

Article

Spatiotemporal Variability and Change in Snowfall in Hokkaido: Effects of Rising Air and Sea Surface Temperatures and Sea Ice

Makoto Higashino 

Department of Civil and Environmental Engineering, National Institute of Technology, Oita College, 1666 Maki, Oita 870-0152, Japan; higashino@oita-ct.ac.jp

Abstract: The impacts of climate change on snowfall have received great interest in cold regions for water resource and flood risk management. This study investigated the effects of rises in air and sea surface temperatures and sea ice on snowfall in Hokkaido, northern Japan, over the period from 1961 to 2020 (60 years). Climate data observed at the 22 weather stations operated by the Japan Meteorological Agency (JMA) were analyzed. Statistics describing the effects of climate change on snowfall were computed. The trend in these quantities was obtained using Sen's slope estimator, and their statistical significance was evaluated by the Mann–Kendall test. The warming trends obtained at these stations were all positive and statistically significant. Annual snowfall increased at seven stations but decreased at two stations. The snowfall period decreased mainly on the southern coast. This is attributed to the fact that these sites are on the leeward side of the Eurasian monsoon, and that air temperatures on the coast and the surface temperature of the sea off Kushiro have risen sufficiently. The results suggest that the flood risk may increase in response to the acceleration of the increase in the level of a river due to early melting snow in spring (March and April). Although the weather stations on the east coast are also on the leeward side, the snowfall period has not shortened. The warming trends in April are very weak on the east coast. The correlation between the air temperature in March and April and the period of sea ice accumulation suggests that melting sea ice in spring plays an important role in preventing the winter period from shortening. Decrease in sea ice due to a rise in both air and sea surface temperatures may increase flood risk in early spring, and thus, some measures may need to be taken in the future.



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Keywords: snowfall; Hokkaido; cold climate; air temperatures; sea surface temperature; sea ice

1. Introduction

The effects of climate change on the hydrological cycle, such as evaporation from the sea surface, precipitation, and loss of ice and glaciers in the Arctic, Antarctic, and high mountains, should be of serious concern for the environment and modern society (e.g., [1–12]). Increases in air temperature due to an increase in greenhouse gases can have significant impacts on spatiotemporal precipitation distributions, sea surface temperatures (SSTs), ocean currents, and other elements, depending on latitude, altitude, proximity to oceans, and other factors. In cold climates, the effects of climate change on snowfall have garnered considerable attention.

Numerous studies have been conducted on the effects of global-scale climate change on snowfall in Japan (e.g., [13–18]). The results complied with reports from the Ministry of Education, Culture, Sports, Science and Technology, the government of Japan (MEXT),

and the Japan Meteorological Agency (JMA) [19]. According to the MEXT and JMA report, future snowfall depends on how much the air temperature rises. For instance, when the average air temperature at the end of the 21st century, which is an average over the period from 2081 to 2100, rises 2 °C higher than that at the end of the 20th century (average in the period of 1980–1999), i.e., RCP2.6, the annual snowfall decreases significantly in southern Japan, whereas it cannot be certain whether snowfall increases or decreases in Hokkaido (northern Japan). When the air temperature at the end of the 21st century rises 4 °C higher than that at the end of the 20th century, i.e., RCP8.5, the annual snowfall decreases throughout the country [19].

The IPCC [20] projected the global average SSTs at the end of the 21st century under the RCP2.6 and RCP8.5 scenarios, where RCP2.6 and RCP8.5 assumed that the global average air temperature at the end of the 21st century would increase 0.9–2.3 and 3.2–5.4 °C, respectively, from that before the Industrial Revolution (1750). Under both scenarios, the SSTs around Japan in the 21st century are expected to increase [19]. Under the 2 °C warming scenario (RCP2.6), it is not certain that the SSTs around Hokkaido will increase, whereas the SSTs will significantly increase on both the west and southeast coasts of Hokkaido under the 4 °C warming scenario (RCP8.5).

The characteristics of snowfall distribution in Hokkaido have been studied (e.g., [21–31]). The climatological wind, due to a quasi-stationary gradient between the Siberian high and the Aleutian low in winter, forms convective snowbands that can bring heavy snowfall to the coastal and island areas of western Hokkaido [21,23]. The frequency of local-scale heavy winter snowfall in Hokkaido and its response to global warming were investigated using self-organizing maps (SOMs) of synoptic-scale sea level pressure anomalies [31]. Their results suggest that the pressure pattern between the Siberian high and the Aleutian low related to the western Pacific pattern will increase in the future. Heavy snowfall days would also increase as a result of the increase in water vapor and preferable weather patterns in a globally warming climate.

These findings are necessary for water resource and flood risk management in cold climates because the characteristics of snowfall distribution can change in response to increases in air temperatures and SSTs. An increase in the level of rivers in March that could be due to earlier thaws was observed in some rivers in Hokkaido [32]. It was not observed in the rivers on the east coast, which can be due to the very weak warming trends in April at Omu, Mombetsu, and Abashiri (see Figure 7 in [32]). This study, therefore, focused on the impacts of melting sea ice in spring on air temperatures on the east coast that have not been taken into account in previous studies.

The main contribution of this study is to develop an understanding of how annual snowfall and the annual snowfall period change due to climate change in Hokkaido. For this purpose, 22 JMA weather stations were chosen, and climate data such as annual average air temperatures, monthly average air temperatures, and annual snowfalls were obtained over the period from 1961 to 2020 (60 years). Based on computed statistics, spatiotemporal variability and changes in annual snowfall and snowfall period over one year on the west, east and southern coasts were investigated.

Section 2 shows the study sites and climate data used in the analyses. Statistics representing the effects of climate change on snowfall, i.e., both the peak of snowfall during a year (μ) and the degree of temporal dispersion of snowfall around the μ values (σ^2) are defined in Section 3. This section also describes the trend analysis. The results of statistical analyses are given in Section 4. In Section 5, characteristics of snowfall on the west, east, and southern coasts of Hokkaido, the effects of sea ice on snowfall on the east coast, and implication of the results are discussed.

2. Study Sites and Climate Data

Figure 1 illustrates the study region, i.e., Hokkaido, northern Japan. Based on the Köppen–Geiger climate classification [33,34], the climate can be classified as Dfb (cold, without dry season, warmer summer). Since Hokkaido is surrounded by the Pacific Ocean, the Sea of Okhotsk, and the Sea of Japan, its climate is governed by monsoons originating from the Eurasian continent during winter, the topography of the land surface, and ocean currents (e.g., [35]). These include warm currents, i.e., the Japan Current and the Tsushima Current, and three cold currents, i.e., the Chishima Current, the Liman Current, and the East Sakhalin Current, around Hokkaido (see Figure 2 in Higashino et al., 2021 [32]). In addition, the Sea of Okhotsk is the southern limit of sea ice (drift-ice) in the Northern Hemisphere.

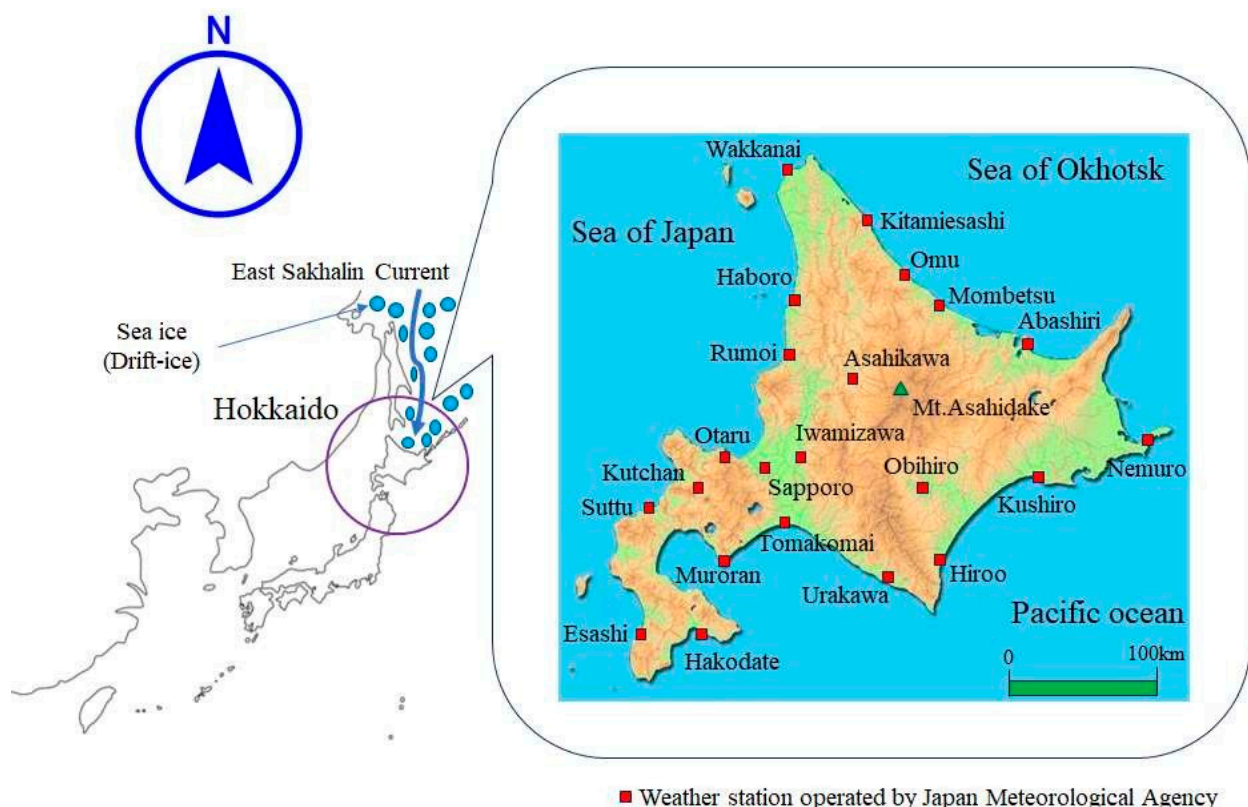


Figure 1. Study sites on Hokkaido in northern Japan.

The land area of Hokkaido is 77,984 km². Hokkaido has extreme elevations ranging from 0 to 2291 m (Mount Asahidake) and the length of the coastline is 2676 km. Approximately 61.5% of the land area is natural (a mountain region and forestland), 25.6% is agricultural, 6.9% is urban, and 6.0% is national park. Although the climate throughout most parts of Hokkaido can be subarctic, the climate in western Hokkaido may be different from that in the eastern region, which is divided by the Daisetsu and Hidaka mountains from north to south (see Figure 1). In winter, cold and dry air arrives from the center of the Eurasian continent and absorbs moisture from the surface of the Sea of Japan before it reaches the west coast, resulting in abundant snowfall on the west side of the mountains. However, the eastern region, which is leeward of the mountains, has a relatively small amount of snowfall annually. During winter (from January to March), sea ice originates from the northern Sea of Okhotsk through the East Sakhalin Current on the east coast (see Figure 1). It was observed from February to March in 2001 that almost the entire Sea of Okhotsk was covered with sea ice for the first time in 20 years [36].

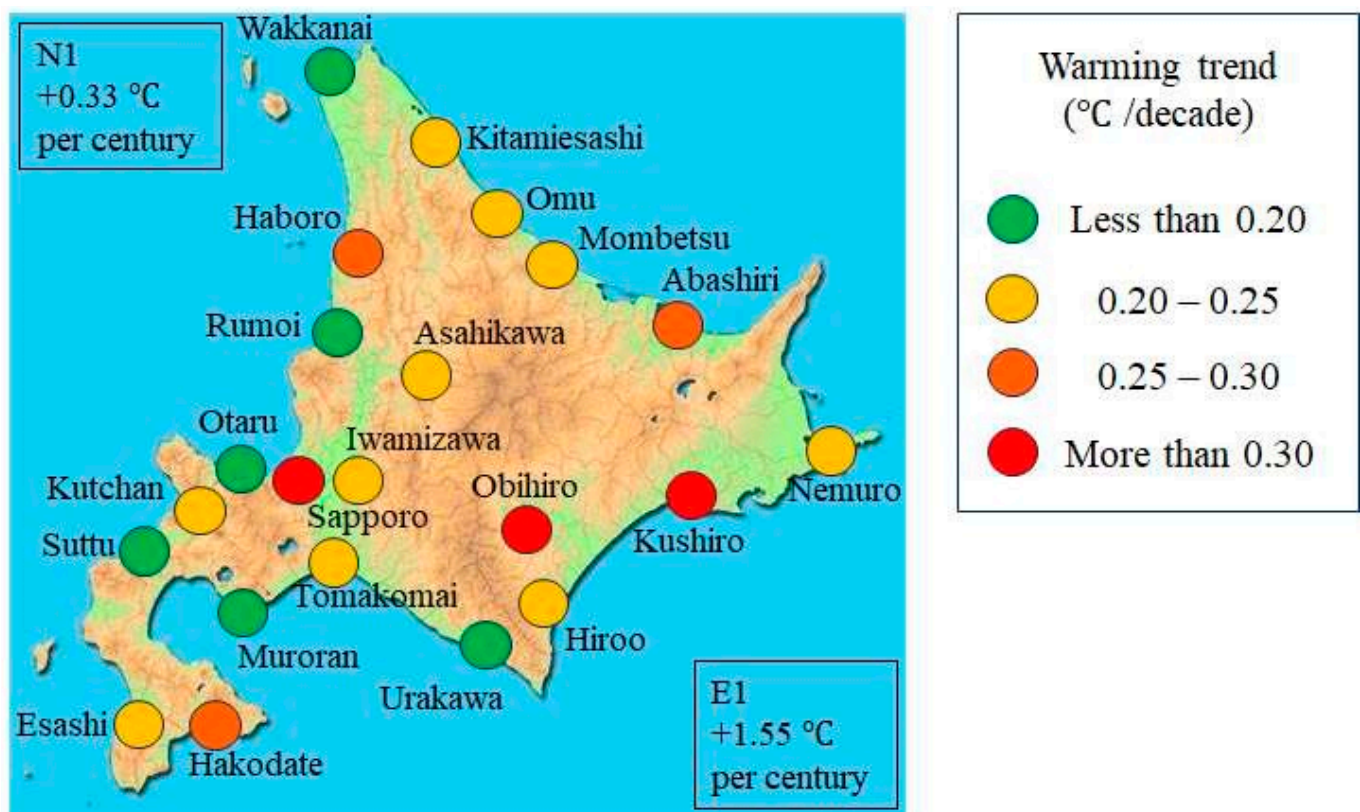


Figure 2. Warming trend at the study sites from 1961–2020. SST has also been observed at the ocean area. The increase rates of the area-averaged annual mean SST in the northern part of the Sea of Japan (N1) and the Sea off Kushiro (E1) are also shown.

The SSTs for 13 areas around Japan have been monitored, and increasing rates over the period from 1891 to 2019 were estimated by the JMA based on the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) created by the National Ocean and Atmospheric Administration (NOAA). The increased rates of the area-averaged annual mean SSTs in the northern part of the Sea of Japan (N1, which is 143–147 degrees east longitude and 41–43 degrees north latitude) and the Sea off Kushiro (E1, which is 138–142 degrees east longitude and 42–50 degrees north latitude) are 0.33 (statistically meaningful trend at a confidence level of 90%) and 1.55 (statistically significant at a confidence level of 99%) °C per century, respectively, as illustrated in Figure 2.

Table 1 summarizes the 22 weather stations (latitude, longitude, location, and nearest ocean). The weather stations were numbered based on latitude. The number increases from north to south, i.e., from No. 1 to 22. Climate data such as annual average air temperature, monthly average air temperature, annual snowfall, and annual ice days (where the ice day is a day on which the daily maximum air temperature is less than 0 °C) in addition to the daily snowfall at the 22 stations for the period of 1961–2020, were obtained from the JMA website (www.jma.go.jp).

The climate data from the 22 JMA weather stations used in this study are sufficiently reliable. However, missing data are included in the given period at Wakkanai, i.e., snowfall on 28 November and 13 December in 2005, and 18–20 December in 2006. The snowfall on these days was taken to be zero when the quantities were calculated. Since the fractions of missing data are 2/365 in 2005 and 3/365 in 2006, the effects of missing data on the results may be negligible.

Table 1. Study sites.

Site Name	Latitude	Longitude	Location	The Nearest Ocean
Wakkanai	45.4	141.7	Northwest	Okhotsk
Kitamiesashi	44.9	142.6	Northeast	Okhotsk
Omu	44.6	143.0	Northeast	Okhotsk
Haboro	44.4	141.7	Northwest	Sea of Japan
Mombetsu	44.3	143.4	Northeast	Okhotsk
Abashiri	44.0	144.3	Northeast	Okhotsk
Rumoi	43.9	141.6	Northwest	Sea of Japan
Asahikawa	43.6	142.4	Center	Endorheic
Nemuro	43.3	145.6	Northeast	Pacific/Okhotsk
Iwamizawa	43.2	141.8	Northwest	Endorheic
Otaru	43.2	141.0	Northwest	Sea of Japan
Sapporo	43.1	141.3	Northwest	Endorheic
Kushiro	43.0	144.4	Southeast	Pacific
Obihiro	42.9	143.2	Southeast	Endorheic
Kutchan	42.9	140.8	Southwest	Endorheic
Suttu	42.8	140.2	Southwest	Sea of Japan
Tomakomai	42.6	141.5	Southwest	Pacific
Muroran	42.3	141.0	Southwest	Pacific
Hiroo	42.3	143.3	Southeast	Pacific
Urakawa	42.2	142.8	Southwest	Pacific
Esashi	41.9	140.1	Southwest	Sea of Japan/Pacific
Hakodate	41.8	140.8	Southwest	Sea of Japan/Pacific

3. Methodology

3.1. Statistics Describing the Effects of Climate Change on Snowfall

The annual pattern of snowfall at Wakkanai from 1 September 1960 to 31 August 1961 is shown in Figure 3 as an example. There is no snowfall from May to September. However, the incidence of snowfall began to increase in December, and a certain amount of snowfall was maintained until the end of March.

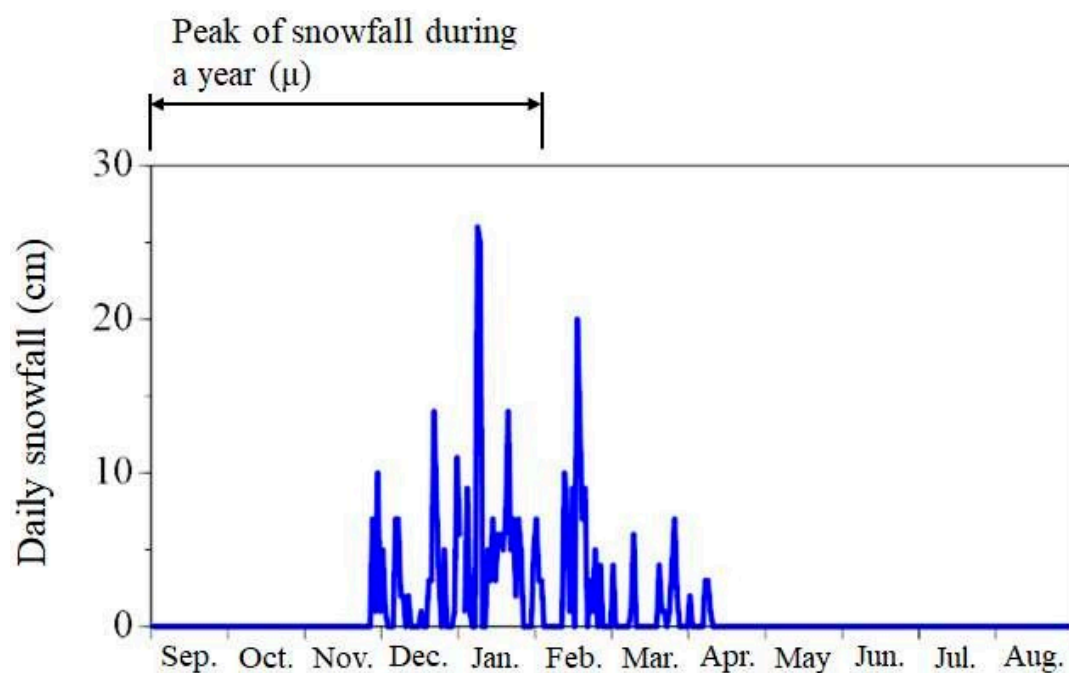


Figure 3. Daily snowfall at Wakkanai from 1 September in 1960 to 31 August in 1961. The peak snowfall amount during a year (μ) is also shown.

This study introduces the peak of snowfall during a year (μ) defined by Equation (1), to depict the impacts of climate change on snowfall.

$$\mu = \frac{\sum_{i=1}^N x_i p_i}{\sum_{i=1}^N p_i} \quad (1)$$

in which p_i is the observed snowfall, x_i is the number of days since 1 September for a given year, and N is the number of elapsed days from 1 September to 31 August, i.e., $N = 365$ days for a normal year or $N = 366$ days for a leap year. The quantity (μ) is the center of gravity for the time series of snowfall from 1 September to 31 August.

The degree of temporal dispersion of snowfall around the μ value (σ^2) is expressed by the following equation:

$$\sigma^2 = \frac{\sum_{i=1}^N (x_i - \mu)^2 p_i}{\sum_{i=1}^N p_i} \quad (2)$$

The σ^2 value can be related to the snowfall period for a given year.

3.2. Trend Analysis

To investigate the changing pattern of snowfall during the period from 1961–2020 in Hokkaido, nonparametric procedures, i.e., Sen's slope estimator and the Mann–Kendall test, were conducted. Sen's slope estimator [37] was used to compute the magnitude of trends for annual average air temperature, monthly average air temperature, annual snowfall, annual ice days, the peak number of snowfall events during a year (μ), and temporal dispersion (σ^2) at the 22 study sites. Weather meteorological organization (WMO) recommends this approach for trend detection in hydrometeorological data [38]. Equation (3) is used to estimate each individual slope (k_i).

$$k_i = \frac{x_j - x_i}{j - i}, \quad i = 1, 2, 3, \dots, N \quad (3)$$

in which x_j and x_i are the values at times j and i , respectively ($j > i$). If there are " n " values of x_j in the time series, the estimates of the slope will be $N = n(n - 1)/2$. The N values of k_i are ranked from smallest to largest, and the median of the slope, i.e., Sen's slope estimator, is determined as

$$k_{median} = \begin{cases} k_{[\frac{N+1}{2}]} & \text{if } N = \text{odd} \\ \frac{k_{[\frac{N}{2}]} + k_{[\frac{N+2}{2}]}}{2} & \text{if } N = \text{even} \end{cases} \quad (4)$$

The significance of each trend was examined using the Mann–Kendall test [39,40]. The WMO recommends that this test be used to detect trends in a set of hydrological data [38]. The Mann–Kendall statistic S was calculated by the following equation:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^n \text{sgn}(x_j - x_k) \quad (5)$$

in which n is the number of data points, x_i and x_j are the values in time series i and j , ($j > i$), respectively, and $\text{sgn}(x_j - x_k)$ is the sign function expressed by the equation.

$$\text{sgn}(x_j - x_k) = \begin{cases} 1 & \text{if } (x_j - x_k) > 0 \\ 0 & \text{if } (x_j - x_k) = 0 \\ -1 & \text{if } (x_j - x_k) < 0 \end{cases} \quad (6)$$

A positive S value indicates an upward trend, while a negative value indicates a downward trend. The variance of the statistic S is expressed as

$$\text{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{j=1}^M \tau_j(\tau_j-1)(2\tau_j+5)}{18} \quad (7)$$

in which M is the number of tied groups that have a set of sample data with the same value, and τ_i is the number of ties for the i value. The standard Mann–Kendall statistic (Z_{MK}) which follows the standard normal distribution with a mean of 0 (zero) and a standard deviation of 1 (unity), can be calculated as

$$Z_{MK} = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (8)$$

The Mann–Kendall test is based on two hypotheses: one is null (H_0), whereas the other is the alternative (H_1) hypothesis. H_0 exhibited no trend, while H_1 exhibited a significant increasing or decreasing trend. On the basis of the 1% significance level, the alternative hypothesis is accepted, indicating the presence of a trend in the data when the p -value < 0.01 . However, H_0 is accepted, indicating the absence of a trend in the data when the p -value > 0.01 .

4. Results

4.1. Air Temperature, Annual Snowfall, and Annual Ice Days

The calculated trends in the annual average air temperature at the 22 study sites from 1961–2020 are summarized in Table 2. The trend ranged from 0.155 (Otaru) to 0.311 (Obihiro) °C/decade, with an average of 0.229 °C/decade, and was statistically significant at the 1% level. The warming trends are large, i.e., more than 0.25 °C/decade at Haboro, Abashiri, Sapporo, Kushiro, Obihiro, and Hakodate. Otherwise, the increasing trends are small, i.e., less than 0.20 °C/decade (Figure 2). The urban heat island effects are likely to be included in the warming trends at Sapporo, Kushiro, Obihiro and Hakodate.

Table 2. Warming tends in the period of 1961–2020 at study sites.

Site Name	Warming Trend (°C/Decade)	Z_{MK}	p -Value	Statistical Significance
Wakkanai	0.194	4.31	$p < 0.01$	Yes
Kitamiesashi	0.226	4.33	$p < 0.01$	Yes
Omu	0.222	4.16	$p < 0.01$	Yes
Haboro	0.250	5.44	$p < 0.01$	Yes
Mombetsu	0.238	4.43	$p < 0.01$	Yes
Abashiri	0.264	4.78	$p < 0.01$	Yes
Rumoi	0.193	4.77	$p < 0.01$	Yes
Asahikawa	0.234	5.22	$p < 0.01$	Yes
Nemuro	0.239	4.65	$p < 0.01$	Yes
Iwamizawa	0.231	4.97	$p < 0.01$	Yes
Otaru	0.155	3.54	$p < 0.01$	Yes
Sapporo	0.310	6.06	$p < 0.01$	Yes
Kushiro	0.300	5.36	$p < 0.01$	Yes
Obihiro	0.311	5.44	$p < 0.01$	Yes
Kutchan	0.226	5.25	$p < 0.01$	Yes
Suttu	0.175	4.06	$p < 0.01$	Yes

Table 2. Cont.

Site Name	Warming Trend (°C/Decade)	Z _{MK}	p-Value	Statistical Significance
Tomakomai	0.207	4.83	$p < 0.01$	Yes
Muroran	0.156	3.63	$p < 0.01$	Yes
Hiroo	0.231	4.43	$p < 0.01$	Yes
Urakawa	0.167	3.74	$p < 0.01$	Yes
Esashi	0.214	5.11	$p < 0.01$	Yes
Hakodate	0.294	6.06	$p < 0.01$	Yes

Figure 4 shows the computed trends in the monthly average air temperature at the 22 weather stations from 1961–2020. Air temperature increases in autumn (September and October) and winter (from January to March) significantly contributed to the increase in the annual average air temperature. Additionally, the warming trends in April are relatively small in the north, which is at a high latitude (Wakkanai–Otaru) compared to those in the south (Kushiro–Hakodate). The relatively low air temperatures and weak warming trends on the east coast can be induced by sea ice coming from the northern Sea of Okhotsk. The latent heat released when sea ice melts keeps the air temperature from rising.

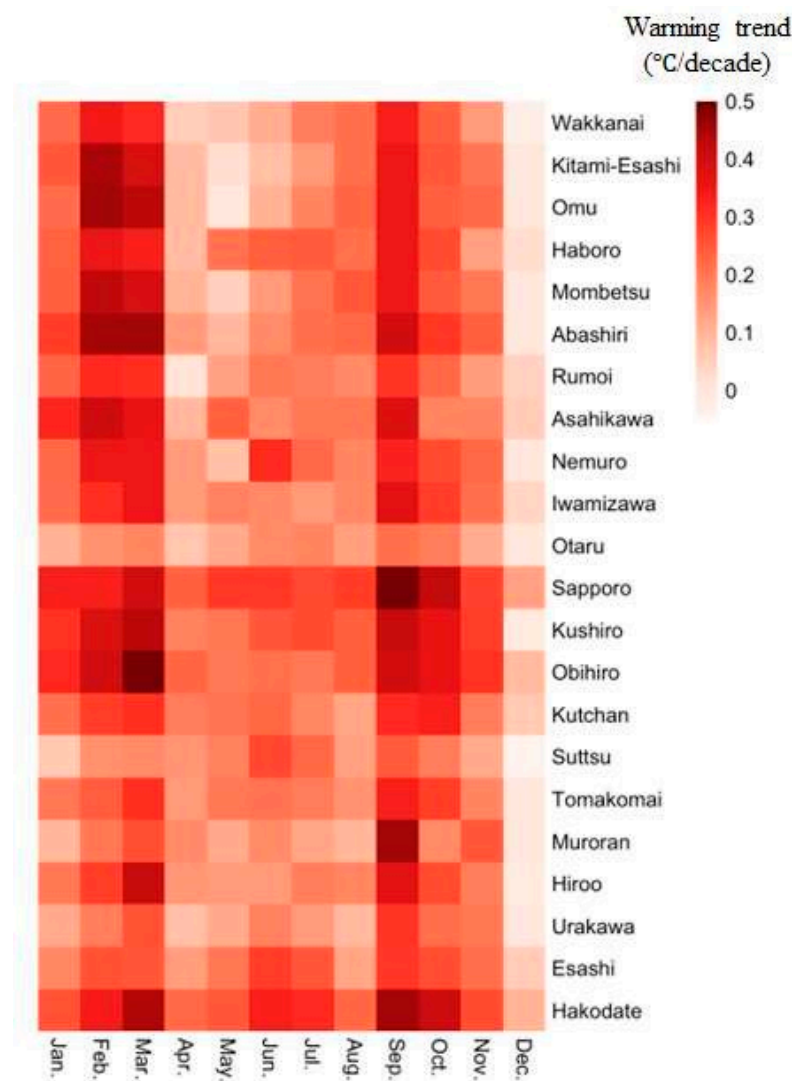


Figure 4. Trends (°C/decade) in the monthly average air temperature from 1961–2020.

The computed trends in annual snowfall at the 22 study sites from 1961–2020 are shown in Table 3. As shown in the table, 16 of the 22 are positive, and six of the 22 are negative. The trends obtained at Nemuro, Kushiro, Kutchan, and Suttu are statistically significant at the 1% level, and those at Haboro (2%), Mombetsu (2%), Abashiri (3%), and Rumoi (5%) are statistically meaningful. These trends are not statistically meaningful at the other 13 stations. Figure 5 illustrates the increasing/decreasing trend of annual snowfall. Annual snowfall has increased at Haboro, Mombetsu, Abashiri, Rumoi, Nemuro, Kushiro, and Suttu but decreased at Kitamiesashi and Kutchan. Except for these nine weather stations, annual snowfall neither increased nor decreased during the period 1961–2020.

Table 3. Trends of annual snowfall in the period of 1961–2020 at study sites.

Site Name	Trend (cm/Decade)	Z _{MK}	p-Value	Statistical Significance
Wakkanai	0.930	0.134	0.447	No
Kitamiesashi	−26.4	−3.02	0.0125	2%
Omu	6.67	1.40	0.0803	No
Haboro	19.5	2.10	0.0177	2%
Mombetsu	9.82	2.10	0.0179	2%
Abashiri	10.3	2.03	0.0213	3%
Rumoi	17.1	1.71	0.0437	5%
Asahikawa	−1.82	−0.191	0.424	No
Nemuro	11.7	2.79	$p < 0.01$	Yes
Iwamizawa	−14.4	−0.982	0.163	No
Otaru	9.21	1.17	0.120	No
Sapporo	0.313	0.0702	0.472	No
Kushiro	0.300	5.36	$p < 0.01$	Yes
Obihiro	−9.05	−1.61	0.0540	No
Kutchan	−76.4	−4.09	$p < 0.01$	Yes
Suttu	41.3	5.12	$p < 0.01$	Yes
Tomakomai	3.00	0.791	0.214	No
Muroran	3.86	1.24	0.107	No
Hiroo	−3.02	−0.287	0.387	No
Urakawa	2.16	0.683	0.247	No
Esashi	0.313	0.0893	0.464	No
Hakodate	10.0	1.53	0.0629	No

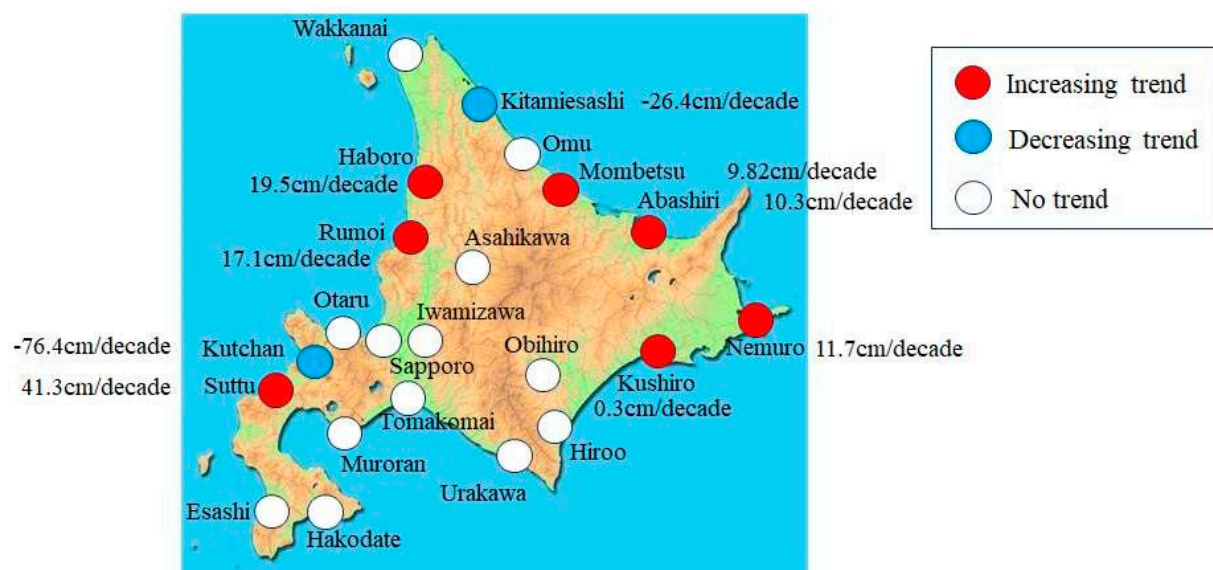


Figure 5. Trends in annual snowfall at the study sites during the period from 1961–2020.

As shown in Table 4, negative trends in annual ice days were obtained at all 22 study sites. However, the trends at Asahikawa, Iwamizawa, Otaru, Sapporo, Kutchan, and Suttu were not significantly different (see Figure 6). The figure illustrates that annual ice days have decreased along the east coast (from Wakkanai to Abashiri) and the south coast (from Nemuro to Hakodate). This may be induced by rising air temperatures on the coasts.

Table 4. Trends of annual ice days in the period from 1961–2020 at study sites.

Site Name	Trend (Days/Decade)	Z _{MK}	p-Value	Statistical Significance
Wakkanai	−2.00	−2.24	0.0125	2%
Kitamiesashi	−1.98	−2.16	0.0155	2%
Omu	−2.34	−2.49	$p < 0.01$	Yes
Haboro	−2.00	−2.06	0.0199	2%
Mombetsu	−1.43	−2.07	0.0192	2%
Abashiri	−2.22	−2.79	$p < 0.01$	Yes
Rumoi	−2.13	−2.04	0.0208	3%
Asahikawa	−1.43	−1.63	0.0517	No
Nemuro	−2.57	−3.01	$p < 0.01$	Yes
Iwamizawa	−0.785	−0.843	0.200	No
Otaru	−0.370	−0.447	0.327	No
Sapporo	−1.01	−1.09	0.138	No
Kushiro	−2.17	−2.64	$p < 0.01$	Yes
Obihiro	−2.18	−2.28	0.0113	2%
Kutchan	−1.07	−1.26	0.103	No
Suttu	−0.779	−0.715	0.237	No
Tomakomai	−3.03	−3.17	$p < 0.01$	Yes
Muroran	−2.61	−2.46	$p < 0.01$	Yes
Hiroo	−1.82	−2.54	$p < 0.01$	Yes
Urakawa	−2.56	−2.78	$p < 0.01$	Yes
Esashi	−1.94	−2.13	0.0164	2%
Hakodate	−2.35	−2.43	$p < 0.01$	Yes

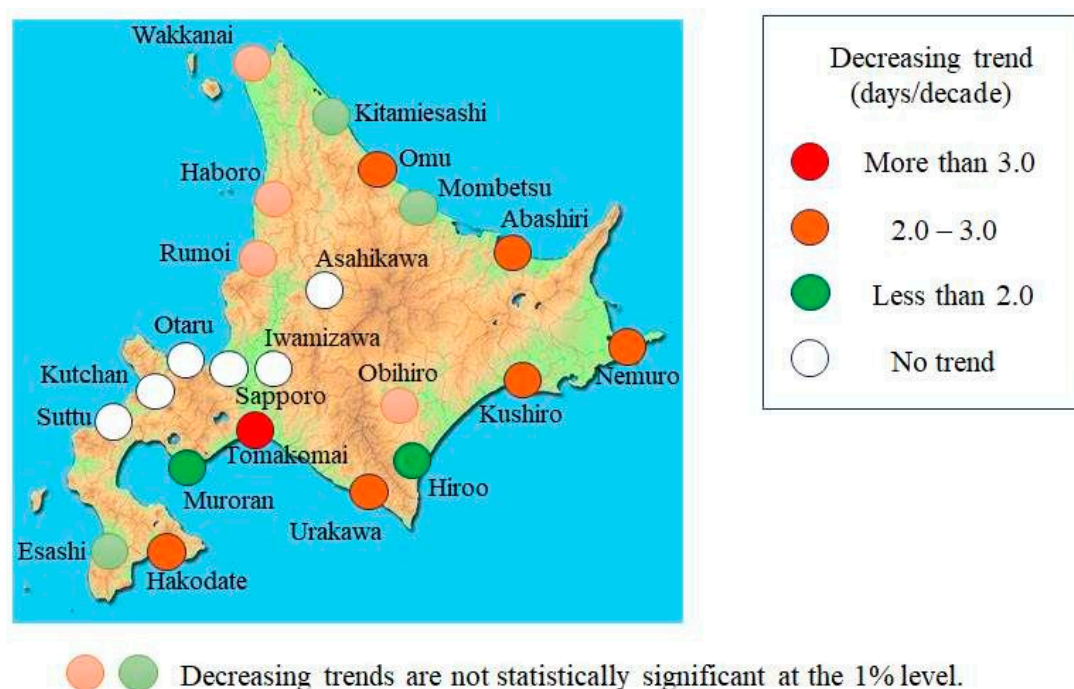


Figure 6. Trends in annual ice days at the study sites during the period from 1961–2020.

4.2. Peak Snowfall During a Year and Temporal Dispersion

The peak number of snowfall events during a year (μ) was calculated via Equation (1) at the 22 study sites, and the results are shown in Table 5. The mean μ value in the period from 1961–2020 ranged from 133.5 (Asahikawa) to 159.8 (Nemuro) days, with an average of 145.4 days. As illustrated in Figure 7, the peak of snowfall reached 145 days on the west coast (Suttu–Wakkanai), whereas it was more than 150 days on the east and south coasts (Omu–Nemuro–Muroran). The principal factors of snowfall in Hokkaido can include monsoons, which are dry and cold and originate from the Eurasian continent; warm currents (e.g., the Tsushima Current); and the surface topography of the land. The peak of snowfall from 1 September was approximately 140 days on the windward side, i.e., the west coast facing the Sea of Japan. It becomes longer, i.e., approximately 150 days or more, on the leeward side along the east and south coasts facing the Sea of Okhotsk and the Pacific Ocean, respectively. The trends are positive (6/22) and negative (16/22). The trends at Esashi and Obihiro are statistically significant at the 2% and 3% levels, respectively. The others are not statistically meaningful. The obtained μ values, therefore, fluctuate without increasing or decreasing trends for the 60-year period.

Table 5. Trends of peak of snowfall during a year (μ) in the period from 1961–2020 at study sites.

Site Name	Average (Days)	Trend (Days/Decade)	Z _{MK}	p-Value	Statistical Significance
Wakkanai	139.7	0.358	0.517	0.303	No
Kitamiesashi	140.2	0.0289	0.580	0.281	No
Omu	146.6	−0.0221	−0.0446	0.482	No
Haboro	138.8	−0.363	−0.555	0.289	No
Mombetsu	148.8	0.0693	0.159	0.437	No
Abashiri	149.5	−0.137	−0.351	0.363	No
Rumoi	139.9	−0.326	−0.529	0.298	No
Asahikawa	133.5	0.141	0.198	0.422	No
Nemuro	159.8	−1.06	−1.18	0.119	No
Iwamizawa	135.3	−0.614	−1.05	0.146	No
Otaru	142.5	−0.169	−0.376	0.353	No
Sapporo	144.1	−0.263	−0.631	0.264	No
Kushiro	156.0	−1.49	−1.54	0.0621	No
Obihiro	151.0	−1.99	−2.01	0.0223	3%
Kutchan	137.9	−0.209	−0.338	0.368	No
Suttu	142.3	0.159	0.210	0.417	No
Tomakomai	152.3	−0.467	−0.625	0.266	No
Muroran	152.5	−0.0429	−0.0957	0.462	No
Hiroo	157.5	−1.12	−1.51	0.0653	No
Urakawa	146.1	0.287	0.638	0.262	No
Esashi	144.2	−1.45	−2.11	0.0174	2%
Hakodate	140.2	−0.275	−0.466	0.321	No

The temporal dispersion of snowfall around the peak value (μ) at the 22 study sites was computed by Equation (2) and is shown in Table 6. The σ^2 value represents the degree of temporal dispersion of snowfall around the peak (μ), which represents the snowfall period in each year. The mean value of σ^2 in the period from 1961–2020 ranged from 30.7 (Esashi) to 38.8 (Kitamiesashi) days² with an average of 34.5 days². The obtained trends are both positive (6/22) and negative (16/22). The trends at Tomakomai, Muroran, and Esashi are statistically significant at the 1% level. Additionally, the trends at Kushiro, Hiroo, and Urakawa, at Abashiri, and at Asahikawa and Obihiro are statistically meaningful at the 2%, 3%, and 4% levels, respectively.

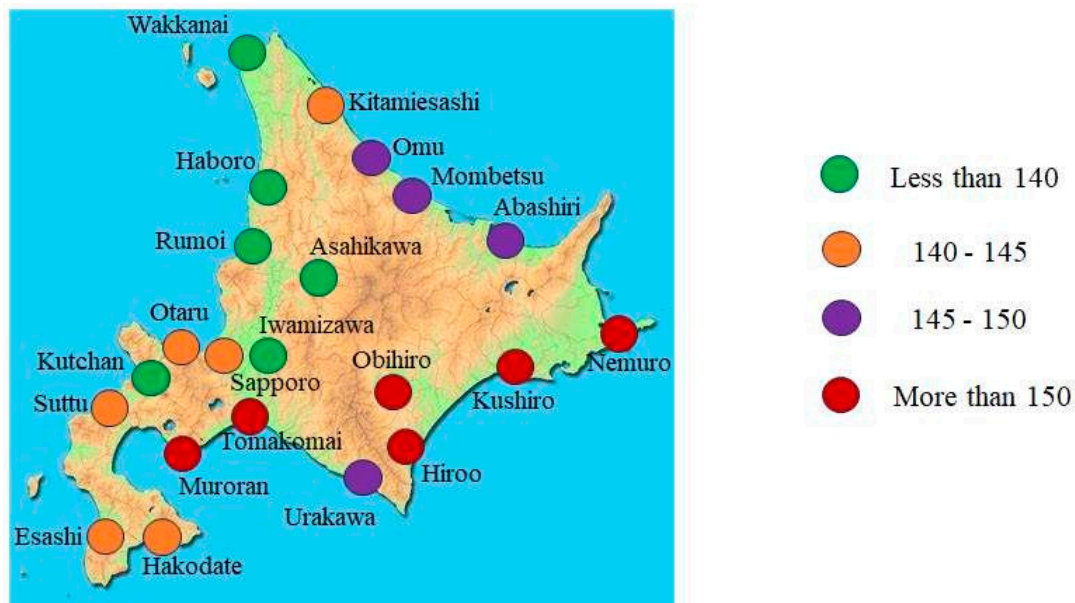


Figure 7. Peaks of snowfall (μ) during the year from 1961–2020.

Table 6. Trends of temporal dispersion of snowfall around the peak (σ^2) in the period from 1961–2020 at study sites.

Site Name	Average (Days ²)	Trend (Days/Decade)	Z _{MK}	p-Value	Statistical Significance
Wakkanai	34.2	0.287	0.733	0.232	No
Kitamiesashi	38.8	−0.360	−1.12	0.132	No
Omu	38.7	−0.190	−0.427	0.335	No
Haboro	33.3	0.146	0.657	0.256	No
Mombetsu	38.0	−0.596	−1.61	0.0533	No
Abashiri	37.3	−0.807	−1.93	0.0266	3%
Rumoi	33.1	−0.257	−0.887	0.188	No
Asahikawa	38.2	−0.502	−1.79	0.0366	4%
Nemuro	33.6	−0.638	−1.23	0.109	No
Iwamizawa	33.5	−0.168	−0.631	0.264	No
Otaru	33.5	0.144	0.568	0.285	No
Sapporo	33.1	0.0495	0.159	0.437	No
Kushiro	35.6	−1.27	−2.12	0.0168	2%
Obihiro	37.6	−0.962	−1.84	0.0326	4%
Kutchan	34.6	0.231	0.899	0.184	No
Suttu	31.0	−0.0759	−0.223	0.412	No
Tomakomai	33.0	−1.31	−3.51	$p < 0.01$	Yes
Muroran	32.1	−1.43	−3.17	$p < 0.01$	Yes
Hiroo	34.9	−1.03	−2.32	0.0103	2%
Urakawa	31.4	−0.963	−2.24	0.0126	2%
Esashi	30.7	1.27	3.32	$p < 0.01$	Yes
Hakodate	32.7	−0.369	−1.26	0.104	No

Figure 8 shows that the σ^2 values decreased over the 60 years (1961–2020) along the southern coast, i.e., Muroran, Tomakomai, Urakawa, Hiroo, Obihiro, and Kushiro, in addition to Abashiri and Asahikawa. This suggests that snowfall becomes temporally more concentrated around the peak (μ). In other words, the snowfall period in a year becomes shorter on the southern coast of Hokkaido. This can be attributed to the fact that both the east and south coasts are on the leeward side of the monsoon from the Eurasian continent, because mountain ranges are present between the west coast and east/south coasts. Additionally, strengthening of the pressure pattern between the Siberian high

and the Aleutian low [31] can offset the effects of air temperature increases, and prevent the snowfall period from shortening on the west coast. In addition, the SST can play an important role; i.e., the warming trend in the SST in the Sea off Kushiro is much stronger than that in the northern part of the Sea of Japan (see Figure 2). The strong increasing trend in the SST caused by global warming may accelerate the shortening of the snowfall period on the southern coast of Hokkaido. However, the snowfall period in a year has not shortened on the west or east coast because the warming trend in the SST is weak, due to the increase in strength of cold currents during winter [41] and sea ice.

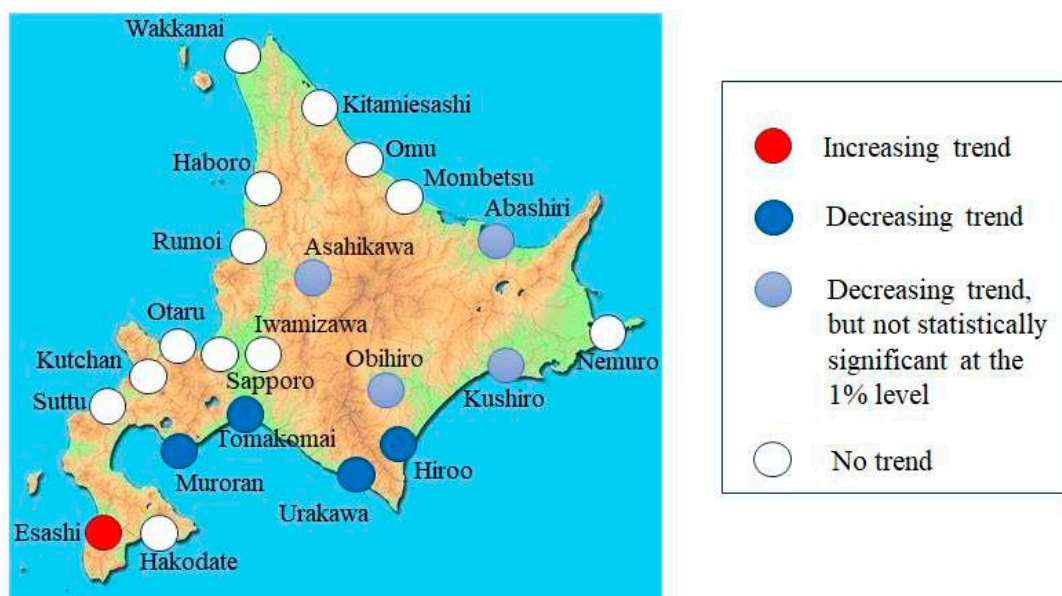


Figure 8. Temporal dispersion of snowfall around the peak (σ) during the year from 1961–2020.

5. Discussion

5.1. Characteristics of Snowfall in Hokkaido on Different Coasts

The climate in Hokkaido can be characterized by monsoons, the topography of the land, the surrounding atmospheric pressure pattern, ocean currents around the region, and sea ice. Although global-scale climate change has impacts on air temperature, snowfall, and so on, the degree of climate change can differ depending on the location, i.e., west, east, or south coast.

The air temperature increased at all 22 study sites over the period from 1961 to 2020. On the west coast, the annual ice days neither increased nor decreased except in the north (Wakkanai, Haboro, and Rumoi) and Esashi. Additionally, the annual snowfall has not increased or decreased significantly. Both Kutchan and Suttu are exceptions, i.e., annual snowfall has increased at Suttu (41.3 cm/decade) but decreased significantly at Kutchan (−76.4 cm/decade). The snowfall period has not shortened or lengthened except for that in Esashi.

On the east coast, the annual snowfall has slightly increased at Mombetsu, Abashiri, and Nemuro but decreased at Kitamiesashi. Although the annual ice days have decreased (see Figure 6), the snowfall period has not shortened except for that in Abashiri. This could be because sea ice originates from the northern Sea of Okhotsk.

On the southern coast, the annual ice days decreased, whereas no significant changes were found in the annual snowfall during the period from 1961–2020. Additionally, the snowfall period described by the value of σ^2 has shortened, which can be induced by rising air temperatures on the coast and by the SST in the Sea of Kushiro. The cold current has little effect on the SST.

5.2. Effects of Sea Ice on Snowfall on the East Coast

Sea ice can play an important role in the climate on the east coast of Hokkaido. Sea ice can be created near the mouth of the Amur River due to low salinity, and is carried to the east coast of Hokkaido by the East Sakhalin Current from January to March. The East Sakhalin Current (cold current) originates from the northern Sea of Okhotsk along the Sakhalin coast [42–44]. The sea ice stays until April and finally melts. As such, it absorbs heat from the surrounding area, contributing to a decrease in temperature.

Figure 9 illustrates the relationship between sea ice and air temperature at Kitamiesashi, Omu, Mombetsu, and Abashiri. In the figure, the vertical axis represents the number of pseudo-winter days (for which the average air temperature is below the freezing point in March and April), and the horizontal axis represents the pseudo-period of sea ice, which is defined as the number of days since 1 April to the last day of sea ice in sight for each year. The pseudo-period of sea ice was determined based on the observed last day of sea ice (<https://www.jma.go.jp>). As shown in the figure, the number of pseudo-winter days increases as the pseudo-period of sea ice increases. The impacts of sea ice on air temperature can be described by Spearman's rank correlation coefficient (ρ_s) and were calculated as $\rho_s = 0.44$ (Kitamiesashi), $\rho_s = 0.54$ (Omu), $\rho_s = 0.56$ (Mombetsu), and $\rho_s = 0.71$ (Abashiri). Considering that air temperature is influenced by not only the presence of sea ice but also by wind speed and direction, pressure patterns, cloud cover, etc., the obtained correlation coefficients of 0.54, 0.56, and 0.71 may be sufficiently strong. Thus, relatively low air temperatures and weak warming trends in April on the east coast can be induced by melting sea ice.

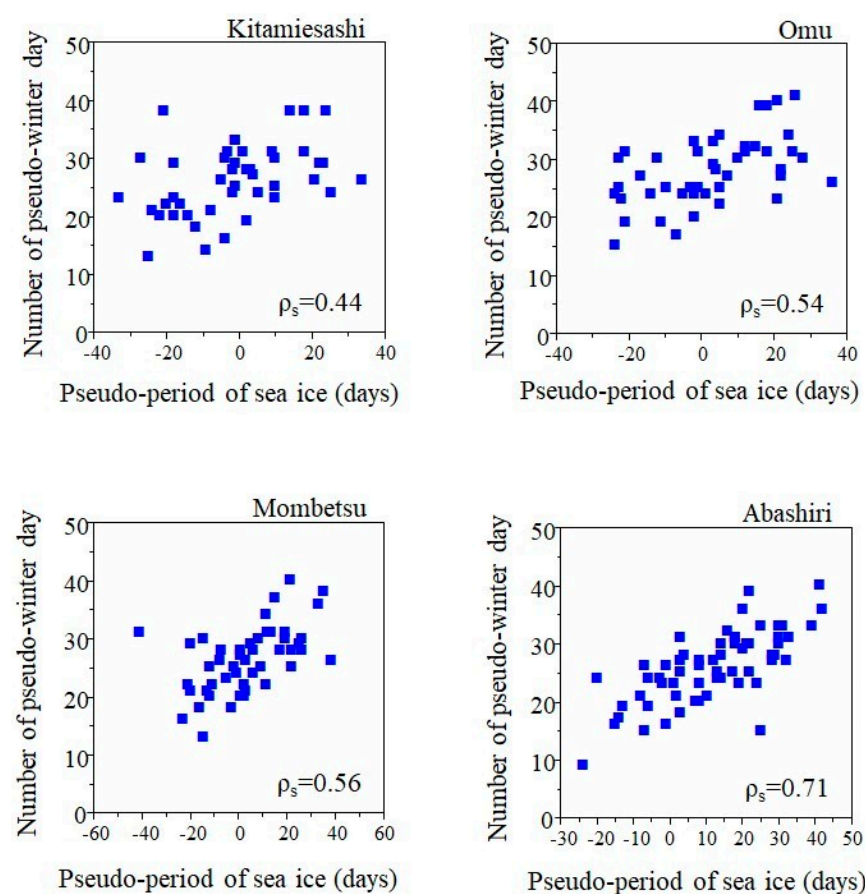


Figure 9. Effects of sea ice on air temperature at Kitamiesashi, Omu, Mombetsu, and Abashiri for the periods from 1961–2004 (Kitamiesashi and Omu), 1961–2007 (Mombetsu), and 1961–2020 (Abashiri).

A pseudo-winter day is a day in which the average air temperature is below the freezing point. The pseudo-period of sea ice is the number of days from 1 April to the last day of sea ice in sight for each given year.

There have been limited studies investigating the effects of climate change on annual snowfall and its duration in Hokkaido between the west coast (Sea of Japan side), east coast (Sea of Okhotsk side), and southern coast (Pacific Ocean side). This needs to be further explored.

The Sea of Okhotsk is considered to be a source of cold water for the northern Pacific Ocean, whereas the ocean in the subarctic North Pacific, which is at the same latitude, can be warmed by the atmosphere [45]. The cold climate on the east coast of Hokkaido is likely caused by cold water in the Sea of Okhotsk and meltwater, i.e., the negative heat flux carried by the East Sakhalin Current from the north.

5.3. Implication of the Result

The sea surface temperature (SST) of the region off Kushiro is likely to increase in the future as global warming progresses. The snowfall period can shorten in response to the increase in the SST on the southern coast. On the east coast, the SST may not increase as much as that on the south coast due to sea ice. As a result, the snowfall period may not be shortened significantly. Since the west coast is on the windward side of the Eurasian monsoon due to the mountain ranges, the SST may not have a strong impact on snowfall. These results are consistent with the findings of Higashino et al. [32]. Accelerations in the rise of a level of the river have been observed in some rivers (e.g., the Teshio River, Ishikari River, Saru River, and Mu River) on the west and south coasts of Hokkaido. This may be induced by rising air temperatures on the coasts and by the SST in the Sea off Kushiro. However, this effect has not been observed on the east coast (Shokotsu River, Yubetsu River, Tokoro River, or Abashiri River) [32]. It could be caused by the weak warming trends in April (see Figure 4).

The annual snowfall and snowfall period on the east coast of Hokkaido may be dependent on sea ice related to the heat balance in the northern Sea of Okhotsk. Under the 2 °C warming scenario (RCP2.6), it is unlikely that the sea surface temperature (SST) in the Sea of Okhotsk will increase and/or that sea ice coming to the east coast will significantly decrease. However, it is likely that the SSTs increase on the west, east, and south coasts of Hokkaido under the 4 °C warming scenario (RCP8.5). Additionally, sea ice may decrease, which can be induced by rising air temperatures and SSTs.

6. Conclusions

This study investigated the effects of air temperature, increasing SSTs, and sea ice on snowfall in Hokkaido, northern Japan, over the period from 1961 to 2020 (60 years). The 22 weather stations operated by the JMA were chosen, and climate data were analyzed.

The warming trends obtained at the 22 study sites were all positive and statistically significant at the 1% level. Annual snowfall has increased at Haboro, Mombetsu, Abashiri, Rumoi, Nemuro, Kushiro, and Suttu but decreased at Kitamiesashi and Kutchan. Except for these nine sites, the incidence of snowfall neither increased nor decreased. The annual ice days have decreased except for those of Asahikawa, Iwamizawa, Otaru, Sapporo, Kutchan, and Suttu. This trend is more pronounced on the east and south coasts.

The temporal dispersion of snowfall around the peak value, which is the center of gravity for a time series of snowfall from 1 September to 31 August, represents the snowfall period in a year. The snowfall period decreased mainly on the southern coast (Kushiro, Tomakomai, Muroran, Hiroo, and Urakawa). This is attributed to the fact that these sites are on the leeward side of the monsoon, and that air temperatures on the coast and the

sea surface temperature (SST) off Kushiro have risen sufficiently. Although the weather stations on the east coast (Kitamiesashi, Omu, and Mombetsu) are also on the leeward side, the snowfall period did not shorten during the period from 1960–2020. The warming trends in April are very weak on the east coast. The correlation coefficients of 0.54 (Omu), 0.56 (Mombetsu), and 0.71 (Abashiri) between the pseudo-winter day, which is a day in which the average air temperature is below the freezing point in March and April, and pseudo-period of sea ice, which is the day from 1 April to the last day of sea ice in sight, suggest that melting sea ice in spring plays an important role in preventing the winter period from shortening.

Although air temperature has risen, annual snowfall has not increased or decreased significantly during the period from 1961–2020 except at a few sites, whereas the snowfall period has decreased mainly on the southern coast due to a rise in both air and sea surface temperatures. The snowfall period has not shortened on the east coast, which may be induced by sea ice coming from the northern Sea of Okhotsk. If sea ice decreases dramatically due to global warming, air temperature may increase in March and April, resulting in not only a decrease in the snowfall period but also an increased flood risk caused by thawing in early spring. Some measures may need to be taken in the future.

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Data Availability Statement: The data used in the analyses in this study are readily available on the Japan Meteorological Agency website (<https://www.jma.go.jp>).

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