Estimation of the Impact of Global Warming on Snow Depth in Japan by the Pseudo-Global-Warming Method

Masayuki Hara¹, Takao Yoshikane², Hiroaki Kawase¹, and Fujio Kimura¹ ²

¹Frontier Research Center for Global Change (FRCGC), Japan Agency for Marine-Earth Science and Technology (JAMSTEC)
²Institute of Life and Environmental Sciences, University of Tsukuba

Abstract:
A series of numerical experiments were conducted in order to investigate the impact of global warming on snow amount in Japan during early winter. After confirming the accuracy of hindcast simulations for a High-Snow-Cover (HSC) year and a Low-Snow-Cover (LSC) year, dynamical downscaling experiments were conducted in order to make future projections using the Pseudo-Global-Warming method. The precipitation, snow depth, and surface air temperature of the hindcast simulations show good agreement with the AMeDAS station data. At the end of December, the decreasing ratios of snow water are more significant in areas with an altitude of less than 1,500 m. The increase in the air temperature is one of the major factors influencing the decrease in snow water since the present mean air temperature in most of these areas is near 0°C even in winter. On the other hand, the change in the mean areal precipitation due to global warming is less than 15% in both years.

KEYWORDS global warming, dynamical downscaling, pseudo-global-warming method, snow cover

INTRODUCTION

Although a heavy snowfall often brings disaster, snow cover is one of the major water resources in Japan. Even during the winter, the monthly mean of the surface air temperature often exceeds 0°C in large parts of the heavy snow areas along the Sea of Japan. Thus, snow cover may be seriously reduced in these areas as a result of global warming, which is caused by an increase in greenhouse gases.

Currently, most GCMs cannot reproduce local climates, which are directly related to orography (IPCC, 2007). Other methods, such as dynamical downscaling (e.g. Kurihara et al., 2005 and Japan Meteorological Agency, 2008), statistical downscaling (e.g. Yokoyama and Inoue, 2007), and direct simulation by high-resolution GCM (e.g. Hosaka et al., 2005), have been employed to project small-scale climate conditions. Extremely high horizontal resolution, for example a grid interval of less than several kilometers, is required to reproduce snow cover because the snow cover depends strongly on the local climate and small-scale orography.

Because of the large interannual variability of snowfall in Japan, long-term dynamical downscaling or ensemble projections are necessary in order to determine the change in snow cover due to global warming. Long-term integration with a several-kilometer grid is, however, quite difficult to obtain because of a lack of computational resources. In order not to concern such a large year-to-year variability with short period numerical experiments, we use the Pseudo-Global-Warming (PGW) method.

The Pseudo-Global-Warming (PGW) method (Kimura and Kitoh, 2007; Sato et al., 2007) is a dynamical downscaling method that allows the projection of regional climate change using a regional climate model. In the PGW method, initial and lateral boundary conditions are given by the sum of 6-hourly reanalysis data and the components of climate change, which are the monthly averaged differences between the future climate projected by a GCM and the present climate. These boundary conditions are expected to have similar climatology to those of the future climate projected by the GCM, but the daily evolution is similar to that in the present years. The PGW method allows a comparison of the climate in the present year and that in a PGW year, which is similar to the control year in terms of the interannual variation but includes future climatology.

The objective of this research is to investigate the impact of global warming on snow amount in Japan during early winter. We used the PGW method to directly compare future snow depth with that of the present without regarding the interannual variability. Numerical simulations in this study are performed with a five-kilometer grid interval to include the effects of small-scale orography.

DESIGN OF NUMERICAL EXPERIMENTS

Our focus is the early winter (December) in 2005 and 2006. The former was an extremely High-Snow-Cover (HSC) year, while the latter was a typical Low-Snow-Cover (LSC) year during the 22-year period from 1985 to 2006. To estimate the difference of the impact of the global warming on snow amount between the HSC and LSC cases, we chose the two extreme cases.

The numerical study included four experiments: two realistic runs (CTL-HSC and CTL-LSC) and two PGW runs (PGW-HSC and PGW-LSC). The CTL runs were simple hindcast runs using 6-hourly NCEP/NCAR reanalysis (Kalnay et al., 1996) for the boundary conditions, including SST given by the skin temperature of the reanalysis. To estimate the amount of snow in the 2070s, we applied the PGW method to both cases. The boundary conditions of the PGW runs were obtained through a reanalysis modified by the global warming components of the 2070s for monthly averaged air temperature, horizontal wind, geopotential height, and SST. The relative humidity was assumed to be the same as the present climate because the estimated change in relative humidity was small (IPCC, 2007).
global warming components were estimated as the monthly averaged difference between the 10-year average of the 21st Century projection from 2071 to 2080 and the 20th Century simulation from 1991 to 2000 by MIROC 3.2 CGCM (Nozawa et al., 2007). The 21st Century projection was performed for 2001 to 2100 based on an A2 scenario presented by the IPCC Special Report on Emissions Scenarios (SRES). The global warming components indicate that the air temperature rises 3–4°C in the troposphere, while the SST rises 2–3°C around Japan in December. A comparison of the CTL and PGW runs allows the projection of the change in snow depth due to global climate changes.

All simulations were conducted by two-way nesting using the WRF ARW-core model V2.2 (Skamarock et al., 2005). The coarse domain is covered by 120 × 100 grids at a 20-km grid interval, while the fine one is covered by 373 × 333 grids at a 5-km grid interval. Both domains have 27 vertical layers. The nudging technique was not used for the internal grid points in the experiments. The WRF-Single-Moment 6-class microphysics scheme and Noah land-surface model were adopted in both domains. The microphysics scheme separately estimates three categories of precipitation: rain, snow, and graupel. In this study, “snow” is assumed to be the sum of the latter two categories. The Noah-land-surface model includes a simple one-layer snow model that can simulate snow accumulation, sublimation, and melting. The simulations started at 00Z 21 November and ran for 41 days in each case. Assuming the first 10 days to be a spin-up duration, we analyzed the remaining 31 days in December.

RESULTS

The simulated results are discussed by focusing on the study areas shown in Figure 1. The observed snow depths at the end of December in the HSC and LSC cases are shown in Figure 2a and 2b, while the simulated snow depths in the CTL-HSC and CTL-LSC runs are shown in Figure 2c and 2d, respectively.

In the HSC case, the stations showing snow depths above 100 cm are distributed mostly in the central mountain range on Honshu Island, and those showing snow depths above 50 cm are distributed along the mountainous area even in southern Honshu Island, i.e., the San-in and Hokuriku areas (Figure 2a). The snow cover is widely extended in the lower regions along the coast of the Sea of Japan and the Western Tohoku and Hokkaido areas. The simulated distribution of snow depth in the CTL-HSC run (Figure 2c) agrees well with the observation. The extent of the snow cover, as well as the areas with a snow depth of more than 100 cm, is quite similar to those of the observation.

In the LSC case, heavy snow cover in excess of 100 cm is difficult to find at the AMeDAS stations, as shown in Figure 2b, although the difference in the extent of snow is insignificant between the HSC and LSC cases. As shown in Figure 2d, the CTL-LSC run accurately simulates these characteristics. Therefore, the heavy snow cover in the CTL-LSC over the mountainous areas is much less than that in the CTL-HSC run, but the extent of snow is not much different from that in the CTL-HSC run.

Table I shows the mean areal monthly precipitation observed at AMeDAS stations and the simulated one in the CTL runs. The former is the mean of all stations, and the latter is the mean of the grid point nearest each station in the study area. In the Hokkaido and Western Tohoku areas, the difference in the observed precipitation is small, i.e., within about 10%, between the HSC and LSC cases. In the Hokuriku and San-in areas, located in the southern part of the snowy areas, the observed precipitation in the HSC case is as much as twice that of the LSC case.

The differences between the observed and simulated precipitation amounts are less than about 30% in all areas. The difference in the observed precipitation between the HSC and LSC cases is small, i.e., within about 20% in the Hokkaido and Tohoku areas, while the simulated precipitation in the LSC case is less than 60% of that of the HSC case in the Hokuriku and San-in areas. The differences of the area mean of the simulated precipitation between the HSC and LSC cases are almost the same as the ones of the observation. These facts indicate that the simulated precipitation agrees well with the observation.

Figure 3 shows the monthly mean air temperature at screen height in the HSC and LSC cases; in this figure,
Estimation of the Impact of Global Warming on Snow Depth in Japan by the Pseudo-Global-Warming Method

Figure 3. Same as Fig. 2 except for the monthly averages of air temperature at screen height in December.

3a and 3b show the observations, and 3c and 3d show the CTL runs. In the HSC case, the observed temperature is about 0°C in the lower parts of the San-in and Hokuriku areas. In the LSC case, on the other hand, the observed temperature is 3-5°C in these areas, i.e., about 4°C higher than that in the HSC case.

The PGW runs indicate a smaller extent of snow cover, as shown in Figure 2e (PGW-HSC run) and 2f (PGW-LSC run). The snow cover nearly disappears along the coastal areas on Honshu Island in the PGW-HSC run, while the extent of snow cover is significantly reduced not only along the coastal areas but also in the mountainous areas of Honshu Island in the PGW-LSC run. The areas where the air temperature is lower than 0°C are almost the same as the areas where the snow depth is greater than 0.1 cm as shown in Figure 2.

Table II indicates the snow depth in the five study areas in the CTL and PGW runs. The mean snow depth is calculated in the same manner as for Table I. The snow depth of the PGW runs in the southern area (Niigata, Hokuriku, and San-in) decreases to less than a quarter of those of the CTL in the HSC and LSC cases. Even in the northern area (Hokkaido and Western Tohoku), the snow depth in the PGW runs decreases to about one-third of those in the HSC and LSC cases.

Table III shows the total snow water in the areas categorized by the elevation of the ground surface. The study area was divided into the northern and southern areas according to the sensitivity of global warming to the snow depth, shown in Table II.

Snow water decreases most drastically at elevations under 500 m in both areas. In the northern area, more than 90% of the total snow water is distributed in the area lower than 1,000 m in the CTL-HSC and CTL-LSC runs. In the HSC case, the decreasing ratio of more than 50% extends to the areas lower than 1,000 m in the HSC case, and it covers the entire area in the LSC case. Snow water disappears at elevations under 500 m in the LSC case. The total snow water of the PGW in all of Japan is 38% and 52% of the CTL in the HSC and LSC cases, respectively.

50% is limited in the area lower than 500 m, while it appears even at 500 to 1,000 m in the LSC case.

In the southern area, on the other hand, the decreasing ratio of more than 50% extends to the areas lower than 1,000 m in the HSC case, and it covers the entire area in the LSC case. Snow water disappears at elevations under 500 m in the LSC case. The total snow water of the PGW in all of Japan is 38% and 52% of the CTL in LSC and HSC cases, respectively.

Table II. Mean estimated snow depth (cm) of the CTL and the PGW at the grid points nearest the AMeDAS stations. PGW/CTL indicates the ratio of mean snow depths of the PGW and the CTL.

| Region         | Hokkaido | Western Tohoku | Niigata | Hokuriku | San-in |
|----------------|----------|----------------|---------|----------|--------|
| CTL-HSC (cm)   | 40.7     | 50.7           | 49.1    | 80.1     | 23.7   |
| PGW-HSC (cm)   | 14.8     | 14.8           | 10.8    | 5.7      | 2.7    |
| PGW/CTL (%)    | 36.5     | 29.2           | 22.1    | 7.2      | 11.4   |
| CTL-LSC (cm)   | 20.3     | 10.5           | 14.4    | 11.0     | 5.1    |
| PGW-LSC (cm)   | 7.0      | 3.0            | 0.1     | 1.9      | 0.4    |
| PGW/CTL (%)    | 34.4     | 29.0           | 0.5     | 17.7     | 7.7    |

Table III. Total snow water (Gt) and the ratio of decreasing snow water in the PGW run and the total snow water in the CTL run of (a) northern area (Hokkaido and Western Tohoku) and (b) southern area (Niigata, Hokuriku, and Sanin) in the five levels categorized by the orographic elevation.

| Region         | (km) | 0–0.5 | 0.5–1 | 1–1.5 | 1.5– | total |
|----------------|------|-------|-------|-------|------|-------|
| (a) Northern part |      |       |       |       |      |       |
| CTL-HSC (Gt)    | 8.2  | 5.9   | 1.3   | 0.09  | 15.5 |
| PGW-HSC (Gt)    | 3.5  | 4.6   | 1.2   | 0.09  | 9.4  |
| Decr. ratio (%) | 57.3 | 22.0  | 7.7   | 0.0   | 39.4 |
| CTL-LSC (Gt)    | 3.6  | 3.0   | 0.80  | 0.06  | 7.5  |
| PGW-LSC (Gt)    | 1.1  | 1.4   | 0.54  | 0.06  | 3.1  |
| Decr. ratio (%) | 69.4 | 53.5  | 32.5  | 0.0   | 58.7 |
| (b) Southern part |      |       |       |       |      |       |
| CTL-HSC (Gt)    | 1.8  | 4.1   | 2.1   | 1.3   | 9.5  |
| PGW-HSC (Gt)    | 0.20 | 1.8   | 1.6   | 1.0   | 4.6  |
| Decr. ratio (%) | 88.9 | 56.1  | 23.8  | 23.1  | 51.6 |
| CTL-LSC (Gt)    | 0.24 | 0.78  | 0.71  | 0.55  | 2.3  |
| PGW-LSC (Gt)    | 0.00 | 0.25  | 0.33  | 0.22  | 0.81 |
| Decr. ratio (%) | 100.0| 67.9  | 53.5  | 60.0  | 64.8 |

DISCUSSION

The snow cover change may depend on the precipitation and air temperature. As shown in Table I, the precipitation changes between the CTL runs and the PGW runs are less than 10% in both cases, which suggests that the prominent reduction in the snow cover is caused primarily by an increase in the air temperature. The similarity between the horizontal distributions of changes in snow depth (Figure 2) and air temperature (Figure 3) is evident. The surface air temperature affects both the snowmelt and the ratios of snow and rain to precipitation. Figure 4 shows the ratio of snowfall to total precipitation. Although the ratio exceeds 80% in a wide area of Japan in the CTL-HSC run, it decreases to less than 50% in most of the lower areas in the PGW-HSC run. Even in the mountains, the ratio of snowfall seldom exceeds 50% on Honshu Island. The distribution of the ratio of snowfall is also quite similar to those of snow cover and air temperature. These results suggest a simple mechanism for the reduction of the snow cover. The surface air temperature increases because of global warming, and the chance of snowfall then decreases so that snow cover is prominently reduced, particularly at the lower elevations of Honshu Island. The results of the dynamical downscaling may depend on the boundary condition given by GCMs and
One of the authors (Kimura) was supported by the Global Environment Research Fund (S-5-3) of the Ministry of the Environment, Japan. We would like to thank Dr. H. G. Takahashi for valuable discussions. We also acknowledge helpful comments from two anonymous reviewers.

SUPPLEMENTS

Supplement 1 Enlarged figures of Figures 2, 3, and 4 are included.

REFERENCES

Hosaka M, Nohara D, Kitoh A. 2005. Changes in Snow Cover and Snow Water Equivalent Due to Global Warming Simulated by a 20km-mesh Global Atmospheric Model. SOLA 1: 93–96, doi:10.2151/sola.2005-025.

IPCC. 2007. Climate Change 2007. The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.); Cambridge University Press: Cambridge, United Kingdom and New York, USA; 996 pp.

JMA. 2008. Global Warming Projection Vol. 7. Tokyo. http://www.data.kishou.go.jp/climate/cpdinfo/GWP/Vol7/pdf/synthesis.pdf. (in Japanese) Accessed: 9 Sep 2008.

Kalnay E, Kanamitsu M, Kistler R, Collins W, Deaven D, Gandin L, Iredell M, Saha S, White G, Woollen J, Zhu Y, Leetmaa A, Reynolds R, Chelliah M, Ebisuzaki W, Higgins W, Janowiak J, Mo K, Ropelewski C, Wang J, Jenne R, Joseph D. 1996. The NCEP/NCAR 40-Year Reanalysis Project. Bulletin of the American Meteorological Society, 77(3): 437–471.

Kimura F, Kitoh A. 2007. Downscaling by pseudo global warming method. In The Final Report of the ICCAP Research Institute for Humanity and Nature (RIHN), Kyoto, Japan.

Kurihara K, Ishihara K, Sasaki H, Fukuyama Y, Saitou H, Takayabu I, Murakami K, Sato Y, Yokomizo S, Noda A. 2005. Projection of climatic change over Japan due to global warming by high-resolution regional climate model in MRI. SOLA 1: 97–100, doi:10.2151/sola.2005-026.

Nozawa T, Nagashima T, Ogura T, Yokohata T, Okada N, Shiogama H. 2007. Climate change and impacts on ocean-atmosphere coupling. In the Global Environmental Change, Solomon S, Qin D, Manning M, Marquis M, Averyt KB, Tignor M, Miller HL (eds.); Cambridge University Press: Cambridge, United Kingdom and New York, USA; 996 pp.

Sato T, Kimura F, Kitoh A. 2007. Projection of global warming onto regional precipitation over Mongolia using a regional climate model. Journal of Hydrology 333: 144–157.

Skamarock WC, Klemp JB, Dudhia J, Gill DO, Barker DM, Wang W, Powers JG. 2005. A description of the advanced research WRF version 2. NCAR Technical Note NCAR/TN-468+ST, National Center for Atmospheric Research, CO, USA; 88 pp.

Yokoyama K, Inoue S. 2007. Snow cover in Japan under global warming condition. Kaiyo 46: 131–139. (in Japanese)