Long-term trends in snowfall characteristics and extremes in Japan from 1961 to 2012

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Abstract
The region of Japan along the Japan Sea is one of the heaviest snowfall regions in the world, and it appears to be increasingly vulnerable to climate variability and global warming. This study investigated the long-term trends in snowfall characteristics and extremes (i.e., heavy snowfall) over Japan mainly using station observations over 51 years from the 1961/1962 to 2011/2012 winter seasons. Long-term trends were examined in terms of total precipitation and the ratio of the numbers of snowfall days to precipitation days \( R(s/p) \). Our results show statistically significant decreasing trends in seasonally accumulated snowfall at most stations in Japan, except for those in northern Tohoku and Hokkaido Districts and the Pacific side of Japan. These significant decreasing snowfall trends were associated with the long-term decrease in \( R(s/p) \). Although long-term decreasing trends in \( R(s/p) \) were also observed over Tohoku District and Pacific side, increasing trends in precipitation cancelled the decreasing trends there, which indicates long-term trends in precipitation likely complicated snowfall trends. Over Hokuriku District, a decrease in precipitation enhanced the decrease in snowfall. Moreover, major snowfall events occurred in the first half of the study period, whereas a recent increase in heavy snowfall was not yet evident.

KEYWORDS
decadal climate variability, East Asian winter monsoon, long-term observational data analysis, ratio between snowfall and precipitation, warmer snowy region

1 | INTRODUCTION

In the context of the global warming and climate variability, it is important to track trends and variability in snowfall over the mid- and high latitudes. Long-term changes in snowfall have been investigated intensively in North America and Northern Eurasia (e.g., Groisman et al., 2016).

The Japan Sea side of Japan experiences some of the heaviest snowfall on Earth. Global warming has the potential to significantly decrease snowfall in this area, as seasonal surface air temperature (SAT) tend to be relatively high (e.g., Hara et al., 2008). In particular, the regional climate at the boundary between snowy regions and surrounding areas may be significantly affected by global warming. Changes in snowfall can also affect river discharge (e.g., Ma et al., 2010; 2013), having a significant social impact.

The Japanese Archipelago extends along the southwest-northeast axis with the complex topography form the horizontal inhomogeneity of snowfall (see Figure 1a), which is associated with differences in
climatological SAT (see Figure 1b). These regions can show regional differences in long-term snowfall trends. Long-term decreasing trends in seasonal maximum snow depth based on administrative districts are partially reported by the operational agency (Japan Meteorological Agency; JMA), but regional characteristics and related factors has not been provided (e.g., JMA, 2017). The spatial distribution of heavy snowfall events is highly variable among year in Japan (e.g., Nakai, 2015).

Heavy snowfalls on the Japan Sea side of Japan are associated with the northwesterly flow of the Asian winter monsoon from Eurasia, often referred to as cold surges or cold outbreaks. The cold, dry northwesterly winds of the Asian winter monsoon are moistened and heated over the Japan Sea and are strongly associated with sea surface temperature (SST). Thus, the winter monsoon northerlies (e.g., Matsumura and Xie, 1998; Hori and Ueda, 2006; Takano et al., 2008; Ueda et al., 2015; Kawase et al., 2018) and the supplied water vapour and heat over the Japan Sea (Hirose and Fukudome, 2006; Yamamoto and Hirose, 2008; Yamamoto and Hirose, 2009; Iizuka, 2010; Sato and Sugimoto, 2013; Takahashi et al., 2013; Takahashi and Idenaga, 2013) are the major factors contributing to variations in snowfall and rainfall on the Japan Sea side of Japan. Many previous studies have analysed variation in precipitation rather than snowfall due to the limited availability of observational data; however, a few recent studies have examined snowfall variation at multiple time-scales (e.g., Takahashi and Idenaga, 2013; Ueda et al., 2015). In particular, Yamazaki et al. (2019) successfully connected regional differences in snowfall near the Japan Sea with large-scale atmospheric circulation.

Generally, when we focus on the regions where climatological mean SAT is closed to the threshold values of SAT between snowfall and rainfall at the near surface, the ratio of snowfall to total precipitation is lower under a warmer climate, which results in a reduction in snowfall and, thus, snow depth. As such, the ratio of snowfall to total precipitation and similar variables have been used to analyse climate changes in snowy regions (e.g., Knowles et al., 2006, Feng and Hu, 2007, Serquet et al., 2011). In most areas on the Japan Sea side (San-in, Hokuriku, and Tohoku districts; see Figure 1a), climatological SAT are close to the threshold value of SAT between snowfall and rainfall, which expects a drastic change in snowfall characteristics.
Moreover, rising SAT or SST can induce an increase in water vapour, which, in turn, can increase precipitation (e.g., Takahashi et al., 2013). Besides, the changes in water vapour largely depend on temperature (Clausius-Clapeyron equation). The two different effects that rising SAT decreases the ratio of snowfall to precipitation and rising SAT increases water vapour bring complexity for the understanding of snowfall variability.

However, snowfall variation is relatively complex, as it is also affected by variation in total precipitation, which itself can show long-term trends (Sato and Sugimoto, 2013, Yasunaga and Tomochika, 2017). Total precipitation can be affected not only by monotonic global warming, but also can vary in response to internal climate variability. This internal climate variability is very difficult to understand from only a finite time-series because we cannot physically decompose an observed trend into some factors, such as global warming and internal climate variability. This study focuses particularly on the contribution of precipitation to snowfall variability.

Compared with studies on long-term trends in precipitation, few studies have addressed long-term trends in snowfall or the regional characteristics of these trends, much less those of heavy snowfall. Despite the scientific importance of these studies and the societal impact of these events, only a few researchers have examined heavy snowfall in Japan, such as Yamazaki et al. (2015), Honda et al. (2016), and Takahashi and Yamazaki (2020), who examined recent heavy snowfall occurrences over the Pacific coastal side of Japan.

In this study, we investigated long-term trends in snowfall over Japan and the associated regional characteristics, with a focus on the relationship between long-term trends in total precipitation and the ratio of snowfall days to total precipitation days. The long-term trends can be related to SAT changes due to global warming and internal climate variability. The data used in the study are described in Section 2. The long-term trends in snowfall over Japan and regional characteristics are presented in Section 3. Long-term trends in winter monsoon flow and possible associated factors are discussed in Section 4. Finally, conclusions are presented in Section 5.

2 | DATA

2.1 | Observational data

To investigate the variations in precipitation, snowfall, and snow depth, excluding Okinawa Prefecture, we used daily precipitation, snowfall, and snow depth observations from 127 meteorological stations of the JMA; the locations of these stations are shown in Figure 1. These stations have monitored precipitation and snowfall continuously for 51 winters (December–January–February; DJF) from 1961/1962 to 2011/2012.

Mainly, we used the seasonally (DJF) accumulated snowfall and seasonal maximum snow depth. The seasonally accumulated snowfall is a simple summation of the daily snowfall depth, which is defined as the 24-hr accumulation of new snow. However, because the daily snowfall data do not consider differences and temporal changes in snow density, comparing daily snowfall accumulations with maximum snow depth or snow water equivalent values is difficult. Also, of the daily snow depth values within a winter, the largest was taken as the seasonal maximum snow depth. In addition, we used daily precipitation, which is the sum of solid and liquid precipitation. These data have been uniformly quality-controlled by the JMA. Besides, we used the variables of snowfall characteristics, which will be defined in Section 2.3. A 51-year climatology dataset of seasonally accumulated snowfall during DJF was shown in Figure 1a, showing distinct regional characteristics in snowfall.

To examine the long-term trends in SAT, we obtained long-term SAT data also from the JMA; these data were collected at the same meteorological stations from which the snow data were obtained. Figure 1b shows the 51-year climatological daily mean SAT during DJF.

To examine long-term trends in atmospheric circulation associated with snowfall, we used the Japanese 55-year Reanalysis dataset (JRA-55; Kobayashi et al., 2015). The monsoon index (MOI; Hanawa et al., 1988) defined as the difference in sea-level pressure between Irkutsk (Russia) and Nemuro (Hokkaido, Japan), was used as an index of the Asian winter monsoon. We also applied the winter monsoon index (WMI; Takahashi and Idenaga, 2013), which represents winter monsoon activity around Japan. Besides, for investigating the long-term changes in SAT in terms of large-scale atmospheric circulation, we additionally use the SAT in the JRA-55.

We also investigated the storm track activity; we calculated 850-hPa disturbance activity using perturbation kinematic energy (PKE). PKE or variance in meridional winds has been used to measure the transient eddy activity over the mid-latitudes and tropical and subtropical regions (e.g., Matthews and Kiladis, 1999; Takahashi et al., 2011; Kamizawa and Takahashi, 2018). PKE can be defined as follows:

\[ PKE = u'^2 + v'^2 \]  

where \( u' \) (\( v' \)) is a disturbance component of zonal (meridional) wind \( u \) (\( v \)), defined as \( u = u - \bar{u} \) (\( v = v - \bar{v} \)). \( \bar{u} \) (\( \bar{v} \)) is an 11-day running average. An 11-day high-pass filter was determined to extract extratropical cyclone activity that their dominant time-scale is around several days.
2.2 | Definition of snowfall characteristics and extremes

To understand the changes in snowfall characteristics, we defined the following snowfall parameters: snowfall day (number of snowfall days), precipitation day (number of snowfall days), the ratio between the numbers of snowfall days and precipitation days, mean snowfall intensity, and the heaviest snowfall period, which are based on the analysis of precipitation characteristics (e.g., Takahashi, 2016), which are explained in the following paragraphs. The values of these snowfall characteristics were calculated at each station. The procedure of the analysis of the heaviest snowfall period is provided in Section 2.3.

A “precipitation day” was identified when the daily precipitation total exceeded 1 mm. Within the precipitation days, a “snowfall day” was recorded when the daily snowfall depth at the station exceeded 1 cm. Thus, all snowfall days are included in the precipitation days.

For an understanding of the variations in snowfall occurrence frequency within the precipitation days, the ratio between the numbers of snowfall days and precipitation days is expressed as a percentage; this ratio is referred to as \(R(s/p)\). We were unable to obtain the snowfall amount (not depth) data, which are very difficult to acquire; therefore, we do not discuss the ratio of snowfall and precipitation amounts in this study.

Changes in snowfall (in this case, snowfall day) can be derived from changes in precipitation frequency (in this case, precipitation day) and snowfall occurrence frequency within the precipitation days (in this case, the ratio between snowfall days and precipitation days \(R(s/p)\)). To identify the contributions of the changes in precipitation day \(P_{\text{day}}\) and the ratio \(R(s/p)\) to snowfall days \(S_{\text{day}}\), we conducted an order estimation as referred to the study on precipitation characteristics (Takahashi and Polcher, 2019). Snowfall day was defined as follows:

\[
S_{\text{day}} = P_{\text{day}}R(s/p) \tag{2}
\]

The changes in snowfall day, precipitation day, and the ratio were expressed as \(\Delta S_{\text{day}}, \Delta P_{\text{day}},\) and \(\Delta R(s/p)\), respectively.

\[
S_{\text{day}} + \Delta S_{\text{day}} = (P_{\text{day}} + \Delta P_{\text{day}})(R(s/p) + \Delta R(s/p)) \tag{3}
\]

Typical values of \(\Delta P_{\text{day}}\) and \(\Delta R(s/p)\) range from 0.01 to 0.1. Thus, \(\Delta P_{\text{day}}\Delta R(s/p)\) is negligibly small. Therefore, the changes in snowfall day may be rewritten as follows:

\[
\Delta S_{\text{day}} \approx P_{\text{day}}\Delta R(s/p) + \Delta P_{\text{day}}R(s/p) \tag{4}
\]

or

\[
\frac{\Delta S_{\text{day}}}{S_{\text{day}}} \approx \frac{\Delta P_{\text{day}}}{P_{\text{day}}} + \frac{\Delta R(s/p)}{R(s/p)} \tag{5}
\]

Thus, the changes in snowfall day can be approximated as a simple linear combination, which can be expressed as a percentage.

Mean snowfall intensity was also calculated as the total values of daily snowfall for all snowfall days divided by the number of snowfall days, which represents the mean snowfall intensity per a snowfall day. For the precipitation characteristics, we sometimes use the term “precipitation intensity” (e.g., Takahashi, 2016) or “conditional precipitation rate,” which is a similar to this mean snowfall intensity. The mean snowfall intensity includes all snowfall events, which may be somewhat different from the long-term tendency of the heaviest snowfall events.

2.3 | Methods

2.3.1 | Statistical analysis

To assess the statistical significance of the 51-year long-term trends, we performed a nonparametric Mann–Kendall test for the time series of the meteorological variables. Because the Mann–Kendall test cannot quantify increasing and decreasing trends, the slope values were estimated using another method.

We adopt the Theil–Sen method to estimate the slope values of meteorological variables, such as snowfall, precipitation, and snow depth, in order to avoid the adverse effect of outliers. The Theil–Sen method is based on direct estimation of the median of pairwise slopes. Generally, if we use the least-squares method for the time-series analysis, we cannot avoid the adverse effect of outliers, particularly the outliers in the beginning and ending periods of the finite time-series.

2.3.2 | Analysis of the heaviest snowfall period

We also examined the long-term trends in the occurrence frequency of heavy snowfall in an attempt to elucidate the possible recent increase in heavy snowfall events. We examined the heaviest snowfall period at each station.
using the following two steps. First, we selected the 10 heaviest daily snowfall events using daily snowfall at each station. Second, we averaged the values of the 10 heaviest snowfall years. For example, when a station has heaviest events in 1960, 1964, 1977, ... and 2000, we averaged the numbers of the year (like, 1960 + 1964 + 1977 + ... + 2000)/10). Though these two steps, we obtained a period characterized by frequent heavy snowfall. When most of the heaviest snowfall events occur in the 1960s (2000s), the averaged values of the number of years can correspond to 1965 (2005). Although a snowfall event can last for more than 1 day, we considered the selected days as separate one-day snowfall events; thus, only 53 of 1,270 events (4.2%) occurred over a 2–3-day period of continuous snowfall.

3 | RESULTS

3.1 | Time-series of snowfall at some stations

In this section, we examine the long-term trends in total precipitation, seasonally accumulated snowfall, and seasonal maximum snow depth. First, we sampled the long-term variation in snowfall at several stations. Four stations were selected: Sapporo (JMA412), Akita (JMA582), Takada (JMA612), and Fukui (JMA605), based on their latitude (Figure 2).

At Sapporo and Akita, there were no clear long-term reductions in snowfall over the study period (Figure 2a,b). In contrast, Takada and Fukui showed marked reductions in snowfall over the long term (Figure 2c,d). This decreasing snowfall trend might also be interpreted as a dramatic change (abrupt decrease/increase), which appeared to occur around 1990. The changes observed at these two stations were evident; however, such apparent changes were not observed at most stations (figure not shown). We applied nonparametric statistical tests to all meteorological variables at each station. In the following sections, we focus on district-level differences in long-term snowfall trends.

3.2 | Regional characteristics of long-term trends in snowfall from 1962 to 2012

This subsection investigates the regional characteristics of long-term trends in snowfall. Long-term decreasing trends in snowfall from 1962 to 2012 were observed at...
most stations, except in Hokkaido District (Figure 3). Significant decreasing trends were observed over the Japan Sea side of the Kyushu, Sanin, and Hokuriku Districts. More than half of all stations recorded significant trends. In contrast, most stations of Tohoku District did not record the significant long-term trends, although snowfall generally decreased. Over Hokkaido District, both decreasing and increasing trends were observed. It should be noted that regional differences were evident, despite using a 51-year study period to examine long-term trends.

Significant decreasing trends were observed more frequently over southwestern Japan, where climatological SAT are higher. SAT increased during the study period, and at most stations, the increases were statistically significant (Figure 4). As mentioned in Section 1, because long-term warming SAT trends were spatially homogeneous, snowfall is sensitive to SAT changes in snowy regions with warmer climatological SAT. Regional differences in climatological SAT may almost explain the spatial patterns of long-term snowfall trends.

In addition to the long-term trends in snowfall, we investigated the long-term trends in seasonal maximum snow depth, which are generally thought to show clear decreasing trends and used in many studies. Unlike what has been suggested, the observed seasonal maximum snow depth showed no clear decreasing trend at many stations (Figure 5). A significant decreasing trend in seasonal maximum snow depth was observed only at several stations in San-in and Hokuriku. Compared with long-term trends in snowfall (Figure 3), statistically significant trends in seasonal maximum snow depth were limited (Figure 5). The difference between the seasonally accumulated snowfall and seasonal maximum snow depth may be due to statistical instabilities since the interannual standard deviation in seasonal maximum snow depth was much larger than that in seasonally accumulated snowfall. This tendency occurred because seasonal maximum snow depth is affected by a specific heavy snowfall event lasting from 1 to several days.

3.3 Contributing factors of long-term trends in snowfall

To understand the factors to explain the regional characteristics of long-term trend in snowfall, we analysed meteorological variables related to long-term trends in snowfall. As we mentioned in Section 1, the snowfall is associated with total precipitation and the ratio of the snowfall days to precipitation days. Thus, this subsection focuses on the following snowfall characteristics: total precipitation,
snowfall days, precipitation days, $R(s/p)$, and mean snowfall intensity, as defined in Section 2.3.

### 3.3.1 Total precipitation

First, we also examined the long-term trends in precipitation (Figure 6). Overall, seasonal precipitation decreased over the Japan Sea side of Japan and increased over the Pacific Ocean side during the 51-year study period, although most of the long-term trends were not significant. It was noteworthy that the decreasing trends in precipitation at most of station of Hokuriku and part of Tohoku very likely contributed to the observed decreasing trends in snowfall there. Besides, the increasing and decreasing trends in precipitation were calculated over Hokkaido, which also contributed the observed trends. Thus, long-term trends in precipitation likely contributed to the complexity of the long-term trends in snowfall. Although significant trends were limited, there was a distinct dipole structure of long-term trends in precipitation between the Japan Sea and Pacific sides of Japan (Figure 6). This dipole structure may be related to the weakening of the winter monsoon and strengthening of storm track activity, according to climatological precipitation features over Japan in winter. Possible changes in atmospheric circulations are discussed in Section 4.

### 3.3.2 Snowfall frequency

Next, we investigate the long-term changes in snowfall day (Figure 7). A reduction in the numbers of snowfall days was observed over the Japan Sea side during the study period, while an increase in snowfall day was found over the Pacific side. Over Hokkaido, both increase and decrease trends were observed. Interestingly, these tendencies were similar to the long-term changes in precipitation, which implies that the long-term changes in snowfall can be affected by those in precipitation. In order to facilitate the comparison between snowfall day and precipitation, we next show the changes in precipitation day. Because the meteorological variable of snowfall day is statistically more stable than snowfall or snow depth, these long-term trends were likely to be robust. In particular, the reduction in snowfall day values along the Japan Sea side and the increase along the Pacific side were significant.

Figure 8 shows long-term trends in precipitation day. The dipole structure of long-term trends in precipitation day on the Japan Sea and Pacific sides of Japan, which was very similar to the structure of long-term trends in precipitation amounts (Figure 6). Notably, the decrease in precipitation day on the Japan Sea side contributed to a long-term reduction in snowfall day. Also, the increase
Trends in precipitation day may explain the long-term increase trends in snowfall day over the Pacific sides. Long-term trends in precipitation day can have essential effects on long-term trends in snowfall day.

To clarify the extent to which the precipitation or precipitation day can explain the long-term trends in snowfall, we also investigated long-term trends in $R(s/p)$, which can be interpreted as snowfall days normalized to precipitation days (Figure 9). In other words, $R(s/p)$ provides relative frequency in snowfall within the precipitation day. A reduction in $R(s/p)$ was observed mainly over southern and western Japan, such as in the Kyushu, San-in, and Hokuriku Districts, where mean SAT were relatively high (Figure 1b), which indicates the relative frequency in snowfall of the precipitation day has been decreasing due to the long-term SAT warming. Tohoku District represented a boundary between positive (or relatively constant) and negative $R(s/p)$ signals or no clear signals, which possibly indicating that the region is a transition zone between areas affected by warming SAT. Thus, the transition zone may be located around Niigata and Yamagata Prefectures. In the future, this transition zone may migrate northward. Moreover, the long-term increases in snowfall day along the Pacific side were due to the increase in precipitation day, although $R(s/p)$ decreased. We explain a possible factor of the
increase in precipitation day over the Pacific side in Section 4.

3.3.3 | Relative contribution between precipitation day and \( R(s/p) \)

This subsection summarizes the regional differences of the relative contribution of the changes in precipitation day \( P_{\text{day}} \) and the ratio of snowfall day to precipitation day \( R(s/p) \) on long-term trends in snowfall (Figure 10). As we provided an approximation of contribution of \( P_{\text{day}} \) and \( R(s/p) \) to snowfall day \( S_{\text{day}} \) in Equations (4) and (5), a linear combination of the long-term changes in \( P_{\text{day}} \) and \( R(s/p) \) can explain the long-term changes in \( S_{\text{day}} \).

\[ \Delta P_{\text{day}} \] contributed approximately \(-20\) to \(10\%\) to \( \Delta S_{\text{day}} \) over the 51 years, although the previous studies have not focused on the changes in precipitation day or total precipitation. Besides, \( \Delta R(s/p) \) were approximate \(\pm 30\%\) at several stations, which implies that both components should be considered to understand the long-term changes in snowfall.

A regional difference in contribution of \( \Delta P_{\text{day}} \) and \( \Delta R(s/p) \) to \( \Delta S_{\text{day}} \) was observed among districts. Over Hokkaido District, positive \( \Delta R(s/p) \) signals, and positive and negative signs for \( \Delta P_{\text{day}} \) were observed. Over Tohoku District, the \( \Delta R(s/p) \) values were generally negative. However, \( \Delta P_{\text{day}} \) showed both positive and negative values, which indicates that an increase in precipitation day cancelled a decrease in \( R(s/p) \). This result means the increase in precipitation events but the decrease in relative frequency in snowfall within the precipitation days. This finding may explain the unclear long-term signals in snowfall over Tohoku District. Over Hokuriku District, both components contributed to decreasing trends in snowfall, leading to more apparent long-term trends in snowfall observed over Hokuriku District. Trends over San-in and Kyushu Districts were similar to that over Hokuriku District (data not shown). Note that this analysis included some uncertainty concerning changes in mean snowfall intensity per a snowfall day.

3.4 | Possible increase in heavy snowfall event

We also examined the long-term trends in mean snowfall intensity and snowfall extremes, given that the long-term trends in rainfall intensity have caused major problems in warmer climates (e.g., Trenberth et al., 2003, Fujibe et al., 2005; 2006, Fujibe, 2013).

3.4.1 | Mean snowfall intensity

Here, we investigated the mean snowfall intensity during a snowfall day. Strengthening and weakening trends in snowfall intensity were observed over the northern Hokuriku, Tohoku, and Hokkaido Districts (Figure 11), which indicates that systematic long-term trends in mean snowfall intensity were not yet evident. Thus, the relationship between mean snowfall intensity and SAT warming remains unclear in the long-term operational observations over Japan, including Hokkaido where climatological SAT is low, although an increase in snowfall is expected to accompany an increase in water vapour due to SAT warming. This tendency should be investigated in future studies using sub-daily datasets and more physical-based analyses, to the fullest extent possible given the limited availability of such datasets.
3.4.2 | Snowfall extremes

To examine whether heavy-snowfall events occurred in recent decades, we averaged the values within the years that experienced the top 10 daily heaviest snowfall records, where several heaviest snowfall events may have occurred in a specific year (Figure 12). Our results show that most of the top 10 heaviest snowfall events occurred in the first half of the analysis period at most stations, implying a decreasing trend in extreme snowfall events or the absence of a long-term trend of extreme snowfall events. Because the decreasing trends were distinct along the Japan Sea side, it may be that a recent increase in extreme snowfall events is not yet evident. Thus, both mean snowfall intensity and heavy snowfall events have not increased over the recent 51-year study period. Nevertheless, continuous monitoring of heavy snowfall events is required.

4 | DISCUSSION

4.1 | Changes in winter monsoon activity

This section investigates the long-term changes in the Asian winter monsoon circulation. Among Asian winter monsoon indices, the MOI is defined as the pressure difference between Irkutusku and Nemuro (Hanawa et al., 1988) and is suitable for examining seasonal mean atmospheric conditions of the Asian winter monsoon.

Generally, long-term decreasing trends in snowfall and snow depth over Japan have been explained by the weakening of Asian winter monsoon circulation. Although a small reduction can be seen in Figure 13a, the non-parametric Mann–Kendall analysis results showed no statistically significant decreasing trend in the MOI during the 51 winters from 1962 to 2012. Another index of the Asian winter monsoon, namely WMI, also showed no significant decreasing trend over the study period (Figure 13b).

The previous studies found the weakening of the Asian winter monsoon until around before 2000 (e.g., Wang et al., 2009). However, the time-series of MOI and WMI (Figure 13) shows that the winter monsoon activity had continued to weaken prior to approximately 2000, but since then we have observed the same level of strong winter monsoon as before, such as 2005, 2006, 2011, and 2012. Besides, recent Eurasian cooling has been discussed (e.g., Mori et al., 2019).

Thus, this finding implies that long-term changes in East Asian winter monsoon are unlikely to explain the
observed long-term trends in snowfall and snow depth, although the interannual variations in snowfall is associated with strength of East Asian winter monsoon. In the future, long-term trends in large-scale circulation may be more significant, as projected by global warming experiments (Hori and Ueda, 2006).

4.2 Extratropical cyclone activity

We examine long-term changes in extratropical cyclone activity using PKE in this subsection. Generally, precipitation and snowfall over the Pacific sides of Japan are associated with the activity of extratropical cyclone activity, which is referred to as storm track activity. As shown in Figures 6 and 8, we found the increases in precipitation and precipitation day over the Pacific side. To understand this, we plotted the long-term changes in PKE over and around Japan (Figure 14). PKE values clearly show the storm track activity during DJF season (Figure 14a).

Positive PKE values are found south and east of Japan, which indicates a recent enhancement of transient extratropical cyclone activity (Figure 14b). The region where positive PKE signals were consistent with the extratropical cyclone activity, which is associated with the precipitation and snowfall over the Pacific side of Japan. Decadal enhancement of storm track activity over the northwestern Pacific has been previously reported (e.g., Nakamura et al., 2002); this is consistent with our results.

FIGURE 13  (a) Time-series of monsoon index (MOI), defined as the pressure difference between Irkutusku and Nemuro. (b) Time-series of winter monsoon index (WMI; Takahashi and Idenaga, 2013), defined as the pressure difference between Nagasaki and Akita. The latter is more specific to winter monsoons over Japan. The Mann–Kendall statistical test was performed for both time series; neither was statistically significant. The statistical p-values are shown in the panel

FIGURE 14  (a) Climatological (1962–2012) PKE at 850 hPa in DJF. (b) Long-term differences [(1988–2012)–(1962–1987)] in PKE at 850 hPa in DJF. The PKE values were averaged during DJF period. On the un plotted grids, we cannot use PKE values due to topography. Unit is m$^2$s$^{-2}$
4.3 | Other factors

Sato and Sugimoto (2013) used a regional climate simulation to show that long-term weakening of the winter monsoon and warming trends in SST over the Japan Sea explain increasing and decreasing trends in precipitation over Tohoku and Hokuriku Districts over the 26 years from 1982/1983 to 2007/2008. However, the analysis period differed considerably from that of the current study. Thus, regional trends in winter monsoon circulations can modulate long-term changes in snowfall via long-term trends in precipitation.

Besides, the increasing trends in SST and SAT could explain the modulation in total precipitation amounts. We also confirmed the statistically significant long-term SAT warming over and around Japan (Figure 15). Other numerical experiments also support the positive contribution of SST to total precipitation (Yamamoto and Hirose, 2009; Iizuka, 2010; Takahashi et al., 2013; Fujita et al., 2014; Seo et al., 2014). Takahashi et al. (2013) showed that SST and SAT warming increases water vapour, although relative humidity is fairly unchanged. In turn, the SAT warming induces an increase in precipitation and a decrease in $R(s/p)$ when the environmental SAT condition is close to the threshold value between snowfall and rainfall. Although monthly and seasonal observational data analyses indicated that SST had a weak impact on precipitation, some studies have suggested a positive contribution of SST to precipitation on intra-seasonal time-scales even under vigorous air-sea interaction environments (Takahashi and Idenaga, 2013; Takahashi and Dado, 2018). Nevertheless, quantitative evaluations are ongoing. These processes, including the modulation of extratropical storm activity, are much more complex (e.g., Seo et al., 2014). Thus, further studies on the impact of long-term trends in SST on snowfall are needed, in conjunction with studies that provide insight into atmospheric global warming trends.

In studies of long-term trends and variability in climate, selection of the data period is critical, because it can affect the conclusions of the study. Modification of seasonal march in snowfall, such as shortening the snowy period (Ma et al., 2010, Yasunaga and Tomochika, 2017), may be related to long-term trends in accumulated snowfall.

5 | CONCLUSION

We investigated long-term trends in snowfall characteristics and snowfall extremes (i.e., heavy snowfall) on Japan, over 51 years from 1962 to 2012, mainly using JMA snowfall data. We focused the long-term trends of the ratio of snowfall day to precipitation day $R(s/p)$ and those of total precipitation (or precipitation days). Besides, the long-term trends in large-scale atmospheric circulation were discussed.

Our results show a statistically significant decrease in seasonally accumulated snowfall for most stations on the Japan Sea side of the country, except for those located in Tohoku and Hokkaido Districts, and the Pacific side of Japan. This reduction in seasonally accumulated snowfall was due to a decrease in the ratio $R(s/p)$. However, the long-term trends in seasonally accumulated snowfall were not apparent at some stations, as these trends tended to be cancelled out by long-term trends in total precipitation (or precipitation days), particularly over part of Tohoku Districts and over the Pacific side. Over the Hokuriku District, the long-term decreases in precipitation and precipitation day more enhanced the long-term decrease in snowfall. Over the Tohoku and Hokkaido Districts, the long-term decrease in $R(s/p)$ was not clear. Besides, the long-term trend in precipitation complicated the long-term trend in snowfall over the Tohoku and Hokkaido District. Thus, the contributions of long-term trends in $R(s/p)$ and precipitation days to snowfall trends differed among districts. Unlike what has been considered, the long-term trends in annual maximum snow depth did not provide further clarification, as the maximum snow depth was likely affected by a specific heavy snowfall event, indicative of the lower statistical stability of this variable compared with accumulated snowfall.

We also examined long-term trends in snowfall intensity because a recent intensification of heavy snowfall events is thought to be caused by climate variability. Systematic long-term trends in mean snowfall intensity were
not found. Moreover, major heavy snowfall events occurred in the first half of the study period; thus, questions remain regarding the possible recent increase in heavy snowfall events.

Because the weakening of the winter monsoon flow was not observed over the study period and recent recovering of the winter monsoon activity, we concluded that the long-term trends in seasonally accumulated snowfall were associated mainly with the trends in the relative frequency of snowfall day through changes in SAT. Nevertheless, a weakening of the winter monsoon flow may be apparent in the near future. The unclear decreasing or some increasing trends in snowfall day over the Pacific side can be explained by the recent enhancement of extratropical cyclone activity over the North Pacific storm track region.

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