Downscaling of Snow Cover Changes in the Late 20th Century
Using a Past Climate Simulation Method over Central Japan

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Abstract

We focus on the dramatic decrease in the snow cover on the Japan Sea side of Central Japan in the late 20th century. Using a regional climate model, a control experiment (CTL) was conducted, and it accurately simulated the dramatic decrease in maximum snow depth (SNDmax) between the 1980s and the 1990s. We then conducted a pseudo climate simulation (PCS) in the 1990s, which assumes the mean atmospheric fields in the 1990s and the perturbation from the mean atmospheric fields in the 1980s. The PCS method is expected to evaluate only the impacts of changes in the mean atmospheric fields on the snow cover changes. The PCS simulates the decreases in SNDmax over the coastal area, which are comparable to the changes simulated by the CTL. On the other hand, changes in SNDmax are negligible in the PCS over the mountainous area, where the slight increases in SNDmax are simulated by the CTL. Therefore, the changes in the mean atmospheric fields, especially, the mean temperature rise, are main factors of the snow cover decrease over the coastal area, while changes in both the mean atmospheric fields and the perturbation contribute to the snow cover changes over the mountainous area.

1. Introduction

The Japan Sea side area is one of the heaviest snow areas in the world. The cold northwesterly obtains much water vapor from the Japan Sea, bringing heavy snow over the Japan Sea side, especially over the mountainous areas. In the mountainous areas, the heavy snow causes serious snow disasters, such as avalanches, while it is an enormous water resource in the spring. On the other hand, the coastal area along the Japan Sea is a warm snowfall area, where the winter mean temperature is higher than 0°C at screen height (Ishizaka 2004). In this area, variations of the snowfall and snow cover have a correlation with the variation of the surface air temperature rather than that of precipitation (Suzuki 2006; Yamaguchi et al. 2011), indicating that the snow cover is vulnerable to global warming due to an increase in greenhouse gases (Intergovernmental Panel on Climate Change (IPCC) 2007).

Based on the Coupled Model Intercomparison Project Phase 3 (CMIP3) multimodel data set, snow would decrease over most regions in the late 21st century except for the region where the surface air temperature is lower than −20°C during the winter (Raisanen 2007). Using dynamical and statistical downscaling methods, the drastic decrease in snow is projected over the coastal area along the Japan Sea due to global warming (e.g., Inoue and Yokoyama 2003; JMA 2008; Hara et al. 2008).

In the late 20th century, a dramatic decrease in snow has been observed over the Japan Sea side in Central Japan (hereafter, Hokuriku District) (Ishizaka 2004; Suzuki 2006). Ishii and Suzuki (2011) reported that the conversion of snowfall to rainfall due to warming was the main factor behind the reduction of the snow cover. Using a regional climate model (RCM), Yoshikane et al. (2011) indicated that the increase in temperature and sunshine duration in February caused the decrease in the snow cover from the 1980s to the 1990s. On the other hand, no significant decrease in the snow cover has been observed over the colder regions, such as high mountainous areas and northern Japan, where the snow cover is controlled by the variation of precipitation rather than that of temperature (Suzuki 2006; Yamaguchi et al. 2011).

It is important to quantitatively evaluate the snow cover changes caused by climatic changes when we assess the impact of global warming on the snow cover. However, previous studies have not separately evaluated the impacts of changes in the mean atmospheric fields and the perturbation from the mean atmospheric fields on snow cover changes in the late 20th century. In this study, we focus on the impacts of the changes in the mean atmospheric fields on the snow cover over the Hokuriku District between the 1980s and the 1990s using an RCM. We compare the impacts on the coastal and mountainous areas.

2. Observational data and model design

We used the Automated Meteorological Data Acquisition System (AMeDAS) and in situ meteorological data obtained by the Japan Meteorological Agency (hereafter, JMA stations). We selected the JMA stations that continuously observed the snow cover and air temperature from 1980 to 2000.

Numerical experiments were conducted using a nonhydrostatic numerical model, the Advanced Research Weather Research and Forecasting (WRF) modeling system Version 3.2.1 (Skamarock et al. 2008). Two-way nested grid systems were adopted (Fig. 1). The grid intervals in coarse and nested fine grid systems were

Fig. 1. Changes in mean atmospheric fields at 850 hPa. Shading shows the differences in temperature between the 1980s and the 1990s. Vectors show the difference in wind. Contours represent the mean temperature in the 1980s. The outer and inner regions enclosed by thick black lines show 1st and 2nd domains in our simulation, respectively.
changes in mean atmospheric fields on the snow cover. which are expected to be able to evaluate the impact of the differences in air temperature and wind at 850 hPa in December that the relative humidity of the boundary condition in the PCS90s is assumed to be equal to that in the 1980s. Figure 1 shows the differences in air temperature and wind at 850 hPa in December between these two decades. The PCS method excludes the impact of changes in perturbation and fixes the interannual variations, which are expected to be able to evaluate the impact of the changes in mean atmospheric fields on the snow cover.

3. Results

3.1 Maximum snow depth simulated by CTL

Figure 2a shows the locations of the JMA stations used in this paper. All JMA stations plotted in Fig. 2a are located below 500 m above sea level (mASL). Figure 2b shows the time series of maximum snow depth (SNDmax) that is calculated from November to April in the next year. The observed and simulated SNDmax shows the mean SNDmax at the JMA stations in Fig. 2a and the mean SNDmax at the nearest grid points of the JMA stations in the model, respectively. More than 150 cm of SNDmax is observed in the early 1980s (80/81, 83/84, 84/85, and 85/86). After the late 1980s, the SNDmax dramatically decreases, as pointed out by the previous studies (e.g., Ishizaka 2004). The interannual variation of SNDmax is well simulated by the CTL; the correlation coefficient (hereafter, R) is 0.945, with a 95% significant level according to the student t-test. The SNDmax, however, is underestimated in heavy snow years in the 1980s. Hence, the decadal mean SNDmax (93.6 cm) is about 25% lower than the observation (125.2 cm) in the 1980s (Table 2). The sea surface temperature in the NNRP dataset that is given to the model is lower than the observation over the Japan Sea, which could result in the underestimation of snowfall and SNDmax especially in the heavy snow years. In the 1990s, the SNDmax is well simulated by the CTL; 75.4 cm in the CTL and 83.0 cm in the observation. The SNDmax decreases by about 35% and 20% relative to that in the 1980s in the observation and the CTL, respectively.

The interannual variation of surface air temperature was also well simulated by the CTL (R = 0.968) although the simulated air temperature at screen height is about 1.5°C lower than the observed temperature (Table 2). The CTL and observation show higher temperature in the 1990s than that in the 1980s; 0.81°C for observation and 0.99°C for the CTL. The low temperature bias in the CTL may cause the underestimated decrease in the snow between the 1980s and the 1990s in the Hokuriku region since the air temperature around 0°C is sensitive to the snowmelt.

The CTL in the 1980s (hereafter, CTL80s) shows about 50 cm of snow over the coastal areas of Ishikawa and Toyama Prefectures and 100 cm–200 cm of snow over the coastal area of Niigata Prefecture (Fig. 3a). Note that the SNDmax over the plain field, whose altitude is lower than 500 m, is underestimated in the CTL80s as shown in Fig. 2 and Table 2. The SNDmax shows more than 600 cm over high mountains. It is reported that the depth of the snow cover is 500 cm–900 cm in the Murododaira (36.58°N, 137.60°E), which has an altitude of 2,450 mASL, in the spring (Aoki and Watanabe 2009). Figures 2b and 3c show the differences in the SNDmax between the CTL80s and the CTL90s, and the ratio of the difference relative to the CTL80s, respectively. A decrease of SNDmax of about 20% relative to that in the 1980s is simulated over the coastal areas of Ishikawa and Toyama Prefectures during the heavy snow years in the 1990s. Hence, we can simulate the different changes in SNDmax in the CTL80s and the CTL90s, respectively.

The CTL simulates the different changes in SNDmax over the mountainous area (Figs. 3b and 3c). The CTL simulates the increase in SNDmax is simulated over the mountainous area (Figs. 3b and 3c). On the other hand, a slight increase in SNDmax is simulated over the coastal area of the JMA stations, respectively.

### Table 1. Main physical processes in the WRF model.

<table>
<thead>
<tr>
<th>Process</th>
<th>Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphysics</td>
<td>WRF Single Moment 6-class microphysics scheme</td>
</tr>
<tr>
<td>Convective rainfall</td>
<td>Kain Fritsch convective parameterization scheme</td>
</tr>
<tr>
<td>Surface-layer process</td>
<td>Mellor-Yamada, Nakanishi and Niño surface layer scheme</td>
</tr>
<tr>
<td>Boundary-layer process</td>
<td>Mellor-Yamada, Nakanishi and Niño Level 2.5</td>
</tr>
<tr>
<td>Land surface process</td>
<td>Noah land surface model (Noah-LSM)</td>
</tr>
</tbody>
</table>

### Table 2. SNDmax and air temperature at screen height observed by the JMA station and simulated by the CTL. The simulated temperature is modified by the difference in altitude between the JMA station and the RCM.

<table>
<thead>
<tr>
<th></th>
<th>1980s (cm)</th>
<th>1990s (cm)</th>
<th>Difference (cm)</th>
<th>Difference (%)</th>
<th>1980s (°C)</th>
<th>1990s (°C)</th>
<th>Difference (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation</td>
<td>125.24</td>
<td>82.99</td>
<td>42.25</td>
<td>33.7</td>
<td>2.66</td>
<td>3.47</td>
<td>0.81</td>
</tr>
<tr>
<td>Model (CTL)</td>
<td>93.57</td>
<td>75.37</td>
<td>18.2</td>
<td>19.5</td>
<td>1.15</td>
<td>2.14</td>
<td>0.99</td>
</tr>
</tbody>
</table>

The SNDmax at the nearest grid points of the JMA stations in Fig. 2a and Table 2. The SNDmax shows well simulated by the CTL (R = 0.968) although the simulated air temperature at screen height is about 1.5°C lower than the observed temperature (Table 2). The CTL and observation show higher temperature in the 1990s than that in the 1980s; 0.81°C for observation and 0.99°C for the CTL. The low temperature bias in the CTL may cause the underestimated decrease in the snow between the 1980s and the 1990s in the Hokuriku region since the air temperature around 0°C is sensitive to the snowmelt.
3.2 Changes in SNDmax simulated by PCS

Figure 3d shows the ratio of the difference in SNDmax relative to the CTL80s between the CTL80s and the PCS90s. Large decreases in SNDmax are found over the coastal area, which are comparable to the decreases in SNDmax simulated by the CTL90s (Fig. 3c). In contrast, negligible changes in SNDmax are simulated over a mountainous area with an altitude higher than 1,500 mASL.

Figure 4 shows the interannual variations of the regional mean SNDmax and 2 m air temperature (hereafter, T2m) simulated by the CTL80s and the PCS90s. The PCS90s shows similar interannual variations for T2m to CTL80s, while the PCS90s simulates an approximately 1°C higher T2m over both the lowland (< 500 mASL) and the highland (> 1,500 mASL) than the CTL80s does. The SNDmax decreases in all years over the lowland, resulting in a similar decrease in the decadal mean SNDmax to that in the CTL90s (Fig. 4a). In contrast, the PCS90s simulates no significant changes in SNDmax over the highland. The decadal mean SNDmax change is a slightly lower than that in the CTL80s, which is different from that in the CTL90s. Table 3 summarizes the decadal changes in SNDmax simulated by the CTL and PCS90s.

4. Discussion

The PCS90s shows a negligible change in precipitation (0.1%) over the lowland during the winter (December, January, and February) (Table 3). We diagnosed snowmelt from snowfall, evaporation, and a difference in snow water equivalent according to Yoshikane et al. (2011). Since the snowfall decreases by 11.9% and the snowmelt increases by 1.8% relative to the CTL80s (Table 3 and Supplement 1), respectively, the warming assumed in the PCS90s (Fig. 1) causes the large decrease in SNDmax over the lowland where the snow cover change is sensitive to the temperature (Suzuki 2006). Over the highland, although the PCS90s simulates the increases in snowfall (2.9%), the amount of the increase in snowfall (23.9 mm corresponding to 2.9%) was canceled out by the increase in snowmelt (25.4 mm) due to the warming during the winter (Supplement 1), resulting in the slight decrease in the SNDmax over the highland.

Synoptic-scale warming and anticyclonic anomalies are found over the Japan Sea at 850 hPa (Fig. 1). The anticyclonic anomaly would suppress the precipitation increase due to the warming according to the Clausius-Clapeyron relation. Similar patterns are shown by Kibe et al. (2011) who compared the composites of atmospheric fields in the colder and warmer winter years from 1979/80 to 2008/09. In addition, they conducted numerical exper-

Table 3. Simulated SNDmax and the differences of SNDmax, precipitation, and snowfall during the winter (December, January, and February) between CTL80s and the other experiments. DIFF means the ratio of the difference between each experiment and the CTL80s relative to the CTL80s.

<table>
<thead>
<tr>
<th>Atmospheric field</th>
<th>Lowland (lower than 500m)</th>
<th>Highland (higher than 1500m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Decadal mean SNDmax (cm)</td>
<td>Decadal mean SNDmax (cm)</td>
</tr>
<tr>
<td>Mean field</td>
<td>Perturbation</td>
<td>DIFF (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DIFF (%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DIFF (%)</td>
</tr>
<tr>
<td>CTL80s 1980s</td>
<td>95.7</td>
<td>*</td>
</tr>
<tr>
<td>PCS90s 1990s</td>
<td>76.6</td>
<td>−19.9</td>
</tr>
<tr>
<td>PPS90s 1980s</td>
<td>96.7</td>
<td>0.0</td>
</tr>
<tr>
<td>CTL90s 1990s</td>
<td>76.8</td>
<td>−19.8</td>
</tr>
</tbody>
</table>
iments and indicated that the heating due to convective activity over the Indian Ocean and Maritime Continent affected these atmospheric patterns around Japan.

In considering the methodology of PCS, the differences between the PCS90s and CTL90s would be regarded as the impact of changes in perturbation, i.e., the frequency of cyclones and cyclone tracks, if the nonlinear effects are negligible. To confirm them, we performed the Pseudo Perturbation Simulation in the 1990s (PPS90s) assuming the mean atmospheric fields in the 1980s and perturbation in the 1990s. The PPS90s shows no changes in the SNDmax (0.0%) over the lowland (Table 3), indicating that the impacts of perturbation changes on the snow cover are negligible over the lowland. In contrast, the PPS90s simulates the increase in SNDmax (7.5%) over the highland, where the PCS90s and the CTL90s simulate the slight decrease (−3.1%) and increase (6.9%) in the SNDmax, respectively. Adachi et al. (2007) suggested that the number of cyclones decreased in the 1990s from that in the 1980s around East Asia, which could affect the changes in SNDmax over the highland.

Hara et al. (2008) assessed the snow cover changes due to global warming using a Pseudo Global Warming method that is similar to the PCS. They focused on the impacts of remarkable warming of about 3−4°C in the late 21st century and suggested that the prominent reduction in the snow cover was primarily caused by the air temperature rise. In the near-future climate projection, our simulations will suggest that the snow cover changes can be evaluated by the changes in the mean atmospheric fields over the lowland, while the effects of perturbation changes on the snow cover should be considered over the highland.

5. Conclusion

Using the WRF model, we conducted a control experiment (CTL) and a pseudo climate simulation (PCS) to separately evaluate the impacts of changes in the mean atmospheric fields and perturbation on the snow cover changes over the Hokuriku District in the late 20th century. The CTL accurately simulated the interannual variations of the maximum snow depth (SNDmax) and the dramatic decrease in SNDmax from the late 1980s. The PCS90s, which applied the mean atmospheric fields in the 1990s and perturbation in the 1990s, simulated a similar decrease in SNDmax to the CTL over the lowland. In addition, the PPS90s, which assumed the mean atmospheric fields in the 1980s and perturbation in the 1990s, simulated no changes in SNDmax over the lowland. Since the PCS simulated a negligible change in precipitation, we concluded that the changes in the mean temperature rise mainly controlled the snow cover decrease in the 1990s over the lowland. On the other hand, the CTL simulated a slight increase in SNDmax over the highland, where a slight decrease and some increases in SNDmax were simulated by the PCS90s and PPS90s, respectively. The impacts of the perturbation changes on the snow cover were not negligible over the highland.

Our results suggest that, in the near-future climate projection, the snow cover changes can be evaluated only by the changes in the mean atmospheric fields due to global warming over the lowland, while the impacts of perturbation changes on the snow cover should also be considered over the highland. However, the projection of perturbation changes is difficult for global climate models (GCMs) with a low resolution because of their low reproducibility of perturbation in the present climate. Further studies are needed to assess the perturbation changes in the future climate using both the GCMs and RCMs. In addition, a more highly resolved regional climate simulation will be needed to accurately simulate the distribution of the snow cover in the complicated mountainous areas.

Supplement

Supplement 1 describes the differences in snowmelt and snowfall during the winter between CTL80s and the three experiments.

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