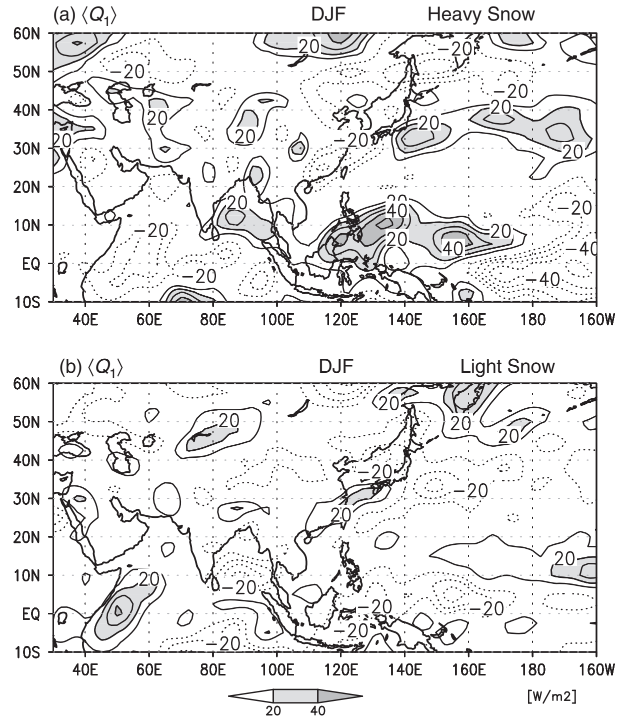

Figure 5. Composite anomalies of wintertime (DJF) vertically integrated diabatic heating $\langle Q_1 \rangle$ for heavy snow years (upper panel) and light snow years (lower panel).

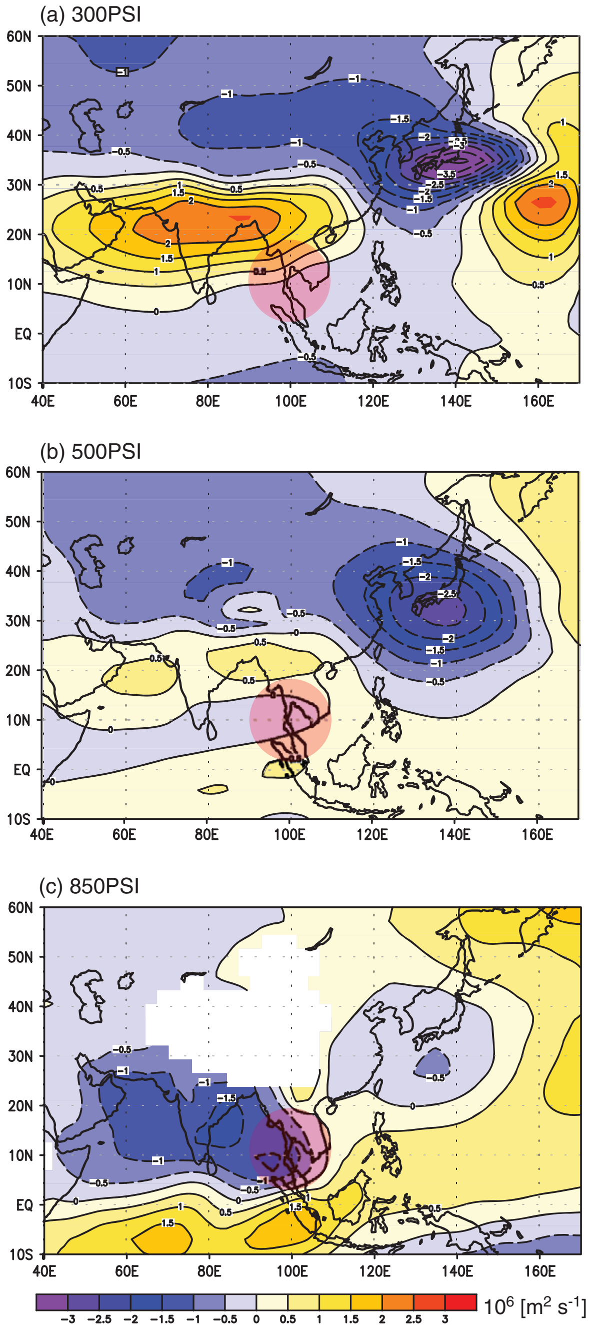

Figure 6. Three-dimensional structure of atmospheric response to a prescribed heating centered around 10°N, 100°E (filled circle) at 15 days. Plotted are streamfunction (contour intervals: 1.0×10^6 m^2 s^{-1}) at (a) 300 hPa, (b) 500 hPa, and (c) 850 hPa. The Tibetan plateau at an altitudes above 1,500 meters is masked out in (c).

suppressed over and around the Asian Maritime Continent. These results are indicative of strong impact of tropical heat source for the snowfall variations in Japan exhibiting different nature of positive $<Q_1>$ covered over the Asian continent seen in excessive snow event in the central-eastern China during January 2008 (Nan and Zhao, 2012).

4. Detection of key heat source for the snowy-type teleconnection

In the previous section, the diagnosis of heavy snow years shows that the enhanced tropical convection plays a crucial role in the formation of cyclonic anomalies around Japan. To elucidate the key domain of the aforementioned snowy-type teleconnection, we conducted 33 sensitivity experiments by prescribing an idealized heat source in the LBM. The imposed heat source exhibits a round shape with a spread of 20° longitude by 20° latitude, which has a heating maximum at the center of the circle. The heating has a deep vertical structure that peaks at ~400 hPa ($\sigma = 0.45$), where the maximum heating rate is 2.0 K day^{-1}. The LBM is integrated for 20 days. The response at day 15 is analysed when the model reaches a quasi-steady state. The nested background state is the seasonal mean climatology averaged from December through February, which is derived from the NCEP/NCAR reanalysis.

Figure 6 shows the three-dimensional structure of streamfunction responses to the anomalous tropical heating centered on 10°N, 100°E. In the lower troposphere (850 hPa), cyclonic circulation emerges over the Bay of Bengal towards the Arabian Sea to the northwest of the imposed heating, while anti-cyclonic circulation appears in the Southern Hemisphere. These atmospheric responses to the anomalous heating are consistent with the Matsuno–Gill pattern.

In an experiment conducted by Gill (1980), neither the responses in the extratropics nor those in the upper troposphere were discussed; therefore, we extended the region in three dimensions to include higher latitudes. In contrast

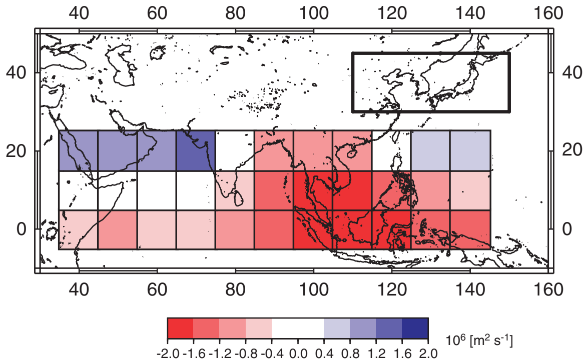

Figure 7. Contribution of heating anomalies to development of cyclonic circulation in the vicinity of Japan (110°–150°E, 30°–45°N). The plotted values of each grid are projection of 500 hPa streamfunction averaged over and around Japan in response to the heating anomaly for the each grid. Negative (positive) values of the each grid indicate that the enhancement of convection strengthens the cyclonic (anti-cyclonic) circulation around Japan.

to the lower troposphere, the upper troposphere exhibits a different response. In Figure 6(a), anti-cyclonic circulation is recognizable at 200 hPa centered on the north of the Indian subcontinent. The direct baroclinic Rossby wave response to the imposed heating is the physical reason for the pair of the low-level cyclonic circulation and the upper-level anti-cyclonic circulation (Gill, 1980; Kawamura, 1998).

As for the wave pattern in the extratropics, cyclonic circulation can be seen throughout the troposphere. The vorticity source embedded in south Asia, caused by the heat-induced baroclinic Rossby wave response, is ascribable to the wave trains towards Japan. In summary, the LBM shows good performance for the atmospheric response to the prescribed heating anomaly.

We conducted sensitivity experiments to elucidate the regionally different contribution of the tropical heat source to the anomalous mid-tropospheric cyclonic circulation around Japan during the heavy snow conditions in the Sea of Japan side (Figure 4(a)). Figure 7 shows the contribution of idealized grid heating to the development of the anomalous cyclonic circulation over Japan. The plotted values of each grid are the regional mean of the stream function at 500 hPa averaged over 110°–150°E, 30°–45°N, corresponding to the same individual heating anomaly. The largest contribution can be seen over the maritime continent and its neighbouring regions, which is consistent with the enhanced convection during heavy snow years (Figure 4(a)), with the exception of the vicinity of Philippines over the western Pacific. The summertime heat-induced response to tropical heating is known as the *Pacific-Japan* (*P–J*) pattern, which exhibits enhancement of convection to the east of Philippines and subsequent development of anti-cyclonic circulation over Japan (Nitta, 1987; Kosaka and Nakamura, 2006). In comparison with the summertime *P–J* pattern, the wintertime teleconnection is characterized by the low-pressure anomalies emerging over Japan. These differences may be ascribed to the background base flow as well as the westward shift of the convection around the maritime continent to the eastern Indian Ocean.

5. Summary

The aim of this study was to explain the general circulation pattern of anomalous wintertime heavy snow in Japan and detect the vorticity source for the wave trains. Our results illustrate that the heavy snowfall over the coastal plains facing the Sea of Japan is characterized by the appearance of cyclonic circulation together with cold air intrusion from the Eurasian continent. In the tropics, the convection is significantly enhanced over the western Pacific through the Eastern Indian Ocean centered on the Philippines. The enhanced convection and resultant baroclinic Rossby wave response give rise to the emergence of anti-cyclonic circulation over the eastern part of China. It is conceivable that the anomalous barotropic cyclonic circulation appearing over Japan is closely connected with the vorticity source in relevance with the anti-cyclonic circulation. Namely, injecting the convection-induced perturbation into the westerly jet over the eastern part of China is an important process for the emergence of the cyclonic circulation during the anomalous snowy winter as the vorticity source for the propagation of the stationary Rossby wave towards Japan.

In this study, the key region of the tropical heat source for the anomalous cyclonic circulation over Japan was examined on the basis of idealized LBM experiments. When we prescribe the wintertime climatological background flow in the model, the anomalous heat sources in the maritime continent and adjacent oceans induce the anti-cyclonic circulation over the eastern part of China and ensuing cyclonic circulation over Japan. The former is caused by the direct baroclinic Rossby wave response to the tropical forcing, and the latter might be caused by the eastward propagation of the stationary Rossby wave relevant to the vorticity source of the aforementioned anti-cyclonic anomalies.

The results obtained in this study include the effect of other teleconnections, such as the AO accompanied by cold air outbreak from the Arctic Sea (Hori *et al.*, 2011). Recent studies have discussed whether the AO affects the modulation of snowfall in Japan. Kawamura and Ogasawara (2007) revealed that there is no clear relationship between the AO index and excessive snowfall in Japan in the last 50 years, which requires an alternative physical process for the modulation of the Asian winter monsoon, including Japan. The duration of tropical convection relevant to the ENSO cycle tends to be longer than that of teleconnection in the atmosphere, which is beneficial for the understanding of the seasonally snowy winter in Japan associated with the intensified winter Asian monsoon.

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