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Short- and Long-Term Variability of Snow Albedo

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The progress of snow albedo for the 1991 winter from Helligdagshaugen research site, Norway, is presented. The temporal reduction of albedo decreases as the snow undergoes a process of metamorphosis, as long as the snow depth is large enough to prevent absorption of solar radiation by the underlying terrain. Later, as the snow depth becomes less than about 10 cm and the area of bare patches grows, there is an increase in the temporal rate of reduction in albedo. An accumulated daily maximum temperature index is shown to be a good predictor of both the long-term development of the snow albedo and the daily mean albedo. The actual albedo deviates from the predicted long-term albedo due to variable meteorological conditions of which solar radiation is the most important one. Solar radiation and snow albedo are negatively correlated. Linear regression is performed for a winter period with no melting and for two distinct melting periods. Snow albedo was first determined as a function of temperature index alone. An improved accuracy of 2-6 per cent in estimated snow albedo was obtained when solar radiation was included. Very similar regression coefficients were found for two different periods.

Introduction

Calculations of energy exchange on the Earth's surface require data from energy fluxes from short- and longwave radiation, convective, sensible and latent heat, heat from precipitation, and conductive ground heat. These measurements are essential in both large-scale studies such as global climate research and small-scale analyses, *e.g.* energy calculations for runoff similations in a snow-covered watershed. One important parameter in the energy budget is the albedo defining how much of the incoming shortwave radiation is reflected at the surface. In this study, the snow albedo is measured, analyzed, and presented during a winter season at the Helligdagshaugen research site, Norway.

The snow albedo shows seasonal and daily variations depending on a wide variety of sources of influence. The most important are snow surface characteristics, snow depth, meteorological conditions, and sensor accuracy. Typically, in most hydrological study areas routine measurements of meteorological parameters are more common than direct measurements of albedo. Thus, the main goal of this particular study is to find the meteorological parameters necessary for an accurate prediction of snow albedo, especially during the snow melt season when the snow degrades rapidly.

Previous work shows that there is a strong relationship between snow albedo and the age of the snow-cover (U.S. Army Corps of Engineers 1956; O'Neill and Gray 1973). For example, the reduction of snow albedo is calculated fairly accurate by using an accumulated daily maximum temperature index (U.S. Army Corps of Engineers 1956). Although the temperature index is a good predictor of the long-term development of snow albedo, other meteorological conditions cause some variation as well. Snow albedo increases in overcast weather due to a spectral shift of the solar radiation reaching the surface (Grenfell and Maykut 1977; Warren 1982; Wendler and Kelley 1988). In this study, analysis is made of the correlation between the residual albedos (*e.g.* deviations from daily mean albedo) and meteorological parameters. This is done to clarify whether predictions of snow albedo based on the temperature index can be improved by including short-term effects from variable meteorological conditions.

Study Area and Data Acquisition

The Helligdagshaugen research site is part of the monitoring system of the Sagelva Representative Basin (Fig. 1). The site lies in a climatic transition zone that is influenced both by continental and coastal climate (Sand 1990). Normally, summers are cool and winters are mild. Periods when warm moist air moves in from the ocean cause rain and temporary snowmelt several times during the winter. This gives an unstable climate with frequent changes between freezing and melting. Usually, snow covers the ground from late November to early May. The location of the site is at 63°18'N, 10°39'E at an elevation of 515 m a.s.l.

The research site includes instrumentation for monitoring of several hydrological and meteorological parameters. The snow albedo was measured during the winter of 1991 using Kipp & Zonen CM 5 sensors mounted with Schott filter glasses. Snow albedo was measured from 300 nm to 2,500 nm (no filter), 529 nm to 2,500 nm (OG

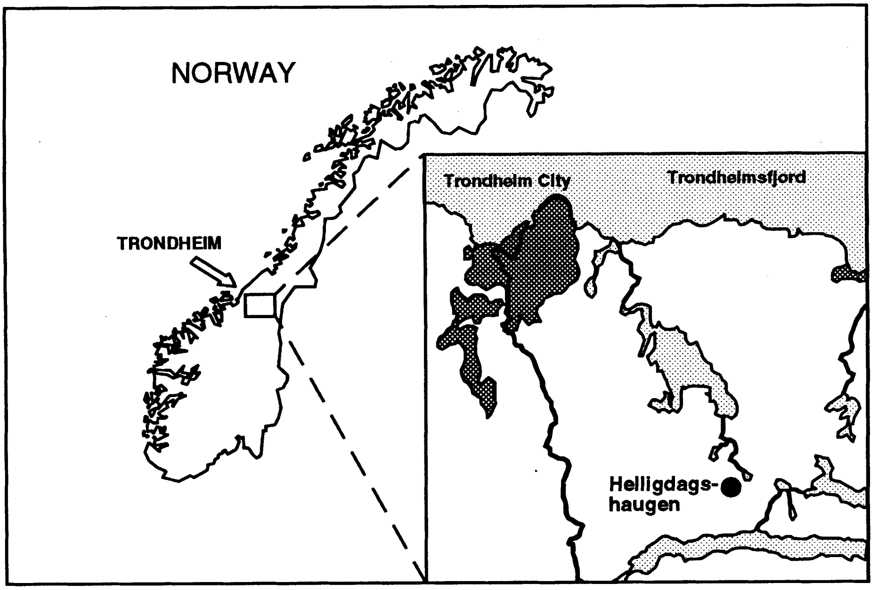

Fig. 1. Map showing the location of the study site, Helligdagshaugen.

530), and 623 to 2,500 nm (RG 630). Some technical problems occurred so that only albedo measurements from 623 to 2,500 nm could be used in the analysis. Thus, a portion of the visible spectrum was excluded, which means that a somewhat too low albedo was calculated. The sensor height was 170 cm over approximately horizontal terrain. Vegetation at the measuring site is sparse, with short coniferous forest, mainly pine and the surface is covered with heather. The closest tree is about 10 metres from where the instruments were set up so shadows could have been a problem at low sun elevations. To avoid effects from shadowing trees and after examining the basic data, only snow albedo recordings for sun elevations larger than 10° were selected for further analysis. The sampling interval was set to 20 minutes. Daily mean albedo is calculated as the average of these discrete single measurements.

Reflectance Characteristics of Snow

The snow reflectance is very high in the visible region of the electromagnetic spectrum. However, the snow albedo decreases rapidly in the infra-red, especially with the onset of melting and associated snow grain size increase (O'Brien and Munis 1975; Warren 1982; Hall *et al.* 1988). Moreover, the snow reflectance is close to zero at wavelengths in the mid-infra-red at about 1,550 nm. The spectral properties of snow are clearly important in many scientific studies, *e.g.* when narrow-band snow albedo is obtained by remote sensing techniques (Dozier 1989; Winther 1992). Then, calculation of the planetary albedo or special studies of snow properties by combinations of satellite bands require knowledge of the spectral characteristics of snow. However, in this study the spectrally *integrated* snow albedo is measured, since the overall albedo is used when the energy exchange between the atmosphere and the snow surface is determined.

Seasonal Variations

Fresh fallen snow scatters solar radiation so that it is almost perfectly diffuse and is considered to be a Lambertian reflector (Hall *et al.* 1990). Even so, once metamorphosis begins the reflectance from snow is higher in the reflected direction of the beam than in other diffuse directions. Thus, the snow becomes an anisotropic reflector and is largely specular (Salomonson and Marlatt 1968; Dirmhirn and Eaton 1975; Warren 1982).

The snow grain size increases as metamorphosis of the snow starts. In general, the albedo drops at all wavelengths as the grain size increases, although the effect is most prominent in the near-infra-red (Dozier *et al.* 1981). The presence of liquid water in the snowpack affects the spectral albedo similarly to the grain size effect (Wiscombe and Warren 1980). Snow surface impurities, however, have a more dominating effect on the visible albedo than on the infra-red albedo (Dozier *et al.* 1981). There seems to be no dependency between snow albedo and density (Bohren and Barkstrom 1974; Choudhury and Chang 1979; Wiscombe and Warren 1980; Warren 1982). When solar radiation begins to penetrate through a thin snow-cover and is absorbed by soil and vegetation, the albedo drops rapidly, O'Neill and Gray (1973).

Daily Variations

The snow albedo increases with decreasing effective solar elevation because the first scattering event happens closer to the surface at low sun angles than at larger ones (Dirmhirn and Eaton 1975; Carroll and Fitch 1981; McGuffie and Henderson-Sellers 1985). The increase in albedo is larger in the infra-red than in the visible part of the spectrum (Bryazgin and Koptev 1969; Wiscombe and Warren 1980).

Clouds absorb a higher portion of infra-red than visible radiation. Thus, a relative high portion of visible radiation reaches the surface under cloudy conditions. Because the visible snow albedo is very high ($> 90\,\%$) compared to the near-infra-red albedo (about $50\,\%$), an increase in surface albedo is to be expected during overcast weather (Wendler and Kelley 1988).

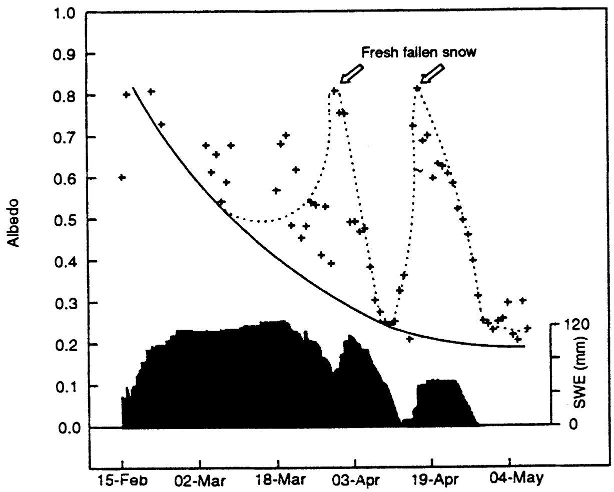

Fig. 2. Long-term variation of albedo for old snow (solid line), water equivalents of snow pack (shaded area) and daily mean albedo (+ and dotted line).

Results

Measurement Data

Fig. 2 presents the development of the snowpack expressed as snow water equivalent (SWE) together with short- and long-term variability of snow albedo during the 1991 winter. The lower line in Fig. 2 indicates the progress of the albedo if no additional snow fall occurred while the dotted line *roughly* shows the real progress of the albedo during the winter. Two major snow falls are indicated. Meteorological registrations, *i.e.* shortwave radiation (mW/cm^2), air temperature (°C), wind speed (m/s), relative humidity (%) and precipitation (mm/h), together with measurements of accumulated melt water (mm) were collected in the same period at a position within 15 metres of the snow albedo measurements site (Fig. 3). The snow water equivalent measurements are based on recordings from a nearby station named Frosketjønnbekken. By using 19 years of SWE measurements prior to 1991, the correlation between Helligdagshaugen and Frosketjønnbekken is computed to be 0.88 (R^2 = 0.88).

Numerous scientists have studied the temporal albedo variations of a melting snowpack (U.S. Army Corps of Engineers 1956; O'Neill and Gray 1973; Robinson and Kukla 1984; McGuffie and Henderson-Sellers 1985). Figs. 4 and 5 display plots of the albedo data from Helligdagshaugen as a function of the age of the snow surface (in days) and the accumulated daily maximum temperature index (degrees Fahrenheit) for the period after the last major snow fall on April 16. Also plotted

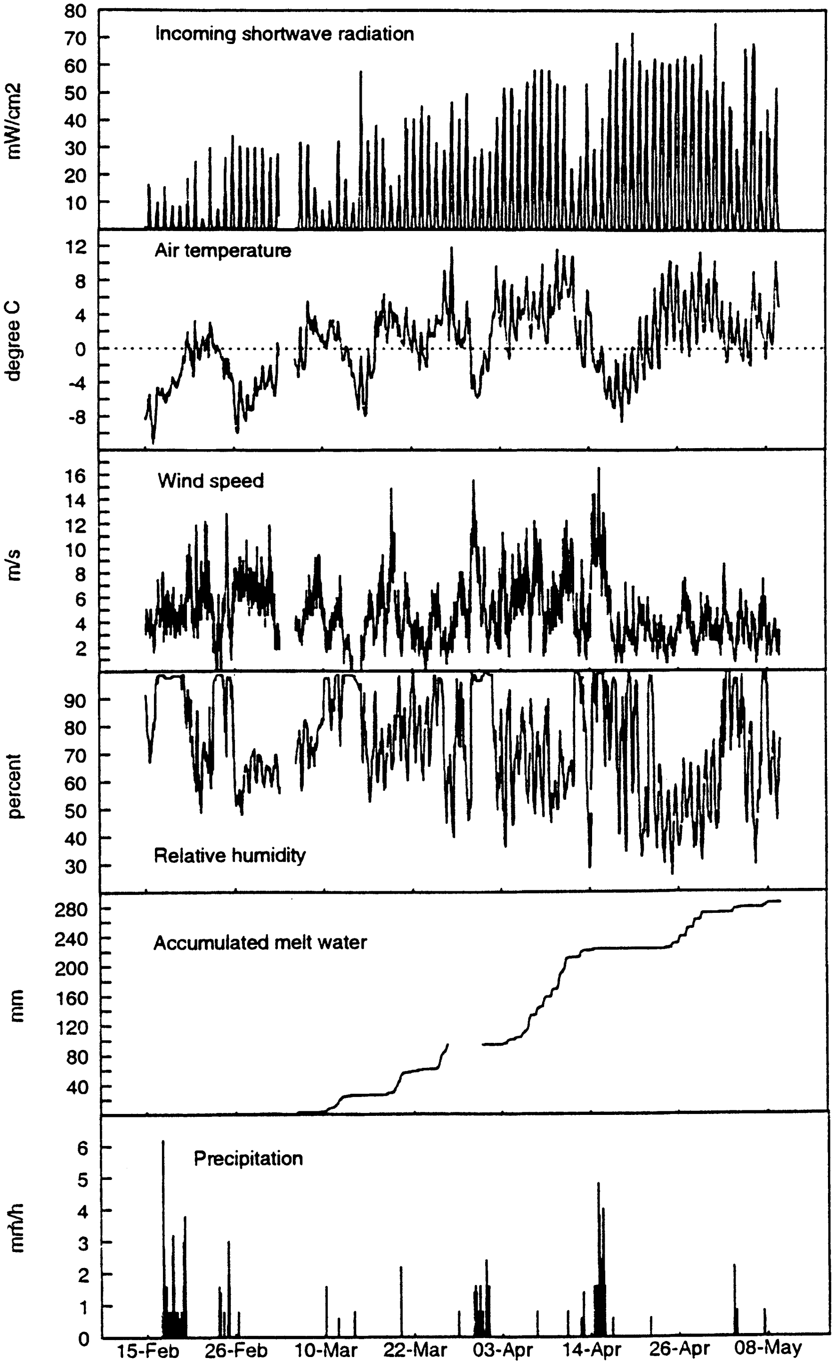

Fig. 3. Meteorological data from Helligdagshaugen research site, February 15 to May 9.

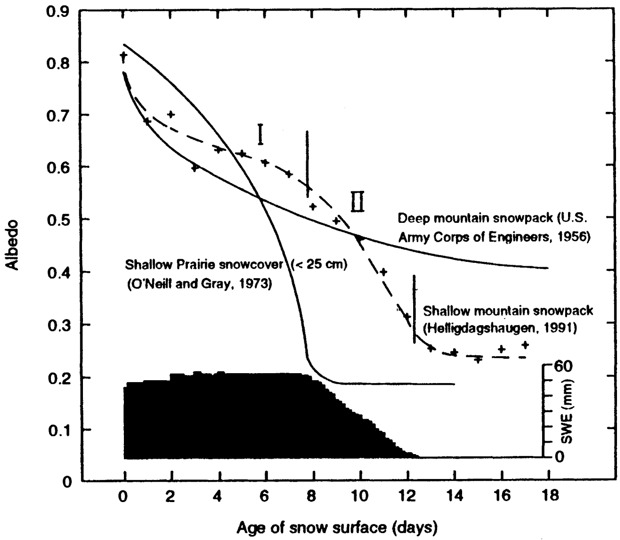

Fig. 4. Temporal albedo variations of a melting snowpack and water equivalents of snow pack at Helligdagshaugen. The Helligdagshaugen data were recorded in the period from the last snow fall until the measurement site was approximately free of snow *i.e.* from April 16 through May 3.

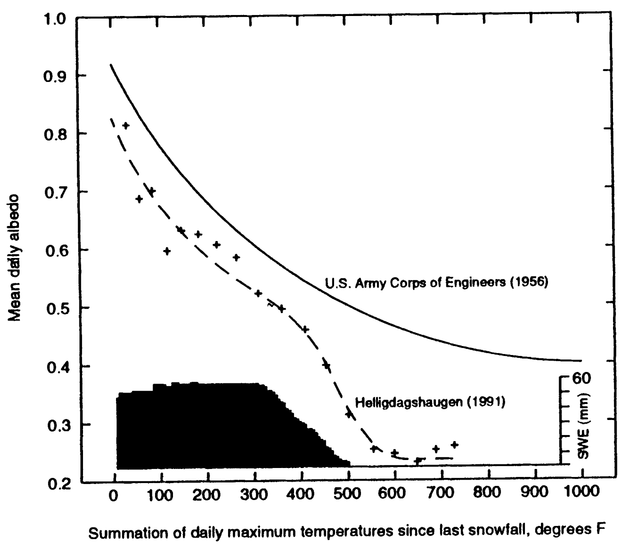

Fig. 5. Variation of albedo as a function of the accumulated daily maximum temperature index, T_{acc}. Temperature and albedo measurements for Helligdagshaugen are from April 16 through May 3. Snow water equivalents are shown as shaded area.

are comparable data from U.S. Army Corps of Engineers (1956) and O'Neill and Gray (1973).

The albedo reduction at Helligdagshaugen underwent two main phases (Fig. 4). In the first phase, the temporal rate of change in albedo decreased similar to that for the deep mountain snowpack reported by U.S. Army Corps of Engineers (1956). A snowpack deeper than 20-30 cm is only slightly affected by the underlying ground (Schwerdtfeger and Weller 1977; Wiscombe and Warren 1980). In the second phase, the temporal rate of change in albedo increases, like the shallow Prairie snow-cover curve (O'Neill and Gray 1973). The second phase reflects when the underlying ground starts to affect the surface reflectance, because solar radiation penetrates through the snowpack and is absorbed by the underlying terrain. This initiates an accelerating reduction of the surface albedo as the snow depth continuously decreases and the area of bare patches grows. Assuming a snow density of 0.33 g/cm^3 on day number 9, the snow depth becomes about 10 cm. Finally, the albedo stabilizes at a level corresponding to the present bare ground albedo when the snow melts. (Fig. 4).

The measured albedo curve (Fig. 5) starts about 10 per cent lower than the curve presented by U.S. Army Corps of Engineers (1956). However, the two curves initially follow a parallel reduction in albedo. The Helligdagshaugen curve significantly drops when the temperature index reaches about 400. This drop occurs when the snow-cover tends to melt and is gradually replaced by ground without snow-cover. Thus, the curve flattens out between 550 and 700 when the snow has more or less disappeared. Overall, there is a good agreement between the two curves for a snow-covered terrain. The discrepancy may be attributed to the spectral sensitivity of the albedometers used for data collection. The U.S. Army Corps of Engineers (1956) made use of Eppley pyrheliometers, thus measuring the whole shortwave wavelength region. The plotted data from Helligdagshaugen, however, are recorded by a Kipp & Zonen albedometer which measured through red filters, reducing the spectral range and consequently the albedo. Another issue is the limited snow depths which propably led to penetration of solar radiation through the snowpack shortly after the snow fall on April 16. This reduces the measured albedo more than the albedo of a deep snowpack.

Statistical Analysis

Statistical analysis was done on the measured data. Table 1 shows the descriptive statistics.

A measure of the relation between two variables, here denoted by r, is the Pearson correlation coefficient (Johnsen and Wichern 1988). Table 2 presents the correlation coefficients of the measured variables.

Multiple linear regression was carried out with albedo as the dependent variable (Y). The regression model can be expressed as

Table 1 – Descriptive statistics from February 15 to May 9. Residual albedo is the deviation from daily mean albedo.

Variable	Mean	Std. Dev.	Minimum	Maximum	No. of Obs.
Wind (m/s)	4.89	2.52	0.00	14.10	574
Precipitation (mm/h)	0.13	0.34	0.00	2.87	567
Temperature (°C)	1.68	4.37	-8.50	11.35	574
Melt water (mm/h)	0.51	1.76	0.00	19.05	546
Relative humidity (%)	69.31	19.01	32.73	99.60	574
Solar radiation (mW/cm^2)	38.40	17.14	14.36	84.67	574
Snow albedo	0.49	0.19	0.19	0.94	420
Residual albedo	0.00	0.05	-0.18	0.25	417
Snow water eq. (mm)	71.85	44.43	0.00	127.19	588

Table 2 – Pearson correlation coefficient pairs of measures variables. The significance level is 1-p. Statistics are performed on all measurements in the period from February 15 to May 9.

	Wind	Precipi-tation	Temper-ature	Meltwater	Relative humidity	Solar radiation	Albedo	Residual albedo	Snow water eq.
Wind	1.000 p = .								
Precipi-tation	.2262 p = .000	1.000 p = .							
Temper-ature	.2030 p = .000	-.1732 p = .000	1.000 p = .						
Meltwater	.0531 p = .153	-.0192 p = .356	.1680 p = .001	1.000 p = .					
Relative humidity	.0433 p = .202	.4061 p = .000	-.5959 p = .000	.0562 p = .140	1.000 p = .				
Solar radiation	-.1415 p = .003	-.2183 p = .000	.4191 p = .000	-.1208 p = .010	-.7496 p = .000	1.000 p = .			
Albedo	.0917 p = .039	.2916 p = .000	-.5799 p = .000	-.1245 p = .008	.3806 p = .000	-.4008 p = .000	1.000 p = .		
Residual albedo	.0007 p = .494	.0913 p = .039	-.0091 p = .431	.0869 p = .047	.0203 p = .348	-.1392 p = .004	.2672 p = .000	1.000 p = .	
Snow water eq.	.1667 p = .001	-.0242 p = .321	-.1669 p = .001	.0235 p = .326	.1945 p = .000	-.3911 p = .000	.5950 p = .000	.0011 p = .492	1.000 p = .

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_i X_i + \epsilon \quad (1)$$

where X_i indicates the value of the ith independent variable, β_0 is a constant and ε is the error term. Independent variables are included stepwise in Eq. (1), the variable with the largest absolute correlation coefficient is included first. The partial correlations between the dependent variable (*i.e.* the albedo) and each of the independent variables not included in Eq. (1) after the previous step, are examined. The variable with the largest partial correlation is the next one to be included. Independent variables included in the regression analysis are the temperature index, wind, precipitation, melt water, relative humidity, solar radiation and snow water equivalent. The test hypothesis is based on the F-test with a 0.05 level of significance.

Linear regression is performed for three different periods, *i.e.* a winter period without melting (February 15-March 17), melting period 1 (March 30-April 11) and melt period 2 (April 16-May 1). Correlations are weak for the winter period, and no variables did meet the criteria given in the test hypothesis in this season.

In the melting periods, however, the correlation is strong, especially between the albedo and the accumulated daily maximum temperature index, T_{acc} (Table 3). For melt period 1, March 30-April 11, the linear model can be written as

$$\text{Albedo} = 0.90 - 9.21\times10^{-4}\, T_{acc} - 0.0042\, SR \quad (2)$$

where

T_{acc} – accumulated daily maximum temperature index (degree F)
SR – solar radiation (mW/cm^2)

The simplified linear model displays the improvement by including solar radiation, expressed by the increase of the R-squared value from 0.920 when T_{acc} was the only independent variable to 0.961 and by the decrease in the standard error from 0.059 to 0.043. This corresponds to an improved accuracy of 1.7 to 6.2 per cent in

Table 3 – Regression is determined by forward selection. Step numbers show in what order the variables were included in the regression model. Measurements are from melting period 1 (March 30-April 11) and melting period 2 (April 16-May 1).

Melt period	Step no.	Variable	R^2	Standard error	β_i	β_0
March 30 - April 11	1 2	Acc. temp. index Solar radiation	0.920 0.961	0.059 0.043	$-9.21 \cdot 10^{-4}$ -0.004158	0.901614
April 16 - May 1	1 2	Acc. temp. index Snow water eq.	0.972 0.983	0.029 0.023	$-5.96 \cdot 10^{-4}$ 0.001936	0.613400

estimated albedo, depending on the absolute level of albedo. Moreover, β_0 indicates that the upper level of the spectrally integrated snow albedo in the model is 0.90. This is consistent with Warren (1982). However, an obvious shortcoming of the linear model is the absence of a positive lower level of the albedo. A natural lower level would be the bare ground albedo. Thus, Eq. (2) is only valid within the measured range of T_{acc} (0 to about 700) and strictly but less determining, also within the range of solar radiation (0 to 85 mW/cm^2).

Regression for the second melt period, April 16-May 1, again with temperature and solar radiation as independent variables, showed

$$\text{Albedo} \equiv 0.93 - 8.26\times10^{-4}\, T_{acc} - 0.0024\, SR \tag{3}$$

which is close to the regression formula obtained for the previous melt period. The R-squared value was 0.95 and the standard error 0.047.

When solar radiation was replaced by snow water equivalent *(SWE)* as the second independent variable the regression formula applicable for the second melt period was

$$\text{Albedo} \equiv 0.61 - 5.96\times10^{-4}\, T_{acc} + 0.0019\, SWE \tag{4}$$

where

T_{acc} – accumulated daily maximum temperature index (degree *F*)
SWE – snow water equivalent (mm)

From Table 2 it is seen that there is a correlation (0.6) between albedo and snow water equivalent. Snow water equivalent has an initial value from which accumulated melt is subtracted. Since melt using a temperature index method can be related to air temperature or air temperature and solar radiation, *SWE* in Eq. (4) can be replaced by T_{acc} or by T_{acc} and *SR* which means that Eq. (4) degenerates to Eq. (3). The explained variance is hardly improved when all three variables T_{acc}, *SR* and *SWE* are included in the regression formula compared to when only T_{acc} and *SR* are included.

Conclusions

Snow albedo varies substantially during the winter due to snow metamorphosis. Snow depth, solar elevation and surface impurities affect the snow albedo as well.

The data from the Helligdagshaugen research site show an exponential decrease of albedo. This tendency is in effect until the snow depth becomes about 10 cm. Then, the solar radiation penetrates through the snow-cover and is absorbed at the ground.

The accumulated daily maximum temperature index (T_{acc}) is a good predictor of the long-term development of the snow albedo ($R^2 > 0.90$). However, albedo variations caused by variable meteorological conditions tend to scatter the actual daily and hourly snow albedo around the long-term trend of the albedo. From regression analysis it was found that solar radiation is the most important meteorological parameter to describe the short-term variability. The predicted snow albedo improves by 2-6 per cent when apart from accumulated temperature the solar radiation term is included in a linear regression formula. Very similar regression coefficients were obtained for an early and a late melt period. No correlations between albedo and meteorological variables were found for a non-melt period.

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