Local rainfall variations over small, flat, cultivated areas

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ABSTRACT

An account is given of precipitation measurements on small, flat, cultivated areas carried out between 1957 and 1960 by means of very dense networks of precipitation stations. The precipitation distributions on single rainfalls were found to vary within large ranges. Clear distribution patterns appeared in the precipitation not only when the precipitation fell from convective clouds but also after frontal precipitation with almost no convection. The results from occasions with almost no convection indicated a close connection between the direction of the wind and the precipitation distribution. Within the investigation area the precipitation increased along the direction of the wind. When considering accumulated precipitation amounts the percentage variations were considerably lower than those which might occur on single rainfalls.

Introduction

Many investigations have shown that the precipitation distribution on a single rainfall may vary considerably even within small areas (e.g. Balchin & Pye 1948; Bergeron 1960, 1968, Geiger 1959, Huff & Neill 1957, Linsley & Koehler 1951, Radomski 1962, Stout 1960, Styber 1961).

From 1957 to 1959 an investigation was carried out at Ultuna in south-eastern Sweden (17°40′ E; 59°49′ N) concerning the precipitation distribution over small flat cultivated areas by means of very dense networks of precipitation stations. Measurements were made after almost every rainfall, the purpose being to separate, to the extent possible, the non-convective and convective precipitation. Fig. 1 shows the precipitation networks. The investigation was started in May 1957 within an area of approximately 1 km^2 [area 1 Fig. 1*a*] and was enlarged in July 1957 to about 2.5 km^2 [area 2 Fig. 1*a*]. In 1958 and 1959 the area used was further extended. Including wooded land it ranged over an area of about 11 km^2 [area 3 Fig. 1*b*]. The dots in Fig. 1 mark the precipitation stations and the distance between the gauges within the areas 1–3 was 300, 300–600 and 300–1000 m respectively.

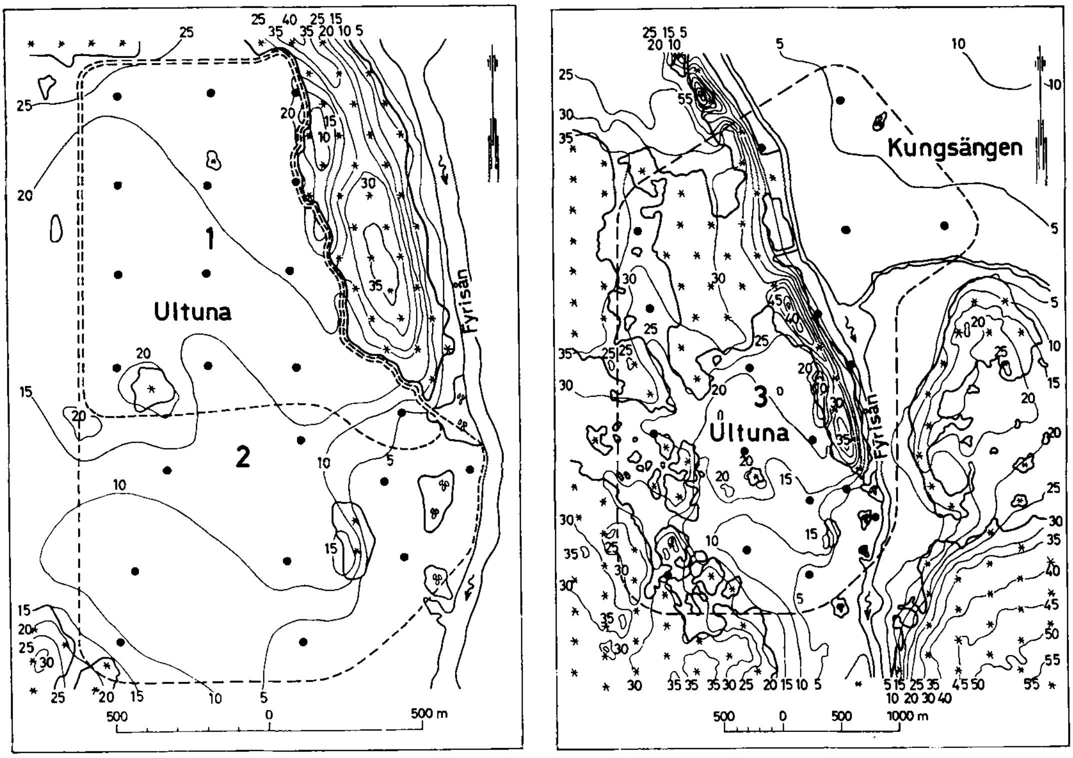
Description of the area of the investigation

The area of investigation (Fig. 1) is situated just south of the town of Uppsala. A ridge, the Uppsala esker, and the river Fyrisån separate two principal parts; the Kungsängen area in north–east and the Ultuna plain in the south and south–west with an average height above sea-level of 5 and 15 m respectively. While the Kungsängen area is almost flat, the Ultuna plain rises to the west and north from about 5 to 25 m height. The Uppsala esker reaches here a height of about 40 m.

The surroundings to the north–east are plain country, to the south–east woodland, with a maximum height of about 60 m. To the south the Ultuna plain continues, and in the sector south–west to north the woodland reappears rising to a height of about 35 m. Further to the north–west lies the town of Uppsala.

Methods

A gauge at an open site catches less rain the higher it is placed over the ground, owing to influences caused by the wind (e.g. Jevons, 1861; Koschnieder, 1930, 1933). Varying wind conditions at the precipitation stations in a network with gauges placed above the ground



(a) (b)

Fig. 1. General map of the area of the investigation. Level curves have an equidistance of 5 m. Wooded area is indicated by the conventional signs for forest (rings = deciduous forest, stars = pine forest). Precipitation networks: (*a*) in 1957; (*b*) in 1958 and 1959.

and exposed to the wind may adversely affect the comparability of the measured precipitation values. Jevons & Koschmieder also point out that the most correct measurements of rainfall are obtained when the orifices of the gauges are level with the soil-surface.

When establishing the precipitation networks the author intended to place the gauges with their orifices level with the soil-surface. However, it soon became clear that such an arrangement was not convenient, as it required a continuous cutting of the vegetation around several gauges. Instead, the gauges at such places were placed with their orifices in the surface of the vegetation. That this arrangement considerably diminished the influences caused by the wind was shown by the following investigation. One gauge was placed level with the soil-surface, one in the surface of grass 40–55 cm in height and one at a height of 50 cm freely exposed to the wind but furnished with a Nipher wind shield. Measured at the soil-surface 28 rainfalls gave a total precipitation of 284 mm. The amounts obtained with the gauge in the grass and with the one freely exposed to the wind were 2 and 5 per cent less.

The measurement of the precipitation after almost every rainfall required the field work to be done in the shortest possible time, since the periods of dry weather could be very short. To reduce the time on the field the transport between the precipitation stations was made by car. After a rainfall the gauges were exchanged and furnished with tightly fitting plastic hoods to prevent evaporation during the transport. The measuring of the precipitation amounts was then made by weighing in the laboratory. A precision balance of a sensitivity of 10 mg was used for the weighing.

Precipitation maps were drawn for every observed rainfall. The rainfalls were divided into the following classes.

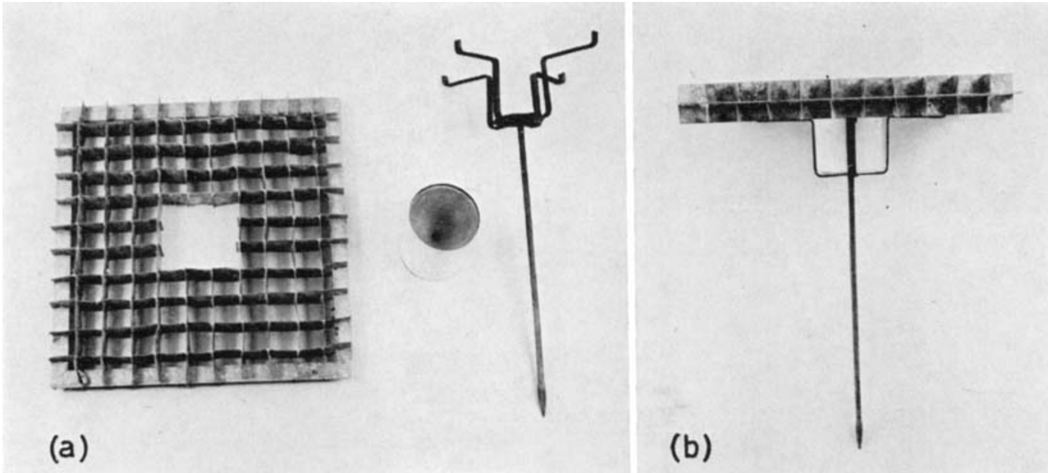


Fig. 2. Photographs of the measuring device: (*a*) unmounted; (*b*) mounted.

1. Precipitation, which had fallen on occasions with almost no convection.

2. Frontal precipitation, which had fallen on occasions with distinct signs of convection.

3. Precipitation, which according to *direct observations* of the clouds had fallen only from convective clouds (Cumulonimbus).

To determine if a rainfall should be referred to class 1 or 2, observations of the clouds were used in combination with studies of the chart from an automatic recording gauge. If the direct studies of the clouds indicated that the precipitation had fallen both from convective and non-convective clouds it was assigned to class 2. The same was done with the precipitation on occasions when the curve on the chart from the automatic recording gauge showed great and varying precipitation intensity. The rest were referred to class 1.

Measuring device

The gauges used in the networks were made out of standard tins for motoroil made of 0.2 mm tin plate, about 18 cm in height and with a diameter of 10 cm. The tins were cut off a few mm below the lids, which resulted in very sharp edges and the outsides were painted white to diminish heating from the sun and to prevent corrosion. Plastic funnels with a diameter of 10 cm were placed inside the tins about 1 cm below the edges to get a further decrease in the evaporation from the collected precipitation (Fig. 2). The question arose, if placing the funnels only 1 cm below the edges of the tins would increase the risk for outsplash. Compairing measurements from the type described above placed level with the soil-surface, with measurements from a SMHI-gauge placed identically, indicated no significant differences in rainfall. The SMHI-gauge is used by the Swedish Meteorological and Hydrological Institute. In this gauge the funnel is placed about 13 cm below the rim.

Measurements of the variation in the catchment areas showed, that the difference between the highest and the lowest value obtained was 0.6 per cent of the mean. A test of the plastic funnels as to their usefulness in preventing evaporation was also made. The evaporation at strong sunshine and high wind from water poured into the gauge was for a gauge placed at the soil-surface, about 0.01 mm per hour, for a gauge placed in the vegetation (grass 50 cm in height) about 0.02 mm per hour.

The gauges were mounted on vertically moveable stands made of iron rods in four lengths, 0.30 m, 0.50 m, 1.00 m and 1.50 m (Fig. 2).

On the stands could be placed a grid 0.45 m square made of galvanized iron plate strips 0.2 mm thick and 5 cm broad (Fig. 2). It was a modification of a device by Koschmieder (1933) constructed to diminish splashing into gauges having their orifices level with the soil-surface.

Gauges with their rims level with the soil-

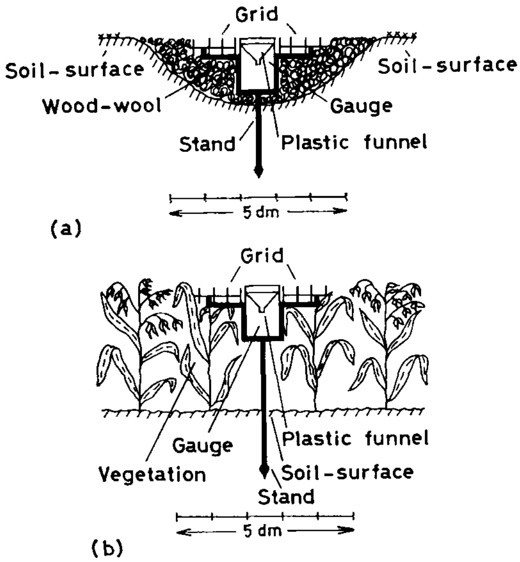


Fig. 3. The arrangement of the gauges: (*a*) level with the soil-surface; (*b*) in the surface of the vegetation.

surface were mounted in pits and surrounded with woodwool after which the grids were fixed [Fig. 3*a*]. The filling of the empty spaces in the pits with woodwool was intended to prevent vertical movements of the air around the gauges.

Gauges put up in vegetation were also furnished with grids [Fig. 3*b*]. In this case they served as shelter against blades of grass, ears of corn etc., which, when precipitation fell in a high wind, could be bent over the gauges, thereby causing errors in the measurements.

Comparability of the measured precipitation values

When using a number of gauges distributed within a given area differences arise in the collected precipitation values irrespective of the extent of the area. These differences may be caused by:

1. Errors of catch originating partly from incorrect measurements of that precipitation, which has passed through the orifices of the gauges, partly from disturbing influences on the precipitation distribution caused by the measuring device.

2. A *real* variation in the precipitation distribution, which may probably occur even within very small areas.

Item 1 includes that part of the variation which, for example, is caused by errors in the actual measurement of the precipitation (in this case incorrect wieghing), evaporation, splashing and influences by the wind.

In the present investigation, however, the aim was not to make absolute measurements, but to get comparable precipitation values. This called for approximately the same error of catch in all the measured values on an observed rainfall. Because of the precautions taken it was reasonable to assume that differences arising from evaporation and splashing were relatively small and fairly constant for all precipitation stations. Also variations caused by differences in the arrangement of the gauges (in vegetation or level with the soil-surface) appeared to be moderate but somewhat varying in magnitude. Comparisons between precipitation values obtained with, on the one hand gauges in the vegetation, and on the other hand with adjacent gauges at the soil-surface, resulted in the former giving 2 per cent less than the latter. This is a confirmation of the result from the investigation earlier described (see page 675).

The discussion above indicates that the precipitation values are comparable; a condition for being able to estimate real variations in the precipitation distribution (item 2).

Observations within a network area can be used to estimate the total variation within that area. The description of this variation is limited down to a scale which is roughly twice the distance between the grid points. Variations of smaller scales can be described by a smaller but denser network and may conveniently be called micro-variations. On the other hand such small networks exclude the study of variations of larger scales. This also means that if the variation over the larger area exceeds the micro-variation, there exists a provable real variation in the precipitation distribution over the larger area.

From this it is clear that determinations of both the total and the micro-variation on single rainfalls are very useful when estimating possible real variations in the precipitation over a given area. In that case simultaneous measurements are required also by one or more very small dense but representative networks.

Such additional measurements, however, were not carried out to the extent desired in the present investigation. To get a picture of the

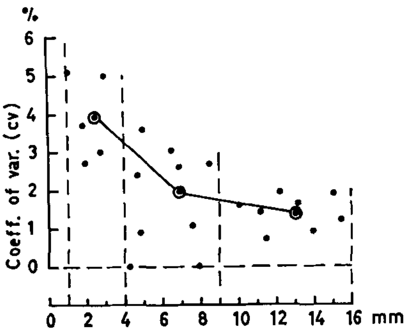


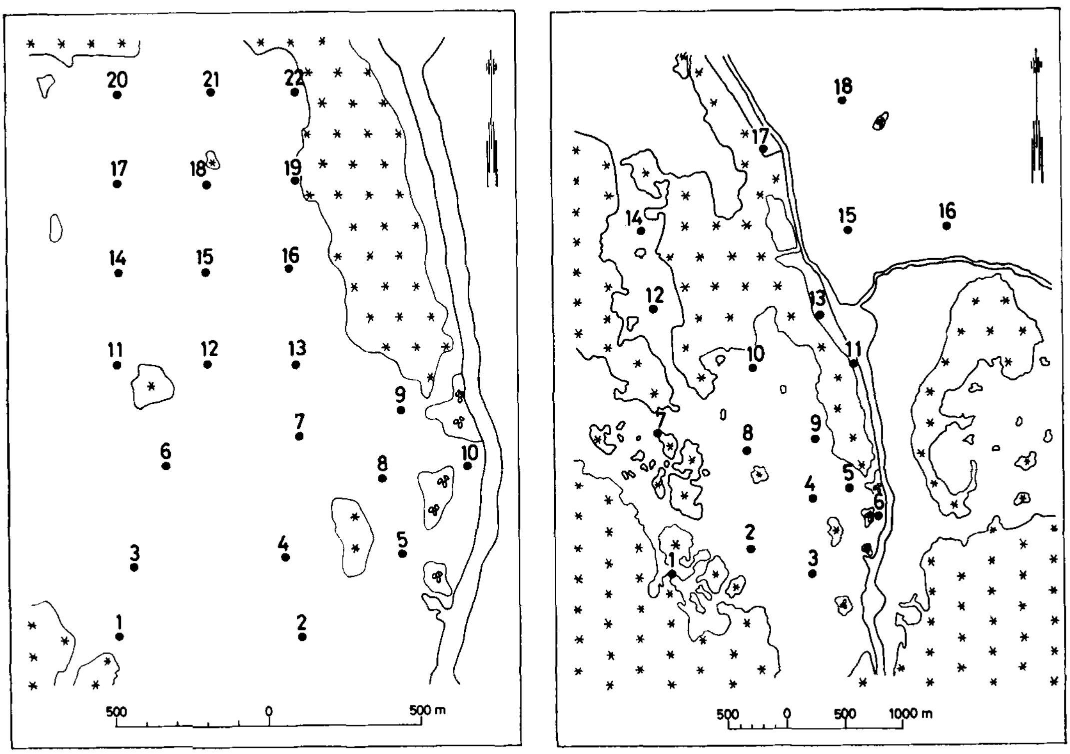
Fig. 4. Variations in the precipitation over a very small area on single rainfalls. Area 20 m² (lawn), number of gauges 5, orifices level with the soil-surface. Means of variations are inserted for the intervals 1–4, 4–9 and 9–16 mm.

variations in the precipitation over a very small area the author made a study on a 20 m² lawn by means of 5 gauges. Since the grass was kept very short the gauges always had their orifices level with the soil-surface. As a measure of the variation in the precipitation the coefficient of variation CV (the standard deviation divided by the mean) in per cent was used. In Fig. 4 are inserted the values of CV in per cent for 22 rainfalls together with the means in the intervals 1–4, 4–9 and 9–16 mm. They are 3.9, 1.9 and 1.4 respectively.

The means of CV for the intervals in Fig. 4 could be used in a comparative study together with values of CV presenting the total variations in the precipitation over larger areas and the precipitation maps (see page 676). This is clear from the following discussion.

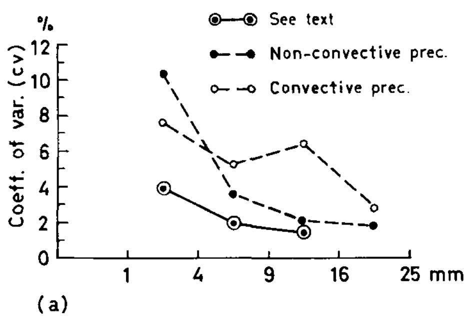
If the values of CV for larger areas are of the same order as for a very small area, experience shows that it is difficult to draw significant isohyets on precipitation maps for these areas. Not until the values of CV have risen to a certain level is it easy to draw such isohyets, which indicates that a systematic geographic variation exists.

The comparative study showed that it was easy to draw isohyets on the maps in all cases



(a) (b)

Fig. 5. Numbered gauges used: (*a*) in 1957; (*b*) in 1958 and 1959.



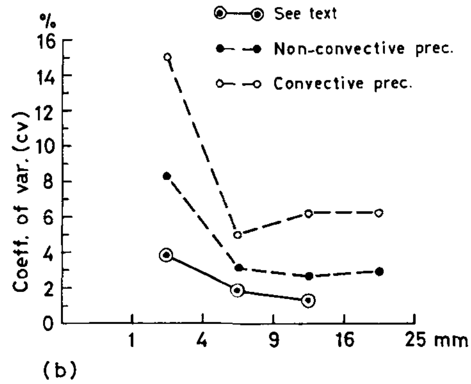


Fig. 6. Mean variation in non-convective and convective precipitation within different intervals for two small flat cultivated areas. Period May–October 1957. Bottom curve, corresponding means for both non-convective and convective precipitation taken from a study on a lawn (area 20 m², 5 gauges): (*a*) area 0.4 km², 4 gauges; (*b*) area 1.0 km², 12 gauges.

where the total variations were higher than the mean micro-variations for the intervals in question. It was a further confirmation of the comparability of the measured precipitation values.

Results

Variations in the precipitation distribution

The gauges have been numbered according to Fig. 5 and the coefficient of variation CV in per cent is used as a measure of variation.

Fig. 6 shows means of CV in different precipitation intervals for occasions with non-convective (prec. class 1) and convective precipitation (prec. classes 2 and 3) obtained from measurements May–October 1957 within two areas of 0.4 and 1.0 km² respectively. The gauges used within the former were nos. 12, 13, 15, 16 and within the latter nos. 11–22 [Fig. 5*a*]. Number of rainfalls with or without convection which are the basis of the means of CV are registered in Table 1.

As comparison Fig. 6 also contains the means of CV for the intervals in question from the investigation on the lawn (see page 677).

In spite of the few precipitation values on which the means of CV are based the diagrams above show specific features. The mean variations in the precipitation are obviously higher than the corresponding mean micro-variations from the study on the lawn. It is evident that the variations decrease with increasing precipitation and that they are greatest on rainfalls with convection. The variation also seem to increase with the size of the area.

In Table 2 the number of observed rainfalls May–October 1957 is given with clear distribution patterns in the precipitation over the areas of 0.4 km² and 1.0 km² respectively. According-

Table 1. *Number of rainfalls with or without convection distributed on different precipitation intervals.* (Period May–October 1957)

Prec. intervals, mm	Non-convective prec.	Convective prec.
1.0–3.9	3	7
4.0–8.9	3	8
9.0–15.9	3	4
16.0–24.9	2	3
Total	11	22

Table 2. *Number of observed rainfalls with or without convection exhibiting clear distribution patterns in the precipitation over the area of 0.4 km² and 1.0 km² respectively.* (Period May–October 1957)

Area, km²	Non-convective prec.	Convective prec.
0.4	5	18
1.0	7	22

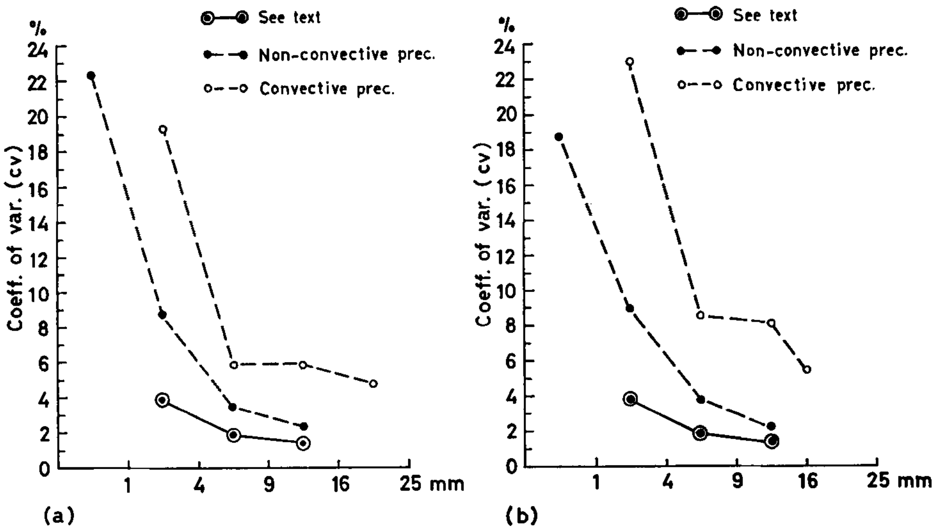


Fig. 7. Mean variation in non-convective and convective precipitation within different precipitation intervals for two small flat cultivated areas. Periods June–November 1958, September–October 1959. Bottom curve, corresponding means for both non-convective and convective precipitation taken from a study on a lawn (area 20 m², 5 gauges): (*a*) area 1.0 km², 4 gauges; (*b*) area 2.5 km², 8 gauges.

ly it was easy to draw isohyets on the precipitation maps.

Concerning the area of 1.0 km² about two-thirds of the total number of rainfalls without convection showed clear patterns in the precipitation distribution (Tables 1 and 2).

Fig. 7 presents corresponding diagrams, as in Fig. 6, for two areas of investigation in 1958 and 1959, 1.0 and 2.5 km² respectively. The gauges used within the area of 1.0 km² were nos. 4, 5, 8, 9; and within the area of 2.5 km² nos. 2–6, 8–10 [Fig. 5*b*, page 677]. The number of rainfalls with or without convection distributed on different precipitation intervals are given in Table 3.

Table 3. *Number of observed rainfalls with or without convection distributed on different precipitation intervals.* (Periods June–November 1958, September–October 1959)

Prec. intervals, mm	Non-convective prec.	Convective prec.
0.0–0.9	3	0
1.0–3.9	17	8
4.0–8.9	8	8
9.0–15.9	2	8
16.0–24.9	1	6
Total	31	30

The number of observed rainfalls in 1958 and 1959 with obvious variations in the precipitation distribution over the areas of 1.0 km² and 2.5 km² respectively are given in Table 4.

From Tables 3 and 4 it is clear that two-thirds of the total number of rainfalls without convection showed clear patterns in the precipitation distribution over the area of 1.0 km². The percentage number is approximately the same as was obtained for an equal area in the investigations 1957 (see above).

Fig. 7 shows the relation between CV and precipitation for the cases just discussed. CV for convective precipitation seems to increase with the size of the area whereas CV for non-convective precipitation is hardly affected.

All areas in the investigations, now given an

Table 4. *Number of observed rainfalls with or without convection exhibiting obvious variations in the precipitation distribution over the areas of 1.0 km² and 2.5 km² respectively.* (Periods June–November 1958, September–October 1959)

Area, km²	Non-convective prec.	Convective prec.
1.0	20	27
2.5	26	28

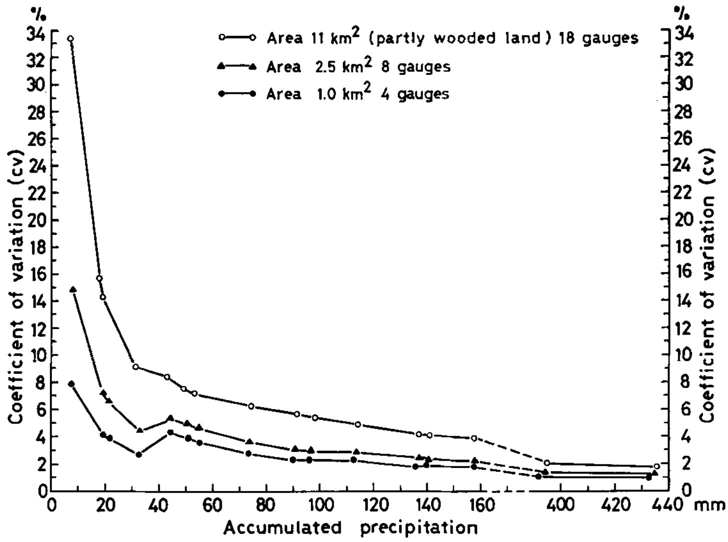


Fig. 8. Variation in the precipitation with accumulated precipitation amounts within three areas of different size. Periods June–November 1958, September–October 1959.

account of, had relatively regular circumferences containing practically no wooded hills. Results from investigations in 1958 and 1959 obtained for two areas partly including wooded land, where no precipitation measurements have been made were in accordance with the results discussed above. The first area extended over cultivated country 4 km², wooded land 2 km²; the second area cultivated country 7 km², wooded land 4 km², total 6 and 11 km² respectively. The gauges used were within the first area nos. 1–10, 12, 14 and within the second area nos. 1–18 [Fig. 5*b*, page 677].

The main feature was the increase of the means of CV with the increase in area. This increase was much more clear for the convective precipitation than for the non-convective.

Fig. 8 shows that CV decreases very rapidly when considering accumulated precipitation amounts. It means that a single rain gauge will represent larger and larger areas as precipitation amounts are added. This is of considerable interest when interpreting records from automatic recording rain gauges. Rapid changes in rainfall recorded with such gauges will apparently represent rather small areas.

Precipitation maps

Another and perhaps more easily understandable way of presenting the variations in the precipitation is offered by the precipitation maps (Sandsborg, 1966). For want of space only a few maps will be discussed here. Fig. 9 clearly demonstrates the great differences in the variation which may occur between occasions with or without convection. It is a common view that precipitation falling on occasions with almost no convection is uniformly distributed over large areas. However, Figs. 9*b* and *d* indicate the contrary: an obvious variation in the precipitation also within small areas.

The author noticed that the precipitation on occasions with almost no convection (prec. class 1, see page 678) and at the same time constant wind directions increased along the direction of the wind. See figures 10*a* and *b*. However, rainfalls with very nearly constant wind directions occurred less frequently; it sometimes happened that the wind veered up to 90° or more. Because of this, occasions with wind directions within the sectors N–E, E–S, S–W and W–N have been collected. In Fig. 11 results from the sectors N–E and E–S are presented. The number of rainfalls, forming the basis of the maps in Fig. 11, are for *a* 5, for *b* 7. The differences between the highest and the lowest value in per cent of the mean are considerable; in Fig. 11*a* about 30 per cent, in Fig. 11*b* about 21 per cent.

The map *a* in Fig. 12 has been drawn after

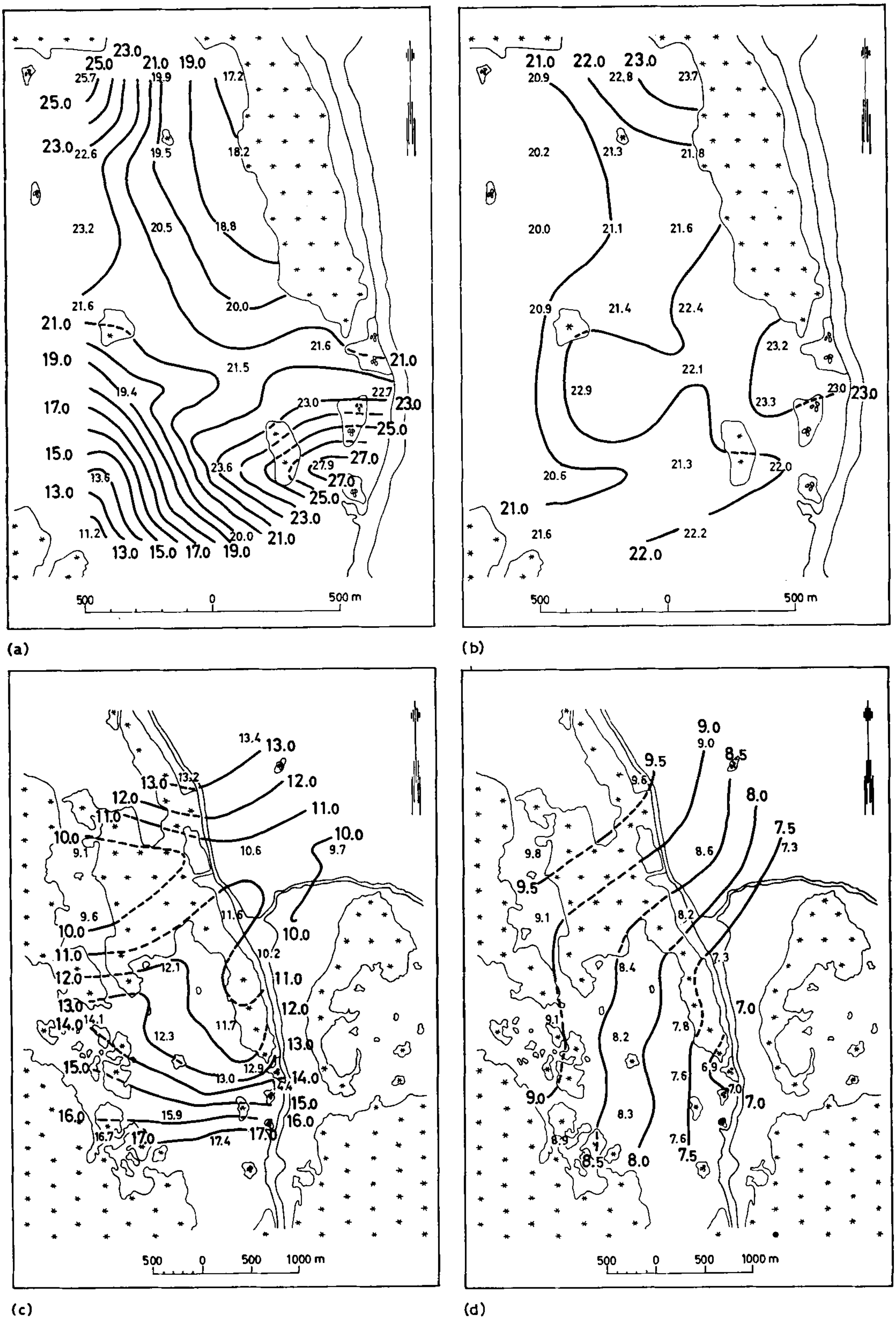
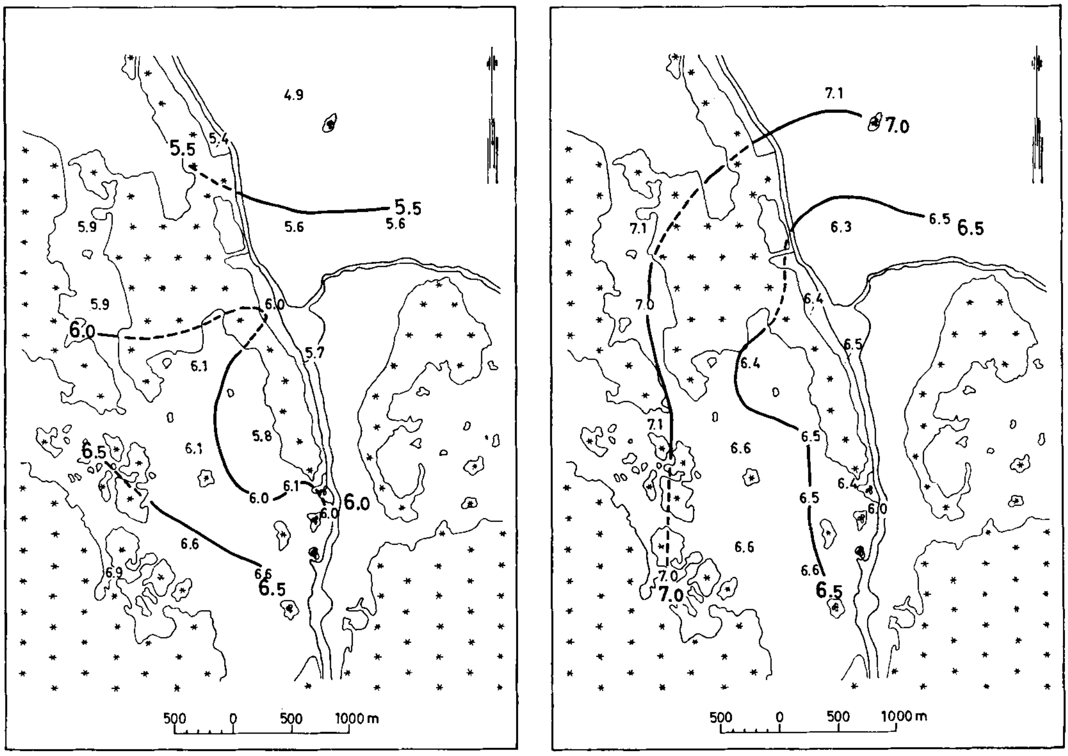


Fig. 9. Precipitation distributions in mm after rainfalls assigned to: (*a*) frontal precipitation with some convection (prec. class 2); (*c*) strong convection (prec. class 3), and (*b*) and (*d*) almost no convection (prec. class 1). The cases shown are: (*a*) 16 and 17 September 1957, calm; (*b*) 3 and 4 October 1957, wind NW, mean wind velocity 9.0 m over the ground 3.8 m per sec; (*c*) 31 July 1958, wind S, corresponding mean wind velocity 3.6 m per sec; (*d*) 7 October 1958, wind SE. corresponding mean wind velocity 1.3 m per sec.



(a) (b)

Fig. 10. Precipitation distributions in mm after rainfalls with almost no convection (prec. class 1): (*a*) wind N–NE, mean wind velocity 9.0 m over the ground 2.4 m per sec; (*b*) wind S–SE, corresponding mean wind velocity, 4.8 m per sec. The cases shown are: (*a*) 16 October 1958; (*b*) 27 October 1958.

summing of the precipitation values for a total of 62 rainfalls June–November 1958, September–October 1959. They are distributed according to the following; 31 cases almost no convection, 21 cases frontal precipitation with some convection and 9 cases with strong convection. In addition one occasion is added where the precipitation at first fell as snow and gradually changed into rain. Fig. 12*a* shows a relatively small variation in the precipitation values. The difference between the highest and the lowest value in per cent of the mean is about 6 per cent. However, the precipitation distribution is not incidental; a gradient can in fact be noted from east to west.

Fig. 12*b* describes the distribution after summation of the precipitation values for all obtained occasions with almost no convection (31 in number, see above). The variation is fairly small, corresponding percentage value is about 7. An obvious precipitation gradient appears also here, from south–east to north–west.

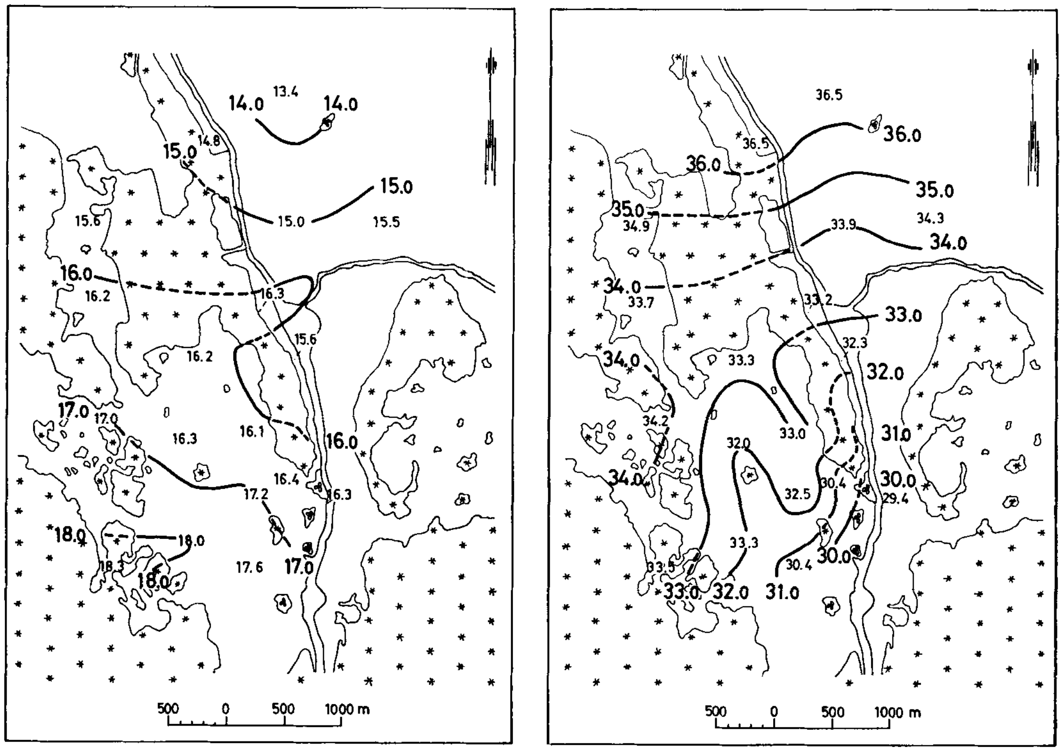
Conclusions

Conclusions from the investigation may be drawn as follows:

(*a*) The precipitation distribution over small

Fig. 11. Precipitation distributions in mm after summation of the precipitation with almost no convection (prec. class 1): (*a*) wind within the sector N–E, number of rainfalls 5; (*b*) wind within the sector E–S, corresponding number 7.

Fig. 12. Precipitation distributions in mm after summation of the precipitation. Periods June–November 1958, September–October 1959; (*a*) total precipitation, number of rainfalls 62; (*b*) 31 cases of almost no convection.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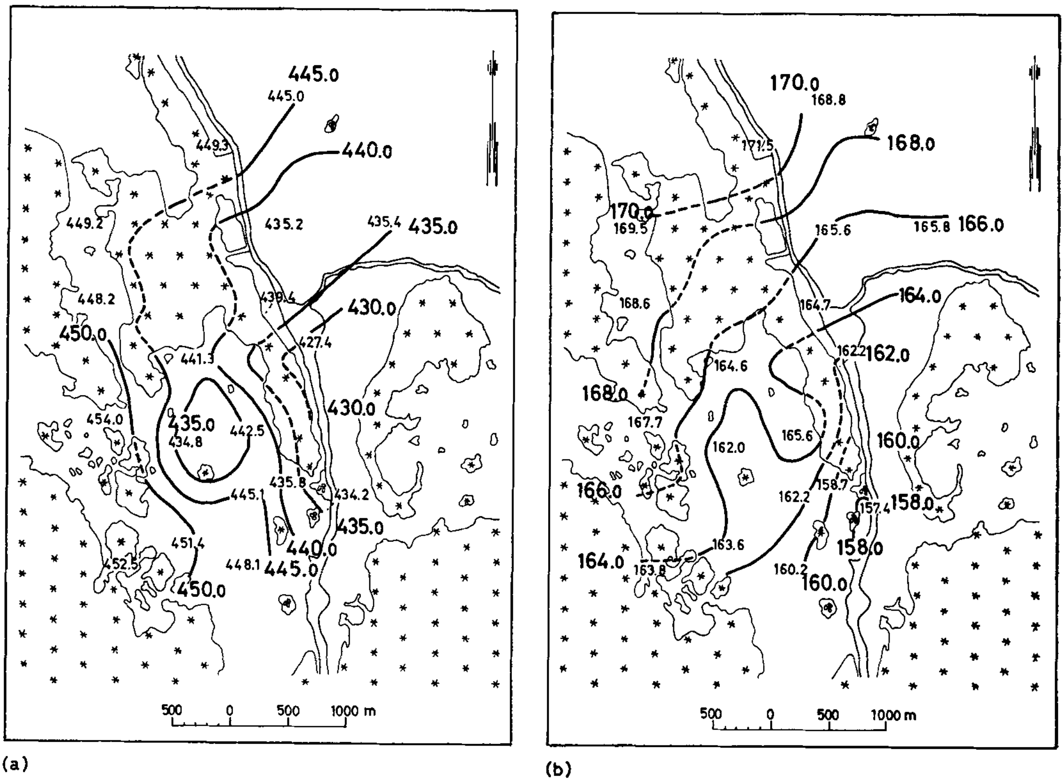
(a)

(b)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(a)

(b)

flat cultivated areas on a single rainfall may vary considerably, not only with precipitation falling from convective clouds, but also with frontal precipitation with almost no convection.

(*b*) The results indicate a close connection between the direction of the wind and the precipitation distribution on occasions with almost no convection. Within the investigation area the precipitation increases along the direction of the wind.

(*c*) When considering accumulated precipitation amounts the percentage variations are considerably lower than those which may occur on single rainfalls.

(*d*) The determinations of both the total and the micro-variations on single rainfalls are very useful when estimating possible real variations in the precipitation over a given area. For these estimations simultaneous measurements are required also on very small dense but representative networks to obtain reference values of the percentage variations.

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ЛОКАЛЬНЫЕ ВАРИАЦИИ ВЫПАДЕНИЯ ДОЖДЯ НАД НЕБОЛЬШИМИ ПЛОСКИМИ ВОЗДЕЛАННЫМИ ОБЛАСТЯМИ

Даётся обзор измерений осадков на небольших плоских возделанных областях, проведенных между 1957 и 1960 г. г. с помощью очень густой сети осадкомерных станций. Распределения осадков в одном дожде оказались меняющимися в больших пределах. Отчётливые структуры распределений появляются в осадках не только при дождях из конвективных облаков, но также и после фронтальных осадков, когда конвекции почти нет. Результаты по случаям почти полного отсутствия конвекции указывают на тесную связь между направлением ветра и распределением осадков. Внутри исследуемых областей осадки увеличиваются в направлении ветра. При рассмотрении накопленных сумм осадков процентные вариации оказались значительно ниже тех, которые могут иметь место в одном дожде.