Simulations of Monthly Variation in Snowfall over Complicated Mountainous Areas around Japan’s Northern Alps

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Abstract

We investigated the seasonal variation of snow cover at different altitudes using station data, satellite data, and a high-resolution numerical model around the Japan’s Northern Alps during three winters (2011/12, 2012/13, and 2013/14). The satellite data showed that the snow cover fraction was largest in 2012/13 before late December, which indicates that much of snowfall occurs at higher elevations in the early winter. In midwinter, the snow cover fraction was over 90% in 2011/12, while it was approximately 70% and 60% in 2012/13 and 2013/14, respectively. The station data also showed the greatest snow depth at lower elevations in 2011/12 among the three winters. The numerical model well simulates the year-to-year and monthly variations of the snow cover fraction, although the threshold of snow depth is larger than that of the satellite data. The numerical simulations indicate that the total amount of snowfall is controlled by spring snowfall as much as by winter snowfall at higher elevations. The year-to-year variations of spring snowfall are relatively larger than those of winter snowfall, resulting in different year-to-year variations of snow cover at lower and higher elevations.

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1. Introduction

Understanding snow cover in mountainous areas is important for managing not only snow disasters, such as avalanches and snowmelt floods, but also water resources, snow activities, winter sports, and sightseeing. However, due to the severe environment during the winter and problems with electric power sources, on-site observation of snow depth in mountainous areas is quite difficult. A polar orbit satellite can provide information regarding snow cover. However, since satellite observation is limited to clear days, it is difficult to capture the daily variation in snow cover. The satellite is also unable to observe snow depth in complex mountainous areas. Therefore, elucidation of the spatial and temporal variations of snow depth in the mountainous area is challenging.

It is well known that snow depth and altitude have a linear relationship (Peck and Brown 1962), hereafter referred to as the altitude dependency of snow depth (ADSD). The ADSD has been applied to a single slope or mountain. However, it is unclear whether the relationship can be applied at higher elevations where surface observations are limited. Uno et al. (2014) investigated the ADSD in the mountainous areas of the Sea of Japan coast and pointed out that the ADSD was influenced by windward mountains with an altitude of more than 500 m above sea level (masl). Based on observation stations that included high mountainous areas, Yamaguchi et al. (2011) reported that the year-to-year variations of snow depth in the coastal plains are different from those in mountainous areas. The former depend on year-to-year variations in temperature, and the latter depend on the year-to-year variations in precipitation.

A simulation using numerical weather models is a useful method for gaining an understanding of the horizontal distribution of snow depth in mountainous areas. Hara et al. (2008) simulated the snow depth in the Japanese archipelago in the winter of 2005/2006 using the Weather Research and Forecasting (WRF) model. Numerical simulations have also been conducted to calculate the winter precipitation around the Rocky Mountains in the United States using the Weather Research and Forecasting (WRF) model (Ikeda et al. 2010; Ramussen et al. 2011; Gutmann et al. 2012). Ikeda et al. (2010) stated that the spatial and temporal distributions of snowfall adequate for a water resource could be achieved with the appropriate choice of horizontal resolutions and physical parameterizations.

The numerical simulation, however, should be validated with some observational data. The validation of snow depth at higher elevations, which is necessary for estimating the ADSD, is a serious problem due to the lack of observation. Every year in late April, the Tateyama snow survey research group investigates the profiles of snow cover at Murododaira, which is located in the Japan’s Northern Alps and has an altitude of 2,450 m asl (Aoki and Watanabe 2009). The Tateyama Caldera Sabo Museum also investigates the snow cover profiles at Murododaira in late March and estimates the total precipitation, judging that the total precipitation exceeds 3,000 mm during the winter.

Although previous studies have investigated the snow cover in complicated mountainous areas, the seasonal and year-to-year variations of snow cover at different altitudes have not been sufficiently understood. The purpose of this study is to elucidate the monthly and year-to-year variations of snowfall around the Japan’s Northern Alps and plains along the Sea of Japan coast using satellite data and numerical simulations. We focused on three winters and springs from 2011/12 to 2013/14.

2. Observational data and model designs

We used in situ snow depth data obtained from the Japan Meteorological Agency (JMA). Snow depth at Murododaira is also used, which were observed by the Tateyama snow survey research group and the Tateyama Caldera Sabo Museum in late April and late March, respectively.

Twice-monthly snow cover datasets by the Japan Aerospace Exploration Agency (JAXA) Satellite Monitoring for Environmental Studies (JASME) project are obtained from JAXA and the Tokai University Research and Information Center (TRIC). The horizontal resolution is 500 m. JAXA has reported that the homogenous and wide snow covers at least 5 cm deep can be de-
Numerical simulations are performed using the Advanced Research WRF v3.2.1 (Skamarock et al. 2008). A two-way nested-grid system is used. Grid intervals are 16 km, 4 km, and 1 km in the first, second, and third domains, respectively (Fig. 1). This study focuses on the third domain with 1-km horizontal resolutions. The number of vertical layers is 30 in a terrain-following hydrostatic-pressure vertical coordinate. The top level is 50 hPa. The WRF single-moment 6-class microphysics scheme (WSM6) (Hong and Lim 2006) is applied as the precipitation process. The Kain-Fritsch convective parameterization scheme (Kain and Fritsch 1993) is also activated in the first coarse domain. The Monin-Obukhov (Janjic Eta) scheme (Janjic 1996) and the Mellor-Yamada-Janjic (Eta) Turbulent Kinetic Energy (TKE) scheme (Janjic 2002) are used to calculate the surface layer and boundary layer processes, respectively. The physical processes of the land surface are calculated using the Noah Land Surface Model (Noah-LSM), which has a single snow layer (Chen and Dudhia 2001). The diagnosis of snowfall for snow accumulation in the Noah-LSM was modified to include both the effects of humidity and the air temperature based on the wet bulb equation (Kondo 1994; Park et al. 2003; Kawase et al. 2013).

The initial and lateral boundary conditions for the coarse grid system are interpolated from the 6-hourly National Centers for Environmental Prediction Final Operational Global Analysis (NCEP-FNL) with 1.0° horizontal grid intervals and 26 vertical levels. The sea surface temperature (SST) is derived from the NOAA Optimum Interpolation Sea Surface Temperature (OI-SST) (Reynolds et al. 2002). The integrations are executed every year from September to August of the following year. The first month is the spin-up duration.

3. Results

3.1 Observed and simulated seasonal variations of snow depth

Figure 2a shows the seasonal variation of snow depth and accumulated snowfall at Toyama observed during the three winters. The accumulated snowfall was calculated from the snow depth at hourly increments, which follows the precedent dataset by JMA. Snow cover started earliest in 2012/13, while the accumulated snowfall was greatest in 2011/12. The accumulated snowfall of 2011/12 exceeded that of 2012/13 at the end of January. The maximum snow depth was 95 cm, observed on February 17 in 2012. Both the maximum snow depth and the accumulated snowfall were lowest in 2013/14.

Maximum snow depth observed at Inotani also shows similar year-to-year variation (Table 1). On the other hand, Murododaira’s year-to-year snow depth variation was different from that at lower elevations (Table 1). The greatest snow depth was observed in 2012/13, when the snow depth at lower elevations was less. It is, however, difficult to discuss the seasonal variation of snow depth with observations twice a year at Murododaira.

The WRF model well simulates the seasonal variations of snow depth and the accumulated snowfall at Toyama (Fig. 2b). The snow depth and snowfall are, however, underestimated as compared with the observation (Fig. 2a). The underestimated snowfall bias corresponds to the underestimation of precipitation in coastal areas, which could be caused by the boundary layer process over the Sea of Japan and the microphysics process in the WRF models. The simulated seasonal variation in accumulated snowfall around Murododaira differs from those in Toyama. The accumulated snowfall was smallest in 2011/12 before April (Figure not shown), which is consistent with the observations in March (Table 1).

3.2 Seasonal variation of the snow cover fraction as observed by satellite

Figure 3a shows the snow cover duration obtained from the JASMES/MODIS dataset in 2011/12. It must be noted that the temporal resolution of the dataset is half a month. The snow cover duration is more than 6 months over mountainous areas and less protected (http://kuroshio.eorc.jaxa.jp/JASMES/). The twice-monthly dataset shows that snow exists at each grid if snow cover is detected at least once in half a month on clear days. We do not use the daily and weekly data since the coastal areas of the Sea of Japan are frequently covered by clouds in the winter. It is difficult to analyze temporal variation of snow cover using the daily dataset with numerous missing values. The temporal variation is discussed by the aid of numerical simulations.

Fig. 1. Model and analysis domains: (a) model domains; (b) topography in the 3rd domain. A rectangular region with a thick black line in (b) shows the analysis area in Section 4.
than 3 months over the plains along the Sea of Japan coast (Figs. 1 and 3a). In some coastal areas, the snow cover duration is less than 2 months. Note that, of the three winters, the 2011/12 winter had the largest snowfall on the plains (Fig. 2a and Table 1).

Figure 3b shows the seasonal variation in the ratio of the grid number with the snow cover to the total grid number over the land enclosed by a thick red line of Fig. 3a, hereafter, the snow cover fraction. In 2012/13, the snow cover fraction increased from November and exceeded 60% in December. The snow cover fractions in 2011/12 and 2013/14 were smaller than that in 2012/13 before late December. These results imply that the mountainous areas had more snow cover in 2012/13 than in the other two years. However, in the midwinter of 2011/12, the snow cover fraction was over 90%, which indicates that the lower areas were widely covered with snow. This is consistent with the station data (Fig. 2a). The midwinter snow cover fraction was approximately 60% in 2013/14, which is the smallest of the three winters. In the snowmelt season, the decreasing curves of the snow cover fraction were similar in all three winters.

### 3.3 Simulated seasonal variation in the snow cover fractions

Figure 3c shows the seasonal variation in the ratio of the grid number with the snow cover to the total grid number over the land enclosed by a thick red line of Fig. 3a during the three years. In the simulation, the thin lines represent daily values at 00 UTC, and the thick lines represent 15-day running means. The snow depth thresholds are (c) 5 cm and (d) 20 cm. In Fig. 3c, the snow depth threshold is 5 cm, which is the same as the threshold of the JASMES/MODIS dataset. The snow cover fraction is overestimated as compared with the JASMES/MODIS dataset, especially in early winter in 2011/12 and 2013/14, in midwinter and early spring in all years (Fig. 3b).

Since there are few clear days along the Sea of Japan coast during the winter, days when the satellite observed the land surface are limited. In addition, the coastal area has little snow even in winter, and the air temperature is frequently above 0°C. Fresh snow cover would melt before the satellite could observe it under clear skies during half a month, resulting in a smaller snow cover fraction than in the simulation. Moreover, surface conditions, such as buildings and vegetation, are quite simplified in the model, which also could influence the difference in the observed and simulated snow cover fractions. The 5-cm threshold in the simulation may be too small to compare with the satellite observation. When the threshold is set to 20 cm (Fig. 3d), the year-to-year and seasonal variations of the snow cover fraction agree with the satellite observation. If the threshold in the simulation is larger, it is possible that the snow cover will remain when the satellite passes over the target area on a clear day. There are, however, some discrepancies between data from the satellite and the simulation. The snow cover fraction is overestimated in the early winter (November and early December) in 2013/14. The WRF model simulates the decrease in the snow cover fraction from late January to early

<table>
<thead>
<tr>
<th>Location</th>
<th>Elevation</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyama (JMA)</td>
<td>9 m</td>
<td>95 cm (2/17)</td>
<td>43 cm (1/4)</td>
<td>25 cm (2/8)</td>
</tr>
<tr>
<td>Inotani (JMA)</td>
<td>215 m</td>
<td>182 cm (2/2)</td>
<td>85 cm (1/27)</td>
<td>82 cm (1/19)</td>
</tr>
<tr>
<td>Murododaira*2</td>
<td>2,450 m</td>
<td>550 cm (3/22)</td>
<td>735 cm (3/25)</td>
<td>670 cm (3/23)</td>
</tr>
<tr>
<td>Murododaira*3</td>
<td>2,450 m</td>
<td>610 cm (4/21)</td>
<td>734 cm (4/21)</td>
<td>617 cm (4/17)</td>
</tr>
</tbody>
</table>

*1 Maximum snow depth in winter  
*2 Observation of the Tateyama Caldera Sabo Museum  
*3 Observation of the Tateyama snow survey research group (e.g., the University of Toyama)
February, while the JASMES/MODIS dataset does not show such a reduction.

4. Seasonal variation in the monthly snowfall at each altitude

Analysis of the snow cover fraction indicated seasonal variation of snow cover, while seasonal variations in snow depth and snowfall cannot be evaluated. Figures 2 and 3 indicate that the WRF well simulates the monthly and interannual variations of snowfall and snow cover although the amount of snowfall is underestimated by the WRF. Here, we discuss the seasonal variation of the monthly snowfall by analyzing the simulation results at each altitude.

Figure 4 shows the accumulated monthly snowfall and precipitation from December to April at each altitude over the enclosed area in Fig. 1b. In all the years, the accumulated snowfall grows more at the higher elevations, indicating the altitudinal dependency of snowfall. On the other hand, the altitudinal dependency of precipitation is less clear than that of snowfall. Below 100 mASL, winter snowfall (December to February) constitutes a large portion of the total snowfall—85.0%, 94.4%, and 86.6% in 2011/12, 2012/13, and 2013/14, respectively (Fig. 5). In contrast, at 2,400−2,500 mASL, which is comparable to the elevation of Murodo daira, the contribution of winter snowfall to total snowfall is relatively small—51.3%, 69.3%, and 61.0% in 2011/12, 2012/13, and 2013/14, respectively.

Figures 4 and 5 show the individual seasonal variations of snowfall in the three winters. In 2012/13, the winter snowfall was greater than in 2011/12, while snowfall in March was much less than that in 2011/12 at all elevations (Fig. 4b). The percentage of March snowfall to total snowfall is only 5–10% (Fig. 5b), which is related to less precipitation in March (Fig. 4c). In 2013/14 (Fig. 4c), the winter snowfall was the least at the elevations lower than 200 m. The snowfall in March accounted for 25–30% of the total snowfall above 1,500 mASL (Fig. 5c). On the other hand, there is much snowfall in April than those in 2011/12 and 2012/13 at all elevations.

As the surface air temperature (SAT) increases in the spring, the variation of SAT would largely influence the snowfall, even at high elevations. Figure 6 shows the monthly mean SAT and the percentage of snowfall in precipitation. In our simulation, the 0°C boundary was located 100−200 mASL in January, 600−900 mASL in March, and 1,500−1,700 mASL in April. The altitude changes in the percentage of snowfall is non-linear (Fig. 6b). In 2011/12, the SAT in March and April were, respectively, the lowest and highest among the three years; therefore, the percentages of snowfall in precipitation in April are much less than those in March below 1,500 mASL (Fig. 6b). The difference between March and April is relatively small above 2,000 mASL where the monthly mean SAT is lower than 0°C in April.

Yamaguchi et al. (2011) reported that mountain snow depth depends on year-to-year variation in precipitation based on stations’ observations. Additionally, our results indicate that, at high elevations above 1,000 m, the total amount of snowfall is controlled not only by winter snowfall but also by spring snowfall (March and April) (Fig. 5). The spring snowfall variation was greater than that in winter at higher elevations during three years (Fig. 4). According to a cyclone tracking analysis, cyclones most frequently pass over Japan in the spring (Chen et al. 1992), which brings heavy rain and snowfall in Japan (Hayasaki and Kawamura 2012). The year-to-year variation in cyclone activity could also affect the snowfall at high elevations during the spring season.

5. Concluding remarks

We have illustrated the monthly variations in snowfall at different elevations using on-site observations, JASMES/MODIS satellite data, and the WRF model over three winters. The JASMES/MODIS snow dataset shows that initial snow cover was earliest in 2012/13, and the snow cover fraction in midwinter was largest in 2011/12; this is consistent with the observations at Toyama. In the
snowmelt season, the decreasing snow cover fraction is similar in the three years. The WRF model well simulates the year-to-year and seasonal variations of the snow cover fraction, while the accumulated snowfall at Toyama was underestimated. The simulated snow cover fraction is overestimated when the threshold is set to 5 cm. The seasonal variation of the simulated snow cover fraction with a 20-cm threshold is close to that estimated by the JASMES/MODIS snow product. The optimal threshold would depend on numerical weather models.

Our simulations indicate that the total snowfall from December to April is mainly controlled by winter snowfall (December to February) at the low elevations below 500 m, while the contribution of winter snowfall to total snowfall is relatively smaller at the higher elevations. The year-to-year variations of spring snowfall (March to April) are relatively larger than those of winter snowfall at the higher elevations, resulting in the different year-to-year variations of snow between the lower and higher elevations.

The Noah-LSM in the WRF model implements a one-layer snow model. More sophisticated snow models, such as SNOWPACK (e.g., Bartelt and Lehning, 2002; Hirashima et al. 2008), would be needed to accurately simulate the snow accumulation, metamorphosis, and melting processes based on the meteorological data simulated in the WRF model. It would be necessary to simulate snow depth for more than 10 years to more accurately discuss the interannual variation of snow cover.

Acknowledgments

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