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ITEM: 4

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CONVERSION OF SNOWFALL DEPTHS TO WATER EQUIVALENTS IN THE SWISS ALPS

(Submitted by Boris Sevruk)

Summary and purpose of document

This document provides a paper published in Zürcher Geographische Schriften, ETH Zürich, which presents an analysis carried out at the a number of sites in the Swiss Alps and investigates the relationship between the depth of fresh snowfall and its water equivalent.

ACTION PROPOSED

The Meeting is invited to take this information into consideration for the analysis of the SPICE data, as appropriate.

Appendix: B. Sevruk: Conversion of Snowfall Depths to Water Equivalents in the Swiss Alps, Zürcher Geographische Schriften, ETH Zürich, 1986, No. 23, 13-23,

Workshop on the Correction of
Precipitation Measurements
1 - 3 April 1985 Zurich
ZÜRCHER GEOGRAPHISCHE
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No 23, 13-23, 1986
(see WMO/TD-No. 104, 1985)

CONVERSION OF SNOWFALL DEPTHS TO WATER EQUIVALENTS IN THE SWISS ALPS

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1. Introduction

Principal instruments used to measure the snowfall are snow samplers and precipitation gauges (WMO 1981). Both instruments are subject to systematic errors which average 4 to 17% for the former and even -15 to -50% for the latter (Sevruk 1982). However, the water content of snowfall (hereafter snowfall) can also be estimated from the measured depth of fresh snow and the estimated snowfall density. The long-term average of the latter is assumed to be 0.1 (10^3 kgm^{-3}) but for a single measurement it may vary from 0.03 to 0.25 (WMO 1981), due to the variability of meteorological conditions during the snowfall.

The unit value of snowfall density of 0.1 the so-called "general rule", is used in many hydrological computations. The error of an individual snowfall estimate is assumed to compensate for the long-term average due to the positive and negative deviations from the general rule. This can be true in cases, when the snowfall density does not show seasonal, regional and local pattern, in particular the effect of temperature and site exposure. Under such conditions and in spite of large losses of conventional precipitation measurements due to wind, the estimated long-term averages of snowfall, based on the general rule, can be more accurate than the snowfall data from the notoriously unreliable precipitation gauges. Moreover, the snowfall estimates could be used to correct the measured snowfall data from precipitation gauges. The additional data needed for such a correction procedure, i.e. the daily measurements of the depth of fresh snow, are available in many meteorological stations.

The present paper focusses mainly on the methodology of correction of snowfall data using the general rule. For this aim, the snowfall density data have been analysed.

- for the seasonal and regional pattern
- for the effects of the altitude and site exposure
- for the effects of temperature and
- wind speed.

Furthermore, the snowfall density values as measured using snow samplers and precipitation gauges have been compared. The error of the Hellmann precipitation gauges due to wind field deformation has been assessed and the correction factor estimated.

2. Data

The effects of season, region altitude and site exposure have been investigated using 5-year data from 41 Swiss locations. These data have been obtained from the daily measurements of snowfall density using the Swiss snow sampler (Ø 70cm^2).

The locations are situated in each of seven Swiss Alpine climatical regions at altitudes from 1100 to 2270 m a.s.l. They are listed in Table 1. The average altitude of all locations is 1550m a.s.l. Five degrees of site exposure have been used to classify the locations as shown in Tab.1.

The time period was from November to April 1973/74 - 1977/78. The data package consisted of 3635 daily values of snowfall density. Only days with snowfall depth larger than 10cm were considered. These data have been taken from the Year-books of the Federal Institute for Snow and Avalanche Research at Weissfluhjoch/Davos.The situation of the 41 locations and the above mentioned seven climatical regions can be also found in the same Year-books.

The effect of temperature has been investigated using two sources of data; (i)the data as extracted from the previous studies and (ii)as measured at present in the Swiss Alps. These data are described in Table 2. They have been acquired in two different ways ; (i)from the standard Hellmann precipitation gauges elevated 1.5 - 2 m above ground and the parallel measurements of snowfall depth, and (ii)from the results of snow sampling as mentioned above (Tab. 2)

The comparison of the results of these two measurement techniques has been made for seven locations. In each case the snow sampling site was situated at a distance of 100 - 600 m from the precipitation gauge site. The daily precipitation, depth of fresh snow and temperature data have been taken from the data bank of the Swiss Meteorological Institute.

3. Methods and Definitions

The following values of snowfall density have been computed for the 41 Swiss locations (Tab. 1) and the period from November to April 1973/74 - 1977/78:

(i) Average of all locations situated in a particular climatical region

Table 1

Mean monthly and seasonal values of snowfall density for 41 Swiss Alpine locations (1100 - 2270 m a.s.l.)

November - April 1973/4 - 1977/8.

Legend:

1 Waadtländer and Berner Alpen
2 Gothard - Nord
3 Glarner Alpen and Alpstein
4 Walliser Alpen
5 Nord and Mittelbünden
6 Gothard - Süd
7 Graubünden - Süd

* very exposed site
** exposed site
*** open site
**** sheltered site
***** completely sheltered site
( ) small number of days (≤3)

Depth of fresh snow is larger than 10 cm.

No.	Location	Altitude [m a.s.l.]	Region	Exposure	Number of days Nov.	Dec.	Jan.	Febr.	March	April	Σ	Average density of snowfall [kg·m⁻³] Nov.	Dec.	Jan.	Febr.	March	April	Average	Ratio Max. Min.
1	Corvatsch	2270	7	***	5	3	14	10	15	14	61	146	122	115	96	79	106	104	1.85
2	Grimsel	1970	4	***	35	32	36	29	35	32	199	117	117	92	100	112	92	105	1.27
3	Robiei	1890	6	**	16	6	20	19	21	16	98	131	112	124	92	124	137	120	1.49
4	Mauvoisin	1840	4	***	19	22	22	21	27	25	136	91	99	93	90	97	76	91	1.30
5	Hasliberg	1830	1	***	2	10	18	20	23	22	95	(79)	116	202	93	113	120	97	1.68
6	Maloja	1810	7	***	6	12	21	20	18	12	89	125	107	87	93	90	109	97	1.44
7	Trübsee	1800	2	***	23	24	33	29	36	35	180	128	117	111	96	106	96	108	1.33
8	Bivio	1770	5	***	3	10	14	5	14	12	58	(161)	128	118	118	109	81	107	1.58
9	Zervreila	1735	5	****	16	12	16	12	16	16	88	87	76	77	81	78	82	80	1.14
10	Ftan	1710	7	***		5	8	4	3	1	21		84	72	105	(163)	(95)	95	1.33
11	La Drossa	1710	7	****	7	8	16	9	11	7	58	76	81	81	101	84	95	86	1.23
12	Zuoz	1710	7	***	4	4	9	7	8	5	37	78	88	92	78	95	75	86	1.27
13	Cardada	1650	6	**		8	18	20	7		53		123	100	124	137		118	1.37
14	Bourg-St.Pierre	1650	4	***	4	7	7	8	5	3	34	122	94	98	95	111	(67)	98	1.18
15	Stockhorn	1650	1	****		9	16	21	12	10	68		111	79	106	104	108	100	1.41
16	Rigi Scheidegg	1640	2	*	11	18	19	19	20	27	114	186	187	204	222	199	175	195	1.27
17	San Bernardino	1630	6	***	5	6	13	13	14	7	58	150	123	108	109	98	129	114	1.53
18	Zermatt	1610	4	****	7	9	12	15	8	4	55	102	83	95	85	88	78	89	1.31
19	Malbun	1600	3	***	20	19	24	18	20	18	119	75	97	71	73	88	68	78	1.43
20	Grindelwald	1570	1	***	15	18	21	21	21	19	115	106	97	79	84	87	90	90	1.34
21	Bosco/Gurin	1510	6	***	13	9	16	27	19	15	99	138	105	98	100	109	112	109	1.41
22	Fionnay	1500	4	***	17	16	19	20	23	20	115	105	91	105	109	117	95	104	1.20
23	Moléson	1500	1	**		1	8	10	12	1	32		(128)	126	151	135	(54)	137	
24	St. Antönien	1480	5	***	10	15	22	17	12	13	89	82	(83)	82	74	78	66	78	1.24
25	Innerferrera	1480	5	***	6	3	10	4	9	6	38	114	92	91	78	78	91	90	1.46
26	Splügen	1460	5	***	7	8	18	9	14	10	66	90	99	88	89	83	107	92	1.29
27	Andermatt	1440	2	****	20	22	23	15	20	22	122	82	78	86	77	84	82	82	1.12
28	Bedretto	1400	6	***	15	15	21	27	22	9	109	111	94	80	86	90	118	93	1.48
29	Sta. Maria	1400	7	***	2	5	12	9	8	3	39	95	86	86	79	82	(69)	83	1.20
30	Morgins	1380	1	***	14	18	17	16	23	7	95	110	104	90	92	92	97	97	1.22
31	Kippel	1370	4	***	10	13	17	14	15	3	72	106	120	116	120	116	(188)	119	1.13
32	Münster	1360	4	***	15	19	25	18	18	11	106	108	128	102	124	113	81	111	1.58
33	Ulrichen	1345	4	***	14	15	19	12	15	9	84	102	103	89	112	94	68	93	1.65
34	Flumserberg	1310	3	***	25	23	27	23	16	21	135	87	112	103	101	84	98	98	1.33
35	Braunwald	1310	3	***	20	29	32	27	21	27	156	87	109	100	89	96	84	95	1.30
36	Schwägalp	1290	3	***	20	28	32	19	19	22	140	102	116	88	103	92	91	99	1.32
37	Stoos	1290	2	***	11	15	24	19	20	20	109	119	123	115	112	104	104	112	1.18
38	Leysin	1250	1	***	9	13	2	10	18	7	59	130	78	(107)	106	101	119	103	1.67
39	Rumein	1200	5	****	3	4	6	6	5	11	35	(99)	90	83	72	93	84	84	1.11
40	Disentis	1170	5	****	7	10	16	6	9	5	53	123	86	105	99	111	74	101	1.66
41	Oberiberg	1100	2	***	15	14	18	12	11	18	88	121	88	78	93	74	71	87	1.70

(ii) Monthly and seasonal average of each individual locations

(iii) As above but for all 41 locations together

(iv) Ratio of the largest and the smallest monthly average for each location.

Only average snowfall density values have been considered. These have been computed from the sum of daily water equivalents (24 hours) divided by the sum of daily depth of fresh snow values (hereafter AV = average value-s). The regional AV (see item (i)) have been compared among the 7 various regions. The seasonal AV of individual locations (item (ii)) have been classified relative to their region and site exposure and plotted against the altitude. The monthly AV (iii) have been analysed for seasonal pattern and the ratios (iv) compared among 41 locations, to see the local pecularities.

In the second step, the snowfall density data from 13 locations, situated in various countries, as listed in Table 2, have been analysed for the effect of temperature. For each location, the daily snowfall density has been averaged in intervals of 1 °C in the range from 0 to -10 °C. These group AV have been plotted against temperature and fitted by hand. For two locations, at Weissfluhjoch and Mauvoisin the wind speed data at the level of 2 m above ground have been included in the analysis. Here, the daily snowfall densities have been divided in two groups according to the wind speeds smaller than 1.5 ms^{-1} and larger than 4 ms^{-1} and plotted against the temperature.

In the third step, the snowfall density data from 7 Swiss locations aquired in two ways, using the snow samplers and the Hellmann precipitation gauges have been compared (Sevruk, 1983). To doing this, the AV of both, the ratio k of sampler/gauge values and of wind speed, were computed for each °C. These k values were plotted against wind speed.

Table 2

List of investigations of snowfall density related to temperature

Legend:

d depth of snowfall	t air temperature	I average of individual p values
P precipitation amount	w water equivalent of snowfall	II regression analysis p=f(t)
p density of snowfall	* d measured in the collector of precipitation gauge	III p computed from w and d $(p=w.d^{-1})$

LOCATION			PERIOD	METHODS OF MEASUREMENT				METHODS OF ANALYSIS				NUMBER OF EVENTS					FIG.	REFERENCES
Country Station	No.	Altitude /m/		Measurement interval	Snowfall density: Snow sampl. (sect. area) $/cm^2/$	Snowfall density: Precipit. gauge	Temperature Measurement level	Temperature Period of average	d_{min} /cm/	P_{min} /mm/	Methods of computing p averages	t -0.1 to -1	t -1.1 to -3	t -3.1 to -5	t -5.1 to -10	t Σ -0.1 to -10		
a) Previous studies																		
SWITZERLAND																		
Rossinière	S1	900	1873-78	24 hr	no	Snowdon	2-4 m	event	1	0.1	I	7	18	4	23	52	3	Ward (1875,1878)
GERMANY																		
München	G1	≈350	1917-32	24 hr	100	no	2 meter	event	0.5		I	74	77	43	34	228	3	Haeuser (1933)
Potsdam	G2	<100	1906-13	24 hr	yes	no	2 meter	event			I	56	58	32	22	168	3	Wengler (1914)
FINLAND																		
Sodankylä	F1		1917-18	event	yes	no	2 meter	event			I	7	5	1	11	24	3	Keränen (1920)
Sodankylä	F2		1921-23	24 hr	yes	no	2 meter	24 hr			I	1	8	11	24	44	3	Korhonen (1926)
Lestijärvi	F3		1921-23	24 hr	yes	no	2 meter	24 hr			I	9	12	12	29	62	3	Korhonen (1926)
Wesanto	F4		1921-23	24 hr	yes	no	2 meter	24 hr			I	21	32	32	62	147	3	Korhonen (1926)
CANADA																		
Moncton	C1		1974	6 hr	no	SMC*	850 mbar	6 hr			II	1	2	1	8	12	3	MacNeil et al. (1977)
Halifax	C2		1974	6 hr	no	SMC*	850 mbar	6 hr			II	1			4	5	3	MacNeil et al. (1977)
Gander	C3		1974	6 hr	no	SMC*	850 mbar	6 hr			II	2		1	9	12	3	MacNeil et al. (1977)
Truro	C4		1974	6 hr	no	SMC*	850 mbar	6 hr			II		1		8	9	3	MacNeil et al. (1977)
Bolton	C5		1974				850 mbar	6 hr			II						3	Goodison (1976)
U.S.A.																		
Sierra Nevada	U1	2100	1951-52	event	?	?	700 mbar	event			II	3	6	11	15	35	3	Diamond et al. (1953)
Sierra Nevada	U1*	2100	1951-52	event	?	?	2 meter	event			II	3	6	11	15	35	3	Diamond et al. (1953)
b) Swiss study																		
SWITZERLAND																		
Weissfluhjoch	S2	2540	1973-78	24 hr	1000	heated g.	150 m	24 hr	1	0.1	III	7	20	56	194	277	6a	Inst. Weissfluhjoch
Mauvoisin	S3	1840	1973-78	24 hr	70	Hellmann	2 meter	24 hr	10	0.1	III	12	29	22	52	115	6a	Swiss Met. Inst. + I.W.
Bivio	S4	1770	1973-78	24 hr	70	Hellmann	2 meter	24 hr	10	0.1	III	6	12	10	18	46	6a	Swiss Met. Inst. + I.W.
San Bernardino	S5	1630	1973-78	24 hr	70	Hellmann	2 meter	24 hr	10	0.1	III	8	25	10	11	54	6a	Swiss Met. Inst. + I.W.
Bosco-Gurin	S6	1510	1973-78	24 hr	70	Hellmann	2 meter	24 hr	10	0.1	III	25	16	14	9	64	6a	Swiss Met. Inst. + I.W.
Andermatt	S7	1440	1973-78	24 hr	70	Hellmann	2 meter	24 hr	10	0.1	III	12	32	28	19	91	6a	Swiss Met. Inst. + I.W.
Disentis	S8	1170	1973-78	24 hr	70	Hellmann	2 meter	24 hr	10	0.1	III	9	18	14	2	43	6a	Swiss Met. Inst. + I.W.
St. Gallen	S9	664	1973-78	24 hr		Hellmann	2 meter	24 hr	5	0.2	III	20	11	11	8	50	6a	Swiss Met. Inst.
Zürich	S10	569	1973-78	24 hr		Hellmann	2 meter	24 hr	5	0.2	III	11	6	6	1	24	6a	Swiss Met. Inst.

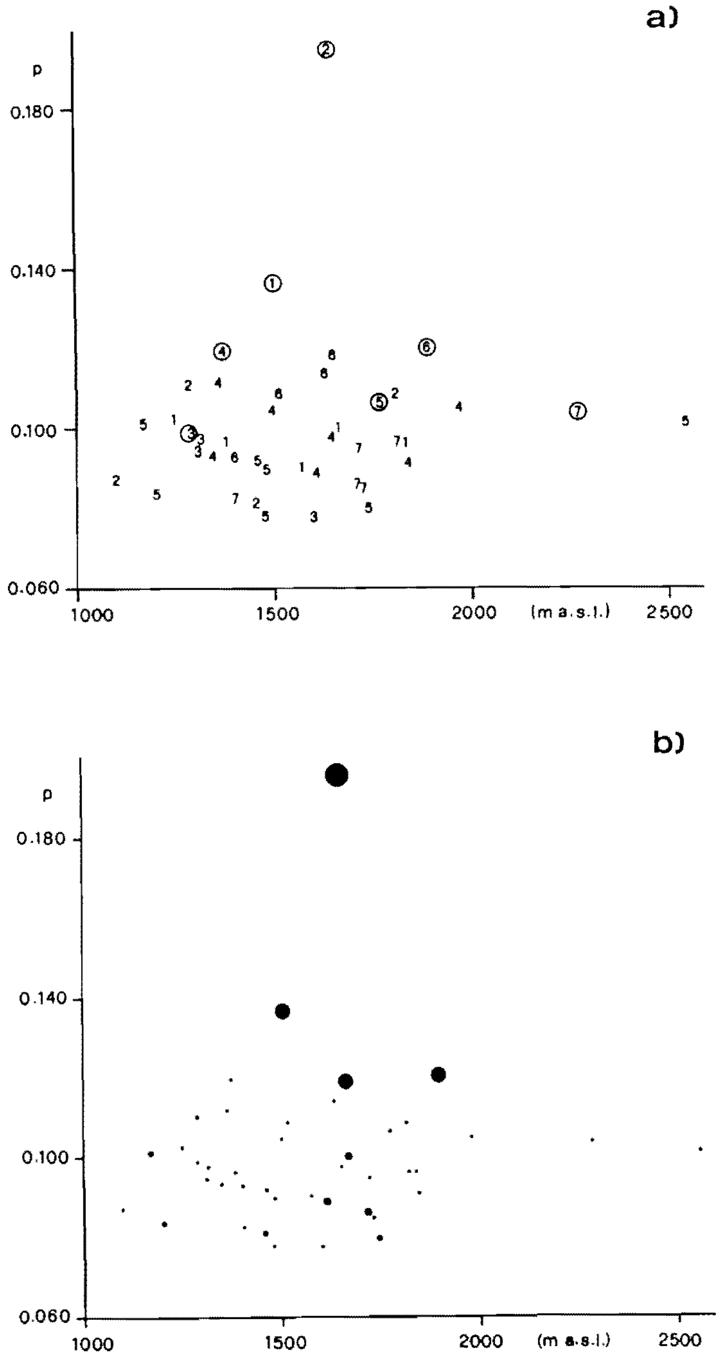

Fig. 1 Snowfall density as related to the altitude.

a) 1 - 7 indicate climatic regions. Rings show maximal regional values.

b) Black circles show classes of site exposure: ● very exposed, ● exposed, • open sheltered, • sheltered, • completely sheltered.

41 Swiss Alpine location. Period from November to April 1973/4 - 1977/8.

In fact, the ratio k is identical with the conversion factor k due to wind field deformation as used for the aims of correction of snowfall data for systematic error in point precipitation measurements. Consequently, the Swiss values of k for the Hellmann gauge have been finaly compared with the k values known from the literature (Gorbunova, 1972; World Water Balance, 1978).

4. Results

The 5-year AV of daily snowfall densities for 41 locations in the Swiss Alps are found in Table 1. They vary between the individual locations from 0.078 to 0.195 (10^{3} kgm^{-3}). They are larger than 0.110 for 8 locations and smaller than 0.090 for 10 locations. The AV for all 41 locations amounts to 0.102 which agree well with the general rule (0.100). The range for 5 individual years is from 0.097 to o.104. The differences between the seven regions are considerable. The range of regional AV snowfall densities is from 0.090 for the region 5 to 0.111 for the region 6. However these differences must not be attributed to the regional pecularities. Almost in each region smaller and larger AV between 0.08 and 0.12 are common (Tab. 1) In the region 1, 2, 4 and 6 at least one location shows an extremely large snowfall density value. In addition, the degree of the site exposure differs considerably from region to region.

The location Rigi-Scheidegg from the region 1 has not been accounted for, because it shows very large snowfall density values. The AV is 0.195 and it is even more than 0.250 for 13% of all days (out of 114 days). The monthly AV for February amounts to 0.222 as is shown in Table 1. These very large values of Rigi-Scheidegg are due to the extremely wind-exposed slope site near the crest.

The effects of the altitude and the exposure are shown in Figure 1. It indicates that the large variety of snowfall density AV can hardly be attributed to the altitude and implicit to the temperature. In some regions (e.g. 2, 6, 7) the snowfall density even increases with the increasing altitude. It follows that in such cases the snowfall density is increasing with decreasing temperature, which would be inconsistent with the findings reported in the literature, and other causal factors than the altitude or temperature should also be taken into consideration.

As may be seen from Table 1 the variability of snowfall density AV depends to some extent on the site exposure. Thus the five classes of site exposure can give an approximation of snowfall density AV . An attempt of a rough classification of site exposures according to the physical characteristics of location is shown in Table 3.

Summarizing the above mentioned it is hardly possible that the one unit value of snowfall density, as suggested by using the general rule, may be generally applicable in the Swiss Alps, and a more complex procedure including the physical characteristics of a location would be more appropriate. It can be assumed further, that the snowfall density as measured one per 24 hours at sheltered locations can approximate the "true" values of natural snowfall at best. These values are, however, considerably smaller than 0.100.

The seasonal pattern of snowfall density can be characterized by slightly larger averages at the beginning of the winter season in November and December when it amounts to 0.107 against roughly 0.100 for January trough April. This can be seen from Figure 2. 27 locations out of 41 show maximum monthly AV in the November - December season. In contrast, extremely small snowfall densities have been observed at some locations in April (locations No 14, 19, 23, 24, 29 and 33). However, deviations from the above mentioned general seasonal pattern can exist for individual locations or even years. They can be due to the yearly or monthly weather changes, in particular, the local wind and temperature conditions. For example, the ratio of the greatest and the smallest monthly snowfall density for all 41 locations varies from 1.16 in 1973/74 to 1.33 in 1976/77. It exceeds 1.5 for nine locations (Tab. 2).

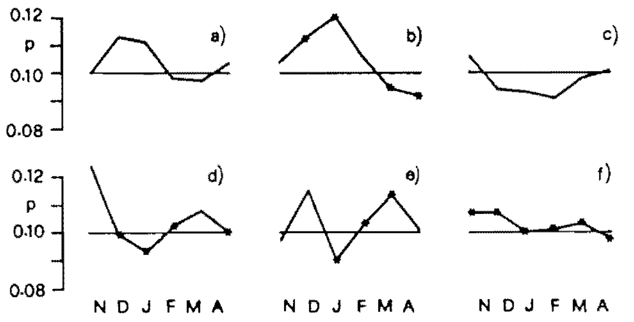

Fig. 2 Seasonal pattern of snowfall density from November to April 1973/4 - 1977/8. 41 Swiss Alpine locations.

a) .... d) indicate years 1973/4 ..... 1977/8

f) is the average over the period of 5 years

* the average is based on at least 150 events.

Table 3

Average values of snowfall density as related to the exposure and physical characteristics of location

	Exposure	Physical characteristics	Snowfall density
*	very exposed	ridge, pass, steep open windward slope	> 0.150
**	exposed	near a ridge, windy plateau, open windward slope, large gully	0.120 -0.150
***	open	open plain valley, slight slope, sparce stock of timber, near a building	0.090 -0.120
****	sheltered	garden, group of buildings wood glade, flat land	0.080 -0.090
*****	completely sheltered	park, yard, town centrum small wood glade	0.080

The effect of temperature as evaluated using the data from literature is shown in Figure 3. The wide range of snowfall density AV for the same temperature can be partly attributed either to the different site exposure, and implicitly to the local wind speed, or to different methods of both, the measurement and analysis of snowfall density data, as applied by various authors and noted in Table 2. In any case, it can be concluded, from Figure 3, that the snowfall density AV decreases with decreasing temperature. This is evident not only for each of 10 locations from various countries as compared in Figure 3, but also for the additional seven Swiss locations, as can be seen from Figure 6a. Looking at both Figures 3 and 6a an interesting question arises concerning the squat vault for three Finnish and two Swiss locations at Weissfluhjoch and Bivio (S2, S4). The relatively very high snowfall density AV occuring somewhere in the interval between -1 to -4 °C, can not be fully explained. However, such values are based on a small number of events and usually occure in November and December. It may refer to possible mixed or liquid precipitation during short time periods.

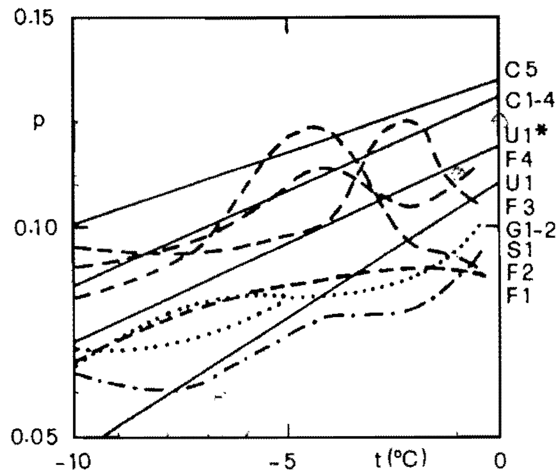

Fig. 3 Snowfall density as related to the air temperature. Compiled data from previous studies as indicated in Table 2.

—— regression lines from Canada and USA. Air temperature refers to values during snowfall at 850 and 700 mbar level in Canada and USA, respectively. The correlation coefficient ranges from 0.4 to 0.64.

.... hand fitted curves from Germany

\- - hand fitted curves from Finland

-.-. hand fitted curves from Switzerland. See Table 2 for symbols and references.

The effect of both, temperature and wind speed is indicated in Figure 4. The snowfall density AV on windy days are considerably larger then on days with small wind speeds (≤1.5 ms^{-1}). This increase due to wind speed, makes 25% at Mauvoisin and 31% at Weissfluhjoch. In both groups of days, the effect of temperature is also obvious as already demonstrated in Figure 3 and 6a. Near 0 °C, the snowfall density quickly increases. This indicates the possible effect of short time intervals with positive temperature on such days.

The data from seven Swiss locations fit the graphical relationships in Figure 4 fairly well as can be seen from Figure 5. Only the data from the completely sheltered location at Andermatt (S7) seem to be very low. Here, the effect of temperature is not obvious at all. The nomogram in Figure 5 can be used to roughly assess the mean snowfall density values for locations with different site exposure.

The differences between the snowfall density values as measured using snow samplers and the Hellmann precipitation gauges are shown in Figure 6. The precipitation gauges indicate on average 36% smaller values than the snow samplers. For the completely sheltered location at Andermatt (S7) the difference is practically zero and for the open locations at Mauvoisin (S3), Bivio (S4) and San Bernardino (S5) it is more than 40%. The ratio k sampler/gauge depends mainly on wind speed but the effect of temperature seems also to be important, mainly for temperature smaller than -9 C (Fig. 6d). In spite of considerable scatter of the average k values from Switzerland in Figure 6d they fit fairly well the known graphical relationship by Gorbunova (1972) and World Water Balance (1978). This indicates that the latter relationships can be used in Switzerland to correct snowfall data for wind-caused losses.

The seasonal pattern of snowfall density is affected by the occasional rainfall or frosen rain in November and December and intense evaporation in April. Moreover, it must be kept in mind that the extreme events with the low probability of accurance (very strong winds, drifting snow) can essentially affect an average value mainly during the time periods with small number of days with snowfall. In this connection the 5 year period seems to be to short to make any definitive statement and some deviations from the general seasonal or any other pattern referred to in this paper must also be accounted to this fact.

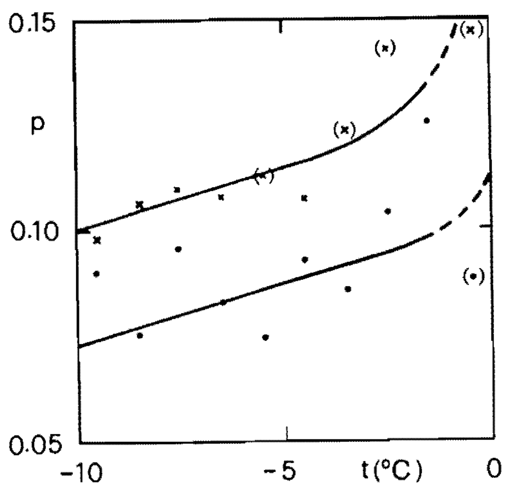

Fig. 4 Snowfall density as related to the mean daily air temperature and wind speed. Weissfluhjoch and Mauvoisin, November - - April 1973/4 - 1977/8.

x wind speed is larger than 4 ms^{-1}

· wind speed is smaller than 1.5 ms^{-1}

( ) the average is based on less than 10 events.

Wind speed data refer to the 2 m height.

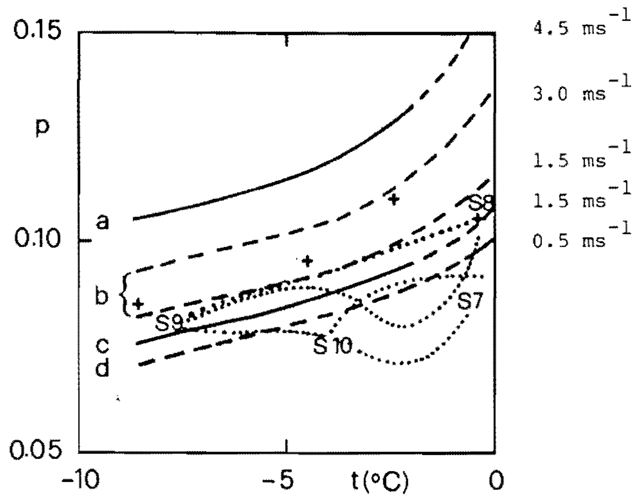

Fig. 5 Nomogram for the assessment of snowfall density. Average values.

a) exposed locations $u > 4\ ms^{-1}$

b) open locations $u = 1.5 - 3\ ms^{-1}$

c) sheltered locations $u \leqslant 1.5\ ms^{-1}$

d) completely shelterd locations ($.5\ ms^{-1}$)

u average wind speed at the 2 m level on days with snowfall.

- - - interpolated values

..... measured values fitted by hand from three control locations Disentis (S 8) St.Gallen (S 9) and Zurich (S 10) with sheltered sites, and one location Andermatt (S 7) with completely sheltered site.

+ x control locations with open sites, Bivio (S 4), San Bernardino (S 5) and Bosco-Gurin (S 6).

5. Discussion

The general rule has been in use since the last century (Symons, 1872). As has been shown already by Ward (1874, 1876, 1878) and Symons (1878) and more recently by Currie (1947), Jackson (1960) and Ferguson and Pollack (1978), it can lead to substancial errors. The present paper confirms this too. However, if there is no other data available, the general rule approximates the average value of snowfall density, in particular at open locations, at best. This has been also confirmed in the present paper. The validity of general rule for the averaged 5 year data from all 41 Swiss locations is due to the large number of open locations (30 out of 41) and to the compensation effect between the remaining 4 exposed and 7 sheltered locations (Tab. 1). At the open locations, the snowfall density varies in a wide range from 0.09 to 0.120 depending completely on the local wind speed.

It is not surprising that the effect of altitude is not evident. Firstly, the altitude difference is small (1000 m) and secondly, the effect of lower temperature in highers altitudes is compensated or even over-compensated at open and exposed locations by that of wind speed, because, in general, wind speed increases along with the altitude. In spite of the predominance of the wind speed effect, the classification of site exposure as defined in Table 3 must be understand as a very rough measure of the local wind speed value for the practical use in regions, where no meteorological data are available. Better results can be expected for locations where wind speed or at least exposure have

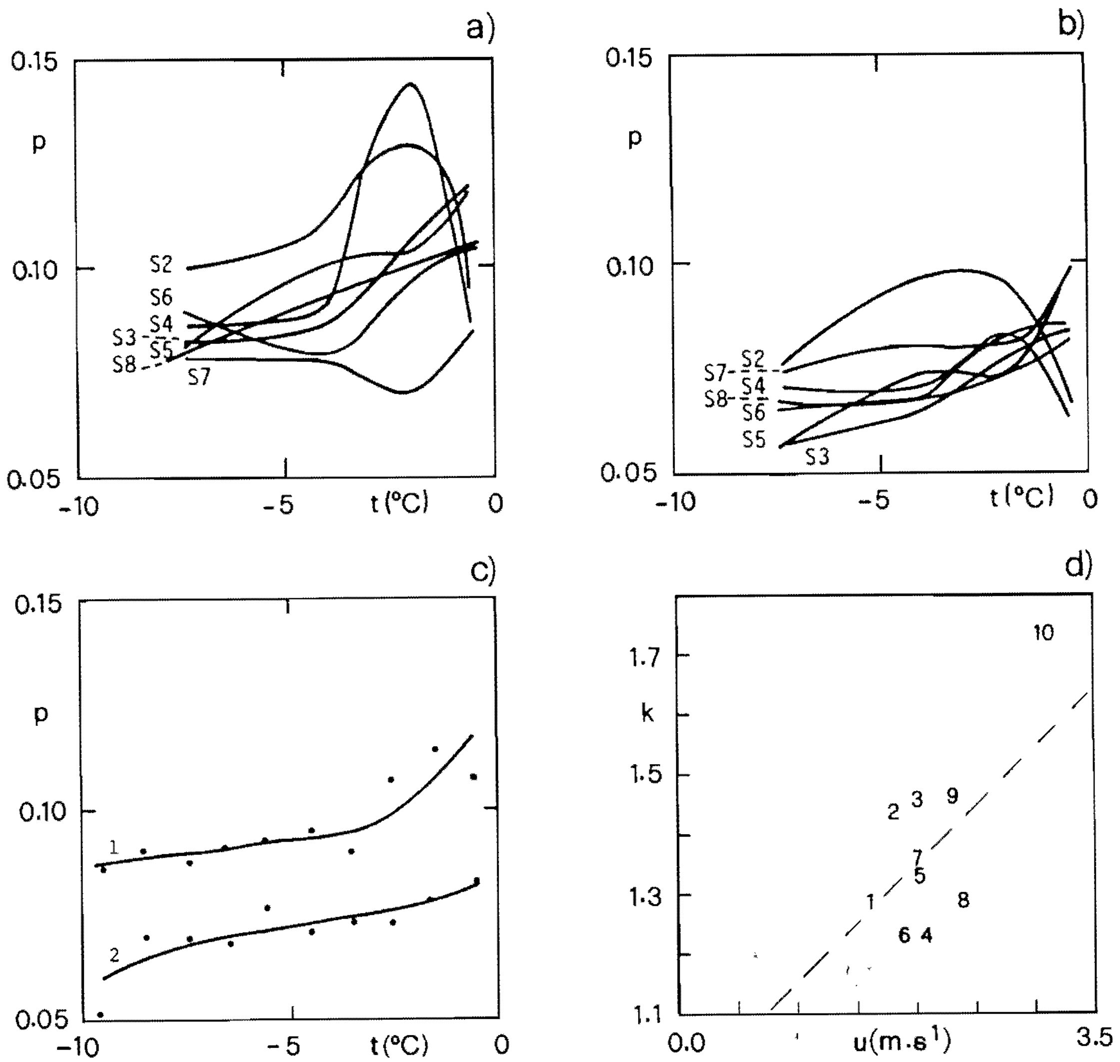

Fig. 6 Comparison of snowfall density values as measured using snow samplers and precipitation gauges for seven Swiss locations. November - April 1973/4 - 1977/8.

Top: a) Swiss snow sampler values b) Hellmann precipitation gauge values

Bottom: c) average values for sampler (1) average values for the Hellmann precipitation gauge (2)

S2 Weissfluhjoch S6 Bosco-Gurin
S3 Mauvoisin S7 Andermatt
S4 Bivio S8 Disentis
S5 San Bernardino

d) ratio k sampler/gauge as related to wind speed at the height of 2 m.
1 ... 10 show temperature interval in °C
1 = 0°C - 1°C etc.
Dashed line shows the relationship between k and u for the Hellmann gauge according to World Water Balance (1978).

been directly measured (Sevruk, 1982). If the above classification would be based on such measured values, as a consequence, some changes in the classification of the location exposure in Table 1 and 3 would certainly be necessary. But also in this case it can not be expected that an average value of wind speed or some limits of it, would be capable to record its large variability during the days with snowfall. This must also be taken into consideration if the snowfall density is to be estimated. Moreover, for a windy location the higher limit of snowfall density in each class should be considered. At locations with altitude above 2000 m a.s.l. smaller values may result due to small temperature in the case when the location is not exposed. In contrast, slightly larger values may be expected at open locations below 1000 m a.s.l. because of large temperatures.

Concerning the effect of temperature on snowfall density it must be noted that the variability of such relationships, as presented in Figure 3 and 6, is a complex physical and methodical problem. Firstly, there are differences between the snowfall values as measured by snow samplers and precipitation gauges. Secondly, snow sampling immediately after the snowfall and once per 24 hours gives different results of snowfall density due to the settling effect (Martinec, 1977), evaporation and condensation, melting snow,wind blow effects etc. in the time between the cessation of snowfall and the measurement. Thirdly a further source of errors relates to the measurement of the snowfall depth. It is usually measured on the snow board, but in some cases snowfall depth was also measured in the collector of precipitation gauge (Tab. 2a). Finally, differences can be also due to different ways of computing the average values of snowfall density and, eventually, of temperature over the period of observation or for a particular group of data (e.g. temperature interval).

Snowfall density can be averaged in two ways, as the arithmetic mean of individual daily snowfall density values or it can be computed from the total of daily water equivalents of snowfall divided by the total of daily snowfall depths for the period of observation. The former are, in general, 3 - 15 % larger than the latter , depending on the number of events (see Korhonen, 1926 and Hauser, 1933).

Temperature can be averaged from one or two observations taken during the snowfall or from the three routine observations on days with snowfall. In addition temperature can be taken from various levels above the ground, e.g. 700 and 850 mbar or 2 m above the surface (Diamond and Lowry, 1953).

Bearing in mind the possible sources of differences, as mentioned above, it is clear that the snowfall density v.s. temperature relationships as derived by various authors are comparable only if the experimental and/or enviromental conditions between the comparing relationships were similar (e.g. curves, G1. G2, and F1 or F2 and F4 in Fig. 3 - see also Tab. 1a). This is an important limit for their practical use.

6. Conclusions

The measured values of snowfall density depend on the local physical and meteorological characteristics, in particular wind speed or site exposure and air temperature. Knowing these characteristics the roughly assessment of snowfall density can be made. The unit value of $0.1(10^3 kg^{-3})$ can be used only in open locations. In exposed locations it is considerably more. The seasonal pattern of snowfall density indicates slightly larger values in November - December as compared with January through April. The ratio of snowfall values as measured using snow samplers and precipitation gauges can be applied to correct the systematic error in point precipitation measurement. It is related to the wind speed at the level of the gauge orifice.

7. References

CURRIE, B.W., 1947 : Water content of snow in cold climates. Bull. Amer. Meteorol. Soc., 28 (March), 150-151.

DIAMOND, M. and W.P., LOWRY 1953 : Correlation of density of new fallen snow with 700 mb temperatures. CRREL U.S. Army SIPRE Research Paper 1, 3p.

FERGUSON, H.L. and D.M. POLLOCK, 1978 : Estimating snowpack accumulation for runoff prediction. Proc. Runoff from Snow and Ice, Hydrology Symposium No. 8.

GORBUNOVA, J.G., 1972 : About the underestimation of the precipitation measurement by Hellmann precipitation gauges (in Russian). Trans. Voyeykov Main Geophys. Observ., 280, 102-114.

GOODISON, B. : Correlation of density of new fallen snow with 800 mb and 700 mb temperatures. (Unpublished Note, 1976, quoted by MacNeil and O'Neill 1977).

HAEUSER, J., 1933 : Hoehe und Wassergehalt der Neuschneedecke: Ergiebigkeit und Dauer starker Schneefaelle in Muenchen. Z. angewandte Meteorol., 50(9), 257-271.

JACKSON, C.I., 1960 : Snowfall measurements in Northern Canada. Quart. J. Roy Meteorol. Soc., 86 (368), 273-275.

Jahresberichte des Eidg. Institutes fuer Schnee- und Lawinenforschung Weissfluhjoch/Davos, 1973/74 - 1977/78.

KERAENEN, J., 1920 : Die Dichte des frischgefallenen Schnees in Sodankylae im Winter 1917/18 nach den Beobachtungen von H. Lindfors, Helsinky.

KORHONEN, W.W., 1926b : Ueber die Dichte des Neuschnees. Meteorologische Zentralanstalt des finnischen Staates, Mitt. 18, 12-19.

MacNEIL, C.F. and A.D.J. O'NEILL, 1977 : Measurements of the water equivalent of freshly fallen snow in Canada's Atlantic provinces. Proc., Eastern Snow Conference, Belleville, Ontario (Feb. 3-4, 1977), p. 118-129.

MARTINEC, J., 1977 : Expected snow loads on structures from incomplete hydrological data, 19(18), 185-195.

SEVRUK, B., 1982 : Methods of correction for systematic error in point precipitation measurement for operational use. World Meteorol. Org., Operational Hydrol. Rep. 21, WMO-No. 589, 91 p.

SEVRUK, B.,1983 : Correction of measured precipitation in the Alps using the water equivalent of new snow. Nord. Hydrol., 14(2), 49-58.

SEVRUK, B., 1985 : Correction of precipitation measurement : Swiss experience.
Workshop on the Correction of precipitation Measurements, 1-3 April 1985 Zurich.

SYMONS, G.J., 1876 : Note on the foregoing papers. British Rainfall 1875, 23-25.

WARD, F.M.S., 1875 : On the measurement of snow. British Rainfall 1874, 25-34.

WARD, F.M.S., 1876 On the measurement of snow. British Rainfall 1875, 21-22.

WARD, F.M.S., 1879 : On snow-fall measurements. British Rainfall 1878, 13-15.

WENGLER, F., 1914 : The specific density of snow (in Germann). Inaugural-Dissertation, Friedrich--Wilhelms-Univ. Berlin. Druck von Julius Abel, Greifswald.

WMO, 1981 : Guide to hydrological practices. World Meteorol. Org., 4th edition, Vol. 1, WMO-No. 168.

World Water Balance and Water Resources of the Earth. UNESCO Ser. : Studies and Reports in Hydrology, No 25, 663 pp., Paris, 1978. (In Russian, Gidrometeorizdat, Leningrad, 1974, 637 pp.).

8. Bibliography

STASHKO, E.V., 1976 : Water in freshly fallen snow. In: Proc. 44th Western Snow Conference, p. 20 -22.