A METHOD OF ESTIMATING WINTER CLIMATE PARAMETERS USING FUTURE PROJECTIONS FROM THE GLOBAL CLIMATE MODEL

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ABSTRACT

Recent years have seen a downward trend in the amount of snowfall in the snowy cold regions of Japan, due to warm winters, whereas areas known for light snowfall have experienced heavier snowfall than before. Data on the winter maximum snow depth and the frequency of heavy snowfall events can be used as basic data for planning snow hazard control, such as the design of snow-control facilities and the allocation of snow removal machinery. In considering long-term plans of snow hazard control, it is necessary to predict future trends in the maximum snow depth and other winter parameters. In light of this, the Global Climate Model (GCM) was used in this study and a future distribution map showing the winter maximum snow depths and the cumulative snowfall in the snowy cold regions of Japan was created to clarify trends in current and future changes. It was found that mean values for the winter maximum snow depth and winter snowfall will decrease from current levels in most parts of the snowy cold regions, suggesting the potential for the reduction of future costs associated with snow hazard control.

1. INTRODUCTION

Recent years have seen a downward trend in the amount of snowfall in the snowy cold regions of Japan, due to warm winters, whereas areas known for light snowfall have experienced heavier snowfall than before. In light of this, the authors analyzed the effects of global warming on winter climate to contribute to the development of long-term snow and ice control plans and measures.

In winter in Japan, seasonal winds carry cold, dry air from eastern Siberia over the Sea of Japan, where the air picks up large amounts of moisture. When the air reaches the backbone range of the Japanese archipelago, it rises and cools, and the moisture precipitates as heavy snowfall [1]. When the air reaches the leeward side of the backbone range, it is dry, so areas along the Pacific Ocean see little snowfall (Figure 1). Figure 2 shows the normal values for annual maximum snow depth [2]. Areas with annual maximum snow depths exceeding 100 cm tend to be found in Hokkaido and on the western side of the mountain ranges of Japan's main island of Honshu. The values are between 0 and 10 cm on the Pacific Ocean side of Honshu.

Analysis of snowfall and snow cover data for the 30 years from 1981 to 2010 found that the winter cumulative snowfall showed a decreasing tendency in most parts of the snowy cold regions of Japan. In contrast, the annual maximum snow depth and the frequency of 24-hour snowfall exceeding 40 cm showed increasing tendencies in eastern Hokkaido and in mountainous areas of northern Honshu [3]. Changes in snowfall patterns and in the distribution of areas with heavy snowfall were also seen.

Data on the annual maximum snow depth and the frequency of heavy snowfall events are primary information for the planning of snow control measures, such as the design of snow-control facilities and the deployment of snow removal machinery. In developing long-range snow control plans, it is necessary to predict trends in the maximum snow depth and other winter climate parameters. In this study, the Global Climate Model (GCM) was used to create a future distribution map showing the predicted maximum snow depth, the frequency of heavy snowfall events and other winter climate parameters in the snowy cold regions of Japan, toward clarifying the trends in current and future changes.

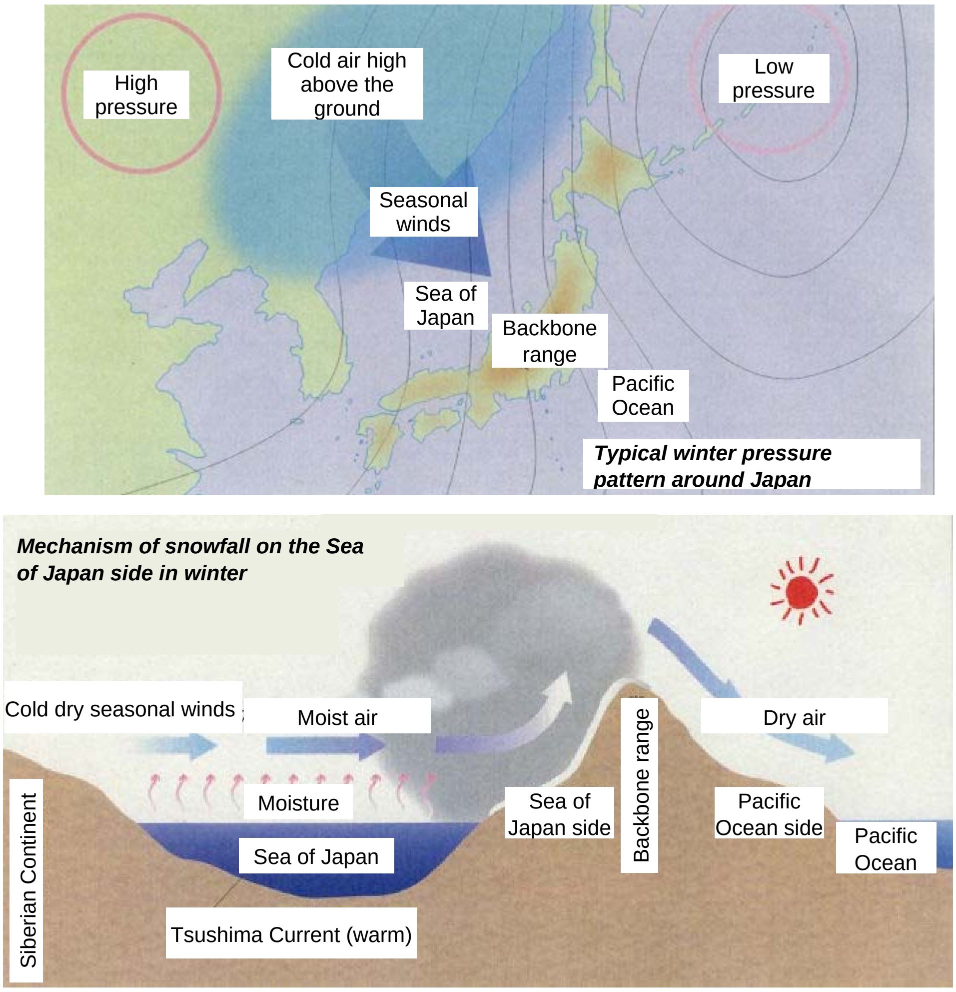


Figure 1 - A typical winter pressure pattern over Japan (upper) and the snowfall mechanism on the Sea of Japan side of Japan (lower) [1]

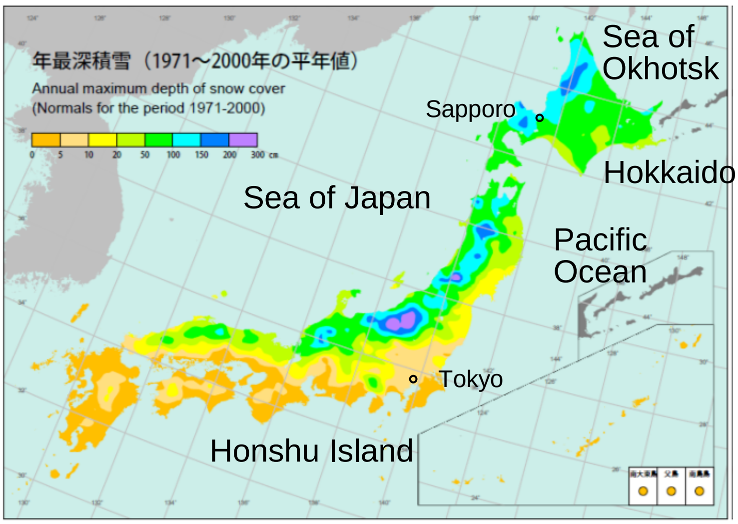


Figure 2 - Normal values for annual maximum snow depth (1971 – 2000) [2]

2. METHOD

2.1. Target area and data

The winter climate parameters analyzed in this study are the maximum snow depth, the maximum 24-hour snowfall and the frequency of 10 cm or more of daily snowfall in one winter season. The reasons for studying these parameters are as follows. In Japan, snow-control facilities are designed based on the 30-year annual maximum snow depth and the width of the snow piling zone at the road shoulder is designed based on the 10-year maximum daily snowfall [4]. Snowplows are deployed to national highways when the depth of newly fallen snow reaches 10 cm and continuous snowfall is expected [5]. In this paper, we define "winter" as the period between November 1 and April 30 of following year. Unless otherwise denoted, "maximum snow depth," "cumulative snowfall" and other winter climate parameters of the analyzed data and analysis results are those of the winter period. We estimated future winter climate parameters using observation data from 161 stations (Automated Meteorological Data Acquisition System (AMeDAS) stations of the Japan Meteorological Agency, and telemeters of the Hokkaido Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism of Japan), and data that were output by the MRI-AGCM3.2S global climate model developed by the Meteorological Research Institute of Japan Meteorological Agency (resolution: 20 km by 20 km)(Figure 3) [6]. The hourly snowfall was defined as the hourly increase in snow depth; it was obtained from the measured data. The data subject to analysis were measured for each winter from 1979/80 to 2002/03. For the locations where measurement started after the 1979/80 winter, only the data measured between the first winter of measurement and the 2002/03 winter were analyzed. The currently available data of MRI-AGCM3.2S are the present climate for 1979-2003, the near-future climate for 2015-2039 and the century-end future climate for 2075-2099. We used output data of hourly temperature and precipitation, daily snow water equivalent and monthly mean snow depth for these periods. The output for near-future climate and century-end future climate are based on the A1B scenario of the International Panel on Climate Change (IPCC), where the concentration of atmospheric greenhouse gasses at the end of the 21st century is twice that at the end of the 20th century. The data for the 161 grids of the climate model that are closest to the locations of AMeDAS stations or road telemeters are compared with the observation data.
The hourly snowfall was calculated by multiplying the hourly precipitation with snowfall density by air temperature. Air temperature is given by Equation (1).

$$\begin{aligned} \rho_s &= 0.04 & (T < -2) \\ \rho_s &= 0.0667 + 0.0133T & (-2 \leq T < 1) \\ \rho_s &= 0.08 & (T \geq 1) \end{aligned} \qquad \text{Equation (1)}$$

Where, ρ_s is the snowfall density (g/m^3) and T is the air temperature (°C) [8]. When the near-ground air temperature is around 3 °C, the precipitation is rain with a probability of 50%. Therefore, we regarded the precipitation as rain when the air temperature was 3 °C or more and as snow when air thermometer was below 3 °C (Figure 4) [9].
The monthly mean snow density is calculated from the daily snow water equivalent data and the monthly mean snow depth data. The winter maximum daily snow water equivalent is multiplied by the mean snow density of the month to obtain the maximum snow depth. Five grids were excluded because they contained seawater bodies where there was no daily snow water equivalent output.
Because the values of winter climate parameters greatly fluctuate from winter to winter, the mean and the maximum values and the standard deviations of the parameters in the respective climate period of the MRI-AGCM3.2S outputs are used as indicators of trends.

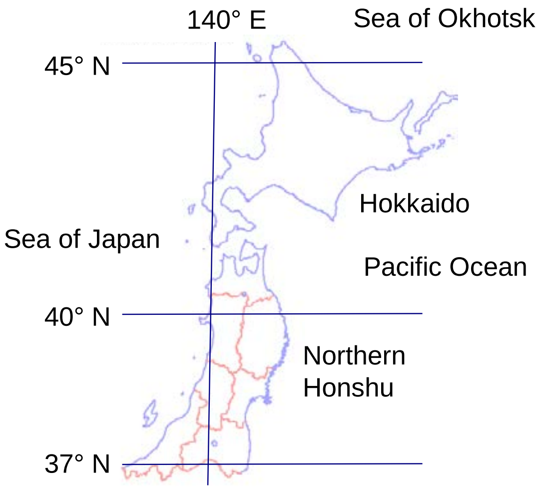


Figure 3 - Regions subject to study

Table 1 - Data collected using MRI-AGCM3.2S

Resolution	Grid size: 20 km × 20 km		
Time interval	Hourly	Daily	Monthly
	Temperature (at 2 m above the ground) (K) Precipitation ($kg/m^2/s$)	Snow water equivalent (kg/m^2)	Average snow depth (cm)
Greenhouse gas emissions scenario	A1B of IPCC		
Climate period	Present climate (1979-2003) Near future (2015-2039) Century-end future climate (2075-2099) Nov. 1 - Apr. 30		

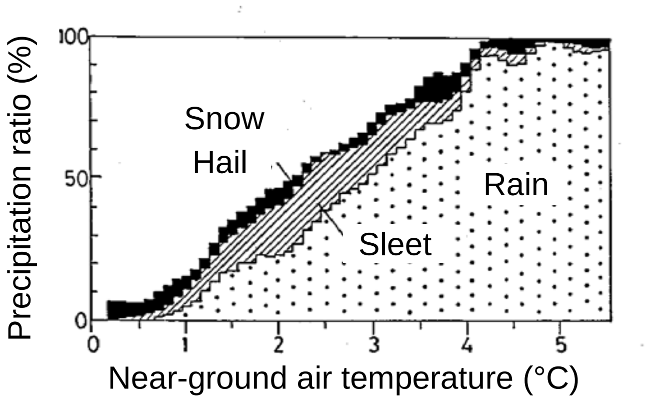


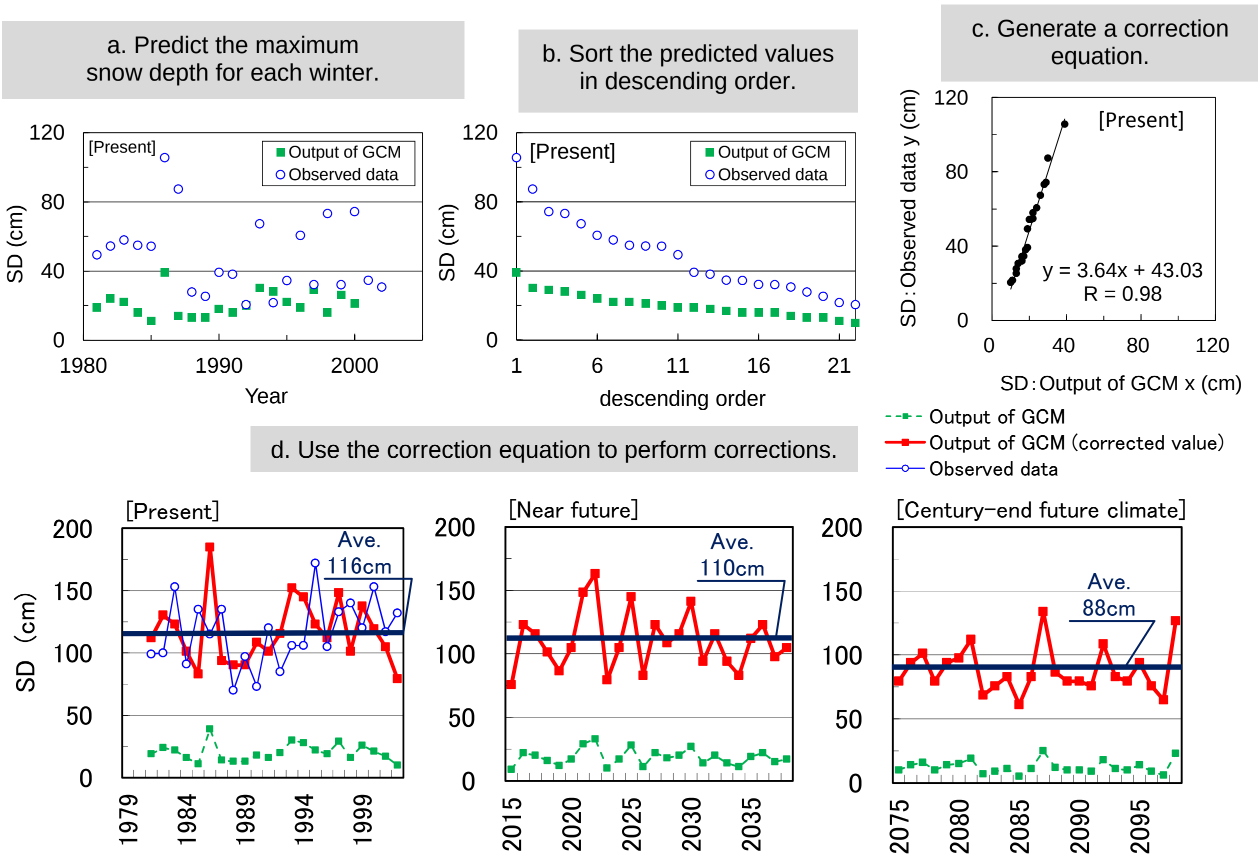
Figure 4 - Type of precipitation by near-ground air temperature [9]

2.2. Prediction of future winter climate parameters

The MRI-AGCM3.2S outputs the average value of a parameter in the area of 20 km by 20 km of the grid. Because the value is the average for the area, it differs from the measured value at a point within the grid. We corrected the outputs obtained by the MRI-AGCM3.2S for each climate period by adopting procedures (1) to (5) below, with reference to Piani et al. (2010) [10], and we predicted winter climate parameters for each observation station. Figure 5 shows an example of the future snow depth prediction for the location of the AMeDAS station in Shinshinotsu (Sea of Japan side of Hokkaido).

(1) Predict a winter climate parameter from the observed value for each winter between 1979 and 2003 (Figure 5a). Sort the predicted values in descending order (Figure 5b).
(2) Predict the maximum snow depth for a grid corresponding to each observation station from the MRI-AGCM3.2S output for each winter in the present climate period (1979-2003) (Figure 5a). Sort the predicted values in descending order (Figure 5b).
(3) Sort values for the predictions of maximum snow depth from the observation values (1) in descending order and for the predictions of maximum snow depth from the MRI-AGCM3.2S output (2) in descending order. Make a scatter diagram of the descending-order values of (1) vs. (2). Obtain a liner regression equation that achieves the least-square error by using the Newton-Raphson method, where the dependent variable is the prediction of maximum snow depth obtained from the observation value and the

independent variable is the prediction of maximum snow depth obtained from the MRI-AGCM3.2S output, and use the equation as a correction equation (Figure 5c).
(4) Correct the predictions of maximum snow depth for the present climate obtained by the MRI-AGCM3.2S with the correction equation obtained in (3). Repeat the same procedures to predict the maximum snow depths for the near-future climate and the century-end future climate periods (Figure 5d).
(5) Obtain the average, the maximum value and the standard deviation of corrected maximum snow depth for each period of the current climate, the near-future climate and the the century-end future climate (Figure 5d). Create a distribution map of the averages.



SD: Maximum snow depth

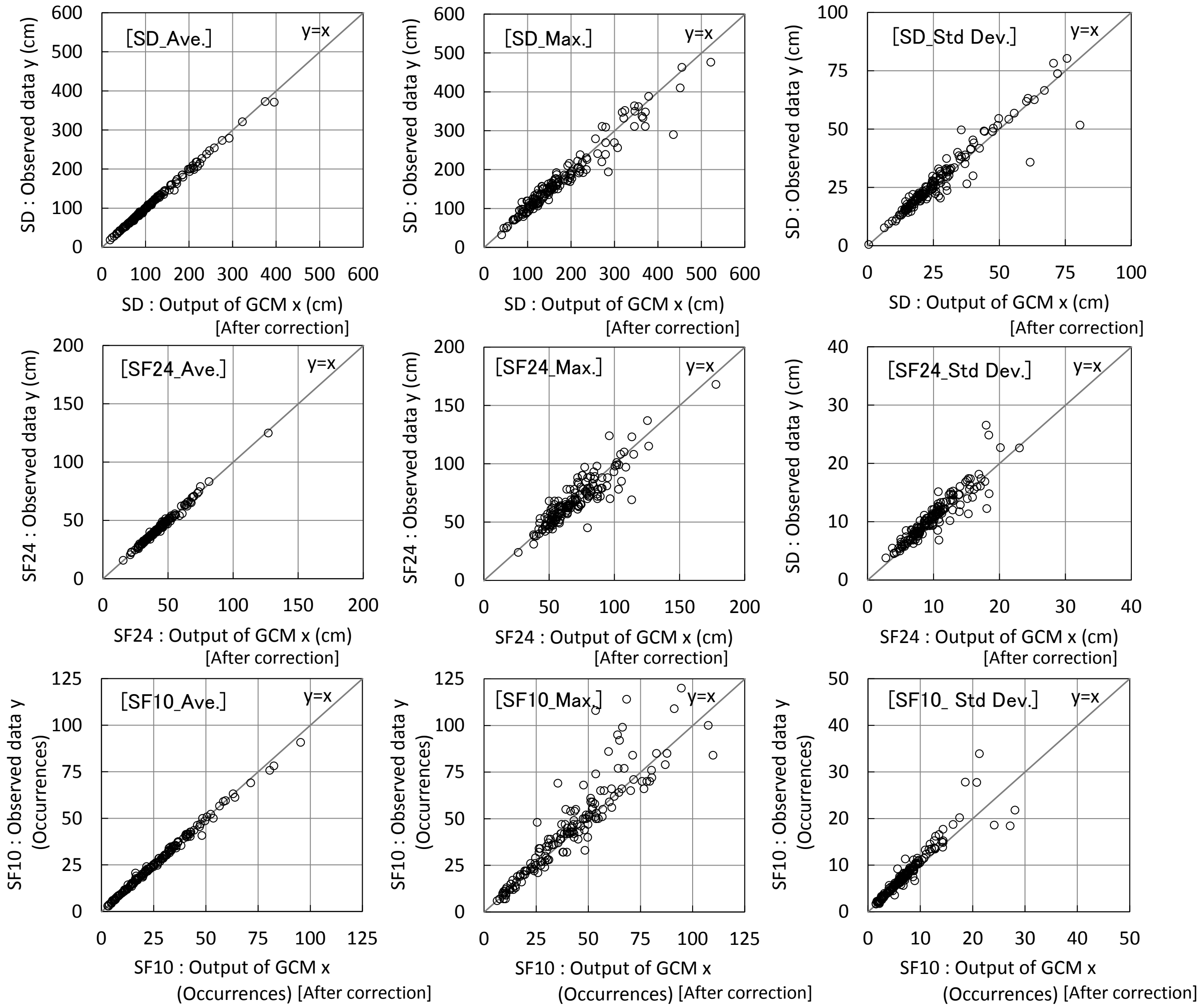
Figure 5 - Predicting the maximum snow depth at the Shinshinotsu AMeDAS station (Sea of Japan side of Hokkaido)

3. RESULTS

3.1. Evaluating the correction equation

Using the same method that was used to develop the correction equation in Section 2.2, we developed a correction equation for the winter climate parameters of each observation station. The averages of the coefficient of correlation of the correction equations were as follows: 0.95 for the maximum snow depth at 156 observation stations, 0.94 for the maximum 24-hour snowfall at 161 observation stations and 0.93 for the frequency of daily snowfall of 10 cm or more for 161 observation stations. These high coefficients of correlation show that there are high correlations between the values of measured winter climate parameter, which are sorted in descending order, and the values obtained from the MRI-AGCM3.2S for the present climate period, which are sorted in descending order.

We made scatter diagrams that plot the values predicted from observation against the values of corrected output of the MRI-AGCM3.2S for the average, the maximum value and the standard deviations of the maximum snow depth, the maximum 24-hour snowfall and the frequency of daily snowfall of 10 cm or more for the present climate period (Figure 6). The averages of all the winter climate parameters of the values predicted from observation values and the values predicted by corrected output of the MRI-AGCM3.2S had a linear relation. In general, the maximum values predicted by the two methods had linear relationships, although there were some deviations from linear relations when the values were higher than 250 cm or more for the maximum snow depth, higher than 100 cm or more for the maximum 24-hour snowfall and higher than 50 occurrences for the frequencies of daily snowfall of 10 cm or more. The standard deviations predicted by the two methods tended to have linear relationships, and only a few deviations were observed from the linear relations at some locations in each climate period.



SD: Maximum snow depth, SF24: Maximum 24-hour snowfall

SF10: Frequency of snowfall of 10 cm or more

Avg.: Average, Max.: Maximum, Std Dev.: Standard deviation

Figure 6 - Relationship of the average, the maximum value and the standard deviations of the predicted winter climate parameters between those from observation values and those from the corrected output values of MRI-AGCM3.2S.

3.2. Trends of the average values of winter climate parameters

Figure 7 shows differences in the values of winter climate parameters between the predictions of the near-future climate period and those of the present climate period (left), and between the predictions of the century-end future climate period and those of the present climate period (right). The upper figures of the differences in the maximum depth show between the preset climate period and the near-future and the century-end climate period show that the maximum snow depth tends to decrease everywhere except in some parts of Hokkaido. On the other hand, the left-hand figure in the middle row for the differences in the maximum 24-hour snowfall between the near-future climate period (2015-2039) and the present climate period shows an increasing tendency for maximum 24-hour snowfall in central and eastern Hokkaido, and on the Sea of Japan side and some central parts of Honshu. The right-hand figure in the middle row for the differences in maximum 24-hour snowfall between the century-end future climate (2075-2099) and the present climate period shows that the maximum 24-hour snowfall tends to increase in central Hokkaido and in some central parts of Honshu. The left-hand figure in the bottom row for differences in the frequency of daily snowfall of 10 cm or more between the near-future climate period (2015-2039) and the present climate period shows that the frequency tends to increase in central Hokkaido, in western Hokkaido and in some inland parts of Honshu. The right-hand figure in the bottom row for the differences in the frequency of daily snowfall of 10 cm or more between the century-end future climate (2075-2099) and the present climate period shows that the the frequency tends to increase in central Hokkaido and to decrease on the Sea of Japan side of Honshu.

These results indicate that the maximum snow depth tends to decrease for the near-future and the century-end future climate periods except for some parts of Hokkaido. Changes in snowfall amounts and air temperatures in each region are considered to cause such differences. In general, snowfall is considered to increase in snowy cold regions even under the trend of global warming, because global warming raises the air and seawater temperatures, which increases the moisture in the air and leads to precipitation. In Hokkaido, due to the cold temperature, snow stays on the ground in winter without melting; thus, the maximum snow depth will increase. In other snowy regions of Japan, the winter temperatures are high enough to melt fresh snow. Thus, the maximum snow depth will decrease and the period of snow cover will decrease [12].

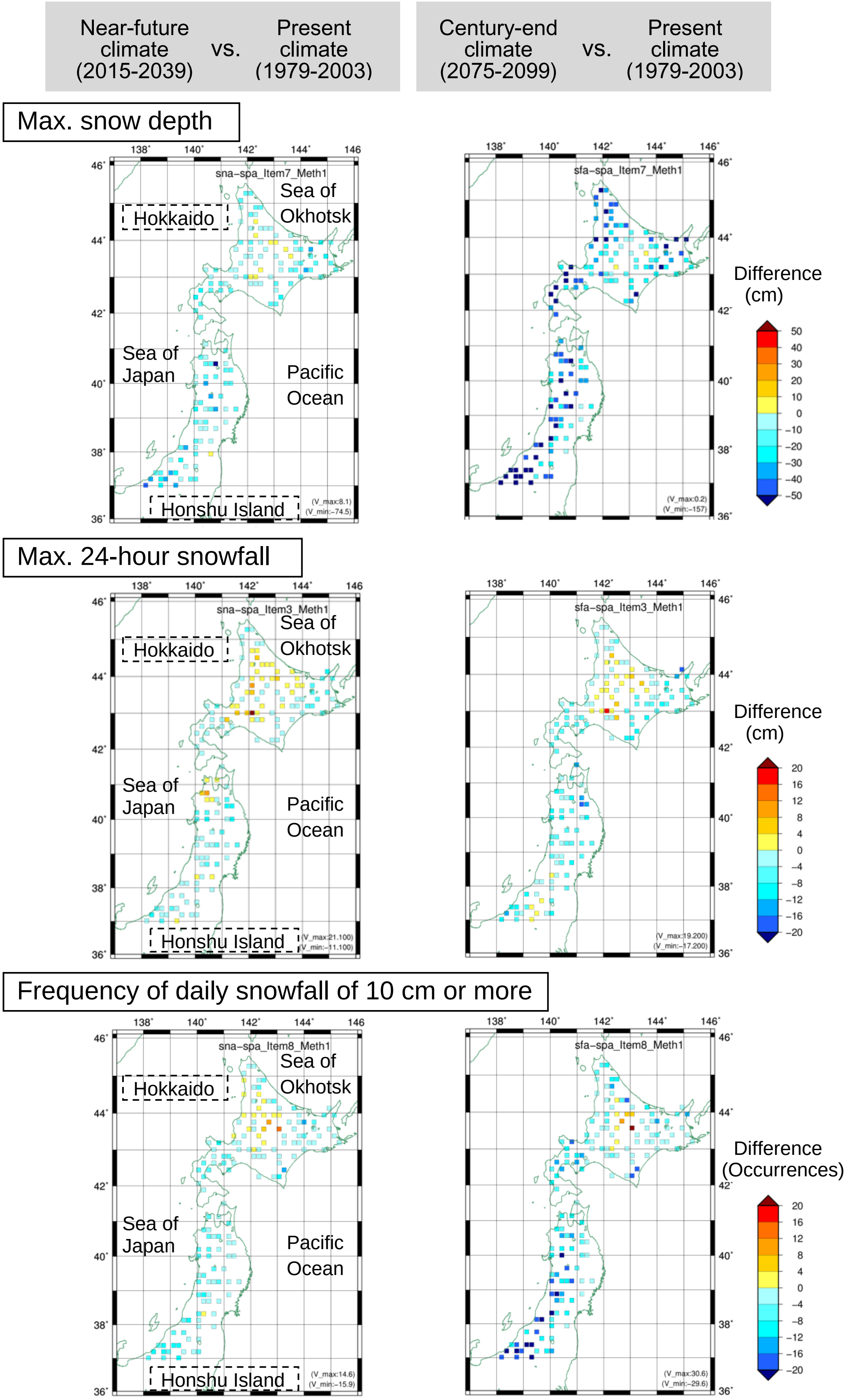


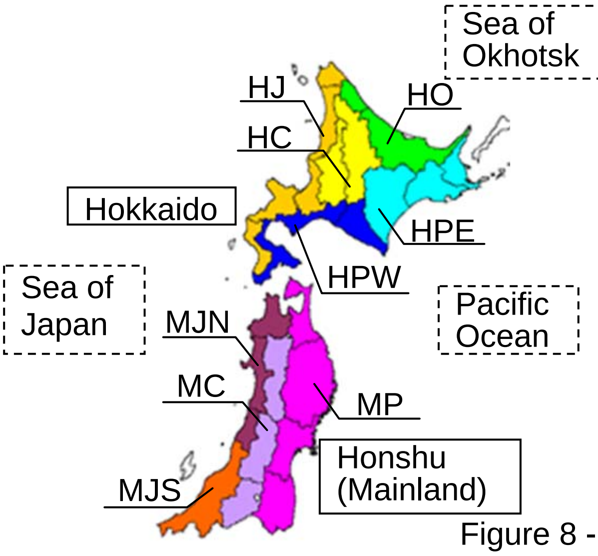
Figure 7 - The differences in the predicted winter climate parameters (top: max. snow depth; middle: max. 24-hour snowfall; bottom: frequency of daily snowfall of 10 cm or more) of the corrected output values obtained by MRI-AGCM3.2S by year: present climate period vs. future climate periods

3.3. Regional trends in winter climate parameters

Figure 8 shows the division of regions, and Figure 9 shows the average and the maximum values, and the standard deviation of winter climate parameters from the MRI-AGCM3.2S output for each region. The average maximum snow depth is predicted to be 30 to 70 cm less in all regions in the future climate periods than in the present climate period. The maximum snow depth is predicted to decrease in the future climate periods, except for the near-future climate period in the Okhotsk region of Hokkaido. The trends of the standard deviations of maximum snow depth in each region are the same as the trends above.

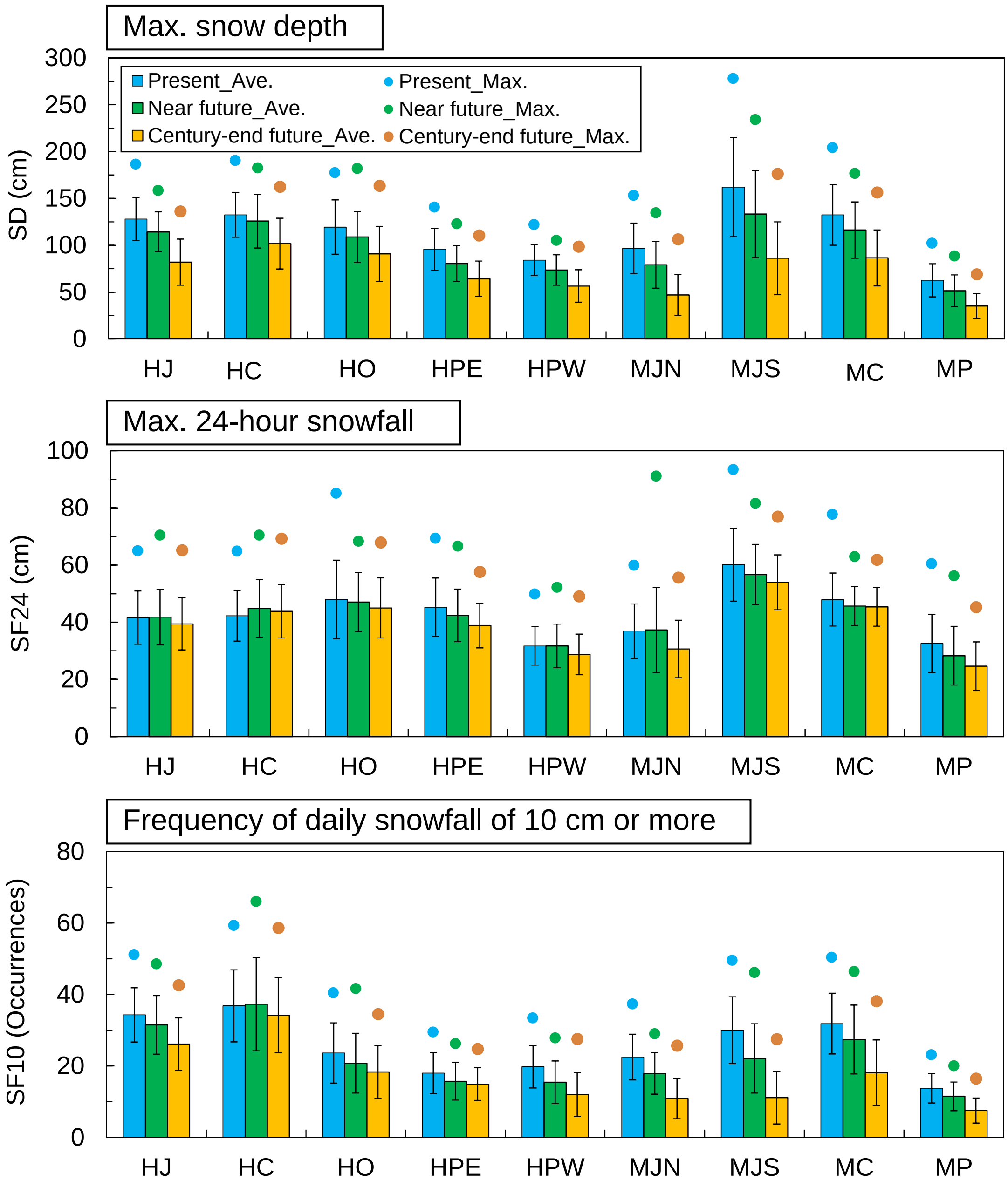
The maximum 24-hour snowfall is predicted to 0 to 10 cm higher or lower in each region on average in the future climate periods than in the present climate period. The maximum 24-hour snowfall is predicted to decrease or remain unchanged in general, except on the Sea of Japan side of Hokkaido, in central Hokkaido and on the Pacific Ocean side of Hokkaido, and in the northern part of the Sea of Japan side of Honshu in the near-future climate period. Also, the standard deviations of maximum 24-hour snowfall are predicted to remain unchanged except in the northern part of the Sea of Japan side of Honshu in the near-future climate period.

The parameter of frequency of daily snowfall of 10 cm or more is predicted to decrease by 3 to 20 occurrences, in general, in the future climate periods, except for the average and the maximum values in central Hokkaido and the maximum values on the Sea of Okhotsk side of Hokkaido in the near-future climate period. The standard deviations are predicted to remain unchanged, except for increases in the near-future climate period in central Hokkaido.



Island	Sea side	direction	Regional sign	Points
Hokkaido	Sea of Japan	–	HJ	N=25
	–	Central	HC	N=20
	Sea of Okhotsk	–	HO	N=14
	Pacific Ocean	East	HPE	N=25
		West	HPW	N=13
Honshu (Mainland)	Sea of Japan	North	MJN	N=12
		South	MJS	N=13
	–	Central	MC	N=22
	Pacific Ocean	–	MP	N=17

Figure 8 - Divisions of studied regions



Vertical axis: standard deviation of annual variation

Figure 9 - Changes in the winter climate parameters by region

4. DISCUSSION

Winter climate parameters such as the maximum snow depth and the maximum 24-hour snowfall are used for developing road snow-control plans and designing snow-control facilities. Currently, statistical data of winter climate parameters are used for such purposes. However, such plans and facilities are expected to still be in place many years in the future. Consequently, they need to be planned or designed so as to secure sufficient snow control in future by considering the future trends of such parameters. This study suggests that the maximum snow depth is expected to decrease in most of the snowy cold regions of Japan. This in turn suggests that the future costs for snow-control facilities may decrease. However, the maximum 24-hour snowfall in future is predicted to decrease by only 0 to 10 cm in each region, which is a much smaller decrease than that for maximum snow depth. The standard deviations are not expected to change, except for the northern part of the Sea of Japan side of Honshu Island in the near-future climate period (2015-2039). This suggests that measures to mitigate the effects of heavy snowfall need to be secured at the same levels as today and that snow piling widths on roadsides also need to be secured at those levels.
Further, both the average and the maximum values of the frequency of daily snowfall of 10 cm or more will increase in central Hokkaido for the near-future climate period (2015-2039). This suggests that the deployment of snow removal vehicles needs to be reexamined. For example, the Hokkaido Regional Development Bureau of the Ministry of Land, Infrastructure, Transport and Tourism, which administers the national highways in Hokkaido, allocates 19 vehicles per 100 km of national highway in the area close to the Sea of Japan (Sapporo Development and Construction Department), while allocating only 14 vehicles per 100 km of national highway in central Hokkaido (Asahikawa Development and Construction Department) [13] (Figure 10). Regions where the frequency of daily snowfall of 10 cm or more is predicted to increase need to consider increasing the number of snow removal vehicles.

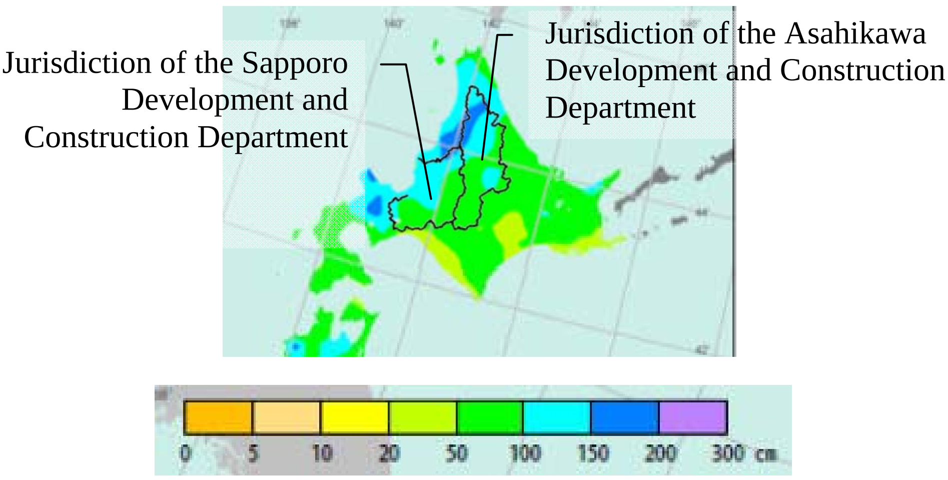


Figure 10 – Normal values for annual maximum snow depth

5. CONCLUSION

This study predicted the winter climate parameters for the future climate period by using the MRI-AGCM3.2S climate model. The aim is to contribute to the long-term planning of snow control policies and measures and to the designing of snow-control facilities. The prediction method is as follows: First, observation data from 161 AMeDAS and road telemeter stations and the present climate output data of the grid geographically closest to each station of the MRI-AGCM3.2S climate model were used to predict winter climate parameters. Using these predictions, a regression equation with a correction equation was developed for each station location, using the Newton-Raphson method. Then, the winter climate parameters of future climate periods were applied to the independent variable of the equation to predict the future winter climate parameters. Next, the differences in the winter climate parameters of the future climate periods and the present climate period were calculated to clarify changes in such parameters in future. The results show that the winter climate parameters decrease except in central Hokkaido.

Because the snow and ice climate is often influenced by local topography, in the future we will conduct a similar study with a higher-resolution climate model (NHRCM; 5-km resolution) to estimate future winter climate parameters, toward contributing to snow-control planning and the designing of snow-control facilities. In considering extreme weather conditions, our future study will also include the development of methods for evaluating the maximum values and the probability of such extreme events. Also, we will identify the road management issues associated with global warming using the recent trends and predictions for the near future and the century-end future climate periods.

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