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Snow pillows: Use and verification

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Recent Advances and Developments

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Snow pillows: Use and verification

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ABSTRACT: Snowmelt yields a substantial contribution to spring floods in Norway. The most severe floods, such as in southeastern Norway in 1995, are fed from snowmelt over extensive snow-covered high-mountain areas. To monitor the temporal evolution of the snow mass during winter and spring, a network of 23 snow pressure pillows has been established in Norway, covering 58°N–71°N, 6°E–28°E, and 30–1400 m a.s.l. Hourly data are supplied twice daily to national authorities. To investigate the performance of the snow pillows, manual snow surveys, a snow accumulation-ablation model and nearby meteorological data were analysed for the 1998-99 winter and spring periods. The results suggest that snow pillows and the snow model represent the accumulation period well. During the melt period, both the snow pillows and the snow model produced data in agreement with manual surveys, but at a lower accuracy than observed during the accumulation period. Problems with ice/crust layers and internal forces were pronounced during freeze-melt cycles. Reduced performance was also observed when the amount of snow was either very high or very low, due to increased disturbance from wind, solar radiation, local topography and internal forces in the snowpack. Snow melt and refreezing were simulated fairly well, but factors not accounted for in the model reduced its accuracy during the melt period. The model could be used to identify periods when the snow pillow showed artefacts related to wind transport of snow and changes in internal forces caused by freeze-melt cycles.

1 INTRODUCTION

The environment in most Norwegian river-systems is strongly influenced by the snow conditions since snowmelt runoff often gives a substantial contribution to floods in many regions. Droughts and power production shortages are also possible results from extreme snow situations. Knowledge of the snow-conditions is also useful for hydropower companies, water suppliers and studies of climatic changes. Other areas of application of snow pillow data are snow avalanche forecasting and research.

NVE is responsible for national flood warning and runoff forecasting in Norway. To forecast the runoff, the HBV-model (Bergström 1976, Bergström 1992) is used. The model simulates snow accumulation from observed precipitation and temperature, and the melting by a degree-day method. This method has proved useful in runoff-simulations in Sweden (Lindström et al. 1996).

Observations of temperature and precipitation are limited, especially in mountainous areas. Furthermore, observed precipitation is usually less than true precipitation due to wind-effects (Førland et al. 1996). For this reason a network of 23 snow pillows (Sorteberg 1998) has been established to get more accurate information about the snow water equivalent (SWE).

Earlier studies show that snow pillows give an accurate point-estimate of the SWE (e.g., Beaumont 1965, Kerr 1976). Some problems with the technique have been reported (Tollan 1970, Tveit 1971, Andersen 1981), mostly related to ice and crust formation.

The objective of this work was to evaluate whether the new snow pillows are reliably measuring the SWE under different climatic conditions and locations, and to investigate whether a snow model could simulate the temporal variation in SWE at each pillow.

2 STUDY AREA AND DATA SETS

NVE has a regional network of snow pillows, in which 19 stations were operated during the 1998-99 winter. To determine the evolution and decay of SWE during the winter and spring, the stations are placed at elevations and locations in the country,

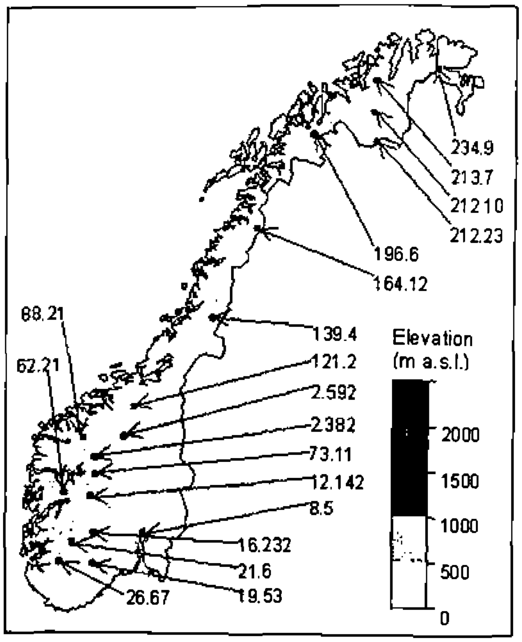

Figure 1. Snow pillows operated by NVE during the winter 1998-99. Three elevation intervals (<500, 500-1000 and >1000 m a.s.l.) are shown.

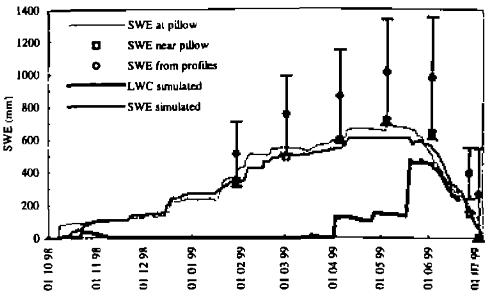

Figure 2. Sognefjellshytta. Observed SWE and simulated SWE and LWC. Standard deviation of SWE surveyed manually from profiles are shown with error bars. Note that LWC has been scaled by a factor of 10.

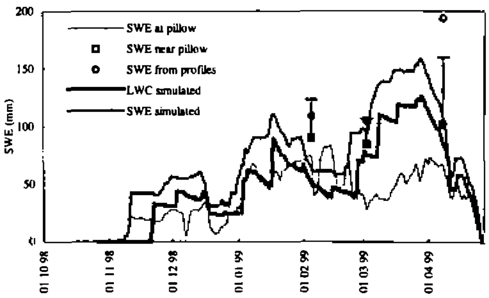

Figure 3. Fjalestad. Observed SWE and simulated SWE and LWC. Standard deviation of SWE surveyed manually from profiles are shown with error bars. Note that LWC has been scaled by a factor of 10.

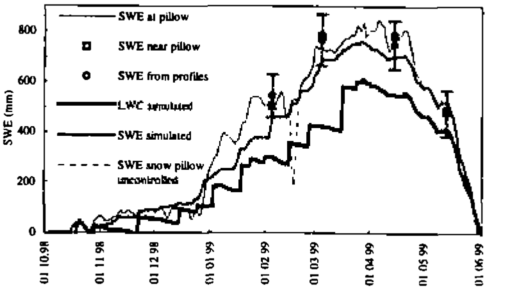

Figure 4. Duge Værstasjon. Observed SWE and simulated SWE and LWC. Standard deviation of SWE surveyed manually from profiles are shown with error bars. Note that LWC has been scaled by a factor of 10.

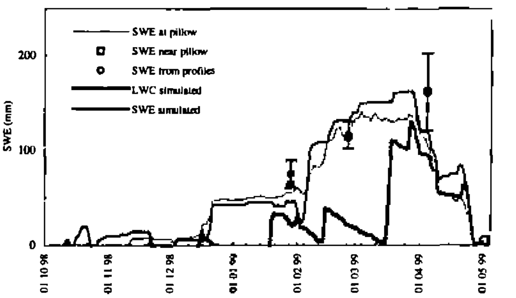

Figure 5. Maurhaugen-Oppdal. Observed SWE and simulated SWE and LWC. Standard deviation of SWE surveyed manually from profiles are shown with error bars. Note that LWC has been scaled by a factor of 10.

which are of interest to the national flood forecasting service. The stations are deployed between 58°N–71°N and 6°E–28°E, and cover the elevation interval 30–1400 m a.s.l. (Fig. 1).

The first snow pillow in Norway was deployed in 1967 at Kyrkjestølane, during the International Hydrological Decade (Andersen 1981, Furmyr & Tollan 1975, Tollan 1970, Tollan 1971). Subsequently, stations were installed at Groset in Telemark (1971) and Brunkollen in Bærum (1983), (Atterås 1991, Myrabø 1994). Additional 11 snow pillows were deployed in 1997 and 5 in 1998 (Tab. 1).

2.1 *Snow pillow observations*

The type of snow pillow operated by NVE is equipped with plastic bags filled with anti-freeze liquid. The new pillows have a diameter of 2 m and register the overburden pressure from the snow using a pressure sensor. The old pillows use a floating device and have a diameter of about 3.7 m (stations 8.5 and 16.232), see Sorteberg (1998, 1999) and Sundøen (1997). Snow pillow data are sampled every hour and automatically transferred to NVE twice a day.

2.2 *Meteorological observations*

Meteorological data from weather stations operated by the Norwegian Meteorological Institute (DNMI) are used for the snow simulations (Tab. 1).

During the winter 1998-99, temperatures were around 0°C at low elevations in parts of southeastern and western Norway. At high elevations of southeastern Norway snow condition were normal, with more snow than usual in the southwestern mountains. Troms, Nordland and Trøndelag had less snow than usual. Finnmark in northern Norway had a long and very cold period. For example, Karasjok observed a temperature of –51.2°C on 28 January (the minimum value for the period from 1888 to present is –51.4°C). In most parts of the country, a long and mild period occurred in April and gave an early start to the snowmelt. Due to the early start the snowmelt period was longer than normal, which reduced flood risk.

3 METHODS

3.1 *Snow measurement*

Manual snow surveys were conducted at each snow pillow site on a monthly basis from January 1999. The observations included:

- four snow depth samples around each pillow
- twenty snow depth samples along two crossing profiles of 50 m
- vertical snow density profile near the pillow
- vertical profile of snow moisture, stratigraphy and ice layers
- ground frost
- snow covered area

3.2 *Snow model*

The snow model simulated accumulation, using wind-catch and dislocation corrected precipitation observed at the nearest synoptic weather station. The model separated precipitation as snow from rain using observed air temperature. Snowmelt was modeled using a degree-day approach (Bergström 1976, Bergström 1992, Engeset & Schjødt-Osmo 1997), as data for the parameters required by energy-balance models were not available. Liquid water and refreezing were also simulated. The accumulation-ablation model used precipitation and air temperature as input variables. Internal variables were used for separating rain from snow using a fixed threshold, and fixed temperature-dependent thresholds were used to identify snowmelt and refreezing. Snowmelt intensity was specified by a time-varying variable, and refreezing intensity was fixed. The state variables described snow water equivalent and snow liquid water content, and were updated on a daily basis. The model also simulated water yield from snowmelt and rain. Studies have indicated that the model performance may improve by introducing other climatic parameters such as radiation (e.g., Kustas et al. 1994) and air humidity (Lindström et al. 1996).

4 RESULTS AND DISCUSSION

A total of 19 snow pillows were investigated. For a comprehensive project report see Engeset et al. (2000).

The results from five pillows are presented in Figures 2-6, which include snow pillow observations, manual snow surveys and results from modelling of snow accumulation, ablation and liquid water content. These graphs represent snow and climate variability at the investigated sites. Figures 2 and 4 represent areas with deep snow (maximum SWE higher than 500 mm) and Figures 3, 5 and 6 represent areas with shallow snow (maximum SWE less than 150 mm). Relatively stable below freezing conditions prevailed during the accumulation period at the pillows shown in Figure 2 (much snow) and Figure 6 (little snow), while a series of melt-refreeze cycles occurred at the pillows in Figure 3 (little snow) and Figure 4 (much snow). Figure 6 shows the effects of wind in the accumulation period and the effect of increased melt due to high solar energy input in the spring.

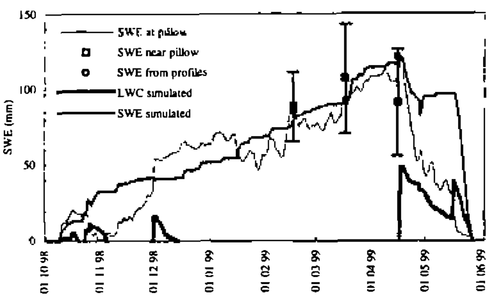

Figure 6. Siccajavre. Observed SWE and simulated SWE and LWC. Standard deviation of SWE surveyed manually from profiles, are shown with error bars. Note that LWC has been scaled by a factor of 10.

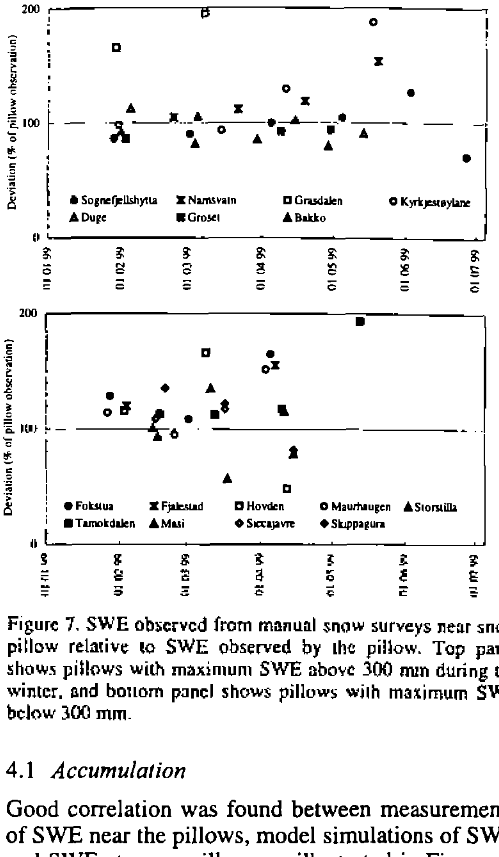

Figure 7. SWE observed from manual snow surveys near snow pillow relative to SWE observed by the pillow. Top panel shows pillows with maximum SWE above 300 mm during the winter, and bottom panel shows pillows with maximum SWE below 300 mm.

4.1 *Accumulation*

Good correlation was found between measurements of SWE near the pillows, model simulations of SWE and SWE at some pillows as illustrated in Figures 2 and 4. The relative deviations between SWE from manual snow surveys near pillows and SWE from pillows are presented in Figure 7.

In the beginning of the winter period the correlation between SWE observed near the pillow and by the pillow was good for most stations, especially in areas where few, if any changes in the air temperature around 0°C occurred, e.g., Sognefjelshytta, Maurhaugen-Oppdal and Tamokdalen (Fig. 7). Under such conditions, a relatively homogenous snow pack was developed, without ice- and crust-layers. The modelling also indicated good correlation with pillow values in under these conditions.

Observed ice- and crust layers did not always influence the registrations of snow accumulation at the pillows, e.g., Duge Værstasjon (Figs 4 and 7). At Duge, both modelling and the measurements agreed fairly well with the pillow observations.

Under some circumstances the values differs a lot between models, pillows and snow measurements. In areas with changes in the air temperature around 0°C, ice- and crust layers forms frequently, and density measurements were thus difficult to conduct. Also, at some stations snow depth and density to the ground were difficult to measure, since thick ice-layers existed (e.g., Hovden and Kyrkjestølane). Problems were also encountered during measurements as a result of ice- and crust layers. This measurement error is well known and several investigations and descriptions of the topic are recorded, e.g. Bader et al. (1954), Goodison et al. (1981), Ramsli (1981), Kuusisto (1984).

The manual surveys indicated that in areas with continually shifts in air temperature around 0°C, the freeze-melt cycles induced large changes in the snow pack. The snow pack was in periods wet and ice-/cruster layers were formed. At Fjalestad (Fig. 3), the snow cover was thin and the snow pack was influenced by temperature variations. Results from Fjalestad (Fig. 3), Hovden and Grasdalen indicated that large deviation between snow pillow and manual observations occurred under such condition (Fig. 7). The explanation could be that the water in the snow pack froze and ice-/crust layers were formed. These layers could influence the snow at the pillow by relief of the weight, like as a bridge. In such a case, the pillows will underestimate the real snow water equivalent. Earlier studies describe similar problems (Furmyr et al. 1975, Tollan 1970, Tollan 1971, Tveit 1971, Tveit 1975). A decrease in observed SWE was observed at several pillows at temperatures far below 0°C. This normally occurred when periods of snowmelt were succeeded by a cold period. An example of this is shown for Duge Værstasjon from 15 to 17 January 1999 (Fig. 4), where a reduction in SWE of 300 mm was observed. These artefacts were not simulated in the model.

Wind has been a climatic factor that influenced snow pillow values, in particular for pillows elevated above the ground (similar problems are described by Furmyr et al. 1975, Tollan 1970). Wind led to snowdrift and may have caused additional snow accumulation or removed snow from the pillow. It is not unlikely that snowdrift has caused sudden changes in addition to melting or precipitation. It was for instance registered a decrease of about 20 mm in SWE at Siccajavre between 15 and 16 January, which the model did not simulate (Fig. 6). Sudden increases were observed 1 December 1998 (20 mm) and 14 February 1999 (30 mm) probably due to accumulation by snowdrift. Strong wind was observed by the weather station in the area and the low temperatures suggest that the snow was dry. Differences in observations at pillows and model simulations are also caused by catch loss at the precipitation gauge. This is in particular pronounced during strong wind and snow precipitation, when gauge observations are known to underestimate the actual amount of precipitation (Furmyr & Tollan 1975, Killingtveit & Sælthun 1995, Førland & Harstveit 1996).

In some situations, rain has been interpreted as snow or vice versa in the model, mainly due to incorrect threshold temperature for snow-rain classification The threshold temperature is a constant value in the model but will in fact vary under different atmospheric conditions (Skaugen 1998). At Fjalestad, an overestimated accumulation in the beginning of the winter resulted in an overestimation of the simulated values the entire winter.

4.2 *Melting*

Only a few snow measurements were carried out during the melting period. Also the melt season is considerably shorter than the accumulation season. Earlier investigations indicated large changes in the snow during the melting period (Male & Gray 1981, Bengtsson 1982, Killingtveit & Sælthun 1995). Manual surveys at a higher temporal frequency are required for assessing the snow pillow and model performance properly. This is a very important period to monitor for flood forecasting.

Table 1. Snow pillow and weather station details.

NVE snow pillow (m a.s.l.)	Obs. period	DNMI weather station (m a.s.l.)	Distance pillow-weather station (km)
2 382 Sognefjellshytta 1435	1998-	55290 Sognefjell 1413	0
		15730 Bråtå 664	40
2 592 Fokstua 1000	1997-	16610 Fokstua 972	1
8 5 0 Brunkollen Klima 370	1983-	18960 Tryvasshøgda 528	10
12.142 Bakko 1020	1998-	25590 Geilo 810	20
16.232 14 Groset 990	1971-	31620 Møsstrand 977	10
19.53 Fjalestad 330	1998-	37230 Tveitsund 252	15
21.6 Hovden 855	1997-9	40880 Hovden 836	0
26 67 Duge Værstasjon 760	1997-	42920 Sirdal-Tjørhom 500	25
62.21 Reimegrend 595	1997-	51590 Voss 125	15
		51800 Mjølfjell 695	5
73.11 Kyrkjestølane 1000	1967-	54120 Lærdal 24	35
88 21 Grasdalen 935	1997-	60500 Tafjord 15	30
121.2 Maurhaugen-Oppdal 660	1998-	66770 Oppdal-Maurhaug. 668	0
139 4 Namsvatn tunnel Vekteren 460	1997-	77420 Majavatn 339	30
		77750 Susendal 265	65
		77550 Fiplingvatn 370	40
164.12 Storstilla nf Balvatn 565	1997-	81680 Saltdal 81	30
196.6 Tamokdalen 230	1997-	91300 Oteren 12	20
		89350 Bardufoss 76	45
212.10 Masi 272	1997-	93300 Solovomi 374	20
212.23 Siccajavre 385	1997-	93900 Siccajavre 382	0
213 7 Øvre Leirbotn 190	1998-	93140 Alta lufthavn 3	20
234.9 Skippagura 35	1997-	96800 Rustefjelbma 9	30

In general, snow surveys observed higher SWE values than recorded by the pillows. Relative deviation is large by several of the pillows during the melting period compared to the winter period (see Fig. 7). During the melting, density measurements at some stations were taken in very wet snow, under circumstances that probably were unrepresentative for the snow wetness and density at the pillow. This could apply to all sites, and in particular uncertain results were recorded at Hovden and Kyrkjestølane.

In general, the model results show good correlation with the pillow observations (e.g., Figs 4 and 6). Nevertheless, at some stations, the models show too little or a slower melting compared to the pillow. Observed melting may be more rapid than that simulated, due to high solar radiation not readily described in a degree-day model. Including a radiation component may in these cases improve the model performance (Bengtsson 1976, Kustas et al. 1994). Under conditions with high insolation and old snow with a low albedo, high melt intensity is expected (Male & Gray 1981, Ramsli 1981) and such effects are not simulated well in the degree-day model, as it simulates snow melt as a function of temperature only. This effect is probably highest at pillows at high elevations and in northern Norway. In these areas melting commences relatively late and high insolation values are experienced on clear days. This effect was seen at Bakko, Groset, Kyrkjestølane, Masi, Siccajavre, Øvre Leirbotn and Skippagurra. The pillow values at Hovden and Grasdalen show slow melting, and the snow measurements and model results correlate poorly with pillow observations. The reason for the late melt could be a thick ice layer covering the pillows.

4.3 *Liquid water content and refreezing*

Simulations of liquid water in the snow pack were in agreement with the qualitative manual observations at several snow pillows, see for example Sognefjellshytta (Fig. 2) and Fokstua.

Occasionally, liquid water was simulates when observations showed that the snow was dry. An incorrect temperature elevation-correction could explain this, e.g. see Grasdalen (Fig. 5), Namsvatn tunnel Vekteren and Maurhaugen-Oppdal (Fig. 6).

In areas with great variations in the temperature, liquid water was observed to decrease slowly by during periods when the temperature fell. This was seen at Fjalestad (Fig. 3), Hovden and Reimegrend. The refreezing appears to have been underestimated in the model. However, no quantitative observations were available for a detailed analysis of the model's performance in terms of liquid water simulations.

5 ASSESSMENT OF SNOW PILLOWS

The manual snow surveys indicated no malfunctions at the snow pillows when the snow was dry and there were no icing and crusting. Icing and crusting lead as expected to problems at some of the snow pillows. These problems were particularly pronounced at temperatures fluctuating around 0°C when subsequent freeze-melt cycles occurred. The snow model was useful to detect these sorts of problems and it seemed clear that temperature measurements are required to assess the quality of the snow pillow observations, e.g., Duge (Fig. 4).

When the snow was wet during the melt period, large differences were seen between the manual measurements and the snow pillow observations. This indicated that the snow density or depth varied in the area around the pillow. The spatial variability of the snow density was not measured, but this will be of high priority in the following studies of the snow pillows. At most of the snow pillows, the manual snow surveys indicated that the snow pillows were representative for the nearby area in the accumulation period and less representative in the melting period, e.g., Maurhaugen-Oppdal (Fig. 5). These problems could in many cases be related to the local topography. Local variations in solar exposition would give similar variations in melt intensity. At pillows with small amounts of snow, high relative difference between measurements and pillow values were identified during the winter season (Fig. 7). Thus the pillows give an uncertain point estimate of the snow amount under such conditions.

The average SWE from snow surveys along the profiles correlated well with SWE measured manually near the pillow. However, great differences were observed at some places, e.g., Sognefjellshytta (Fig. 2). To achieve good drainage this pillow was situated too high and did obviously not represent the amount of snow in the nearby area. Another pillow, Hovden, was situated too low compared to the surrounding ground, which reduced drainage from the pillow during the most intense melting.

Wind-drift seemed to be a problem at some of the pillows, e.g., Siccajavre (Fig. 6). At this pillow, and other pillows situated in dry areas, the wind drift at occasions gave relatively large fluctuation in the observed data during the accumulation period when the snow was dry. Although relevant, redistribution of snow under different wind-speeds and directions were not assessed during this project.

Other problems concerning the reliability of the snow pillows were human activity and extreme high amounts of snow (e.g., Grasdalen).

6 CONCLUSIONS

Daily observations of the evolution and decay of the snow cover, observed as the snow water equivalent by 19 snow pillows, have been assessed using manual snow surveys on a monthly basis and daily simulations from a snow model. The results suggest that both snow pillows and the snow model represent the accumulation well. During the melt period, both the snow pillows and the snow model produced data in agreement with manual surveys, but at a lower accuracy than observed during the accumulation period. However, the changes in SWE during the melt period occurred during a rather short timespan, and manual snow samples should be performed more frequently and from more points in the vicinity of the pillows to better assess the performance during the spring. In areas where the air temperature was frequently oscillating around 0°C, problems with ice- and crust layers within the snow pack were evident and thus the pillows underestimated the SWE at certain periods. Furthermore, pillow reliability was reduced when the amount of snow was either very high or very low, due to increased disturbances from wind, solar insulation, local topography and internal forces in the snowpack.

The snow model proved to model accumulation very well. Snow melt and refreezing were also simulated well, but the results suggest that factors not accounted for in the model reduced the accuracy of the model results during the melt period. The model could be used to identify periods when the snow pillow results showed artefacts related to such effects as wind transport of snow and changes in internal forces caused by freeze-melt cycles.

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