Changes in Snow Cover and Snow Water Equivalent Due to Global Warming Simulated by a 20km-mesh Global Atmospheric Model

Masahiro Hosaka¹, Daisuke Nohara², and Akio Kitoh¹
¹Meteorological Research Institute, Tsukuba, Japan
²Japan Science and Technology Agency/MRI, Tsukuba, Japan

Abstract

Simulations under present (end of the 20th Century) and future conditions (end of the 21st Century with SRES A1B scenario) by using a 20 km-mesh atmospheric general circulation model (AGCM) over 10 years are conducted and the changes in snow due to global warming are investigated.

The seasonal march of the snow cover in the present simulation is comparable to that of satellite-based observational data. The distributions of the simulated snow cover and snow water equivalent (SWE) reflect the detailed geographical features.

Due to global warming, the beginning of the snow-accumulating season (the end of the snow-melting season) will occur later (earlier) in most snow regions, and the snow cover will decrease except for very few exceptions. SWE will also decrease in wide areas, but over the cold regions (Siberia and the northern parts of North America), SWE will increase due to increases of snowfall in the coldest season.

In both the change and the percentage change of the SWE, we can find that the detailed geographical features effect on them. In Japan, the SWE will decrease over the heavy snow areas. However, the percentage changes are relatively smaller over the colder areas.

1. Introduction

Changes in snow cover and snow water equivalent (SWE) affect the climate system through ice-albedo feedback which is a strong positive feedback. Global warming will increase remarkably the surface temperature in high latitudes and this will delay the beginning of the snow accumulation period. On the other hand, the increase of atmospheric moisture content may cause an increase in snowfall. These two opposite reasons make it difficult to determine whether the SWE will increase or decrease and whether the melt-off will be earlier or later in future climate projections. Changes in snow and its seasonal march will affect climate, water resources such as river discharge, and human living conditions.

In past reports published by Intergovernmental Panel on Climate Change (IPCC), changes of snow were described; “there are very likely to have been decreases of about 10% in the extent of snow cover since the late 1960s”, and “northern hemisphere snow cover, permafrost, and sea-ice extent are projected to decrease further” (IPCC 2001).

Distribution of snow depends heavily on local geographical features and altitude. Generally, climate models can not simulate the small-scale structures owing to coarse resolution. Therefore, regional climate models with a resolution of less than 100 km were used (Räisänen et al. 2003; Leung et al. 2004). However, the applied areas were limited and regional climate models do not offer global information.

1.1 Integration Period

Table 1. Period and SST/GHG of each run

<table>
<thead>
<tr>
<th>Integration Period</th>
<th>SST</th>
<th>GHG</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>SST_Clim</td>
<td>GHG_Clim</td>
</tr>
<tr>
<td>11 years</td>
<td>SST_Clim+ASST</td>
<td>GHG_Clim+AGHG</td>
</tr>
<tr>
<td>SST_Clim: Climate SST averaged from 1982 to 1993</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASST: SST difference between 2080–2099 average and 1979–1998 average by MRI/GCCM2.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GHG_Clim: GHG averaged from 1979 to 1998</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AGHG: GHG difference between 2080–2099 average and 1979–1998 average</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Recently, the Japan Meteorological Agency and the Meteorological Research Institute succeeded in simulating climate for a period in excess of 10 years using a 20 km-mesh global AGCM for the present (end of the 20th Century) and future (end of the 21st Century) conditions. The results of the present simulation show, for the most part, good agreement with the observational data in the distributions of precipitation, snow cover and others. This manuscript describes changes in snow cover and SWE due to global warming.

2. Model and experiments

The model used is an atmospheric global model developed by the Japan Meteorological Agency and the Meteorological Research Institute. The resolution is TL95L60 and the spatial grid scale is close to 20 km. This model is currently used operationally for short-range forecasts at a resolution of TL319L40. It can also be used as a climate model at TL95L40. Special tunings were conducted for the long range integration at this high resolution. Details are reported in Mizuta et al. (2005).

The land surface scheme has been developed at MRI and JMA. The surface flux is based on SIB (Sellers et al. 1986), and the treatment of snow and soil was improved for climate research purposes. In the soil model, the phase change of H2Oi is included. The number of snow layers depends on the SWE with a maximum of three. Snow cover (Sc) also depends on the SWE; Sc = min (SWE/4mm, 1). The snow albedo follows Aoki et al. (2003) and depends on the temperature and the snow age. The classification of rainfall or snowfall is determined by the temperature of the atmospheric lowest level (ca. 10 m).

We conducted two simulations for the present (PC) and future (FC) situations. The situations do not include the interannual variation in the sea surface temperature (SST) and greenhouse effect gases (GHG). SST and the fraction of sea ice for PC are based on observation, and those for FC are made by adding the global warming signal (Yukimoto et al. 2005) to the observational data. The fraction of sea ice used in model is modified to 0 or 1, which is determined by whether the fraction is less than a specific threshold (0.55) or not. The monthly average data for the last 10 years is used. More detailed information about these simulations is described in Kusunoki et al. (2005).
Hosaka et al., Changes in snow cover

In these runs, grids with perpetual snow are seen in Greenland, Antarctica, eastern Siberia, and Alaska. Because it is inappropriate to use such grids in this analysis, grids in which snow survives summer for more than half the integrated years in any of the two runs are excluded.

3. Simulated snow in the present run

In the PC simulation, basic atmospheric field (global distributions of the seasonal mean precipitation, surface air temperature, geopotential height, zonal-mean wind and zonal-mean temperature, etc. (Mizuta et al. 2005)), and Baiu Front structure (Kusunoki et al. 2005) agree well with the observations; however, the global mean precipitation (2.9 mm/day) is slightly larger than that from the observation (2.4–2.6 mm/day). In this section, the seasonal march of snow cover is demonstrated to be well simulated, and the distribution of snow is shown to reflect the local geographical features.

Figure 1 shows a PC simulation of snow cover during a melt-off and satellite-based observational data provided by the NOAA-CIRES Climate Diagnostics Center (http://www.cdc.noaa.gov). These figures show that the large scale spatial patterns, including the seasonal changes are well simulated. It is noteworthy that the resolution of the observational data is 1x1 degrees, which is coarser than that of our model, so the detailed structure is smoothed out accordingly.

Figure 2 shows the PC simulation of snow cover and SWE over Europe in January. The altitude which was used in the simulation is also shown. Snow distributions clearly correspond with altitude, and among others, the Alps, the Caucasus, the Scandinavian mountains are all clearly evident.

4. Changes in snow cover and SWE due to global warming

As mentioned previously, increase in surface air temperature due to global warming is remarkably large in high latitudes, therefore future onsets of snow accumulation seasons will take place later. However, the total precipitation will probably increase over the region.

Therefore, it is uncertain whether the peak SWE will increase or decrease and whether the thaw will be earlier or later. In this section, the changes in our simulations are described.

Figure 3 shows the snow cover in PC and its change; the difference between FC and PC. During the snow accumulating and melting seasons, snow cover will
decrease in almost entire snow area. This means that the
beginning of snow accumulation will be later and the
end of snow melt will be earlier. However, the difference
due to global warming (FC-PC) is almost the same or
smaller than the difference between the PC and the ob-
servation (not shown).

Exceptional cases, where snow cover will increase,
are seen in the dry regions-Mongolia and the mountain-
ous part of USA in Fig. 3(d). In these regions, the SWE is
less than 4mm; therefore the snow cover estimated in
the model is less than unity and rather depends on SWE;
Sc = min (SWE/4 mm, 1).

Figure 4 shows the SWE in PC and its change due to
global warming. The SWE will decrease in most of the
regions and seasons, including the beginning of accu-
mulation and the end of snow melt. However, in
February (Fig. 4d), the regions with increases are seen in
high latitudes. These features are statistically signifi-
cant.

Figures 5(a)–(e) show the seasonal march of changes
in SWE between 50N-80N. The area with increases
(blue) spreads from autumn to winter, and after that, it
narrows and diminishes. The regions are limited to
northern Siberia and the northern parts of North
America in thecoldest period.

Figures 5(f) and 5(g) describe the changes in the
time-integrated accumulated precipitation and snowfall
from September to February. Precipitation (rainfall +
snowfall) increases over relatively wide areas in high
latitudes, partly due to the increased atmospheric
moisture content. However, regions with increased
snowfall are limited. To the south of 50N, the snowfall
decreases. To the south of 50N, the snowfall
decreases even if the precipitation increases, excluding
the high altitude regions. For example, in the western
part of Europe, the precipitation decreases, and the
snowfall decreases even in the high altitude regions
such as the Alps. There are similarities between the dis-
tributions in Fig. 5(g) and Fig. 5(d), which indicate
where accumulated snowfall has increased and where
SWE has also increased in February. The necessary
factors for the increase in SWE are the following: (1) an
increase in precipitation and (2) a constantly low tem-
perature leading to an increased snowfall which will
then make up for the loss resulting from the delayed
snow accumulation.

5. An example of local change: northern
Japan

In this section, as an example of regional changes, we
will show the change in snow in northern Japan.
Figures 6(a) and (b) show the altitude and the surface air temperature in February in northern Japan. There is a mountain ridge running from north to south, and the temperature is low over Hokkaido and the mountain area. Snow distribution differs on both sides of the mountain ridge. Along the shore of the Sea of Japan, which is the northwestern side of the ridge, there is a considerable amount of snowfall. In contrast, only a little snow could be identified on the southeastern side of the ridge along the Pacific Ocean. Figure 6(c) shows the SWE simulated in PC in February. These features are clearly evident owing to the high resolution.

Figure 6(d) describes the changes in SWE in February due to global warming. It shows that even in the coldest season in Japan, the SWE decreases significantly, in agreement with the decrease in snowfall (Fig. 5g). The particularly large decreases in SWE occur over the heavy snow areas.

Figure 6(e) shows the percentage change in SWE ((PC-FC)/PC) in February. It has better correspondence with the surface air temperature (Fig. 6b) than with the change in the SWE (Fig. 6d). This feature of significant SWE decrease occurring over the heavy snow areas but with a small percentage of decrease is commonly seen in mid-latitudes such as the Alps in Europe and the Rocky Mountains in the United States. This finding suggests that the high-resolution geographical features are very important for the expression and projection of snow.

6. Discussion

Simulations under present and future conditions for over a 10 year period were conducted using a 20 km-mesh atmospheric general circulation model (AGCM), and changes in snow due to global warming were investigated, excluding areas with perpetual snow. In accumulating and melting seasons, the snow cover decreases in almost the entire snow area; for the SWE, there are regions with increased snow on coldest months.

The regions where the SWE increases are limited to northern Siberia and the northern parts of North America in the coldest period. In other regions, the delay in the beginning of snowfall is less than one month, but the increased precipitation from autumn to winter will not bring a snowfall increase. Only the regions with constant low temperature could make up for the loss caused by the delay of snow accumulation. In our simulation, the increase in the SWE of the snow from autumn to winter is almost 70–90% in higher latitudes, and the ratio does not change very much due to global warming. This result is shown in Fig. 5(c) and 5(g); the absolute value in Fig. 5(c) is slightly smaller than that in Fig. 5(g).

Therefore, the major factor determining the increase or decrease of SWE is the snowfall change in our simulation. The snowfall/precipitation accumulations from September to February over the poleward of 60°N are 152(mm)/252–0.60 in PC and 154/301–0.51 in FC. In between 50–60°N, they are 134/476–0.28 and 112/516–0.22. However, there are many other physical processes such as snow melt, re-freezing, sublimation, and frost. Their effects on SWE strongly depend on the snow parameterizations. In addition, it is evident from Fig. 5(f) that the changes of the storm track in the mid-latitude regions occur, and such changes of global atmospheric circulation also affect SWE.

Moreover, the distribution of percentage change in SWE differs from that of the change in SWE. In Japan, the SWE will decrease over the heavy snow areas and the percentage decreases are relatively smaller over the colder areas. The SWE, its change, and its percentage change depend on geographical features; therefore, high resolution is preferable for reproducibility and projections.

An unavoidable question is whether this distribution of the increased SWE region is peculiar for this model, because of the uncertainty of our climate model projection. We started comparing the results from state-of-the-art AGCMs with our result. From the analysis of these results, the models are roughly divided into two types. One is the “Zonal”, in which the increased regions are located at high latitudes in winter, and another is the “Siberia increasing”, in which they are located in Siberia and in the northern parts of North America. This preliminary finding above suggests that our results are reliable.

In our experiments, the treatment of sea ice is very simple. A constant value (2 m) sea ice thickness was used in all simulations, though climate models predict that the thickness will continue to decrease. The fraction of sea ice, which is also evident to affect snowfall, is treated also simply (100% or 0%), and snow on sea ice is not included. Improvements in the treatment and further investigation of the effects concerning sea ice are planned.

Acknowledgements

DN is supported by the Core Research for Evolution Science and Technology (CREST) of Japan Science and Technology Agency (JST). This work is based on the results of experiments performed by the Global Warming Group under the framework of the “Kyosei Project 4: Development of Super High Resolution Global and Regional Climate Models” supported by the Research Revolution 2002 (RR2002) of the Ministry of Education, Sports, Culture, Science and Technology of Japan (MEXT). The 20 km-mesh model results were made on the Earth Simulator. The authors also acknowledge the JMA, MRI and Kyosei-4 global model developing groups for providing their data for analysis.

References


Manuscript received 11 May 2005, accepted 24 June 2005
SOLA: http://www.jstage.jst.go.jp/browse/sola/