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Temporal variability in snow distribution

ELI ALFNES, LISS M. ANDREASSEN, RUNE V. ENGESET, THOMAS SKAUGEN, HANS-CHRISTIAN UDNÆS

Glacier and Snow Section, Norwegian Water Resources and Energy Directorate (NVE), P.O. Box 5091, Majorstua, N-0301 Oslo, Norway
E-mail: eli@nve.no

ABSTRACT. Snow-courses data have been collected in order to investigate the temporal variability of snow distribution in two catchments in southern Norway during the 2002 melt season. The profiles represent different elevations, aspects and terrain types. At snow maximum the spatial distribution of snow above the tree line was positively skewed (long tail in the positive direction), whereas the spatial distribution below the tree line followed a more normal distribution. During the snowmelt season the spatial distribution of snow became increasingly skewed. By separating the datasets into two terrain classes, alpine and forest, the snow distribution could be described by a time-variant gamma distribution function, one for each terrain class. The results of the study will be used to formulate a new snow routine in the Swedish rainfall–runoff model HBV, which is used for flood forecasting in Norway.

INTRODUCTION

Nearly half of the annual precipitation in Norway falls as snow. Knowledge of snow conditions is essential for runoff forecasting, power production, water supply and for studies of climate change. Snow distribution changes during the winter due to spatially variable snowfall and snowmelt events as well as wind-induced redistribution of the snow. In spring, this influences the spatial distribution of the melting process and thus the dynamics of the spring flood. The shape of the distribution is important when the snow-covered area (SCA) starts to play a role in the ablation season. When only a fraction of the catchment produces meltwater, the possibility of predicting errors in runoff caused by wrongly estimated SCA increases. Norwegian Water Resources and Energy Directorate (NVE) is responsible for flood warning and runoff forecasting in Norway. The HBV model (Bergström 1976, 1992) is used for runoff predictions. This model uses a temporal-invariant snow-distribution function, and may therefore fail to predict melt floods correctly.

Previous studies have focused on snow distribution at snow maximum (Bruland, 2002; Marchand and Killingtveit, 2002), changes in snow distribution on an annual basis (e.g. Johnsrud, 1985) and how terrain parameters (such as altitude, slope and aspect) can be used to explain the snow distribution (e.g. Andersson and Lundberg, 2002). To our knowledge there are no published studies of temporal variation of the spatial distribution of snow throughout the accumulation and melt season.

The objective of this study is to investigate the temporal variability in snow distribution. How does the snow distribution change during the melt season? Are there any differences with respect to terrain type or aspect? We examine whether a time-variant gamma distribution, as proposed by Skaugen (1999) and Skaugen and others (2004), is suitable to describe the dynamics in snow water equivalent (SWE) distribution during the melt season. Throughout this paper we consider the spatial distribution of SWE conditioned on snow, i.e. excluding the zero values.

FIELD DESCRIPTION AND DATA COLLECTION

Snow depth and snow density were collected in the Aursunden and Atnasjø catchments during the 2002 melt season (Fig. 1). The Aursunden catchment (62°40′41″N, 11°27′48″E) has an area of 835 km^2 and ranges from 690 to 1553 m a.s.l. (median of 840 m). The terrain is gently sloping and hilly. About half of the catchment is located below the tree line. The vegetation is birch, pine and spruce forest as well as swamp and cultivated land. The Atnasjø catchment (61°50′45″N, 10°47′31″E) is 465 km^2 and ranges from 701 to 2114 m a.s.l. (median of 1186 m). It has a more alpine character with steeper mountain hills than the Aursunden catch-

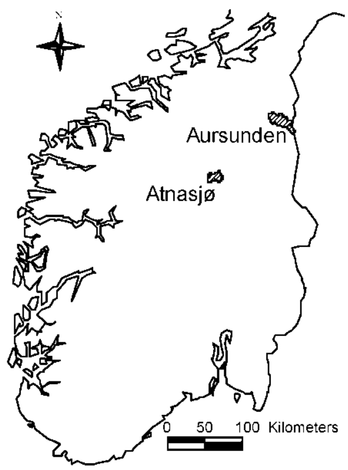

Fig. 1. Location map showing the Aursunden and Atnasjø catchments, south Norway.

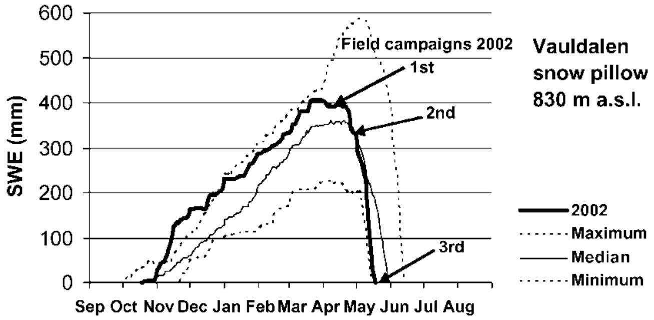

Fig. 2. SWE observed at the Vauldalen snow pillow (Glommens and Laagens Water Management Association (GLB)) located in the Aursunden catchment. Statistics are calculated for the period 1987–2000. Timing of the 2002 field campaigns is shown with arrows.

ment. About 85% of the catchment is located above the tree line. The vegetation is mostly pine forest with some swamp and cultivated areas.

Three field campaigns were carried out in order to measure the snow distribution at the SWE maximum (week 15) and twice during the melt period (weeks 18 and 21). The timing of the field campaigns in relation to SWE recorded at a snow pillow located at 830 m altitude in the catchment Aursunden is shown in Figure 2. Snow depth and density were measured along 16 courses: 11 in the Aursunden catchment and 5 in the Atnasjø catchment (Table 1). The snow courses were distributed at different elevation levels, representing alpine terrain and sparse birch and pine forest, and different aspects. The snow courses were positioned using global positioning system (GPS) receivers. Snow depth was measured every 10 m, providing datasets of 60–220 sampling points for each course. Snow depths were recorded to the nearest 1 cm using snow probes. Some uncertainty was connected to distinguishing the ground surface since surface cover varied between marsh, heather and rock. This is considered to have only minor influence on the study

Table 1. Description of the snow courses in the Aursunden and Atnasjø catchments

Course	Aspect	Terrain type	Course length	Altitude
			m	m a.s.l.
Au-1[1]	Southwest	Alpine	1640	950
Au-2[1]	Northeast	Alpine	967	950
Au-3[1]	Horizontal	Alpine	643	920–950
Au-4[2]	Horizontal	Birch forest	1400	840
Au-5[2]	Horizontal	Birch forest	1400	840
Au-6[3]	Horizontal	Alpine	968	930
Au-7[3]	East	Alpine	1410	930
Au-8[3]	West	Alpine	1520	930
Au-9[4]	Southwest	Alpine	1430	930
Au-10[4]	Northeast	Alpine	1400	930
Au-11[4]	Southwest	Birch forest	1340	870
At-1[5]	West	Pine forest	900	800
At-2[5]	West	Pine forest	650	900
At-3[5]	West	Alpine	1230	1000
At-4[5]	West	Alpine	1980	1100
At-5[5]	West	Alpine	2240	1200

[1]Aursunden Storhåmmaren. [2]Aursunden Vauldalen. [3]Aursunden Pikstenshøgda. [4]Aursunden Syndre Langsvola. [5]Atnasjø Storbekken.

Table 2. Temporal variation of snow properties in the Aursunden catchment

	Week					
	Alpine			Forest		
	15	18	21	15	18	21
SCA (%)	90	80	30	99	95	24
SWE (mm)	503	458	351	484	374	186
Density (kg m^{-3})	414	450	506	393	451	536

because of the large number of sampling points. Snow density was sampled at mean snow depth (one to two samples) and at 0.5 m snow depth (one sample) at each course. SWE was calculated by multiplying the measured snow depth by the averaged snow density of the snow course, and a time series was established.

RESULTS AND DISCUSSION

In Aursunden the amount of snow was approximately 115% of the median snow maximum (observation period 1987–2000) (Fig. 2). Snowmelt started 1 week before the first field campaign. However, most of the water was still in the snowpack according to measured SWE at the snow pillow (Fig. 2). Snow-cover area (SCA) was approximately 90% at the alpine courses and 99% at the forested courses in the first campaign, decreasing to 30% and 24% respectively in the last campaign (Table 2). Mean SWE (excluding the zero values) showed a large variation between the various courses (Fig. 3). The average SWE decreased from 503 mm to 351 mm in the alpine areas and from 484 mm to 186 mm in the birch forest between the first and the last field campaigns (Table 2). High standard deviations were seen for

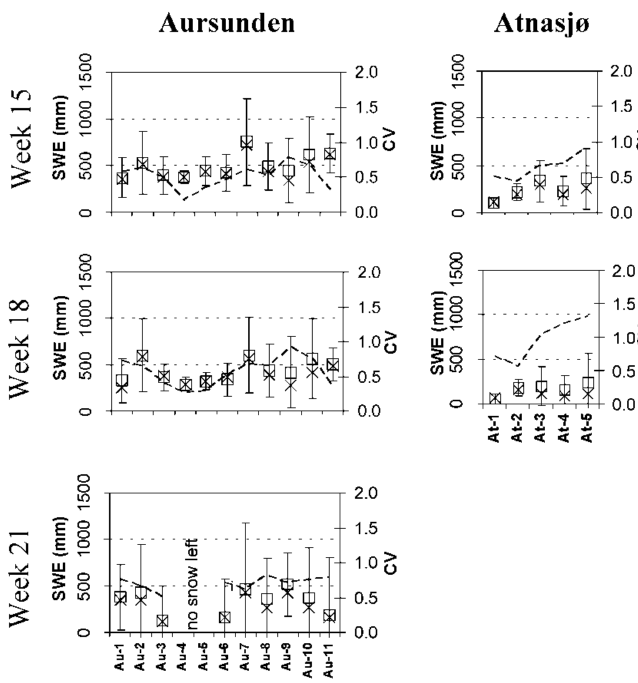

Fig. 3. SWE shown as mean, median (x), standard deviation (vertical error bars) and coefficient of variation (CV; dashed line) for the snow courses. Zero values are excluded from the statistics.

Table 3. Temporal variation of snow properties in the Atnasjø catchment

	Week			
	Alpine		*Forest*	
	15	*18*	*15*	*18*
SCA (%)	61	76	65	21
SWE (mm)	306	198	156	121
Density (kg m^{-3})	434	457	338	397

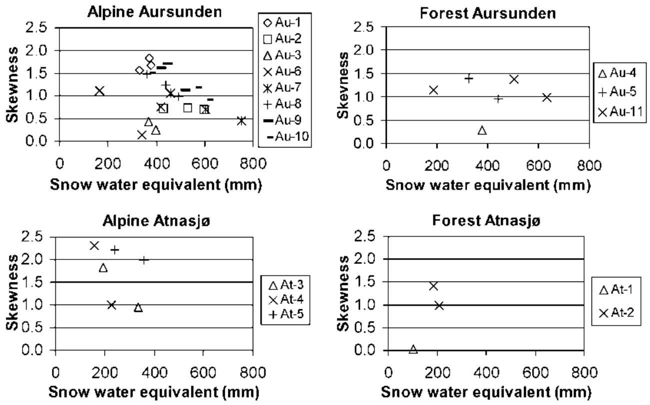

Fig. 5. Skewness as function of SWE in the melt season 2002. Data series with < 20 snow-depth observations are excluded.

the alpine courses, whereas the birch courses had much lower standard deviations (Fig. 3). Average snow density increased from 400 to 540 kg m^{-3} during the melt season (Table 2).

Atnasjø had approximately 65% of normal SWE (observation period 1987-2000) at snow maximum. The amount of snow was less than for Aursunden, with the average SWE equal to 305 mm in the alpine and 156 mm in the forested terrain in the first campaign, decreasing to 198 and 121 mm respectively in the second campaign (Table 3). Only two campaigns were carried out in Atnasjø, since there was very little snow left at the time of the third campaign. As in Aursunden, the alpine courses showed larger variation in SWE than the forested courses (Fig. 3). SCA was less than in Aursunden, approximately 65% in the forest and 61% in the alpine terrain (Table 3). In the second campaign the SCA had decreased to 21% in the forest, whereas it had increased to 76% in the alpine terrain. The increased SCA was caused by a snowfall a few days ahead of the field campaign. As would be expected, an increase in snow density was observed during the melt season (Table 3).

Generally, the recorded SWE revealed a large variability of the mean and standard deviation for the various snow courses in both catchments (Fig. 3). No trend between mean SWE and altitude, terrain type or aspect was found. However, nearby there was a tendency of higher SWE for northeasterly-exposed courses than for those exposed towards the southwest. The coefficient of variation (CV) was higher in alpine than in forested terrain (Fig. 3). A CV increase was observed as the melting proceeded, indicating an increase in the variability of the snow cover. No trend between CV and aspect was found. The alpine snow courses revealed a positively skewed distribution, whereas the forested snow courses followed an approximately normal distribution at snow maximum (Fig. 4). This agrees with results reported by Bruland (2002) and Marchand and Killingtveit (2002). During the melt season, as SWE decreased, a change towards more skewed distributions was observed for the snow courses in both terrain classes (Fig. 5).

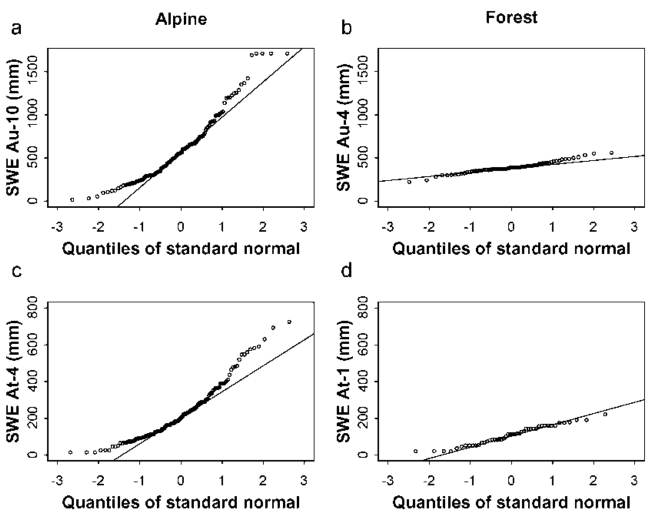

Fig. 4. Quantile–quantile plot of the empirical distribution at snow maximum vs standard normal distribution. Snow courses from the two catchments: Aursunden (alpine (a) and birch forest (b)) and Atnasjø (alpine (c) and pine forest (d)).

The results of this study reveal that a time-variant frequency function is required to describe the spatial SWE distribution during the melt season because of the temporal change in skewness. In addition, the frequency distribution should be able to capture terrain-specific differences and variations in annual precipitation between catchments. It is possible to implement these features in a two-parameter gamma distribution function as proposed by Skaugen (1999) and Skaugen and others (2004).

Let y be a gamma-distributed random variable, representing a unit snowfall (mean snowfall event), with probability density function (PDF):

$$F_{\alpha,\nu}(y) = \frac{1}{\Gamma(\nu)}\alpha^{\nu}y^{\nu-1}e^{-\alpha y} \qquad \alpha, \nu, y > 0\,, \tag{1}$$

where $\Gamma(\nu)$ is the gamma function, α is the scale parameter and ν is the shape parameter. The mean equals $E(y) = \nu/\alpha$ and the variance equals $\mathrm{Var}(y) = \nu/\alpha^2$. If the variables y_i are independent and identically distributed gamma variables in time and space, then $z_t(x) = y_1 + y_2 + \ldots + y_n$ is distributed as a gamma variable with parameters α and $n\nu$ (Feller, 1971, p. 47). The scale parameter α is a global value for each of the terrain classes, and the shape parameter $n\nu$ is expressed as a terrain- and catchment-dependent constant (ν) multiplied with a variable representing the accumulated number of snow equivalents (n) in the snowfalls and melting events. That means that n is the accumulated SWE divided by the SWE of a unit snowfall and thereby gives the seasonal dynamics of the distribution function. The spatial distribution of accumulated SWE (z) at a given time has mean and variance equal to:

$$E(z) = N\nu/\alpha \tag{2}$$

$$\mathrm{Var}(z) = n\nu/\alpha^2\,. \tag{3}$$

To test the hypothesis that a time-variant gamma distri-

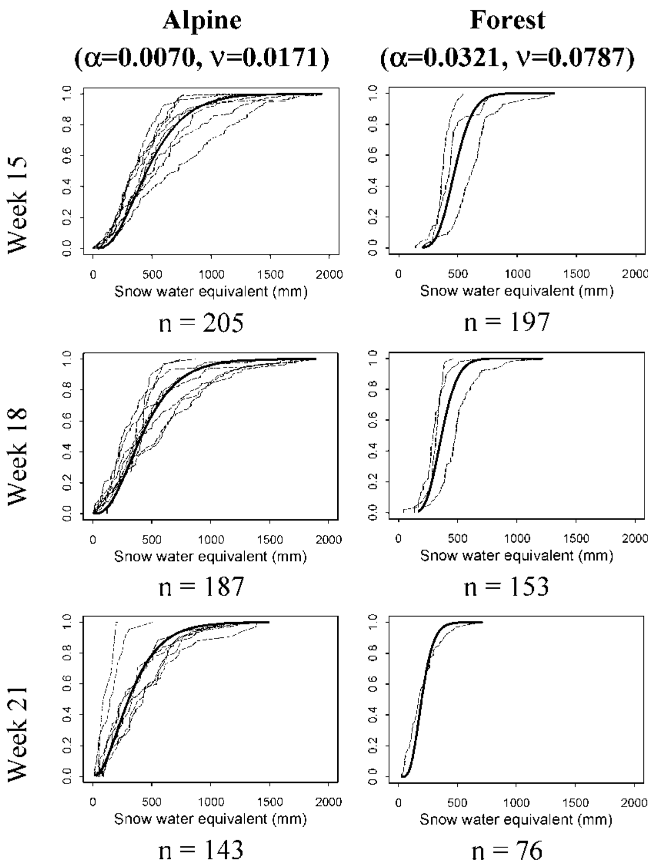

Fig. 6. Empirical CDFs (dashed lines) and theoretical gamma (solid lines; $n\nu =$ shape, $\alpha =$ rate) CDF for Aursunden, spring 2002.

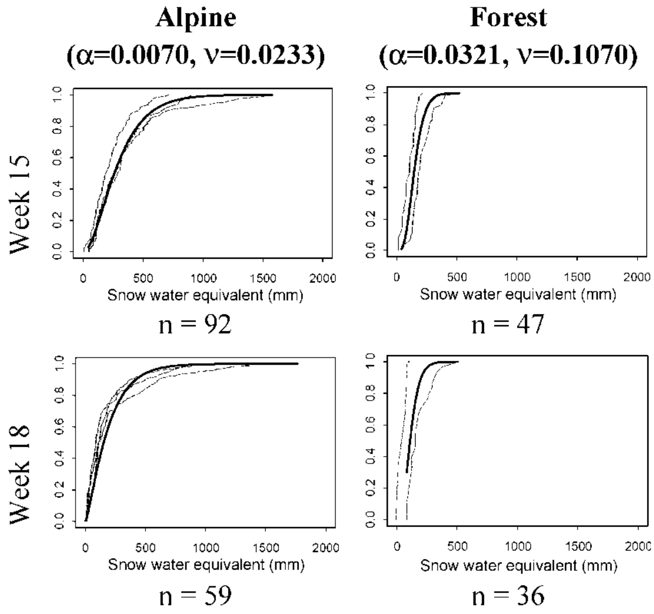

Fig. 7. Empirical CDFs (dashed lines) and theoretical gamma (solid lines; $n\nu =$ shape, $\alpha =$ rate) CDF for Atnasjø, spring 2002.

bution is suitable to describe the dynamics in SWE, the parameters α and $n\nu$ were calculated for each snow course using Equations (2) and (3). Thereafter, α parameters for each of the terrain classes, alpine and forest, were determined by averaging over the snow courses. Terrain- and catchment-dependent ν values were derived assuming that the mean daily precipitation, for days with precipitation, is equal to the expectation value of a unit snowfall, $E(y) = \nu/\alpha$. This resulted in a time-dependent parameter set for each terrain class, with n representing the number of events.

Figures 6 and 7 show the empirical cumulative density function (CDF) for the observed snow courses, as well as the theoretical CDF for the Aursunden and Atnasjø catchments. The empirical CDFs vary, except for the alpine courses in the catchment Atnasjø, but the theoretical gamma distribution gives a relatively good representation of the empirical distributions. The temporal variation in SWE as well as the different behaviour in alpine and forested terrain is captured by the model.

CONCLUSIONS

The field study showed that the mean SWE varies considerably from one location to another. No trend between SWE and altitude, terrain type or aspect was found. However, the coefficient of variation was larger for the alpine courses than for the forested ones.

The spatial distribution of SWE at the end of the accumulation season was positively skewed in alpine terrain and had a more normal distribution in forested terrain. Throughout the melt season the spatial distribution of SWE was increasingly skewed for both terrain classes.

Using a two-parameter gamma distribution gave an appropriate description of the temporal changes in the SWE distribution. A global rate parameter, dependent only on the terrain class, was determined from the snow courses. The time-variant part of the shape parameter was given as the number of snowfall accumulations, and the time-invariant part was determined from the mean daily precipitation for the area. Thus, a time series from a representative precipitation station is all that is required in order to implement the model in new catchments.

The study will continue throughout 2003, with repeated field campaigns in Aursunden and Atnasjø. In addition, a 2 km long course at an alpine location is recorded throughout the winter. The results of the studies will be used to improve the Swedish rainfall–runoff model HBV used for flood forecasting at NVE.

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