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Accuracy of Point Precipitation Measurements

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The normal-exposed Hellmann raingauge only catches about 85% of the true precipitation on yearly basis. This is mainly due to aerodynamic effects. A statistical model analysing the ratio of the daily amounts of precipitation measured at ground level and at standard height is set up for describing this influence. Corrections due to liquid and solid precipitation and three different kind of exposures are presented. Further the statistical errors on the corrections are estimated.

Introduction

The first attempt to investigate the importance of the exposure to the precipitation measurements in Denmark was initiated in 1952, and the results have been analysed (Madsen 1972). Discussions of the classification of exposure of raingauges lead to an investigation in 1969 of the relationship between raingauges installed at different distances to a windbreak. The few results supported previous theories concerning places suitable for setting up raingauges.

While these investigations were taking place, we received in February 1971 a request from the World Meteorological Organization (WMO) to participate in an international comparison of the national precipitation gauge and the reference pit gauge. The project was concentrated on liquid precipitation, and on attempts to determine the systematic errors especially those due to the wind (the aerodynamic effect). As reference gauge a Snowdon raingauge surrounded by a grid was used at 20 stations.

According to the WMO project the national raingauges had to be placed unsheltered for an investigation of the maximum size of the aerodynamic error. While this procedure was followed at most stations, some gauges were located at sheltered places corresponding to such exposure characteristic for precipitation stations. In this way we hoped to get an idea of the error, which at ordinary stations exists on precipitation measurements.

In addition to the measurements at the 20 stations, measurements were later initiated with a less expensive reference gauge consisting of a Hellmann gauge installed in a pipe with orifice 3 cm above the ground level.

The present paper deals with the estimate of sources of errors in precipitation measurements, due to aerodynamic effect, evaporation (condensation), and wetting. Taking into account the nature of the single rainfall events we have based the analysis on daily rainfall measurements. This is in contrast to Rasmussen and Halgreen (1978) which deals with weekly measurements and does not explicitly include wind speed and rain intensity.

Instruments

The national raingauge is a 200 cm^2 Hellmann gauge made of zinc and placed with its orifice 1.5 m above the ground. The gauge consists of an upper part, which at the bottom takes the form of a funnel, and a lower part with a container. In the winter the raingauge is provided with a metal »snowcross« in order to prevent the snow blowing out of the gauge.

The reference is a 127 cm^2 W5000/1 Snowdon raingauge (Fig. 1). The Snowdon gauge is installed in a pit with its orifice 3 cm above the ground level and surrounded by a grid (Fig. 1) preventing splash-in. The height of orifice corresponds to the height of a medium cut grass field. Fig. 1 also shows a Hellmann raingauge installed in a pipe with its orifice 3 cm above ground level. This requires that the gauge up to an adequate distance is surrounded by grass preventing splash-in, and that the grass is closely cut in order to avoid interception.

Sources of Error

If R denotes the true and R_i the measured precipitation amount we have

$$R = f(R_i, R_{iE}, R_{iW}, R_{iA}, R_{iP}, R_{iS}, R_{iD}, R_{iR})$$

indicating that R is a function of R_i, evaporation (R_{iE}), wetting (R_{iW}), aerodynamics (R_{iA}), unsuitable position (R_{iP}), splashing (R_{iS}), defects of raingauge (R_{iD}) and reading errors and unforeseen incidents (R_{iR}).

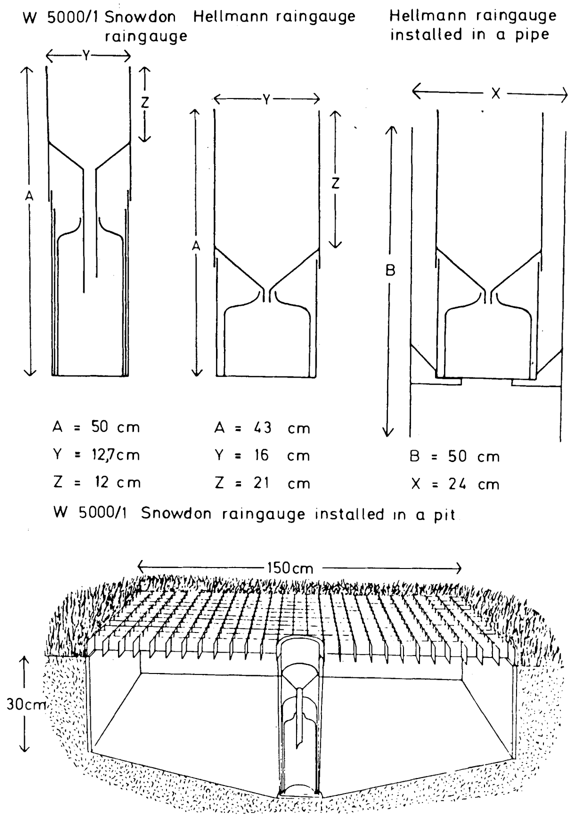

Fig. 1. Instruments used for the WMO-project.

Among these errors the last three have shown to be negligible (Allerup and Madsen 1979), and R_{iA} by far the largest.

In Sweden f has been taken to be a simple additive function (Dahlström 1970 and 1973).

Evaporation

In the following evaporation from raingauges means evaporation from the precipitation already in the container.

In the period June 3rd – November 2nd 1973, 54 evaporation experiments with a Hellmann raingauge placed at standard height was carried out. The observation site was a rather open garden situated about 25 km NNW of Copenhagen. All experiments were carried out in the daytime on rainfree days and each experiment lasted normally more than 10 hours.

Like Sevruk (1974) we found, that evaporation losses from a Hellmann raingauge are small and only amounted to 0.24% of the yearly precipitation. Also errors due to condensation were small and as for evaporation it seems reasonable to ignore these errors.

Results from 8 evaporation experiments show that the evaporation loss from a Snowdon raingauge placed at ground level only amounts to a fifth of the loss from a Hellmann gauge placed at standard height.

Wetting

Due to surface adhesion from the bottom and the inner walls, water will remain in the container after being emptied. If no rain falls after emptying, this residual water will be reduced or vanish through evaporation. In the same way residual water will remain on the inner walls of the funnel after rainfall and gradually evaporate. In either case the precipitation measurements will be invalidated by an error named *wetting*.

Laboratory tests have shown that the average wetting for the container in a Hellmann raingauge is 0.1 mm depending slightly on the precipitation amount. Sevruk (1974) found the value 0.15 mm during his laboratory tests. For the Snowdon raingauge, where the container is a plastic or a glass bottle, the wetting loss also was about 0.1 mm.

It is more difficult to determine the wetting loss for the funnel. The wet area of the funnel can be influenced by the duration and rates of the rainfalls and the windfield during precipitation. In the laboratory tests we tried to wet the funnel to imitate true rainfall events. For the Hellmann gauge and the Snowdon gauge we determined the wetting as 0.1 mm per event. Later field tests with rain intensities about 1.0 mm/hour gave for Snowdon gauge an average wetting of 0.09 mm. Sevruk (1974) found by his field tests a value of 0.1 mm (ranging from 0.05 to 0.20 mm) for the Hellmann gauge.

Furthermore full determination of the wetting calls for an estimate of the drying time, i.e. the time for drying the container or the funnel after an emptying or rainfall event. Therefore some experiments for determining the drying times have been undertaken. The drying times are compared to the potential evapotranspiration measured at the Climate and Waterbalance Station, Højbakkegård, 22 km SSW of the area, where the evaporation and wetting experiments took place. The results from the container of a Hellmann gauge appear from Fig. 2, where an exponential curve has been drawn to fit the experimental points.

By means of data from a pluviograph at St. Hareskov, about 15 km NW of København and hourly values of potential evapotranspiration, the total wetting loss (including both the loss from the container and the funnel) are calculated for every precipitation day in the periods April 1972 – March 1973 and June – October 1973. From these values monthly averages of total wetting losses per precipitation day are calculated (Table 1). No significant differences between the wetting

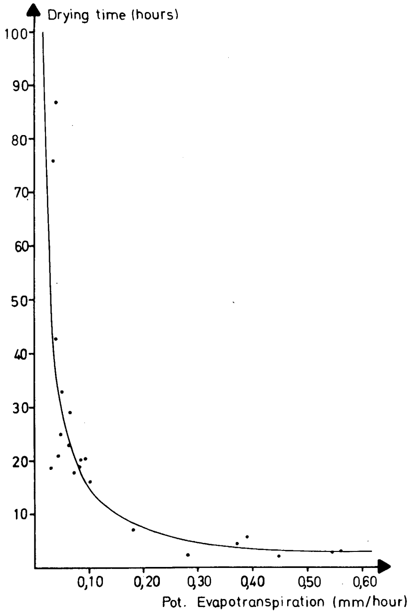

Fig. 2. Drying time of a Hellmann raingauge container.

losses for the Hellmann and the Snowdon gauge exist. The wetting loss amounts to about 4% of annual precipitation (1931-60) ranging from 3% in winter to 6% in the summer. Note that the estimated wetting losses are assumed to apply both to liquid and solid precipitation.

Table 1 - Monthly values of total wetting loss per precipitation day for a Snowdon raingauge.

	J,	F,	M,	A,	M,	J,	J,	A,	S,	O,	N,	D,	Y,
wetting loss per precipitation day (mm)	.09	.10	.13	.18	.22	.24	.24	.21	.18	.14	.11	.09	
per cent of precipitation (1931-60)	2.5	3.3	3.9	5.5	5.8	5.5	4.2	3.7	3.5	3.0	2.9	2.7	3.8

Aerodynamic Effect

Exposure of the Raingauge

Raingauges installed at some height above the ground cause disturbances in the surrounding air flow, which gives rise to a deflection of the trajectories of the precipitation particles. The result is that the gauge does not catch all of the precipitation. This error is normally denoted the aerodynamic effect (Robinson and Rodda 1969, Andersson 1970, Green and Helliwell 1972, Dahlström 1973, Bugge and Maribo Pedersen 1976) and its magnitude depends on the wind speed, the shape of the raingauge, the terminal speed and the type of precipitation particles.

By placing the raingauge on a sheltered site the aerodynamic effect can be reduced by reducing the windfield. However, in case of overprotection the precipitation may be caught by the surrounding objects, the so-called interception error.

The error of greatest magnitude in precipitation measurements is the aerodynamic effect. Assuming that the error at ground level is negligible we get this error as the difference between the precipitation measured at ground level (R_I) and at standard height (R_{II}).

659 measurements of daily precipitation, wind speeds, and rain intensities constitute the sample (Allerup and Madsen 1979). All measurements took place at unsheltered sites. For small amounts of rainfall inaccuracy of the records will have great influence on the ratios R_I/R_{II}. Hence only cases with daily amounts larger than 1.0 mm (measured at ground level) are included. Comparisons of data from two gauges must be carried out considering the *ratio* of precipitation observations (Madsen 1972 and Allerup 1975).

A statistical model for describing the aerodynamic effect therefore has to be based on ratios of daily amounts of liquid precipitation. The model describes these ratios by means of wind speed during rain (measured at 10 m level) and rain intensity, noting that the measure of rain intensity is defined as R_{II}/t (t total time of rain during one day) instead of referring to drop size (Allerup and Madsen 1979).

Our first try to describe the aerodynamic effect in relation to the wind speed and rain intensity started at the department of Fluid Mechanic, Technical University of Denmark. These analyses performed as a strictly deterministic approach (Bugge and Maribo Pedersen 1976) resulted in calculated aerodynamic effects which proved infinitesimal compared to the observed precipitation differences. Like Green and Helliwell's investigation (1972) the model was based on considerations in the symmetry plane of the raingauge. Therefore we felt compelled to set up a purely statistical model from scratch. Now we have

$$\frac{R_I}{R_{II}} = \frac{R-R_{IW}}{R-R_{IIA}-R_{IIW}} = \frac{R}{R-R_{IIA}} \left(\frac{1-R_{IW}/R}{1-R_{IIW}/(R-R_{IIA})} \right)) \tag{1}$$

Due to certain assumptions concerning the relations between R_{IW} and R_{IIW} the last term is approx. one (Allerup and Madsen 1979). Hence a statistical model build on the empirical ratios R_I/R_{II} will be as well a statistical model for the »true« ratios $R/R-R_{IIA}$, i.e. the aerodynamic effect R_{IIA}.

We also have

$$\frac{R_I}{R_{II}} = \frac{R_I/t}{R_{II}/t} = \frac{I_I}{I_{II}} \tag{2}$$

where t is the total time of precipitation within one day, and I_{II} is the rain intensity measured by a pluviograph placed at standard height (influenced by an aerodynamic effect of the same size as for the Hellmann gauge).

Fig. 3 illustrates ln I_I plotted against ln I_{II} (I_I and I_{II} 0.1 mm/hour) for one of the wind speeds V : $V = 1,2, \dots 18$ m/sec (here $V = 2$ m/sec). A close linear relationship between ln I_I and ln I_{II} seems to emerge. For all other values of V in data similar linear relations emerge with varying values of $A(V)$ and $H(V)$ (Allerup and Madsen 1979), and we obtain

$$\ln I_I = H(V) \ln I_{II} + A(V) \tag{3}$$

A great step towards simpler description is taken if $A(V)$ and $H(V)$ are well-related to one another. A plot of $A(V)$ versus $H(V)$ is shown below (Fig. 4).

It is not to be expected that the observed relation can be described as simple as a linear function, but as an approximation for the further work we will assume

$$H(V) = \alpha A(V) + \beta \tag{4}$$

Attempts on explaning the variation of the slopes *H(V)* from a meteorological point of view have failed so far.

From Fig. 5 we further approximate

$$H(V) = \eta V + \tau \tag{5}$$

Incorporating (4) and (5) into the relation (3) and (2) leads to the following structure of R_I/R_{II}

$$\frac{R_I}{R_{II}} \approx e^{\alpha_1 \ln I_{II} + \alpha_2 V \ln I_{II} + \alpha_3 V + \alpha_4} \equiv e^{\psi(I_{II}, V)} \tag{6}$$

where ψ (I, V) thus represents the systematic factor behind the variation of R_I/R_{II}.

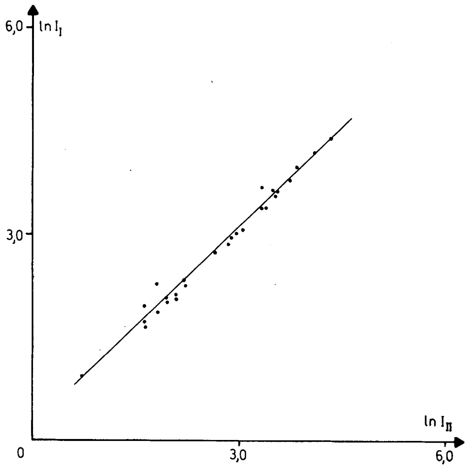

Fig. 3. Relation between rain intensity measures I_I and I_{II} on days with wind speed $V = 2$ m/sec.

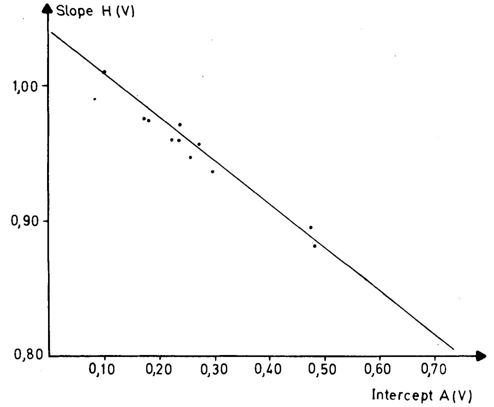

Fig. 4. Relation between the coefficients $H(V)$ and $A(V)$.

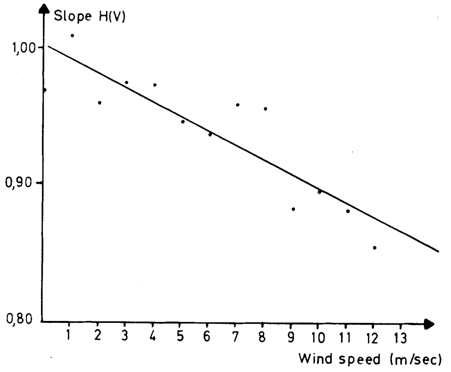

Fig. 5. Slope $H(V)$ as a function of wind speed (m/sec).

It seems reasonable considering the residuals in (6) to be distributed according to normal distribution (Allerup and Madsen 1979). Hence standard procedures in regression theory provides the following estimates

$$\alpha_1 = -0.0010, \quad \alpha_2 = -0.0082, \quad \alpha_3 = 0.0420, \text{ and } \alpha_4 = 0.0100 .$$

$e^{\psi(I_{II},V)}$ is the correction factor for the aerodynamic effect. It is seen that this factor increases with decreasing rain intensity and increasing wind speed as one would expect.

However, the quantity by which R_{II} is to be corrected is usually given as the relative difference of precipitation $(R_I\text{-}R_{II})/R_{II} = e^{\psi(I_{II},V)}\text{-}1$ (Madsen 1972). The estimate of $e^{\psi(I_{II},V)}\text{-}1$ is tabulated (Table 2) only for wind speed ≤ 20 m/sec and rain intensities ≤ 15.0 mm/hour, taken into account limitations of the model concerning extrapolation. Note, that the aerodynamic effect is estimated to be 1% at wind speed zero, in which case the theoretical value is zero.

Corrections

Correcting the precipitation we correct for aerodynamic effect and for wetting loss. Furthermore, this will be carried out due to temperature and exposure: Solid/liquid precipitation and sheltered/unsheltered sites.

Liquid Precipitation

Only in few cases the Hellmann gauge is installed unsheltered. Therefore determination of corrections for sheltered gauges has greatest importance.

At three stations parallel measurements are carried out placing the Hellmann gauge at standard height in gardens with shelter corresponding to normal sitings

Table 2 - Correction values (%) for aerodynamic effect, liquid precipitation measured at unsheltered stations.

Rain intensity	Wind speed (m/sec) measured at 10 m level																			
(0.1 mm/h)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	5	10	15	19	25	30	36	41	47	54	60	67	74	82	90	98	106	115	124	134
2	5	9	13	17	21	26	30	35	40	45	50	56	62	68	74	80	87	94	101	109
3	4	8	11	15	19	23	27	31	36	40	45	50	55	60	65	71	77	83	89	95
4	4	7	11	14	18	21	25	29	33	37	41	46	50	55	60	65	70	75	81	86
5	4	7	10	13	16	20	23	27	31	35	38	42	47	51	55	60	65	69	74	79
6	4	6	9	12	16	19	22	25	29	32	36	40	44	48	52	56	60	65	69	74
7	3	6	9	12	15	18	21	24	27	31	34	38	41	45	49	53	57	61	65	70
8	3	6	9	11	14	17	20	23	26	29	33	36	39	43	47	50	54	58	62	66
9	3	6	8	11	14	16	19	22	25	28	31	34	38	41	44	48	52	55	59	63
10	3	6	8	11	13	16	18	21	24	27	30	33	36	39	43	46	49	53	56	60
15	3	5	7	9	11	13	16	18	20	23	25	28	30	33	36	38	41	44	47	50
20	2	4	6	8	10	12	14	16	18	20	22	24	26	29	31	33	35	38	40	43
25	2	4	6	7	9	11	12	14	16	18	20	21	23	25	27	29	31	33	35	38
30	2	4	5	7	8	10	11	13	14	16	18	19	21	23	24	26	28	30	32	33
35	2	3	5	6	7	9	10	12	13	14	16	17	19	20	22	24	25	27	28	30
40	2	3	4	5	7	8	9	11	12	13	15	16	17	19	20	21	23	24	26	27
45	2	3	4	5	6	7	9	10	11	12	13	15	16	17	18	20	21	22	24	25
50	2	3	4	5	6	7	8	9	10	11	12	13	14	16	17	18	19	20	21	23
55	2	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	18	19	20	21
60	1	2	3	4	5	6	7	8	9	9	10	11	12	13	14	15	16	17	18	19
65	1	2	3	4	5	5	6	7	8	9	10	10	11	12	13	14	15	16	17	17
70	1	2	3	3	4	5	6	7	7	8	9	10	10	11	12	13	14	14	15	16
75	1	2	3	3	4	5	5	6	7	7	8	9	10	10	11	12	13	13	14	15
80	1	2	2	3	4	4	5	6	6	7	8	8	9	9	10	11	11	12	13	14
85	1	2	2	3	3	4	5	5	6	6	7	8	8	9	9	10	11	11	12	12
90	1	2	2	3	3	4	4	5	5	6	6	7	7	8	9	9	10	10	11	11
95	1	1	2	2	3	3	4	4	5	5	6	6	7	7	8	8	9	9	10	10
100	1	1	2	2	3	3	4	4	4	5	5	6	6	7	7	8	8	9	9	9
105	1	1	2	2	2	3	3	4	4	4	5	5	6	6	6	7	7	8	8	9
110	1	1	2	2	2	3	3	3	4	4	4	5	5	6	6	6	7	7	7	8
115	1	1	1	2	2	2	3	3	3	4	4	4	5	5	5	6	6	6	7	7
120	1	1	1	2	2	2	2	3	3	3	4	4	4	4	5	5	5	6	6	6
125	1	1	1	1	2	2	2	2	3	3	3	3	4	4	4	4	5	5	5	5
130	1	1	1	1	2	2	2	2	2	3	3	3	3	3	4	4	4	4	5	5
135	1	1	1	1	1	2	2	2	2	2	2	3	3	3	3	3	4	4	4	4
140	1	1	1	1	1	1	2	2	2	2	2	2	2	3	3	3	3	3	3	4
145	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	3	3	3	3
150	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2

and the Snowdon gauge at ground level, unsheltered. In the same period measurements at another station were undertaken with a Snowdon gauge and two Hellmann gauges placed unsheltered and well-sheltered.

As a consequence of these measurements we found

A) Well-sheltered (k=0.5)
B) Moderately sheltered (k=0.75)
C) Unsheltered (k=1)

where k is the constant to multiply entries in Table 2. Correction for more than one day is based on series of precipitation, rain intensity and wind speed ($R_{II}^{(i)}$, $I^{(i)}$, $V^{(i)}$) $i = 1, \ldots q$. To be able to calculate how much the q-total precipitation $\Sigma R_{II}^{(i)}$ is to be corrected, we proceed in this way

$$\frac{\sum R_I^{(i)} - \sum R_{II}^{(i)}}{\sum R_{II}^{(i)}} = \frac{\sum \left(\frac{\Delta R(i)}{R_{II}^{(i)}} \right) R_{II}^{(i)}}{\sum R_{II}^{(i)}} \approx \frac{\sum \hat{\Delta}(I,V)\, R_{II}^{(i)}}{\sum R_{II}^{(i)}} \equiv MK_q \qquad (7)$$

Thus estimating q-totals by means of daily corrections $\hat{\Delta}$ (I, V). From simulations based random selections of q-totals (q=10-15) on daily observations, and as a special case a calculation for 12 monthly totals, it is our experience that the estimate MK_q is slightly biased, (possibly because of skewness of distributions of the ratio R_I/R_{II}). An improved estimate can be obtained when using $MK_q \cdot 0.85$ for monthly corrections.

Solid Precipitation

The aerodynamic error in the measurements is greatest when precipitation falls as snow, since the trajectories of the snow particles compared with rain drops are influenced yet more by the wind. The error increases with decreasing temperature according to the change of the structure of snow particles. Furthermore the wind may cause that the collected snow may blow out of the raingauge funnel and thereby further contribute to the errors. When snow falls at temperature below 0°, it may drift and therefore reliable measurements for gauges placed at ground level will not be obtained. When correcting snow we therefore have to distinguish between snowfall at temperature ≥ 0° and at temperature <0°.

If snow has fallen at *temperature* ≥ 0° it may be reasonable to assume that gauges at ground level can be used as reference gauge in a similar way as for liquid precipitation and so the aerodynamic effect may also be calculated as the difference between the amounts of precipitation measured at ground level and standard height.

Facing that it is impossible to set up a model for the size of the aerodynamic effect, i.e. owing to the difficulty determining the size and shape of snowflakes we have calculated only an average without regard to particle size and wind speed on the basis of daily values.

For solid precipitation we only distinguish between sheltered and unsheltered stations, since due to interception errors well-sheltered sites will not be better than moderately sheltered.

The correction due to aerodynamic effect for unsheltered and sheltered stations is found to be 32% and 22% respectively.

No attempts have been made to determine the correction of solid precipitation at *temperature* <0°. For Denmark the following correction values due to aerodynamic effect seems to be reasonable: Unsheltered sites 50% and sheltered 30%.

For solid precipitation we have calculated wetting loss as for liquid precipitation.

Standardnormals 1931 - 60

Solid precipitation can be corrected according to above-mentioned correction values but for liquid precipitation we need data of wind speed during precipitation and rain intensity for the standard period. Data from 1959 – 74 for two places in Central Jutland and North Zealand are available. However, the temporal changes of wind speed and rain intensity has shown to be very moderate. In fact no significant differences are imposed the monthly correction values for the two places.

We are now able to correct the standardnormals of precipitation 1931 – 60 considering exposition of the station. Table 3 contains the correction values (%) for aerodynamic effect and wetting loss for the standardnormals. We emphasize that the large corrections in the winter are due to the snow. The relatively large corrections in the spring and the early summer are owing to wetting loss.

If you want correction values applying to the entire country the values corresponding to moderately sheltered sites will probably be the best estimate. By correcting the standardnormals of precipitation 1931 – 60 with these values we obtain Table 4.

It is seen that on a yearly basis the measured precipitation is to be corrected with 16% corresponding to 105 mm.

Table 3 - Corrections (%) of standardnormals of precipitation 1931-60 due to aerodynamic effect and wetting loss.

Site	J	F	M	A	M	J	J	A	S	O	N	D	Y
unsheltered	29	31	31	22	18	17	14	13	16	18	20	25	20
moderately sheltered	21	22	22	18	15	14	12	11	13	14	16	19	16
well-sheltered	18	19	20	14	12	11	9	9	10	10	12	15	12

Table 4 - Corrected and uncorrected standardnormals of precipitation (mm) 1931-60 for the entire country.

	J	F	M	A	M	J	J	A	S	O	N	D	Y
corrected	67	48	40	46	44	55	83	89	81	80	70	64	767
uncorrected	55	39	33	39	38	48	74	80	72	70	60	54	662

Table 5 - Distribution of corrected precipitation (%) for the entire country 1931-60.

	J	F	M	A	M	J	J	A	S	O	N	D	Y
rain	59	56	57	93	100	100	100	100	100	100	97	76	88.7
snow	41	44	43	7	0	0	0	0	0	0	3	24	11.3

Table 5 shows the distribution of liquid (rain) and solid (snow) precipitation 1931 – 60 for the entire country corrected according to moderately sheltered sites. The snow amounts to be about 11% of the yearly precipitation.

Statistical Errors on the Correction Values

Liquid Precipitation

Errors on correction values due to aerodynamic effect are compounded of a statistical and a shelter conditioned component. For the statistical part the 95% confidence limits for one day can be derived from confidence limits on the regression function $\Psi\ (I, V)$, leading to the following approximate expression $(C+1)e^{\pm 0.05}-1$.C being the estimate of correction (note that C is the values from Table 2 divided by 100). For more than one precipitation day the variance on the correction value, MK_q can be estimated as follows

$$\sigma^2\{MK_q \mid R_{II}^{(1)} \ldots R_{II}^{(q)}\} = \left[\frac{1}{\sum R_{II}^{(i)}}\right]^2 \sum \sigma^2\{\hat{\Delta}(I,V)\}\, R_{II}^{(i)^2} \qquad (8)$$

Now

$$\sigma^2\{\hat{\Delta}(I,V)\} = \mathrm{Var}(e^{\hat{\psi}(I,V)}) \approx \tilde{e}^{\,\sigma^2(\hat{\psi})}\,(e^{\sigma^2(\hat{\psi})} - 1)\, e^{2\hat{\Psi}(I,V)} \qquad (9)$$

which is dependent of I and V. The need for a single common value for the variance in practical work implies (Allerup and Madsen 1979) $\sigma^2\{\hat{\Delta}(I,V)\} \simeq (0.03)^2$, thus giving

$$\sigma^2\{MK_q \mid R_{II}^{(1)} \ldots R_{II}^{(q)}\} \simeq \left[\frac{0.03}{\sum R_{II}^{(i)}}\right]^2 \sum R_{II}^{(i)^2} \qquad (10)$$

Hence we get the 95% confidence limits for correction values corresponding to a total of q days

$$MK_q \pm 2\sigma\{MK_q \,|\, R_{II}^{(1)} \ldots R_{II}^{(q)}\} \tag{11}$$

Concerning monthly standardnormals 1931 – 60 no seasonal variation can be observed when analysing standard deviations for the correction values and therefore a common value of 3.3% applying to all the months can be used.

The shelter component falls in three classes. It seems reasonable letting the constant k(cf. p.[66]) vary as:

A) Well-sheltered stations: 0.4 – 0.6
B) Moderately sheltered stations: 0.6 – 0.9
C) Unsheltered stations: 0.9 – 1.0

As example the 95% confidence limits for one precipitation day, the precipitation measured at a moderately sheltered station, will be

$$0.6[(C+1)e^{-0.05} - 1] \quad \text{and} \quad 0.9[(C+1)e^{0.05} - 1]$$

Solid Precipitation

To express the error on the correction values for solid precipitation at temperature above 0°C we may use the standard deviation as follows

$$E = \frac{1}{2}(e^{\bar{x}+s} - 1 - (e^{\bar{x}-s} - 1)) \tag{12}$$

where $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} \ln(R_{Ii}/R_{IIi})$

and s is the standard deviation in the distribution of $\ln(R_{Ii}/R_{IIi})$.

For *unsheltered* stations the standard deviation of the correction values for daily amounts of precipitation is 34% and for *sheltered* 22%.

For a period of n (independent) precipitation days the error is $E/\sqrt{n}$.

Conclusion

The essential systematic errors on point precipitation measurements are due to aerodynamic effect and wetting loss – the first mentioned being the far most significant factor. It is possible to correct precipitation amounts originating from a single rainfall event up to monthly sums.

As concerns the aerodynamic effect a statistical model based on daily precipitation amounts has been constructed. This model relates the ratio between liquid precipitation measured at ground level and at standard height to wind speed during rain and rain intensity.

Analysis of the conditions with sheltered stations was resulting in a three-class definition of the degree of shelter for which correction factors have been calculated.

It has throughout been an important part of the analysis to estimate variances on the correction values, and this has been done for the aerodynamic effect.

This model is well suited for automatic weather-stations where simultaneous measurements of wind speed and rain intensity are performed.

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