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SNOW EVAPORATION IN SOUTH AND NORTH FINLAND, 1969/70 AND 1970/71

Pentti Kaitera and Heikki Teräsvirta

Despite its obvious effect on the hydrological water balance, evaporation from the snow surface has seldom been studied. Kaitera (1939) and Niinivaara (1953) have presented rough estimates of this evaporation in Finland. Kaitera measured diurnal evaporation in late winter, using pans. Niinivaara calculated total evaporation for entire winters, November to April inclusive, from the water balance. According to Niinivaara, evaporation during his extended winter season came to as much as a third of the whole year's. This was a far higher figure than those obtained by Kaitera and others, but during Niinivaara's season there were many days with no snow cover at all. According to Hutchison (1966), evaporation from »bare» soil is over four times that from a snow surface under otherwise similar conditions.

In the winter seasons of 1969/70 and 1970/71 we measured snow evaporation at two localities — Otaniemi near Helsinki, in South Finland, and Sodankylä in North Finland. For this we used evaporation pans. As such measurements had previously been performed in Finland only by Kaitera (1939) and Lemmelä (1970), the method will be described in detail.

In discussing the results, we shall concentrate mainly on the dependence of snow evaporation on meteorological factors. The total evaporation during the two winters will also be estimated. Two seasons' observations may give some idea of the amount of water lost from the snow by evaporation.

These measurements were being continued in winter 1971/72.

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1. Factors Affecting Snow Evaporation

The same factors as cause evaporation from water surfaces also affect evaporation from snow. Considerable study has been made of evaporation from water surfaces, both theoretical and experimental. The relative part played by the various factors, however, is not easy to analyze because many of them are mutually correlated. The most important of these factors are:

— the difference between the water-vapour pressure of the evaporating surface and the air

— air temperature and humidity

— wind strength

— air pressure

— radiation energy.

The maximum temperature of snow is zero. Consequently the same equations cannot be used, as such, to calculate evaporation from a snow surface as from a water surface, even if the contributing factors are the same.

The difference between the water-vapour pressure of the evaporating surface and the air, $e_w—e_a$, affects evaporation as follows: evaporation occurs when $e_w—e_a > 0$, and increases as the difference grows; when $e_w—e_a < 0$, condensation occurs and increases as e_a grows higher than e_w. At zero, the maximum temperature of snow, the water-vapour pressure e_s is 6.11 mb. So it might seem that there can be no evaporation from a snow surface if the mean air temperature above the snow is higher than zero because, in this case, $e_s—e_a < 0$. This sometimes occurs during persistent thaw in late winter, in which case there is condensation instead of evaporation. On the other hand, before the thaw gets under way, the water-vapour pressure difference $e_s—e_a$ may be fairly high while radiation is warming the snow surface but the dewpoint is below zero. It can further be assumed that in midwinter, when total radiation in Finland is low and the ratio of reflected to total radiation is high, $e_s—e_a$ is approximately zero, so not much evaporation can occur.

Linsley, Kohler & Paulhus (1949) and Konstantinov (1966), among others, have demonstrated the decisive effect of wind on the exchange of humidity between the snow surface and the air, but these results are not analyzed in this study.

2. Earlier Studies

Apart from the results of this study, evaporation from snow surfaces in Finland has been measured by Kaitera (1939) and Lemmelä (1970). Both of them used evaporation pans for their measurements.

Kaitera made his measurements in the Ilmala Observatory area in Helsinki in the late winters of 1937 and 1938. The observation points numbered 12 and the measurements were made daily between 07^{00} h and 09^{00} h. He found that evaporation began to decrease when the temperature rose above zero. The reason for this, he concluded, was that the dewpoint rose above zero in the warmer air, so condensation on the snow surface occurred in addition to evaporation from it. Table 1 gives his results, distributed according to mean diurnal temperatures:

Table 1. Group averages of diurnal temperature t, saturation deficit d and evaporation E, after Kaitera. n = number of observations.

Group	n	t [°C]	d [mm]	E [mm/vrk.]
1	43	—2.6	0.7	0.64 ± 0.08
2	64	1.4	1.0	0.26 ± 0.05
3	53	4.3	1.2	0.05 ± 0.04

Kaitera's measurements also clearly showed that wind increases evaporation; evaporation was greater in windy places than in sheltered ones.

Lemmelä (1970) performed his measurements at Hyrylä (20 km north of Helsinki) in the late winters of 1968 and 1969. He weighed his pans daily at 08^{00} h and 19^{00} h. Between 13th March and 12th April 1969 he measured a total net evaporation of 9.4 mm, which was 6 % of the maximum measured water content of the snow. During the persistent thaw between 3rd and 12th April, the evaporation was 3.1 mm — a reduction of only 2 % of the water content of the snow at the time.

3. Methods

The measurements of snow evaporation reported here were made at Otaniemi and Sodankylä in 1969/70 and 1970/71. Two kinds of evaporation pans were used:

1. Most of the measurements were made in unpainted aluminium pans of a model commonly used in the Soviet Union (Hooli 1969) and specially designed to facilitate sample-taking. They were 1000 cm^2 in area, 10 cm deep and about 1600 g in weight.
2. In addition to the aluminium pans, we used pans made of white plastic with an area of 500 cm^2, 10 cm deep and weighing about 1200 g.

»Facilitating sample-taking» means that every effort was made to ensure that the samples would resemble snow in the natural state. When a pan filled up with snow, it was weighed and placed in a dip made in the snow cover, so that the snow surface of the sample was level with that of the natural snow. Evaporation and condensation were measured at fixed intervals. In midwinter the samples were renewed 1…3 times a week, depending on the amount of snowfall and drift. In late winter, when temperatures were higher, they had to be renewed daily because melted snow accumulated at the bottom of the pans.

At Otaniemi the measurements were performed daily at 08oo and 20oo h, and also at 14oo h in late winter. At Sodankylä they were made only at 08oo h until 15th February, at 08oo and 20oo h thereafter, and later also at 14oo h.

The samples were weighed on scales with an accuracy of 1 g. This corresponds to an accuracy of 0.02 mm of water in the 500 cm^2 pans, and of 0.01 mm in the 1000 cm^2 pans.

At Otaniemi (60°11' N, 24°49' E, H_s = 1.5 m), the observations were made in a Water Resource Laboratory test field of the Helsinki University of Technology — a level, fenced-in but otherwise open area of 70 × 50 m^2. The area was unsheltered from the wind and fully exposed to radiation.

At Sodankylä (67°22' N, 26°39' E, H_s = 240 m) the measurements were performed in the Observatory area of the Finnish Meteorological Office, on two types of terrain: in the open, and in the forest. The pans in the open were located to receive the full effect of the wind and radiation. The others were placed in a sparsish pine forest containing both fully-grown pines and seedlings.

In addition to evaporation, the following were measured at both places:

- — air temperature and humidity
- — precipitation
- — total radiation
- — temperature of the snow at a depth of 2 cm
- — wind speed 50 cm above the snow surface.

4. Results

Though measurements were made daily, those in which snowfall or high wind affected the pans have been omitted from the analysis. This has meant rejecting a little over half of the observations.

Table 2 shows the measured evaporation in monthly averages. In December to February there was more condensation than evaporation in both localities. Condensation in December averaged 0.10 mm a day — the highest monthly value observed. Condensation in January and February was 0.05…0.07 mm a day, with no notable difference between Otaniemi and Sodankylä. Similarly, condensation was roughly the same by day and night: 0.02…0.05 mm per 12 hours. In March, evaporation exceeded condensation at all the measurement points because daytime evaporation was higher than nighttime condensation. In April and May evaporation came to 0.22…0.71 mm a day, with considerable local variation. This notably reduced the water content of the snow. The nighttime evaporation was far lower than the daytime.

Table 2. Monthly evaporation (+) and condensation (—) averages in mm, at Otaniemi and Sodankylä by day (08oo—20oo h) and night (20oo—08oo h), and diurnally (08oo—08oo h).

Time and place	Dec	Jan			Feb			Mar			Apr			May		
	8—8	8—20	20—8	8—8	8—20	20—8	8—8	8—20	20—8	8—8	8—20	20—8	8—8	8—20	20—8	8—8
69/70																
Otaniemi		—0.02	—0.03	—0.05	—0.03	—0.05	—0.07	0.21	—0.03	0.17	0.35	0.04	0.53			
Sodankylä, open				—0.05	—0.04	—0.04	—0.07	0.06	—0.03	0.08	0.36	0.02	0.27	0.31	0.09	0.48
Sodankylä, forest				—0.05	—0.04	—0.03	—0.06	0.01	—0.03	0.03	0.25	—0.02	0.22	0.30	0.05	0.38
70/71																
Otaniemi								0.16	—0.02	0.14						
Sodankylä, open	—0.10			—0.05	—0.02	—0.02	—0.05	0.06	—0.04	0.02	0.49	0.02	0.51	0.54	0.10	0.71
Sodankylä, forest	—0.10			—0.06	—0.03	—0.02	—0.05	0.04	—0.04	0	0.34	0.01	0.35	0.41	0.05	0.54

The evaporation in March and April was considerably greater at Otaniemi than at Sodankylä. In May, when all the snow had melted in South Finland, the evaporation at Sodankylä was roughly the same as it had been at Otaniemi in April.

Total Evaporation in Winters 1969/70 and 1970/71

Owing to snowfall and drifts it was nowhere near possible to measure evaporation every day, so monthly evaporation from the snow surface has had to be calculated from diurnal averages (Table 3):

The total evaporation quantities in Table 3 are quite small compared to the average annual maxima of water content in the snow, which are 100···115 mm in the Helsinki area (Otaniemi lies lies 7 km west of Helsinki) and 150···180 mm at the Sodankylä Observatory. The total evaporation measured at Otaniemi in winter 1969/70 came to 9···10 % of the maximum water content for the year; at Sodankylä it amounted to 8···10 % in the open and 7···9 % in the forest. The corresponding percentages in winter 1970/71 were 9···11 % in the open and 8···10 % in the forest at Sodankylä (these percentages include the observations for December, which were missing from the 1969/70 figures; poor conditions impeded measurements near Helsinki). Winter 1969/70 was quite near the normal as regards snow-cover times and temperatures at both Otaniemi and Sodankylä. Winter 1970/71 was exceptionally warm in South Finland, so there was less snow there than usual; at Sodankylä the snow-cover times during that winter were normal — i.e. the permanent snow cover began in November and melted in the forest by about 25th May.

Table 3. Total evaporation per month in mm, calculated from diurnal averages.

	Dec	Jan	Feb	Mar	Apr	May	Total
1969/71							
Otaniemi							
1. 1. ··· 15. 4.		—1.55	—1.96	5.58	7.95		10.0
Sodankylä, open							
1. 1. ··· 15. 5.		—1.55	—1.96	2.48	8.37	7.20	14.5
Sodankylä, forest							
1. 1. ··· 23. 5.		—1.55	—1.68	0.93	6.60	8.74	13.0
1970/71							
Otaniemi							
1. 3. ··· 31. 3.				4.34			
Sodankylä, open							
1. 12. ··· 10. 5.	—3.10	—1.55	—1.40	0.62	15.30	7.10	17.0
Sodankylä, forest							
1. 12. ··· 20. 5.	—3.10	—1.86	—1.40	0	10.50	10.80	14.9

Observed Maxima

The highest condensation and evaporation quantities observed are given in Table 4. Evaporation was far greater than condensation. The maxima were not reached in the coldest months of the two winters, evidently because the water-vapour pressure differences between the snow and air were small.

Differences in Evaporation in the Open and in the Forest

At Sodankylä, evaporation was measured in both an open place and in the forest. In midwinter, when condensation exceeded evaporation, there were no notable differences between the two. In late winter, evaporation was clearly greater in the open than in the forest,

Table 4. Maximum measured condensation and evaporation quantities in mm.

	08oo—20oo	Date	20oo—08oo	Date	08oo—08oo	Date
condensation						
Otaniemi	—0.15	19. 2. -71 26. 3. -71	—0.14	11. 3. -71	—0.26	19. 2. -71
Sodankylä, open	—0.14	13. 3. -70	—0.09	24. 3. -71	—0.35	27. 12. -70
Sodankylä, forest	—0.13	13. 3. -70	—0.14	12. 3. -70	—0.35	27. 12. -70
evaporation						
Otaniemi	0.83	14. 4. -70	0.14	5. 3. -71	0.85	14. 4. -70
Sodankylä, open	0.99	7. 4. -71	0.33	9. 4. -70	1.20	13. 5. -70
Sodankylä, forest	0.85	7. 5. -71	0.28	9. 4. -70	0.95	7. 5. -71

Table 5. Measured evaporation and condensation in mm, in the open and in the forest at Sodankylä.

time	08oo—20oo			20oo—08oo		
	open	forest	f/o	open	forest	f/o
1969/70						
evaporation	8.49	5.33	0.6	1.45	0.72	0.5
condensation	—0.32	—0.36	1.1	—0.60	—0.81	1.35
1970/71						
evaporation	14.51	10.76	0.7	1.36	0.84	0.6
condensation	—0.13	—0.15	1.2	—0.99	—1.08	1.1

while condensation was greater in the forest than in the open. Table 5 shows the calculated total evaporation and condensation in the open and forest. In both years the evaporation in the forest came to 50···70 % of that in the open, the corresponding figures for condensation being 110···135 %.

Dependence of Snow Evaporation of Meteorological Factors

Kaitera (1939) studied correlations between snow evaporation and air temperature by grouping his observations according to diurnal mean temperatures — see Table 1. We have grouped our observations for winters 1969/70 and 1970/71 in a similar way — see Table 6:

Table 6. Evaporation E observed in the daytime (08oo—20oo h) at Otaniemi and Sodankylä, grouped according to diurnal mean temperatures t. n = number of observations.

t [°C]	1969/70		1970/71	
	n	E [mm]	n	E [mm]
$\leq$ —10	26	—0.02	22	0.07
—9.9 ··· —5.0	12	0.05	12	0.16
—4.9 ··· 0.0	28	0.30	15	0.47
0.1 ··· 5.0	11	0.36	14	0.39
$>$ 5.0	8	0.10	3	0.17

Table 6 differs from Kaitera's in that it includes observations made on cold days in midwinter, when evaporation was slight owing to the low amount of energy available for it. Evaporation was highest when the temperature was around zero. It diminished again when the temperature rose above 5°C, because then the dewpoint rose to zero or above.

The quantity of evaporation depends on the difference between the water-vapour pressure prevailing just below the snow surface and in the air above it. This difference, e_s—e_a, has been calculated for our observations separately for 08oo—20oo h and 20oo—08oo h. e_s was calculated from the temperature of the snow at a depth of 2 cm and e_a from the dewpoint 2 m above the ground. Fig. 1 shows evaporation measurements from Otaniemi as a function of e_s—e_a; evaporation increased as the difference grew — as could be expected. The same trend can be seen in the nighttime observations, though evaporation was much smaller then. The points on the graph are widely scattered, probably due to contributory factors such as temperature, wind and radiation, whose effect could not always be determined.

To bring out the effect of differences in water-vapour pressure more clearly, Figs. 2 and 3 depict evaporation as a

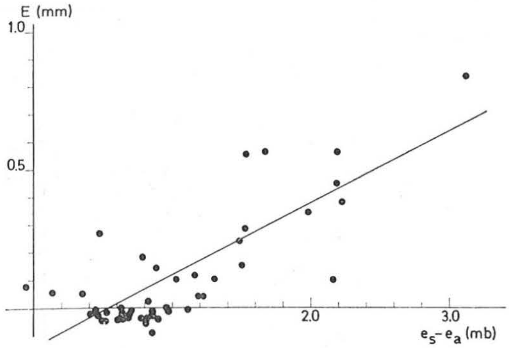

Fig. 1. Evaporation E (08$_{00}$—20$_{00}$) at Otaniemi as a function of the difference between the water-vapour pressure prevailing just below the snow surface and in the air above it (e_s-e_a) in winter 1969/70.

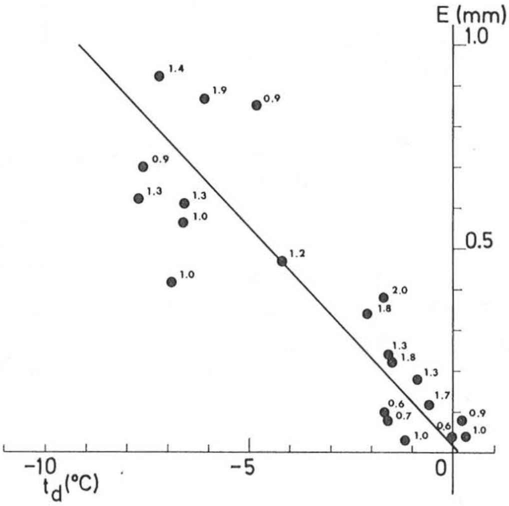

Fig. 2. Evaporation E (08$_{00}$—20$_{00}$) as a function of dewpoint t_d at Sodankylä (open) in winters 1969/70 and 1970/71. Wind speed (m/s) half a metre above the snow surface has been shown against the evaporation points.

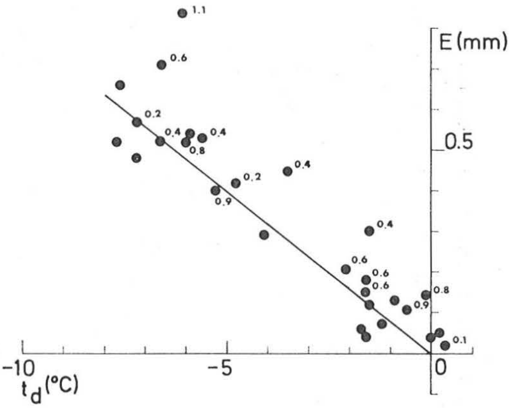

Fig. 3. Evaporation E (08$_{00}$—20$_{00}$) as a function of dewpoint t_d at Sodankylä (forest) in winters 1969/70 and 1970/71. Wind speed (m/s) half a metre above the snow surface has been shown against the evaporation points.

function of dewpoint on days on which the average temperature of the snow was —1.0···0.0°C, so that the water-vapour pressures were 5.63···6.11 mb. Such high snow temperatures occurred only in late winter, when the snow was beginning to melt. Fig. 2 gives the evaporation at Sodankylä in the open, Fig. 3 in the forest — between 08$_{00}$ h and 20$_{00}$ h in both cases. The correlation between evaporation and dewpoint is quite clear. Evaporation increases as dewpoint and water-vapour pressure decrease. The graphs also show how much greater evaporation was in the open than in the forest. Wind speed half a metre above the snow surface has been shown against the evaporation points in Fig. 2. and 3. It is clear from Figs. 2 and 3 that, during the thaw, evaporation from a snow surface can be estimated with remarkable accuracy provided the dewpoint is known.

From 08$_{00}$ h on 6th April to 24$_{00}$ h on 7th April, evaporation was measured every second hour at Otaniemi except during the night of 6th/7th, when no observations were made between 24$_{00}$ h and 08$_{00}$ h. Evaporation was quite strong on these two days; the wind was high and radiation, too, was strong for the time of the year: it totalled 363 cal/cm^2 between 08$_{00}$ and 20$_{00}$ h on 6th April. The evaporation was measured with two pans, taking the averages between them.

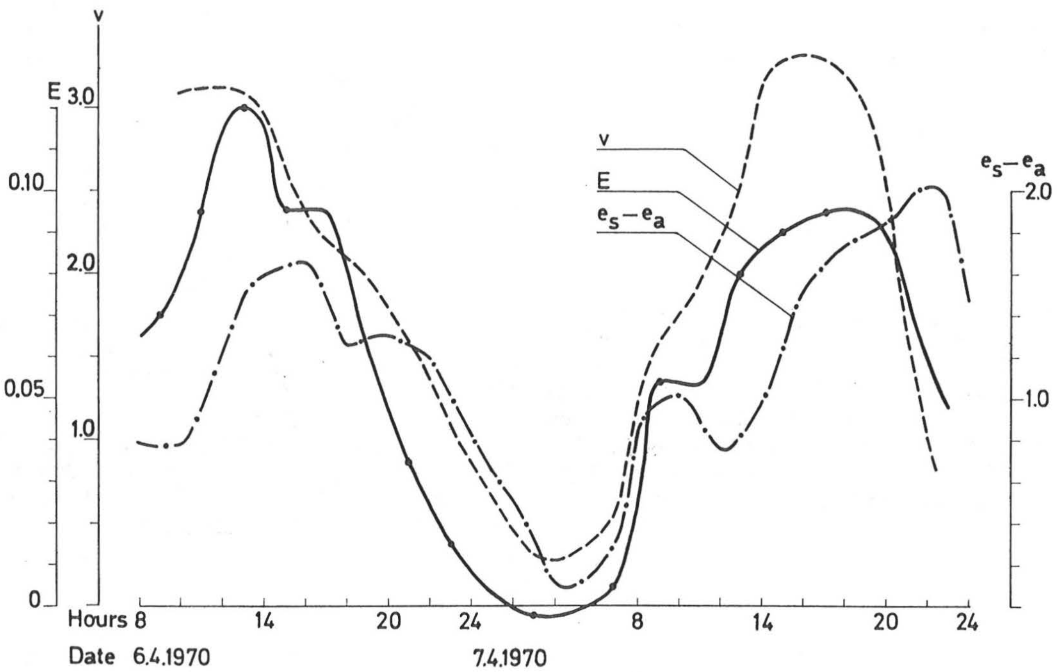

Fig. 4. The evaporation E (mm/2 h), water lapour difference e_s—e_a (mb) and wind speed v (m/s) at Otaniemi from 08oo h on 6th April to 24oo h on 7th April.

The evaporation, water-vapour pressure difference e_s—e_a and wind speed v are depicted in Fig. 4. The effect of the latter two factors on evaporation is clear: the wind-speed and evaporation peaks coincide. During the night of 6th/7th April, e_s—e_a and v were almost down to zero, and simultaneously there was condensation. The tail end of the curves, after 20oo h on 7th April, is interesting; the water-vapour pressure difference grew but evaporation decreased. The probable reason was a simultaneous drop in the wind speed.

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Tiivistelmä

Lumen pinnasta tapahtuva haihdunta on vähän tutkittu ilmiö, vaikka sillä on ilmeistä merkitystä hydrologiseen vesibilanssiin. Tämä seikka on johtanut tutkimuksen syntyyn. Talvikausina 1969/70 ja 1970/71 tehtiin tätä työtä varten lumen haihdunnan mittauksia kahdella paikkakunnalla, nimittäin Otaniemessä ja Sodankylässä. Mittaukset suoritettiin haihdunta-asioilla, joiden pinta-alat olivat tyypistä riippuen 1000 cm^2 tai 500 cm^2. Haihdunta (tai tiivistyntä) havaittiin punnitsemalla astioihin sijoitettu mahdollisimman häiriintymätön luminäyte päivittäin klo 8 ja 20 sekä kevättalvella myös klo 14. Samalla suoritettiin tarpeelliset meteorologiset havainnot. Otaniemessä tehtiin mittaukset TKK:n vesitalouden laboratorion koekentällä, joka sijaitsee laajalla aukiolla. Sodankylässä tehtiin mittaukset Ilmatieteen laitoksen observatorion alueella sekä aukealla että metsämaastossa.

Mitatut talvikausien kokonaishaihdunnat olivat molemmilla paikkakunnilla n. 10 % lumen vesiarvon vuosimaksimista, joka on Helsingin seuduilla n. 100···115 mm ja Sodankylän observatoriolla n. 150 ···180 mm. Talvikautena 1969/70 oli kokonaishaihdunta Otaniemessä 10,1 mm, Sodankylässä aukealla 14,5 mm ja metsässä 13,0 mm. Talvikautena 1970/71 mitattiin Sodankylässä aukealla 17,0 mm:n ja metsässä 14,9 mm:n kokonaishaihdunnat (taulukko 3.). Suurin havaittu vuorokausihaihdunta oli 1,20 mm ja suurin vuorokausitiivistyntä —0,35 mm (taulukko 4.). Metsässä haihtui keskimäärin n. 50···70 % vastaavasta aukean haihdunnasta.

Haihdunnan suuruus riippui lumen pinnan ja yläpuolisen ilman välisestä vesihöyrynpaine-erosta siten, että mitä suurempi ero oli, sitä enemmän haihtui. Suurimmat haihdunnat mitattiin kevättalvella silloin, kun lumen lämpötila oli nollan vaiheilla, mutta ilman kastepistelämpötila huomattavasti sen alle. Sen sijaan tehokkaan sulamisen aikana, jolloin ilman kastepistelämpötila oli lähellä nollaa, oli haihdunta vähäistä (kuvat 2. ja 3.). Mittauksilla todettiin myös, että joulu—helmikuussa lumen pintaan tiivistyi enemmän vesihöyryä kuin mitä siitä haihtui, mutta tiivistyntä oli pientä, vain n. —0,05···—0,10 mm/vrk. Höyrynpaine-eron lisäksi todettiin, että tuulen nopeuden kasvu lisäsi haihduntaa.