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THE INFLUENCE OF TOPOGRAPHY AND OROGRAPHY ON THE PRECIPITATION PATTERNS IN THE NETHERLANDS

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1. INTRODUCTION

The influence of the topography and the orography on the precipitation pattern in a certain area, such as the Netherlands, depends to a very high extent on the wind direction. It is of course well known that in addition precipitation patterns are also affected by other factors, as there are the distribution of convective cells, the presence of condensation nuclei, etc. The influence of the latter factors makes it difficult to draw conclusions about the influence of the topography and orography by studying the patterns originating from individual days. However, by grouping cases according to wind direction the influence of the wind direction will dominate over that of the other factors, which in this way will be more or less eliminated.

The present study describes the distribution over the Netherlands of the number of rainy days and of the then observed precipitation amounts for various wind directions. As the number of days with rain in the various wind direction groups were too small no attempt was made with respect to the differentiation of the wind speed.

2. EXAMINATION OF THE DATA

Observations, made during the period 1901–1954, from 24 rain-stations with sufficiently long records have been used in our investigation.

These stations are the following:

1. Utrecht
2. Den Helder
3. Leeuwarden
4. Groningen
5. Maastricht
6. Vlissingen
7. Hoofddorp
8. Putten
9. Roermond
10. Helmond
11. Heusden
12. Scheveningen
13. Lemmer
14. Velp
15. Winterswijk
16. Kerkwerve
17. Hoorn
18. West-Terschelling
19. Oudenbosch
20. Dwingelo
21. Ter Apel
22. Heerde
23. Denekamp
24. Axel.

The observations of a few additional stations, for instance Noordgouwe, Giethoorn and Emmen, have been used for checking certain conspicuous details in a number of the patterns. See fig. 1.

Precipitation observations were made every day at 08.40 MET. It is not known during which period of the preceding 24 hours the precipitation occurred; information about the wind direction during the precipitation period(s) is also lacking.

In order to obtain a reliable relationship between topography or orography and the rainfall patterns only those days in which the wind direction remained rather steady were used in this investigation. The following criterion was introduced for selecting days with sufficiently steady wind direction. A day belonged to a certain wind direction group when 20 or more out of the 24 hourly observations of that day at De Bilt fell within a range of 90 degrees between 0° and 90°, 45 and 135°, 90 and 180° etc. Overlapping wind direction groups were studied; this was necessary in order to obtain a sufficient number of cases representing the main points of the compass.

The wind direction at De Bilt was considered sufficiently representative for the wind direction over the whole area. In order to investigate whether this is indeed the case the wind direction observations of De Bilt were compared with those of Den Helder, Vlissingen, Groningen and Maastricht during the months March, June, September and December of an arbitrary year. It appeared that the hypothesis that there exists no agreement between the distribution over the wind directions at De Bilt and the distribution at any of the other stations had to be rejected. This implies that a constant wind direction at De Bilt is apparently a reliable indication of a constant wind direction in the same group elsewhere in the Netherlands.

The above mentioned criterion made it possible to assign to 72% of the total number of days during the period 1901-1954 one, or rather two, wind direction groups. The distribution of the number of cases over the various wind direction groups within the seasons is indicated in the following table.

TABLE 1

Number of days in various wind direction groups

	N-E	NE-SE	E-S	SE-SW	S-W	SW-NW	W-N	NW-NE
Spring (March, April, May)	586	292	238	344	622	482	394	407
Summer (June, July, August)	359	127	122	240	830	623	547	345
Autumn (Sept., Oct., Nov.)	374	350	429	646	895	441	258	167
Winter (Dec., Jan., Febr.)	400	352	426	757	958	532	226	126

For each wind direction group and for each season the percentage of wet days (the rain frequency) and the average amount of precipitation were computed and maps demonstrating the distribution of these quantities have been constructed. It should be noted that at a certain station a day was called a "wet day" when the precipitation observation of 08.40 MET indicated a precipitation amount over the preceding 24 hours of 0.3 mm or more.

In order to investigate the significance of the differences in frequencies and amounts the observational material was divided into two groups, one of them containing the even and the other the odd years. KENDALL's test (11) was then applied to these two samples; the level of significance was taken at 5%.

The results of these tests for various wind direction groups and for various seasons are given in table 2. The left hand side of each column refers to rain frequencies, the right hand side to precipitation amounts; S indicates significant, NS non-significant.

TABLE 2

Results of the test of Kendall

	N-E	NE-SE	E-S	SE-SW	S-W	SW-NW	W-N	NW-NE
Spring	S NS	S S	S S	S S	S S	S S	S S	S S
Summer	S NS	NS NS	NS S	S S	S S	S S	S S	S S
Autumn	S S	S NS	S S	S S	S S	S S	S NS	S NS
Winter	NS S	S NS	S S	S S	S S	S S	S NS	S S

Significant differences may be caused by the topography or the orography of the earth's surface. They may, however, also result from the fact that the observations have been grouped according to wind directions and consequently to the direction of the pressure gradient. Since rain frequency and precipitation amount usually increase with decreasing pressure, the distribution of these quantities will show systematic differences in the direction of the pressure gradient.

A non-significant result indicates that there are no local differences or it may be caused by the sampling effect.

KENDALL's tests show that in most cases the differences in rain frequencies and precipitation amounts are significant.

3. THE RELATIVE RAIN FREQUENCY AND THE AVERAGE AMOUNT OF RAIN AT VARIOUS WIND DIRECTIONS

Figures 2 to 33 give for each station the relative rain frequency, i.e. the rain frequency expressed in percent, and the average amount of precipitation in mm. The numbers between brackets are only given if the number of observations is different from that mentioned below the figures. The figures also contain isolines, as for the frequencies every 5 percent and as for the amounts every 0,2 mm.

3.1 GENERAL REMARKS

In some cases the patterns of the rain frequencies are more pronounced than those of the amounts. BRAAK [4] has already indicated that less careful observers sometimes forget to measure the precipitation on days with little rainfall. This then would lead to too low values of the frequency without however influencing the average precipitation in an appreciable way. It is clear from the figures that for instance the stations Kerkwerve, Lemmer and Ter Apel have a considerable influence on the frequency pattern. For this reason the observations of these stations were, for the January-months of the years 1932-1940, compared with the observations of neighbouring stations, namely with respectively Noordgouwe, Giethoorn and Emmen.

During this period the mean absolute rain frequency of the 21 "wet" stations was 152 with a standard deviation of 9.5. From this it may be concluded that the chance that an arbitrarily chosen station in the Netherlands shows a rain frequency $\leqq 136$ is less than 5%. The absolute rain frequencies of Noordgouwe, Giethoorn and Emmen are 132, 131 and 130 respectively. This implies that these stations must be considered not belonging to the universe of the 21 "wet" stations. It seems very unlikely that all three stations are inaccurate and it seems more obvious that the low frequencies of Noordgouwe, Giethoorn and Emmen are real, thereby corroborating the low frequencies of the stations Kerkwerve, Lemmer and Ter Apel.

The conclusion that the differences in the absolute rain frequency are not caused by differences in the reliability of the observers was also drawn by BRAAK [4], who observed that the stations with a low rain frequency showed a systematic distribution.

If indeed the low frequencies of Kerkwerve, Lemmer and Ter Apel are real, then there must exist a large physical cause for its phenomenon. It may then be assumed that this cause has a relatively large influence on small rainfalls, so that the frequency patterns are considerably influenced and that the patterns of the amounts undergo less influence.

3.2 DISCUSSION OF PATTERNS FOR VARIOUS WIND DIRECTIONS

Wind direction N-E (fig. 2-5)

Winds between N and E bring little precipitation activity. The figures show that there is a distinct annual variation, in particular in the rain frequency in the northern part of the Netherlands. This is apparently connected with the annual variation of the surface temperature of the North Sea, which is traversed by the air coming from the N tot NE and has a stabilizing influence on the air masses in spring and summer. The IJsselmeer apparently exercises a lowering influence on frequency and amount in various seasons. In summer the influence of the Veluwe on the precipitation amounts can be found.

The rain activity increases in general towards the south presumably in connection with the decreasing pressure from NW to SE.

The systematic difference between Vlissingen and Kerkwerve, especially in the rain frequency, is noted.

Wind direction NE-SE (fig. 6-9)

Winds between NE and SE carry the smallest rain activity. The figures show that the rain frequency and the rainfall increase towards the south, which may be a result of the decreasing pressure.

There are rather conspicuous differences in the rain frequency during the winter in Zeeland. Furthermore there is a tendency towards decreasing rain activity in the environment of the IJsselmeer. In summer the influence of the Veluwe on the precipitation amounts can again be found.

Wind direction E-S (fig. 10-13)

The precipitation frequencies and amounts clearly show the effect of the pressure by an increase in southwesterly direction. Especially the rain frequency pattern of all seasons, except the summer for which the test of KENDALL was not significant, show a rather characteristic pattern, marked by low frequency values in Limburg and especially in the southeast of Drente and Overijssel, then a belt of high frequencies along the line Velp-Dwingelo and again lower frequencies in the vicinity of the IJsselmeer.

There is also an indication that in the northwest the rain activity increases in the direction of the North Sea. The rain amounts show the influence of the Veluwe, especially in summer.

Again the large difference between the frequency values of Vlissingen and Kerkwerve is striking.

Wind direction SE-SW (fig. 14-17)

The rain frequencies are relatively low in the lee-side of the Ardennes. They increase over the Veluwe. There is again a lower rain activity near the IJsselmeer and in the environment of Ter Apel; in Friesland the rain activity generally increases from the south to the north.

The rain amounts also show low values in the south of Limburg in all seasons but the summer. The influence of the pressure distribution is also clearly visible in the increase of the rain activity towards the west.

Wind direction S-W (fig. 18-21)

The rain frequencies show patterns which are almost similar for all seasons. Their characteristics are: low frequencies in the environment of the IJsselmeer, Ter Apel and Denekamp, also in the southern part of Limburg and in Kerkwerve, whereas the frequencies are high in Groningen, Friesland and in the southeastern part of Gelderland; these two areas of high frequency are connected via Overijssel and Drente.

There is a conspicuous maximum in the precipitation amounts on the area of Drente and the adjacent parts of Friesland, Groningen and Overijssel in spring, summer and winter.

The low values over the southern part of the country may be partly orographic and partly due to higher pressures.

Wind direction SW-NW (fig. 22-25)

The pattern of the frequencies shows agreement with that of the wind direction S-W. Again the frequencies are low near the IJsselmeer, sometimes near Ter Apel and Denekamp, and also near Kerkwerve. In Groningen and Friesland and in the southeastern part of Gelderland the frequencies are again high. There exists furthermore a region with high frequencies, which extends southward over the eastern part of Noord-Holland.

The pattern of the amounts of rainfall shows two influences, viz. the decrease in southerly direction with increasing pressure and an increase with the distance from the westcoast. Moreover, the influence of the IJsselmeer shows up.

Wind direction W-N (fig. 26-29)

The frequency pattern with these winds shows strong differences. As an example, in winter Winterswijk shows 82% and Lemmer and Putten only 52 and 53%. The most important aspects are the low frequencies in the vicinity of the IJsselmeer. High frequencies are found in Groningen and Friesland and in the southeastern part of Gelderland; the autumn and winter frequencies of Groningen and Leeuwarden are higher than those of West-Terschelling.

Generally speaking there is a good agreement between the pattern of the frequencies and those of the amounts. In spring, autumn and winter there is a rainfall maximum along the coast-line. The influence of the Veluwe is very conspicuous in summer.

Wind direction NW-NE (fig. 30-33)

The rain frequencies show large differences in winter. There is a region of high frequencies in Groningen, Friesland and the southeastern part of Gelderland; the area round the IJsselmeer shows low values.

The rain amounts show an analogous pattern. The increase of the amount of rain in southerly direction over Limburg is to be noted.

3.3 SOME GENERAL REMARKS

It is clear that there must be several physical factors, responsible for the patterns as observed with various wind directions.

There is the influence of the friction, related to the land-sea distribution and to the roughness of the earth's surface. There is the influence of the topography of the earth's surface. Furthermore the thermal effect of the North Sea can be mentioned. Probably the differences in soil and soil cover are of importance. Differences in pressure influence the precipitation pattern too. The frictional effect, the influence of topography and the differential heating will be discussed in paragraph 5, 6 and 7.

There are some features which are less easy to explain, to mention the low frequencies which occasionally occur in the east of Drente and Overijssel and the high frequencies in the southeast of Gelderland. There exists also a conspicuous difference in the frequencies of Kerkwerve and Vlissingen, which difference does not show up in the amounts of rain. It must finally be observed that in some cases the rain activity increases in the direction of higher pressure; then orography is apparently a dominating factor.

4. REVIEW OF PREVIOUS INVESTIGATIONS

HARTMANN [9] has discussed the rain maxima in the near-coastal areas which clearly stood out in his maps of the average rainfall. He mentioned the importance of the influence of friction and differential heating at the transition from water to land.

Also PRAGER [13] emphasized the frictional effect when discussing the fact that onshore winds bring, even in autumn and winter, more rain at landstations than at coastal stations.

COPPOOLSE [7] who also investigated the rainfall at various wind directions again stressed the importance of the influence of friction at the transition from see to land.

BERGERON [2] is of the opinion that the dunes cause standing waves and that the pattern of vertical motions is reflected in the rainfall pattern with maxima at various distances from the coast. According to BERGERON the wavelength is approximately 20 km. BERGERON restricted himself to the study of some individual cases which indeed seem to support his theory. However, it is difficult to find characteristic patterns of precipitation since many factors are influencing the precipitation. So there always exists the possibility that the patterns were formed accidentally.

It should be stated that on the basis of the present investigation BERGERON's theory can neither be confirmed nor rejected since the distance between the stations is greater than the wavelength proposed in BERGERON's theory. It may be observed that many figures give the impression of a wave-like structure in the precipitation pattern; this structure is, however, obviously related to the geographical constellation North Sea, land, IJsselmeer, land.

The results of the project "Pluvius", started by BERGERON in the environment of Uppsala in Sweden [3] should also be mentioned. This project was carried out with a very dense network of stations (1000 rain-gauges at a surface of 400 square miles). From the analogy between the precipitation patterns during two successive nights BERGERON concluded that towns, hills not higher than 50 meters and forests have a considerable influence on the precipitation pattern. A town can be considered a local source of heat and condensation nuclei; forests exercise an influence via the frictional effects.

According to BERGERON the precipitation on the leeward side of a town is about 20% higher than that on the windward side. Differences of the same order are found around forested areas. Small hills of the order of 50 meters give an increase of precipitation of 1-2 mm in case of rains of 5 mm and an increase of 2-5 mm in rains of about 15 mm.

5. FRICTIONAL EFFECTS

Differences in friction over land and sea may cause convergence or divergence in coastal areas especially if the wind is normal to the coast, but also if the wind is parallel to the coast. In the figures relating to the wind direction from SW to N one generally observes that the rain amounts and the rain frequencies increase with increasing distance from the coast, up to a maximum value which is reached 30-35 km off the coast. This increase in rain activity must be attributed to the convergence connected with the increase of friction at the transition from sea to land. In order to obtain a quantitative idea of the magnitude of the effect the differences between Oudenbosch and Vlissingen were determined for the wind group SW-NW and the differences between West-Terschelling and Leeuwarden for the wind groups W-N and NW-NE. Table 3 gives the relevant information.

TABLE 3

OUDENBOSCH — VLISSINGEN

SW-NW	Odb	Vs	Odb	Vs	differences	
Spring	54%	49%	2,1 mm	1,7 mm	5%	0,4 mm
Summer	52%	45%	3,0 mm	2,0 mm	7%	1,0 mm
Autumn	63%	54%	3,3 mm	2,9 mm	9%	0,4 mm
Winter	62%	55%	2,5 mm	1,8 mm	7%	0,7 mm

LEEUWARDEN — WEST-TERSCHELLING

W-N	Lw	WT	Lw	WT	differences	
Spring	59%	49%	1,6 mm	1,3 mm	10%	0,3 mm
Summer	47%	38%	1,7 mm	1,3 mm	9%	0,4 mm
Autumn	74%	72%	3,2 mm	3,0 mm	2%	0,2 mm
Winter	78%	72%	2,2 mm	1,8 mm	6%	0,4 mm

LEEUWARDEN — WEST-TERSCHELLING

NW-NE	Lw	WT	Lw	WT	differences	
Spring	31%	28%	0,6 mm	0,5 mm	3%	0,1 mm
Summer	18%	15%	1,0 mm	0,7 mm	3%	0,3 mm
Autumn	47%	41%	1,4 mm	1,4 mm	6%	0,0 mm
Winter	47%	40%	1,0 mm	1,0 mm	7%	0,0 mm

It appears that the frequencies increase with 5-10% and the rainfall amounts on the average with 0,3 mm.

It is interesting to note that the position of the maximum coincides with the location where according te BRAAK [5] the wind speed decreases rapidly. The position of the maximum, furthermore, does not deviate substantially from the centre of the area of convergence, 50 kilometer from the coast, observed in case of onshore winds of force 6 Beaufort and more by VON SCHUBERT [14] and DAUBERT [8].

In this paragraph an attempt will be made to relate the observed differences in rain activity to the frictional convergence. The following symbols are introduced:

z = height above the earth's surface in meters;
$\varrho\ (z)$ = density of the air (ton^{-3});
$c\ (z)$ = frictional convergence (sec^{-1});
$a\ (z)$ = amount of water condensed when the air rises 1 meter (tons per ton of air);
$w_c\ (z)$ = vertical speed of air due to frictional convergence only (m sec^{-1});
A_c = total amount of water (tons) condensed per second in a column of air of 1 m^2 cross-section and a height of 1000 m.

It is necessary to introduce a number of assumptions in order to arrive at some quantitative estimates. They are the following:

1. We will consider a vertical column of air (1000 m high and 1 m^2 cross-section) in which precipitation is already released. Due to the frictional convergence an extra amount of water vapour takes part in the condensation process equivalent to A_c tons per second, which leads to an increase of the precipitation.

2. The relative humidity in the column is 100% and the lapse rate between 0 and 1000 meter is saturated adiabatic with a potential wet bulb tempe-

rature of 10° C. This implies that $a(0) = 1{,}7 \times 10^{-6}$ and $a(1000) = 1{,}5 \times 10^{-6}$ ton per ton of air.

3. The density of the air is constant between $z = 0$ and $z = 1000$; $\varrho = 1.2 \times 10^{-3}$ ton m ^{3}.

4. The value of $a(z)$ decreases linearly with height; $a(z) = 1.7 \times 10^{-6} - 0.2 \times 10^{-9}\, z$.

5. The convergence decreases linearly from a value $c(0)$ to zero at 500 m and to $-c(0)$ at 1000 m.

$$c(z) = c(0) - \frac{c(0)}{500}\, z$$

6. The vertical wind speed due to frictional convergence increases from zero at $z = 0$ to a maximum at 500 m and decreases again to zero at 1000 m.

Since $\frac{dw_c}{dz} = c(z)$, it follows that $w\ (z) = \int_o^z c(z)\, dz$, or

$$w\ (z) = c(0)z - \frac{c(0)}{500}\, z^2$$

On the basis of these assumptions we may write:

$$A_c = \varrho \int_0^{1000} a(z)\, w_c(z)\, dz \qquad (1)$$

The value of $c(0)$, i.e. the surface convergence due to friction has been computed for the northern part of the Netherlands on days with an almost constant geostrophic wind by using BELLAMY's method [1]. An average value of $c = 2 \times 10^{-4}$ sec^{-1} was found.

Substitution and integration of equation (1) lead to a value of $A_c = 6.4 \times 10^{-8}$ m^3.

In order to determine the extra amount of rainfall which may result from the excess condensation of water vapour in the area of the highest frictional convergence it is necessary to make an estimate of the average duration of the rainfall. This may be assumed to be approximately equal to the average duration of the rainfall per day in the Netherlands, which is two hours (7200 seconds).

It should furthermore be realized that not all the extra water will reach the earth's surface as rain. Investigations of the water balance of Cumulonimbus clouds (BRAHAM [6]) have taught that only 20% of the condensed water reaches the ground as precipitation; the rest of the water re-evaporates, either under the cloud or at the border or when the cloud dissolves as a whole. In view of the fact that many of the cloud systems in the Netherlands have larger dimensions than a Cumulonimbus and considering furthermore that the duration of the rainfall (2 hours) is long enough to bring the air under the cloud close to saturation, a higher efficiency than 20%, say 50%, may be assumed.

The extra amount of rainfall due to frictional convergence is therefore: $0.5 \times 7200 \times 6.4 \times 10^{-8} \times 10^{-3}\ \text{mm} = 0.2\ \text{mm}$.

The aim of this computation was only to show that the values indicated in table 3 can be explained as resulting from frictional convergence, as they are of the same order of magnitude as those found on the basis of theoretical considerations.

6. THE INFLUENCE OF TOPOGRAPHY

There exists, as has been noted in paragraph 3.2 and 3.3, also an influence of the topography of the earth's surface on the rainfall patterns in the Netherlands. In the southern part of Limburg the rain activity is relatively small during southerly wind, probably as a result of the presence of the Ardennes and the Eifel. On the other hand northerly winds stimulate the rainfall over the hilly southern part of Limburg. The following table demonstrates the differences between Maastricht in South Limburg and the station Helmond, about 75 km to the north in a rather flat region.

TABLE 4

HELMOND–MAASTRICHT

SE-SW	Hm	Mt	Hm	Mt	differences	
Spring	54%	46%	2,2 mm	1,3 mm	8%	0,9 mm
Summer	59%	54%	2,9 mm	2,7 mm	5%	0,2 mm
Autumn	47%	41%	1,8 mm	1,3 mm	6%	0,5 mm
Winter	43%	37%	1,6 mm	1,0 mm	6%	0,6 mm

HELMOND–MAASTRICHT

NW-NE	Hm	Mt	Hm	Mt	differences	
Spring	33%	36%	1,1 mm	1,4 mm	-3%	-0,3 mm
Summer	26%	26%	1,6 mm	2,0 mm	0%	-0,4 mm
Autumn	45%	43%	1,7 mm	1,8 mm	2%	-0,1 mm
Winter	36%	40%	1,1 mm	1,1 mm	-4%	0,0 mm

When the wind is from southerly directions the average precipitation in Maastricht is 0,6 mm less than that in Helmond; when the wind is from the north the precipitation in Maastricht is 0,2 mm higher. The lower rainfall in Maastricht during southerly winds may result from a forced descending motion which, when caused bij the Ardennes and the Eifel, would amount to 500 m over a distance of 100 km. The higher rainfall in Maastricht during northerly winds may be caused by a forced ascending motion of 100 m over a distance of 50 km.

We will try to compute along the same lines as in the preceding paragraph the order of magnitude of these orographic effects.

The following assumptions, pertaining to this case are made:

1. We will consider a vertical column of air (5000 m high and 1 m^2 cross-section) in which precipitation is already released. Due to the forced ascent along the slope of a hill an extra amount of water vapour takes part in the condensation process equivalent to A_o tons per 1 m^2 per second which again leads to an increase of precipitation.

2. The relative humidity in the column is 100% and the lapse rate between 0 and 5000 meter is saturated adiabatic with a potential wet bulb temperature of 10° C. This implies that the amount of water condensed when the air rises 1 meter at the surface and at 5000 meter, has the following values: $a(0) = 1.7 \times 10^{-6}$ and $a(5000) = 0.7 \times 10^{-6}$ ton per ton of air.

3. The density of the air at he surface and at 5000 m has the values $\varrho(0) = 1.3 \times 10^{-3}$ and $\varrho(5000) = 0.7 \times 10^{-3}$ ton m^{-3}.

4. The horizontal wind speed in the direction normal to lines of equal height is 10 m.sec^{-1}. This implies that the vertical wind speed at the earth's surface caused by the orography $w_o = 10 \times \mathrm{tg}\,\alpha$ m sec^{-1}, where α indicates the slope.

5. The vertical wind speed at 5000 m will be zero.

On the basis of these assumptions we may again write:

$$A_o = \int_o^{5000} \varrho(z)\, a(z)\, w_o(z)\, dz \qquad (2)$$

Again assuming that $\varrho(z)$, $a(z)$ and $w_o(z)$ change linearly with height, one finds by substitution and integration of equation (2) a value of $A_o = 4 \times 10^{-5}\,\mathrm{tg}\,\alpha\, m^3$.

As in the previous paragraph the rain duration will be assumed as 2 hours with an efficiency of 0,5. For northerly winds one finds for

$$\operatorname{tg} \alpha = \frac{100}{50000},$$

so that the extra amount of rainfall will be:

$$0.5 \times 7200 \times 4 \times 10^{-5} \times \frac{100}{50000} \times 10^{3} \text{ mm} = 0.3 \text{ mm}.$$

This value is in agreement with those given in table 4.

For the computation of the influence of the Ardennes and Eifel during southerly winds an analogous reasoning may be followed, when we assume that in a precipitation system downward motion leads to evaporation of the same amount of water as would have been found during the same upward motion. In this case

$$\operatorname{tg} \alpha = \frac{500}{100000},$$

so that the amount of rain depleted from the system is approximately 0.7 mm.

It is finally to be noted that there exist, even over a flat country like the Netherlands, hills of 50-100 meters, such as the Veluwe, the Utrecht hills and the hills of Overijssel. With height changes of 100 meter over a distance of say 10 kilometers one can expect, on the basis of the above computations, with a wind of 10 m $\sec^{-1}$ from a suitable direction extra rain amounts of 0.6 to 1.3 mm. This amount agrees with the amount of the extra precipitation over hills as found by BERGERON (3) in two individual cases of the Pluvius project.

7. THE INFLUENCE OF DIFFERENTIAL HEATING

It is obvious that the differences in temperature between the sea and the land also lead to differences in frequency and amount of precipitation.

There is for instance a small-scale differential heating in coastal areas which lead to coastal convergence over land during day-time and over sea during night-time. The influence of this convergence on the precipitation could not be studied as information about day-time precipitation and night-time precipitation was lacking.

The differential heating and cooling on a larger scale may lead to seasonal differences in precipitation over sea and land, which influence the coastal areas if the wind is blowing from the sea. This can be shown by studying the rain frequencies and the rain amounts during onshore winds at coastal stations as Den Helder, Scheveningen and West-Terschelling and by comparing them with those of a continental station as Winterswijk. Table 5 gives some relevant information.

TABLE 5

WINTERSWIJK–DEN HELDER

SW-NW	Wtw	Hedr	Wtw	Hedr	differences	
Spring	62%	52%	2.1 mm	1.1 mm	10%	1.0 mm
Summer	50%	37%	2.7 mm	1.3 mm	13%	1.4 mm
Autumn	71%	72%	2.9 mm	2.9 mm	–1%	0.0 mm
Winter	82%	72%	2.5 mm	1.7 mm	10%	0.8 mm

WINTERSWIJK–SCHEVENINGEN

W-N	Wtw	Svn	Wtw	Svn	differences	
Spring	62%	54%	2.6 mm	1.9 mm	8%	0.7 mm
Summer	62%	46%	3.2 mm	2.3 mm	16%	0.9 mm
Autumn	72%	62%	3.9 mm	3.4 mm	10%	0.5 mm
Winter	77%	59%	3.5 mm	2.0 mm	18%	1.5 mm

WINTERSWIJK — WEST-TERSCHELLING

N-E	Wtw	WT	Wtw	WT	differences	
Spring	20%	13%	0.8 mm	0.6 mm	7%	0.2 mm
Summer	17%	8%	0.9 mm	0.4 mm	9%	0.5 mm
Autumn	20%	23%	0.7 mm	0.8 mm	-3%	-0.1 mm
Winter	18%	22%	0.5 mm	0.5 mm	-4%	0.0 mm

It can be seen from this table that in spring, summer and winter the rainfall of Winterswijk is considerably higher than that of coastal stations. In autumn, however, the difference is smaller and the relatively high value of Den Helder, Scheveningen and West-Terschelling may be due to the rain brought by onshore winds, during the period that the water temperature is appreciably higher than the temperatures over land. Judging from the average ratio inland/coast in spring, summer and winter, the rainfall at the coastal stations may be increased in autumn with an amount of 1,1 mm for winds between SW and N. For winds between N and E the increase amounts to 0.3 mm.

We will now see whether a rough computation of the rainfall due to increased convection over sea renders figures of the same order of magnitude.

The following assumptions are made:

1. We will consider the condensation and release of precipitation in an atmosphere in which the vertical temperature distribution from surface to 400 mb coincides with the saturated adiabat of 11° C potential wet bulb temperature.
2. The ascending air has a surface temperature of 13° C and the maximum mixing ratio at the beginning of the ascent is 9×10^{-3} tons water per ton of air and at 400 mb 0.5×10^{-3} tons water per ton of air; the average density is 1×10^{-3} ton m^{-3}.
3. The wind normal to the coast is 10 m sec^{-1}, the duration of the rain is 3 hours for SW-N winds, and 1 hour for N-E winds.
4. The layer of air which takes part in the ascending motion is 250 m thick.
5. The precipitation is released over an area of 40 km deep.

Assumption 1 is based on observations of Downham Market [15]; assumption 2 is derived from the Climatology of seawater temperatures in the northwestern part of Europe [16]. The assumption about the thickness of the layer in ascending motion is in agreement with the value for the dimensions of "air bubbles" given by MALKUS [12].

Since the precipitation is of a showery character we may finally take a value of 20% for its efficiency (BRAHAM [6]).

The amount of water which reaches the ground as precipitation is for a rain duration of 1 hour and averaged over the coastal area 0.4 mm, for 3 hours 1.1 mm, which values are in accordance with those derived from table 5.

8. SOME INDIVIDUAL CASES

The preceding paragraphs show the influence of friction, topography, orography and instability due to surface heating on the precipitation pattern over the Netherlands. In this paragraph we will try to demonstrate the effects of these factors in a few selected individual cases.

Figure 34 demonstrates the meteorological situation on 1 May, 1957, 1200z. An open wave cyclone with its top off the Danish coast lies over the North Sea and moves rather slowly in southeasterly direction. The position of its warm front on 1 May 1800z and 2 May 0000 and 0600z has also been indicated. Fig. 35 shows the amounts of rain collected during the period 1 May 0840 to 2 May 0840 MET; this rain is exclusively warm front rain as the cold front did not pass the Netherlands during this period. During the rain the wind was W to NW, later on mainly NW, with a mean speed of 6 m $\sec^{-1}$.

It will be seen from fig. 35 that the rain only fell in the region where the frictional convergence was of importance and in the areas where the air was lifted due to topography. When travelling south the front apparently became weaker and weaker, so that in the southern part of Limburg no rain was observed.

Fig. 36 shows the weathermap of 26 October 1956 1200z and fig. 37 the rain amounts collected between 26 October 0840 and 27 October 0840 MET. Arctic air with a temperature of approximately 9° C invades the North Sea where the surface water temperature is 11° C and shower activity is reported from a number of ships. The showers drift into the continent, so that rather high amounts of rainfall are observed in the coastal areas. The influence of topography is clearly seen from the higher rainfall figures over the Veluwe and the southern part of Limburg.

9. SUMMARY

This paper demonstrates the distribution of rain frequency and amount over the Netherlands for various wind directions.

It can be shown that the patterns are strongly influenced by frictional effects, by the relief of the earth's surface and by thermal effects. It can be shown by means of a simple model that the observed effects are of the same order of magnitude as the theoretically computed values.

ACKNOWLEDGEMENTS

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Fig. 1 Situation of the stations

Utrecht
Den Helder
Leeuwarden
Groningen
Maastricht
Vlissingen

7. Hoofddorp
8. Putten
9. Roermond
10. Helmond
11. Heusden
12. Scheveningen

13. Lemmer
14. Velp
15. Winterswijk
16. Kerkwerve
17. Hoorn
18. West-Terschelling

19. Oudenbosch
20. Dwingelo
21. Ter Apel
22. Heerde
23. Denekamp
24. Axel

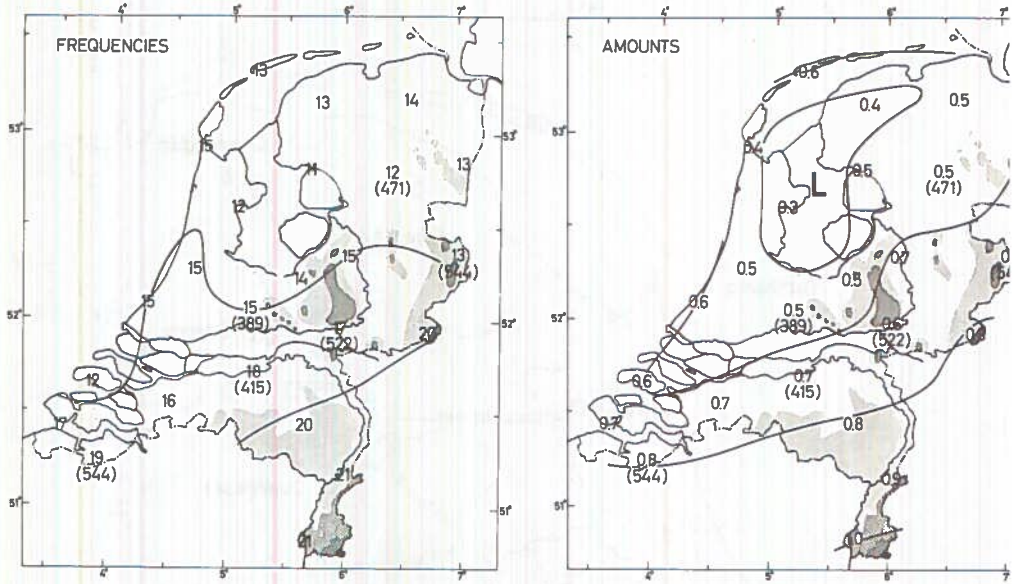
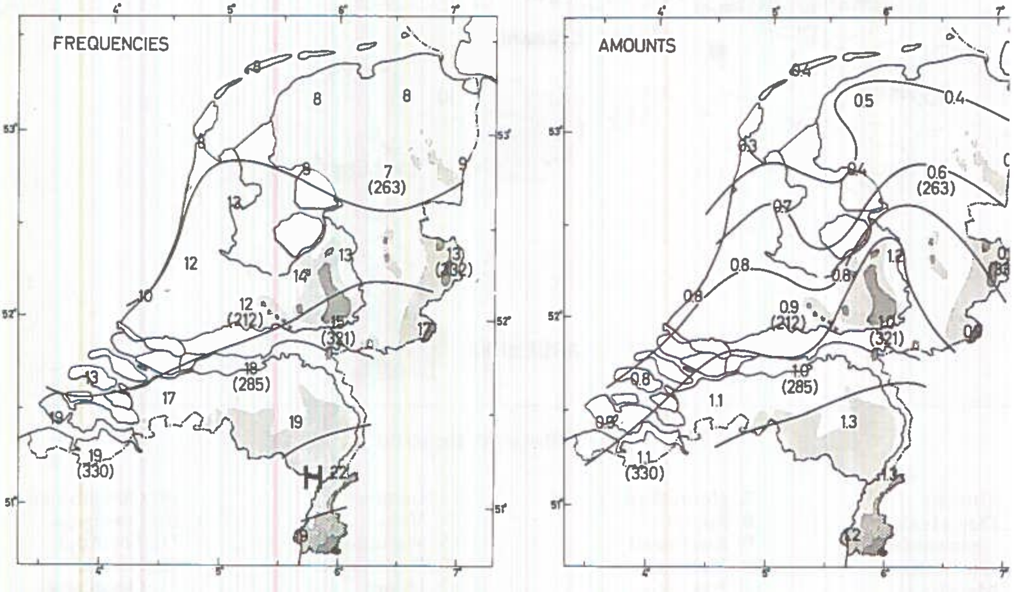


Fig. 2 Spring 586 days

Frequencies in percents, isolines every 5 percent

Amounts in mm, isolines every 0.2



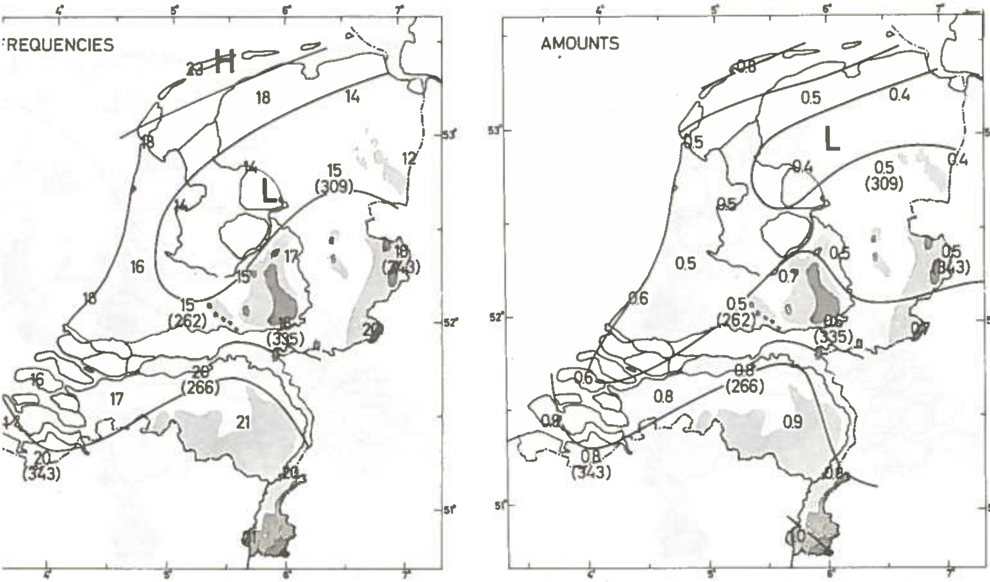
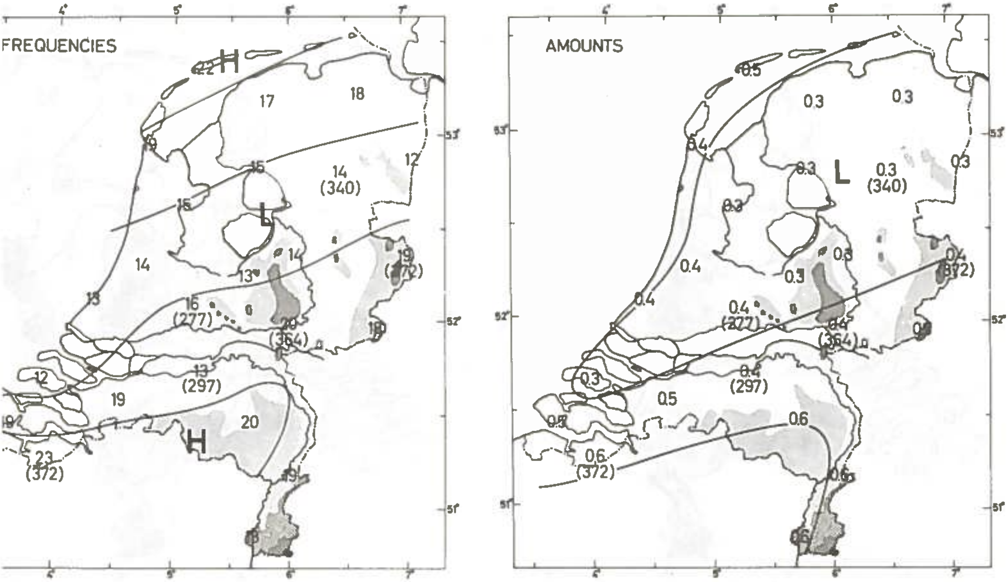


Fig. 4 Autumn 374 days



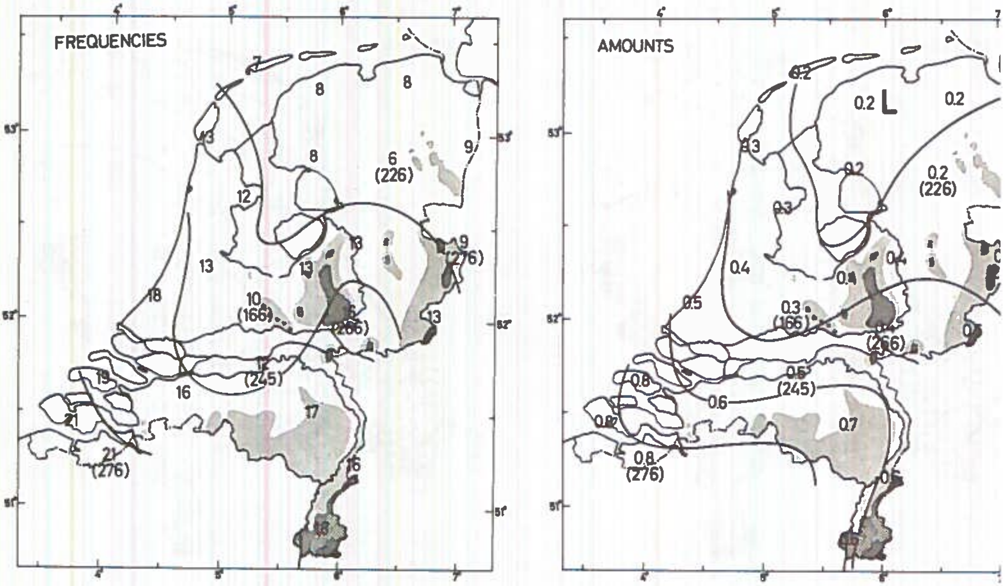
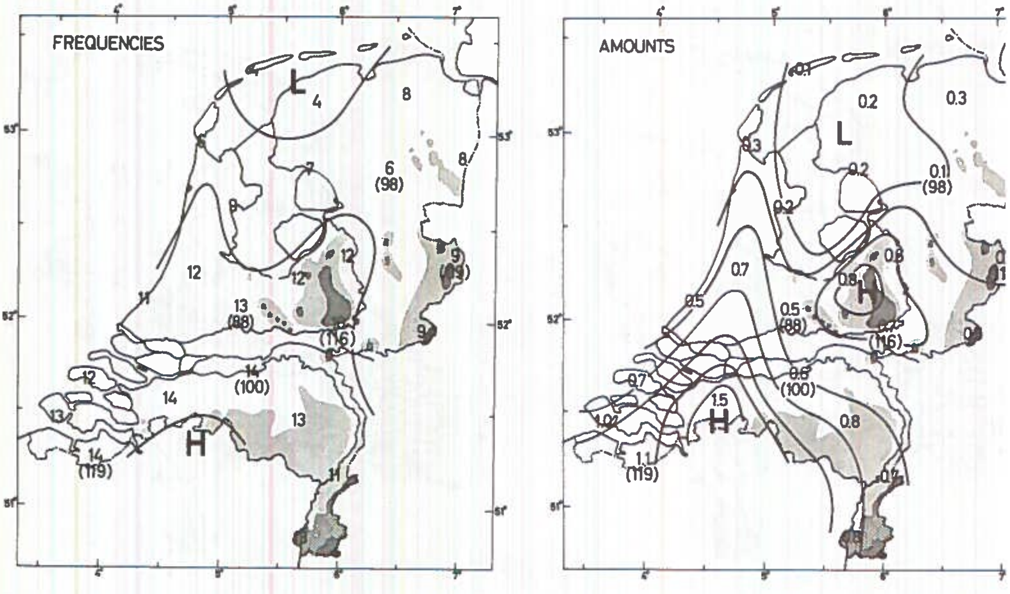


Fig. 6 Spring 292 days



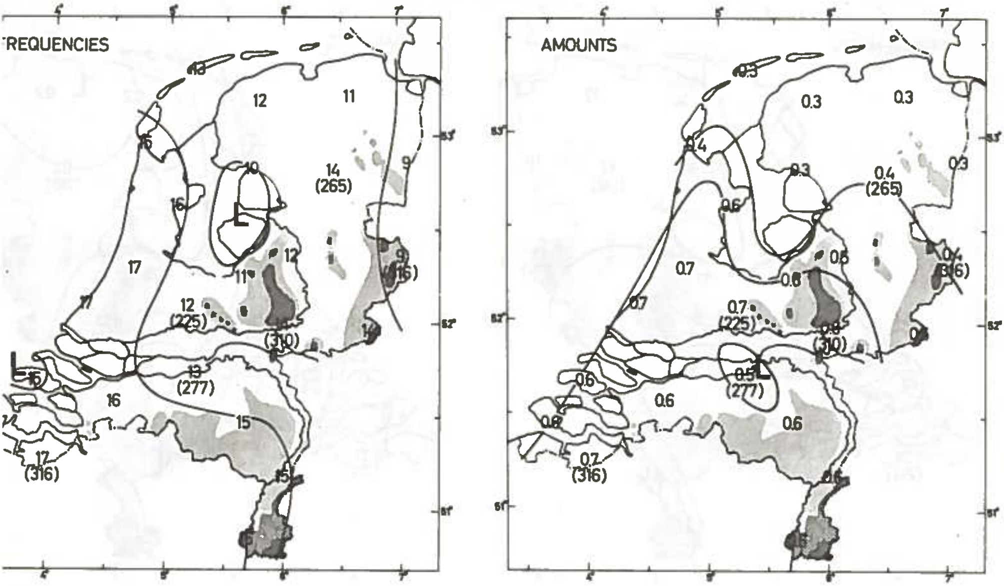
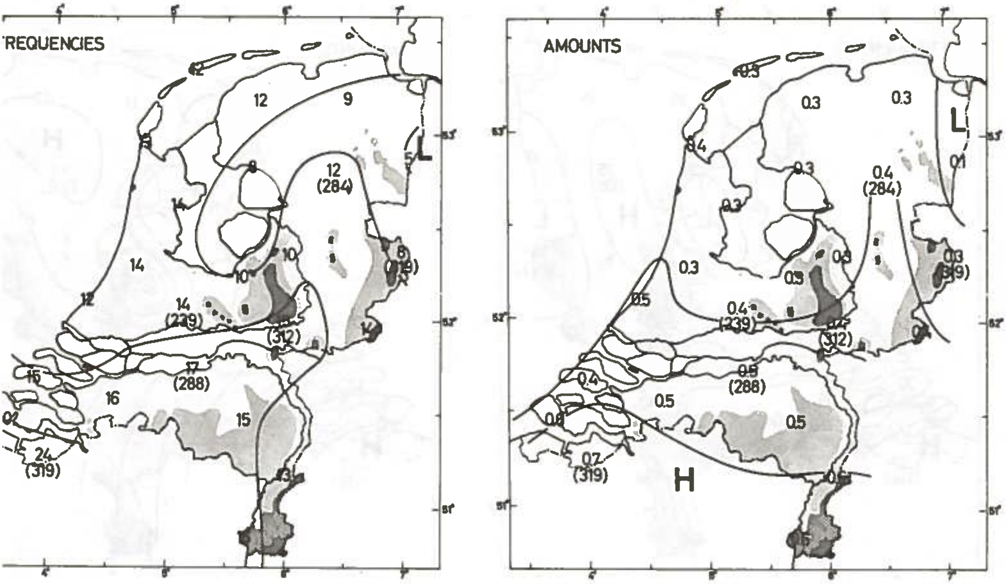


Fig. 8 Autumn 350 days



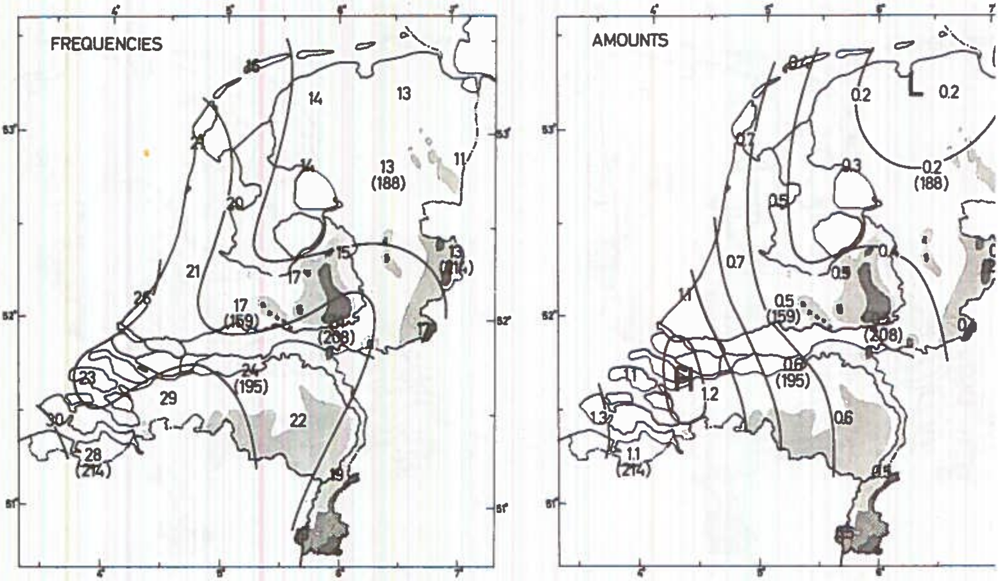
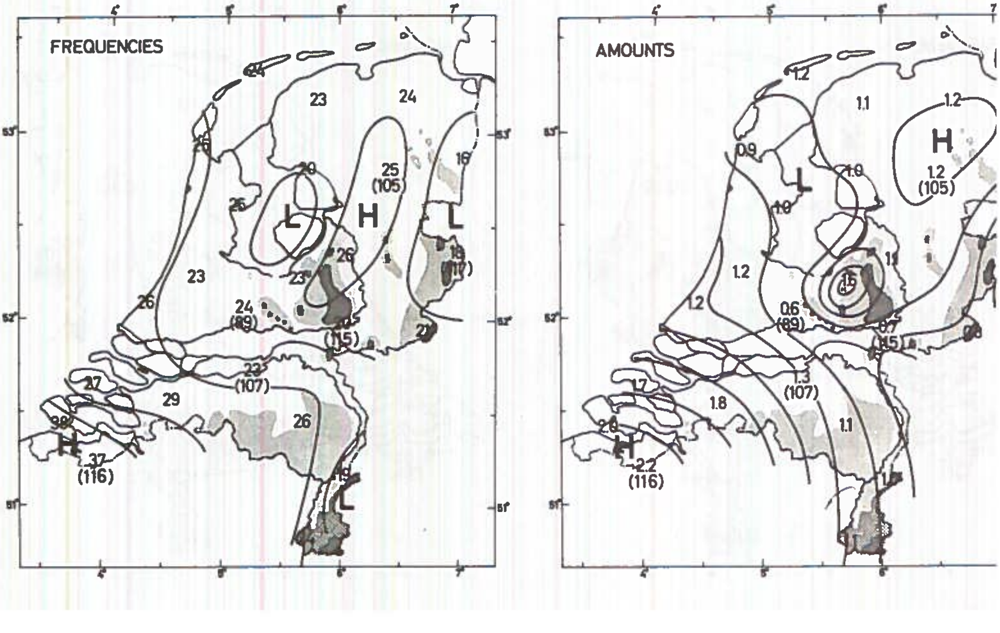


Fig. 10 Spring 238 days



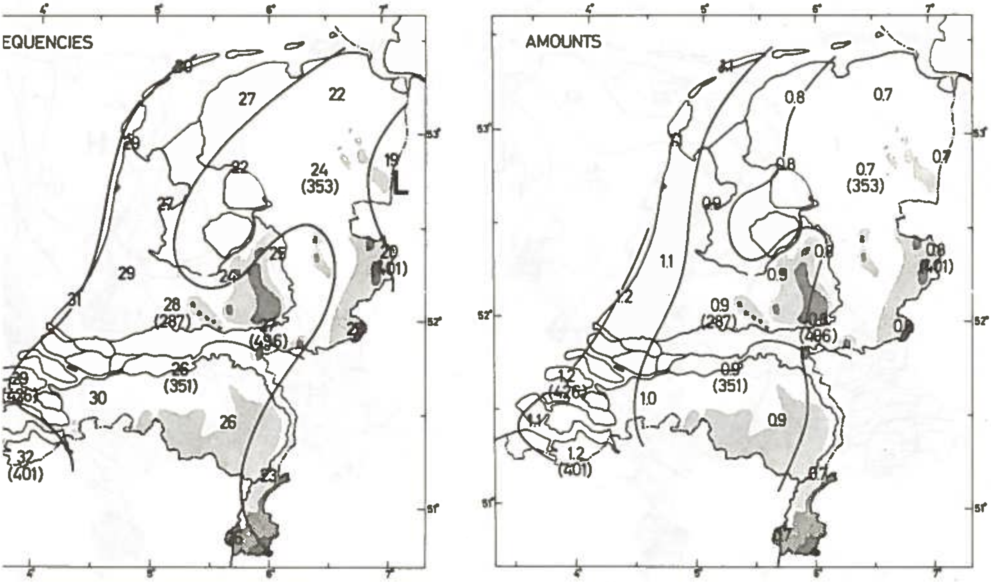
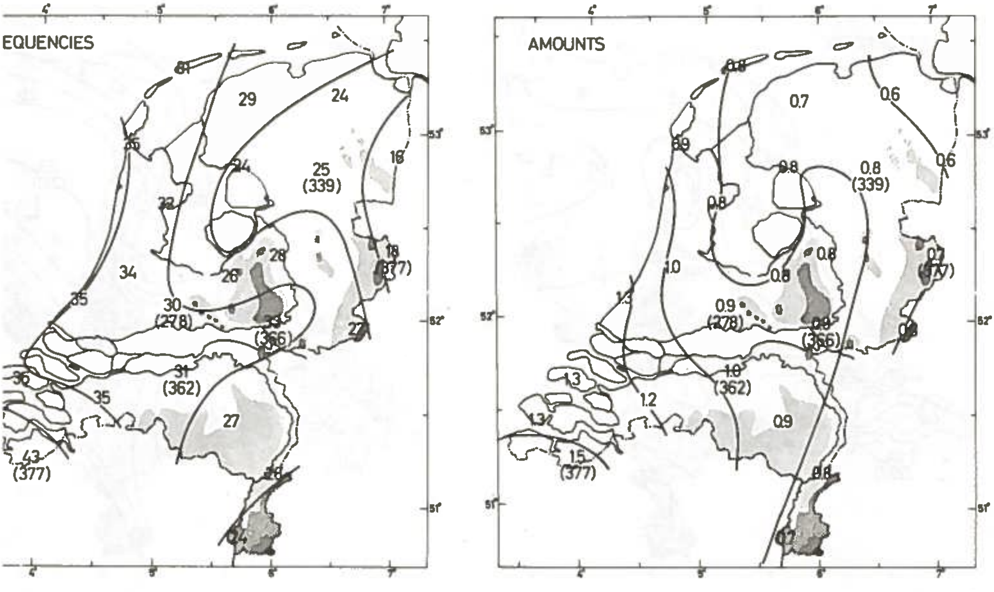


Fig. 12 Autumn 429 days



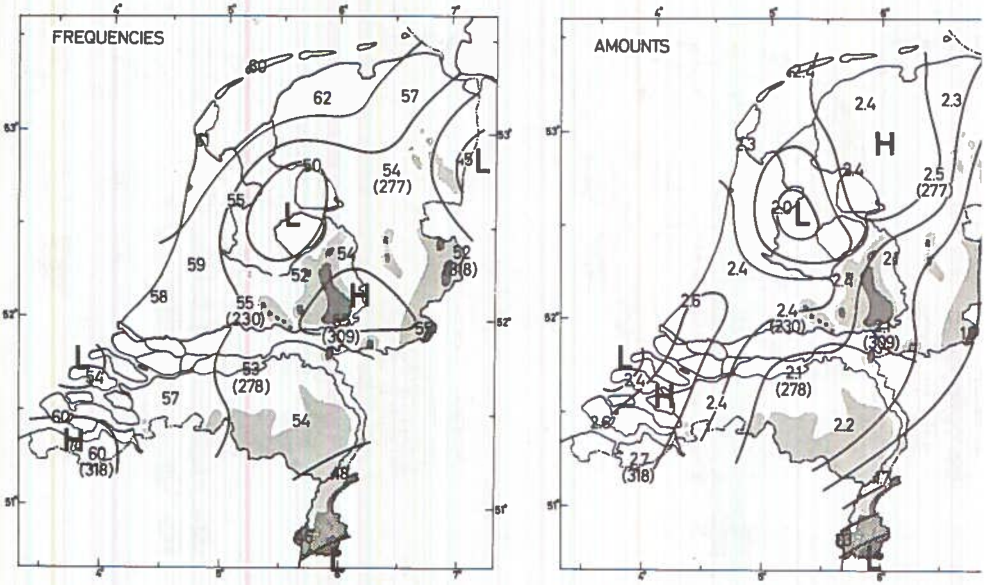
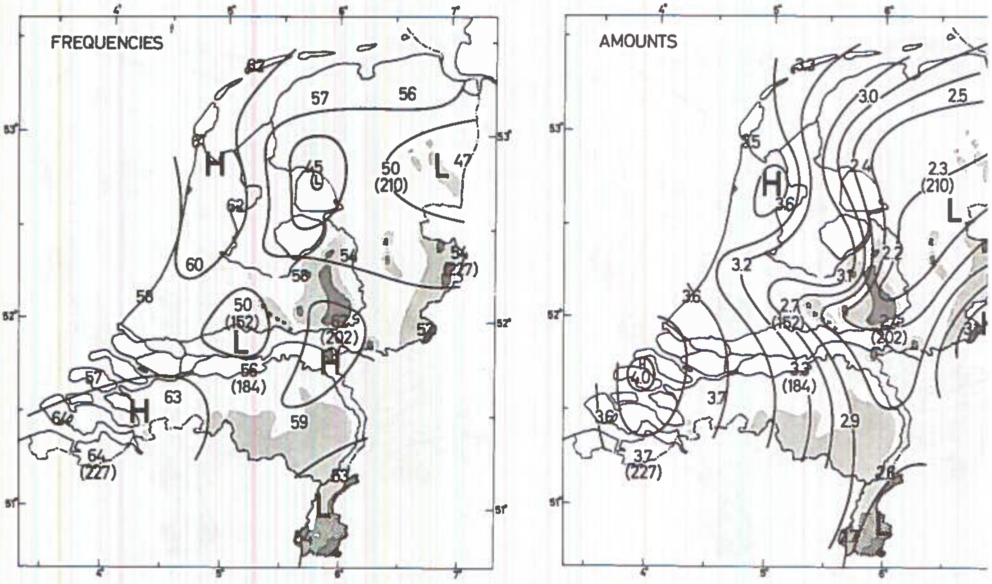


Fig. 14 Spring 344 days



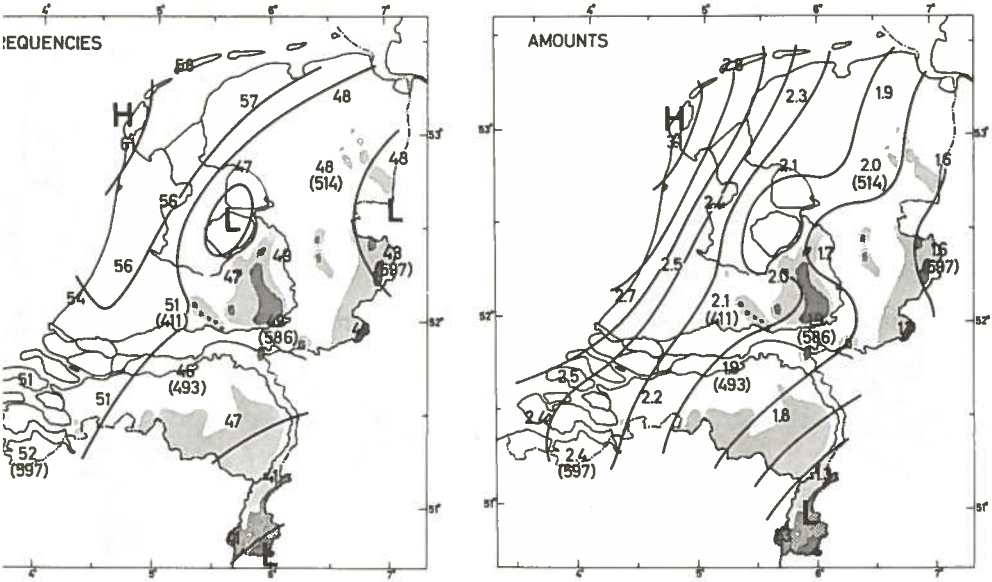
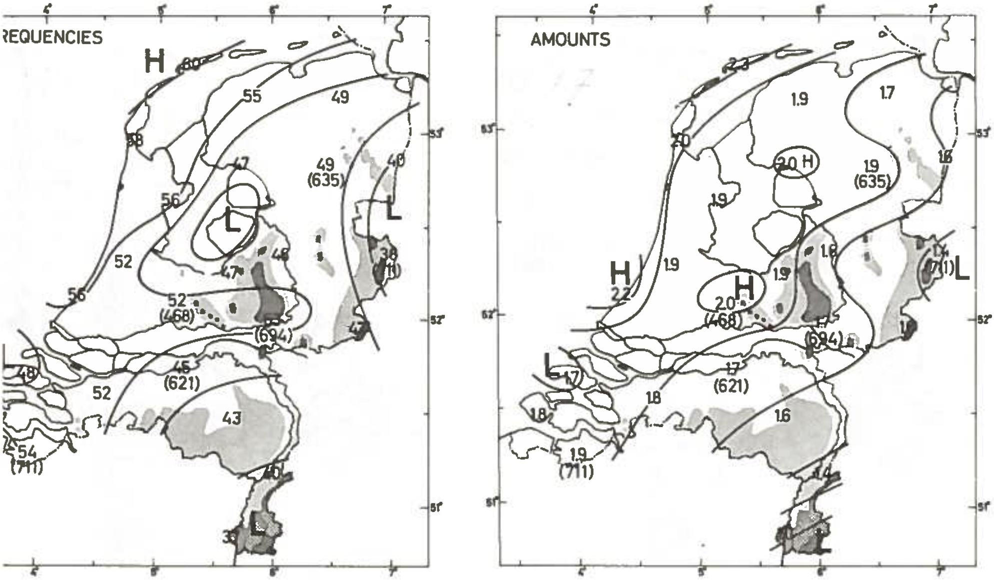


Fig. 16 Autumn 646 days



WINDDIRECTION S-W

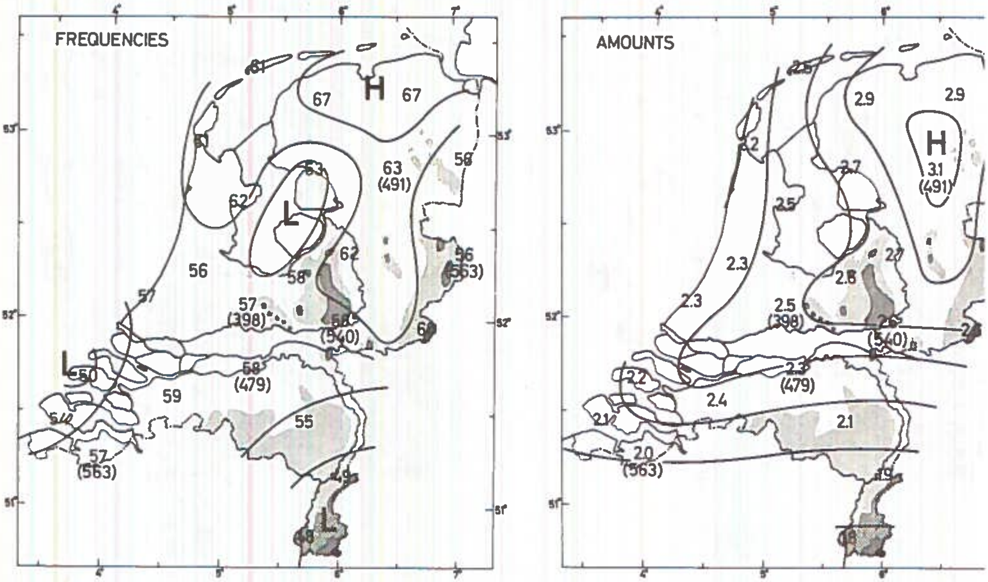
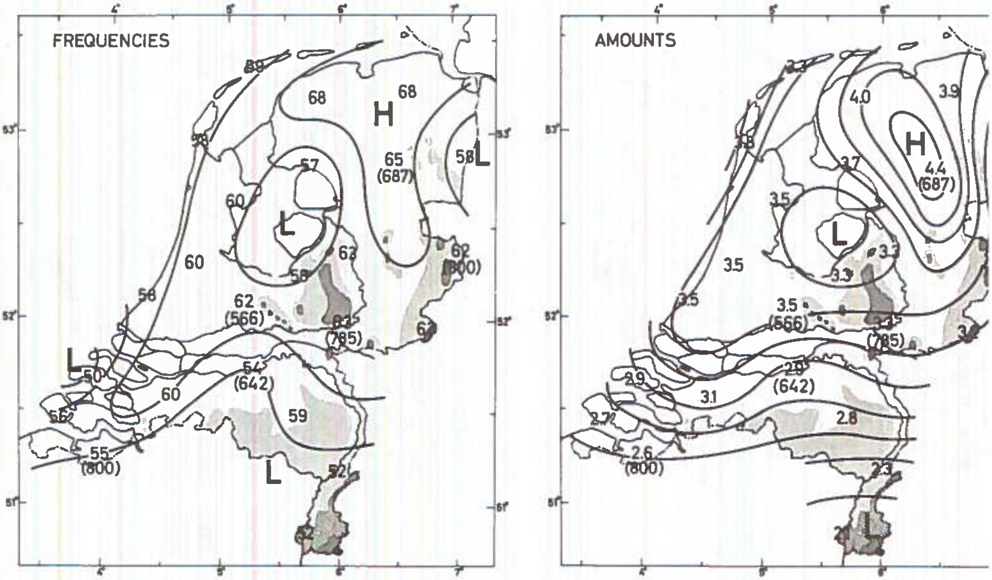


Fig. 18 Spring 622 days



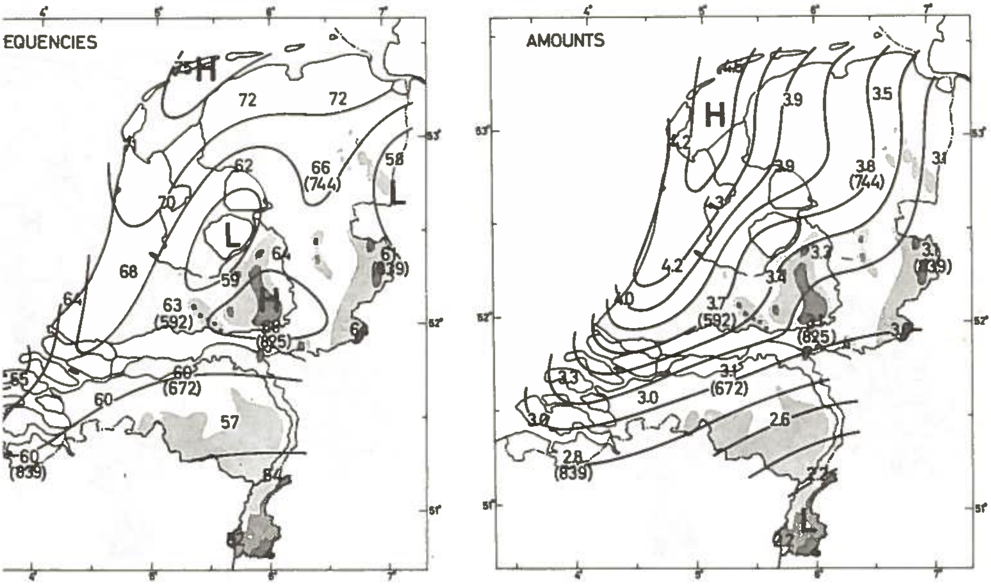
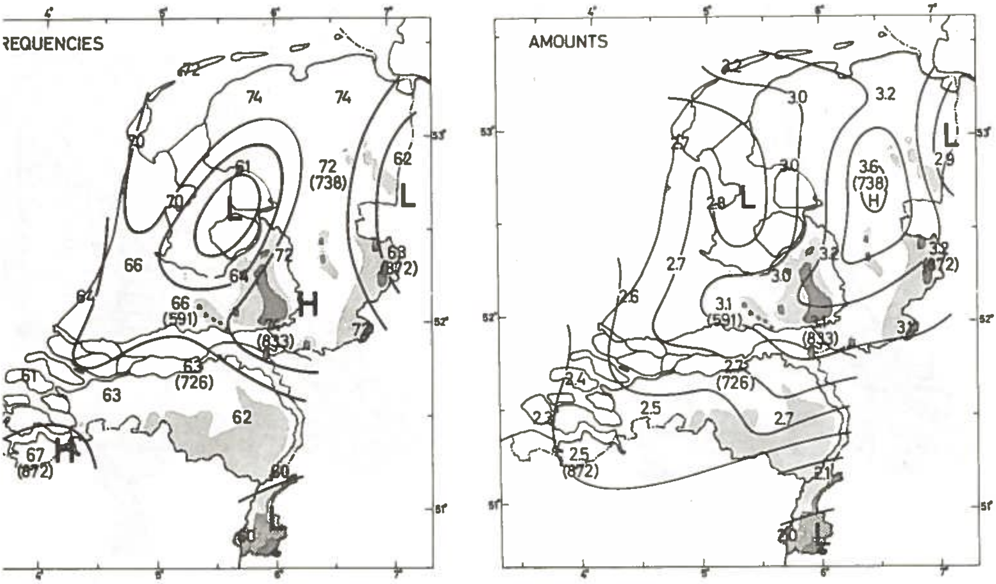


Fig. 20 Autumn 895 days



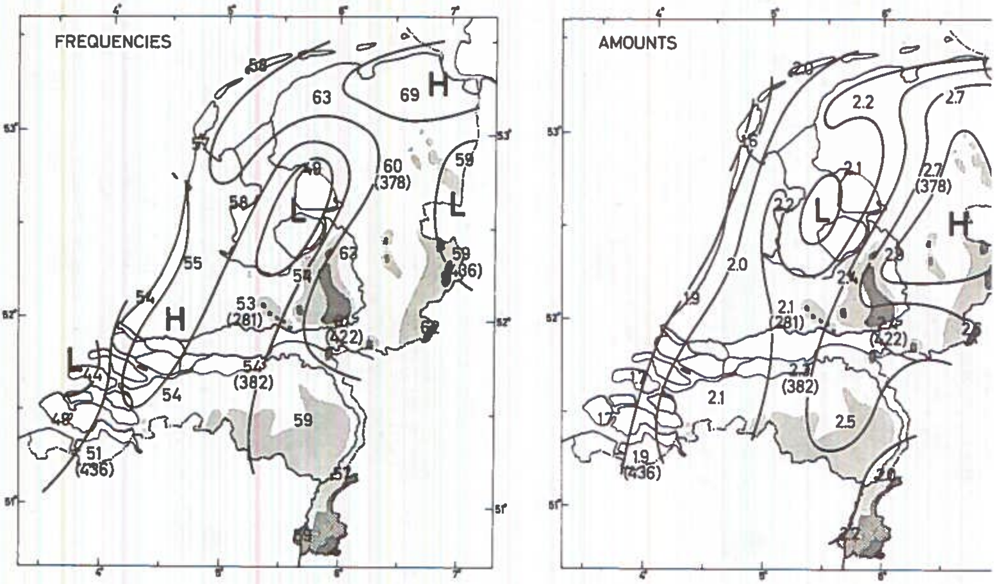
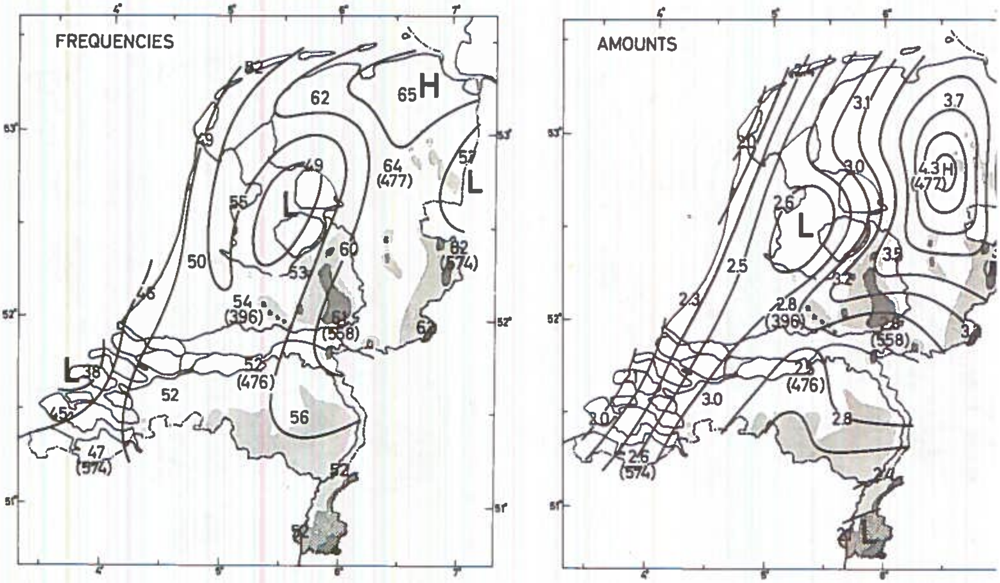


Fig. 22 Spring 482 days



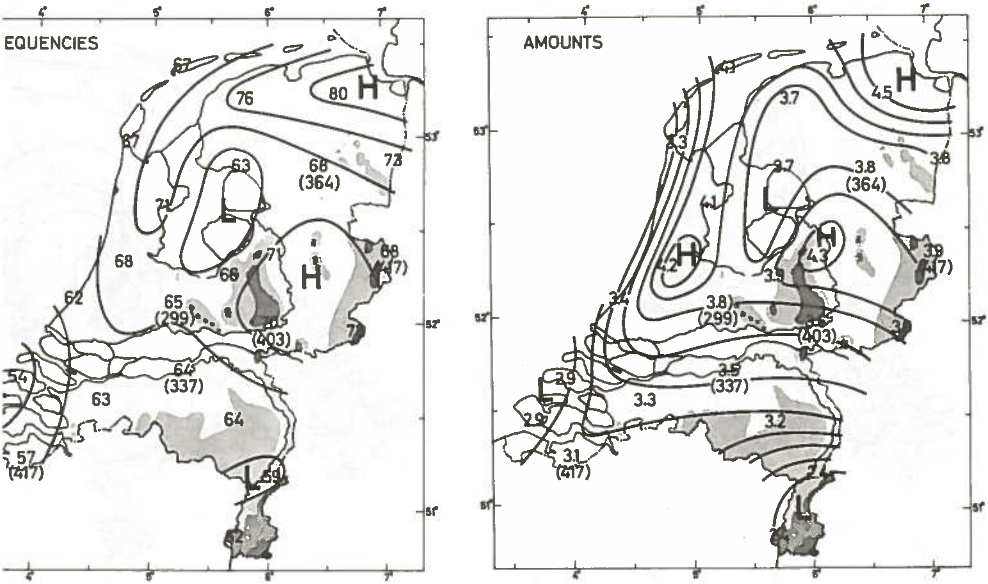
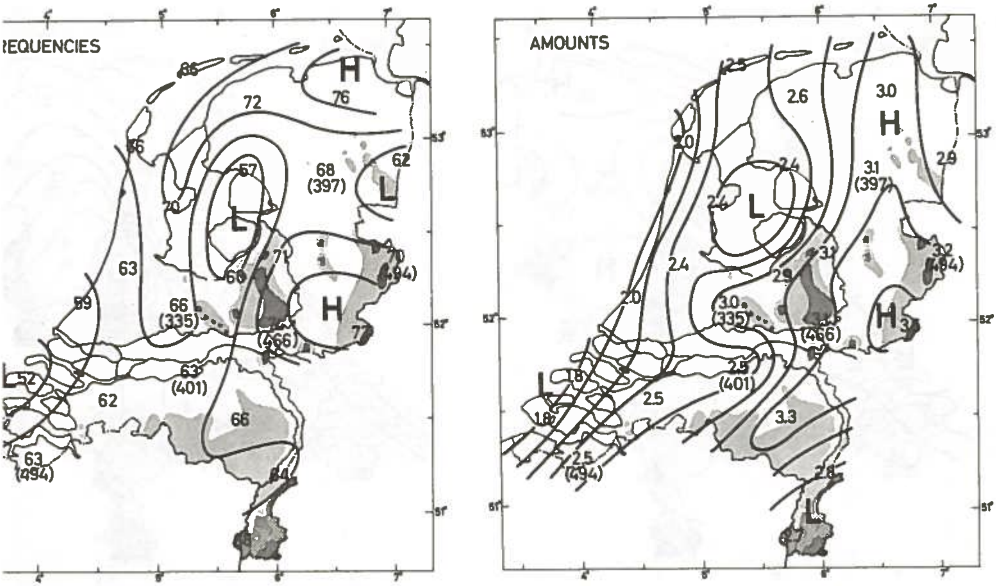


Fig. 24 Autumn 441 days



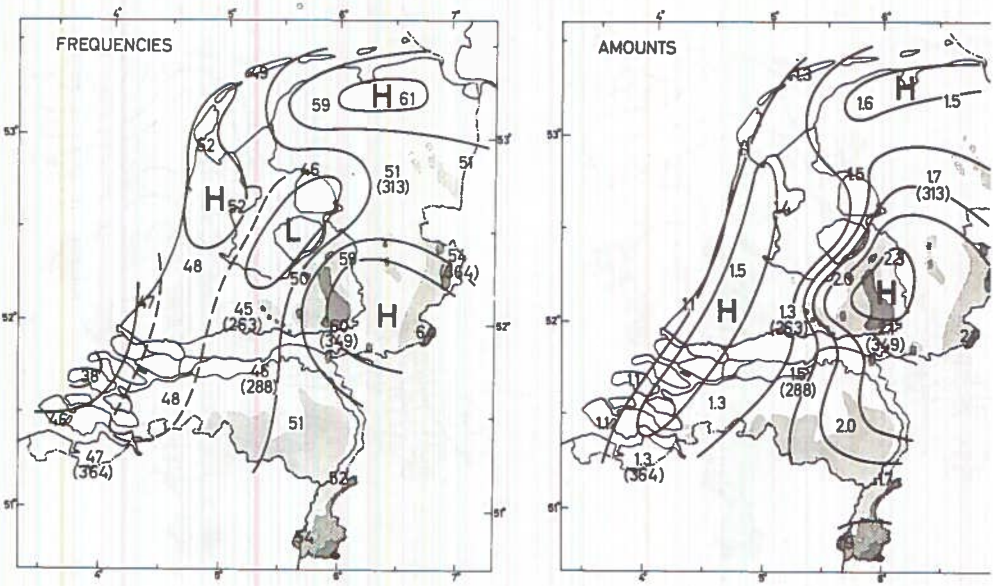
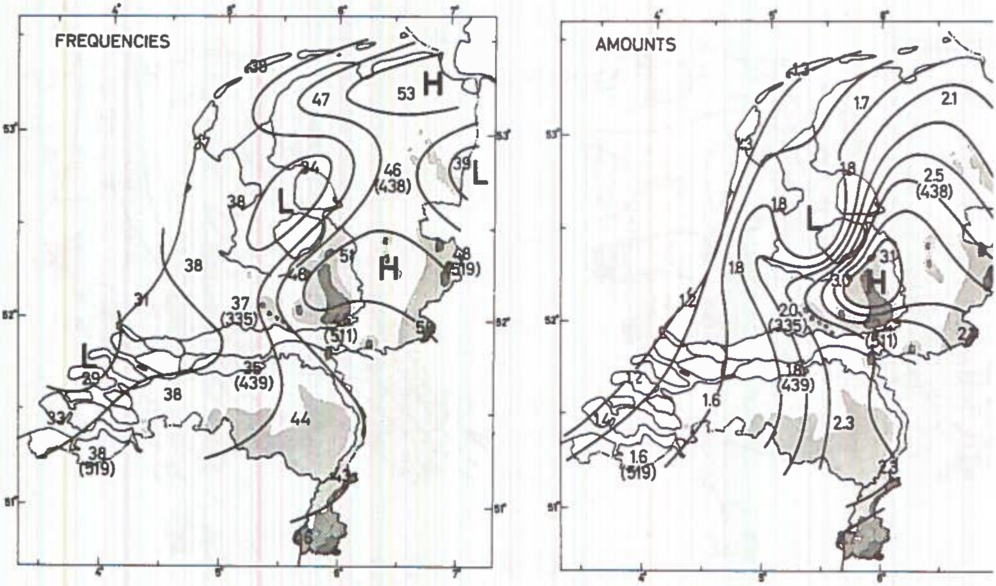


Fig. 26 Spring 394 days



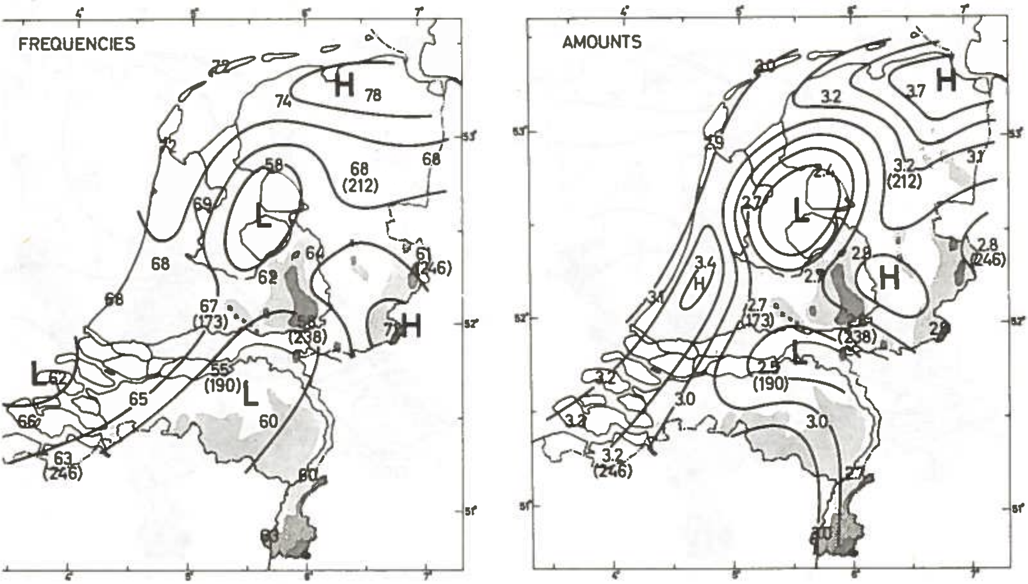
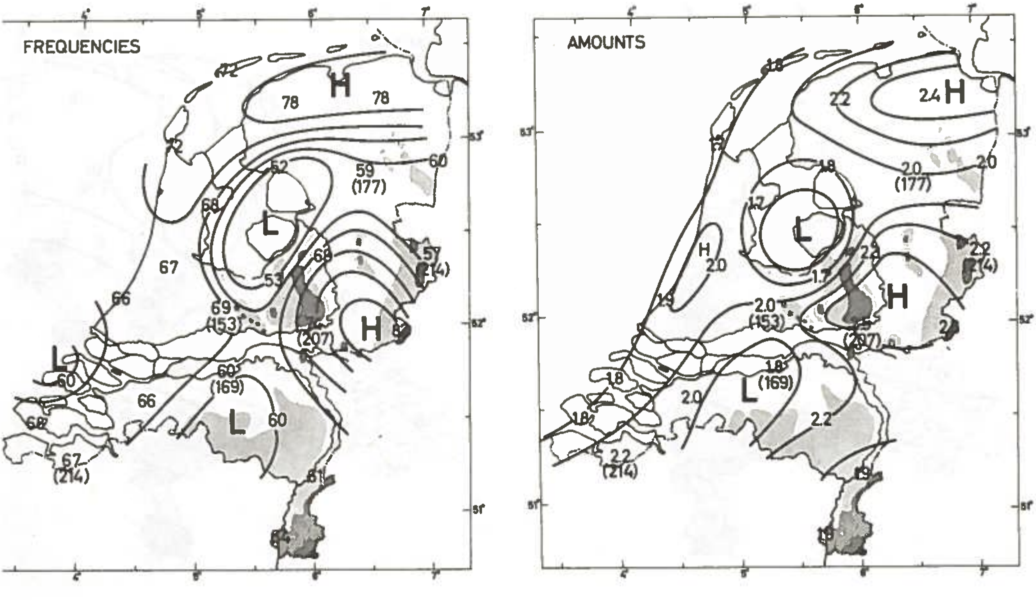


Fig. 28 Autumn 258 days



WINDDIRECTION NW-NE

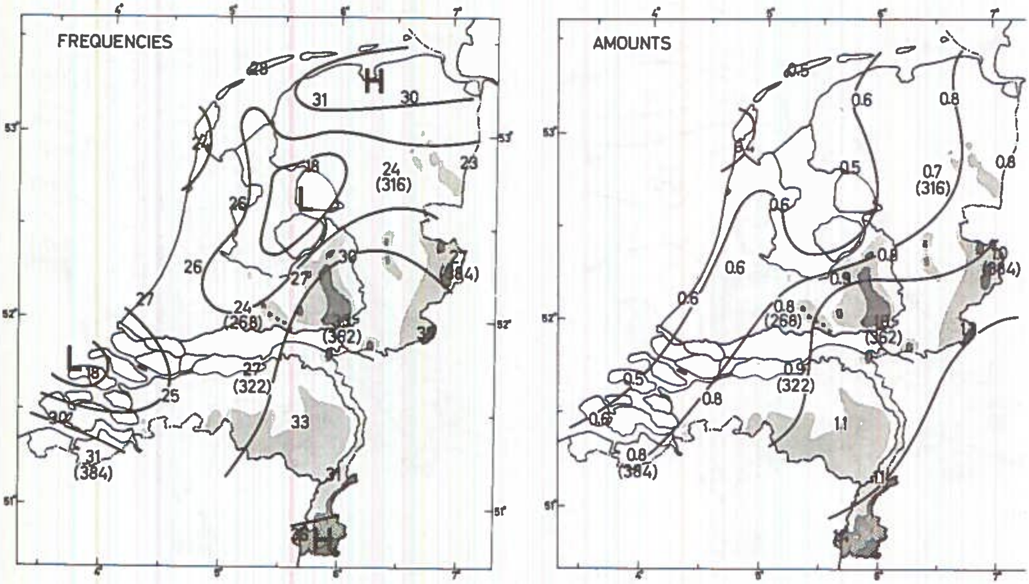
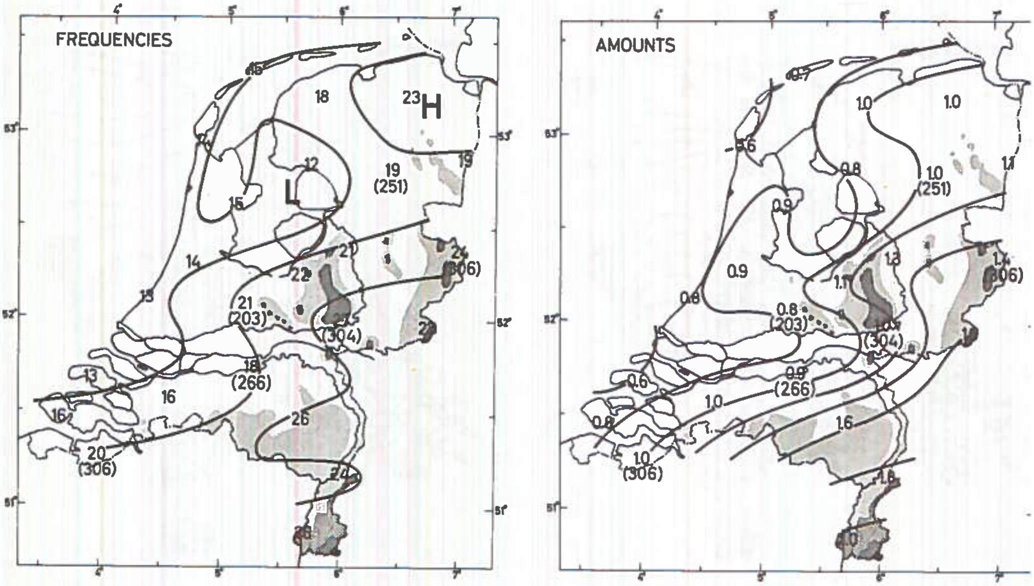


Fig. 30 Spring 407 days



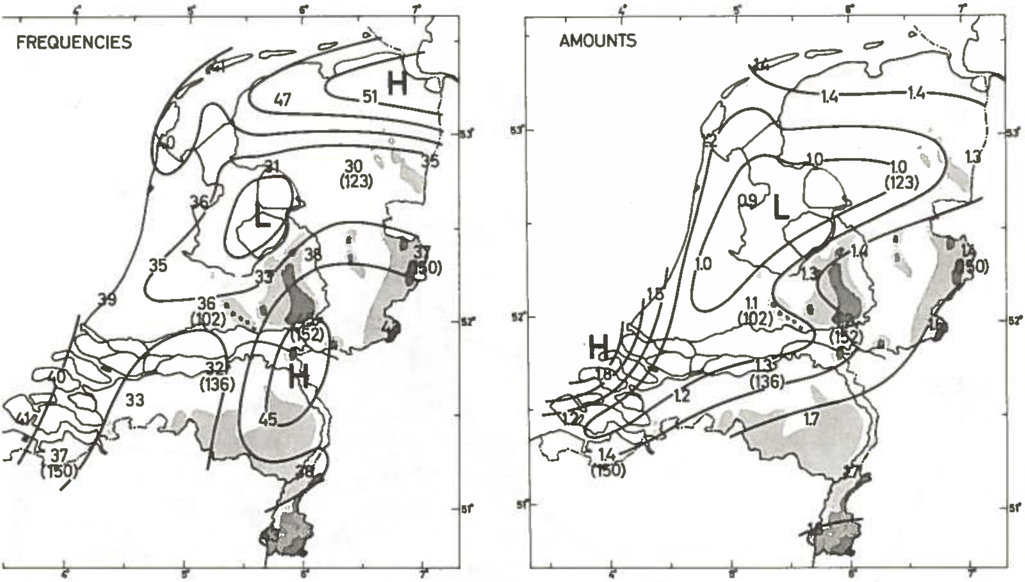
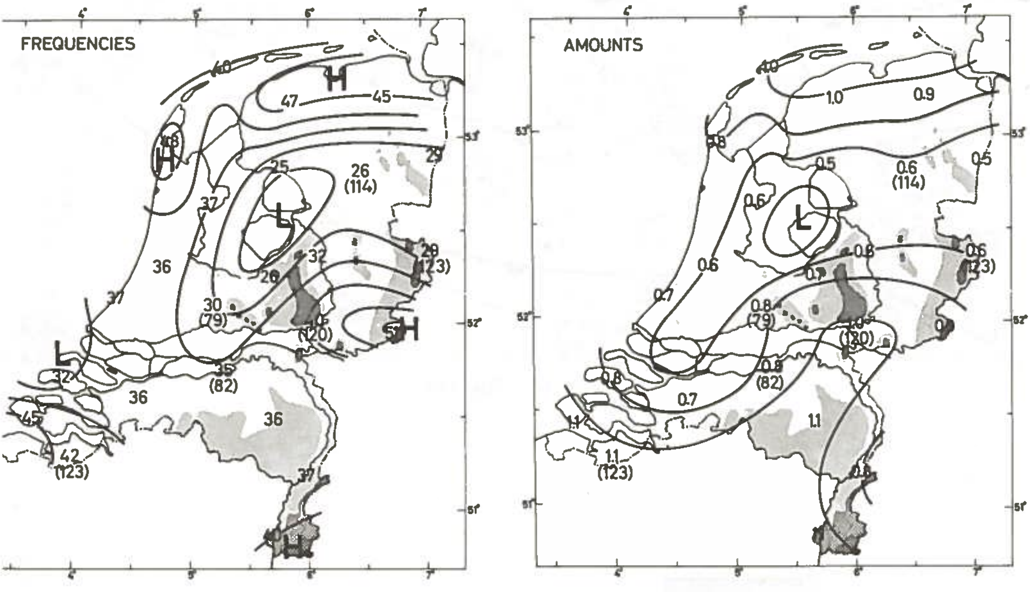


Fig. 32 Autumn 167 days



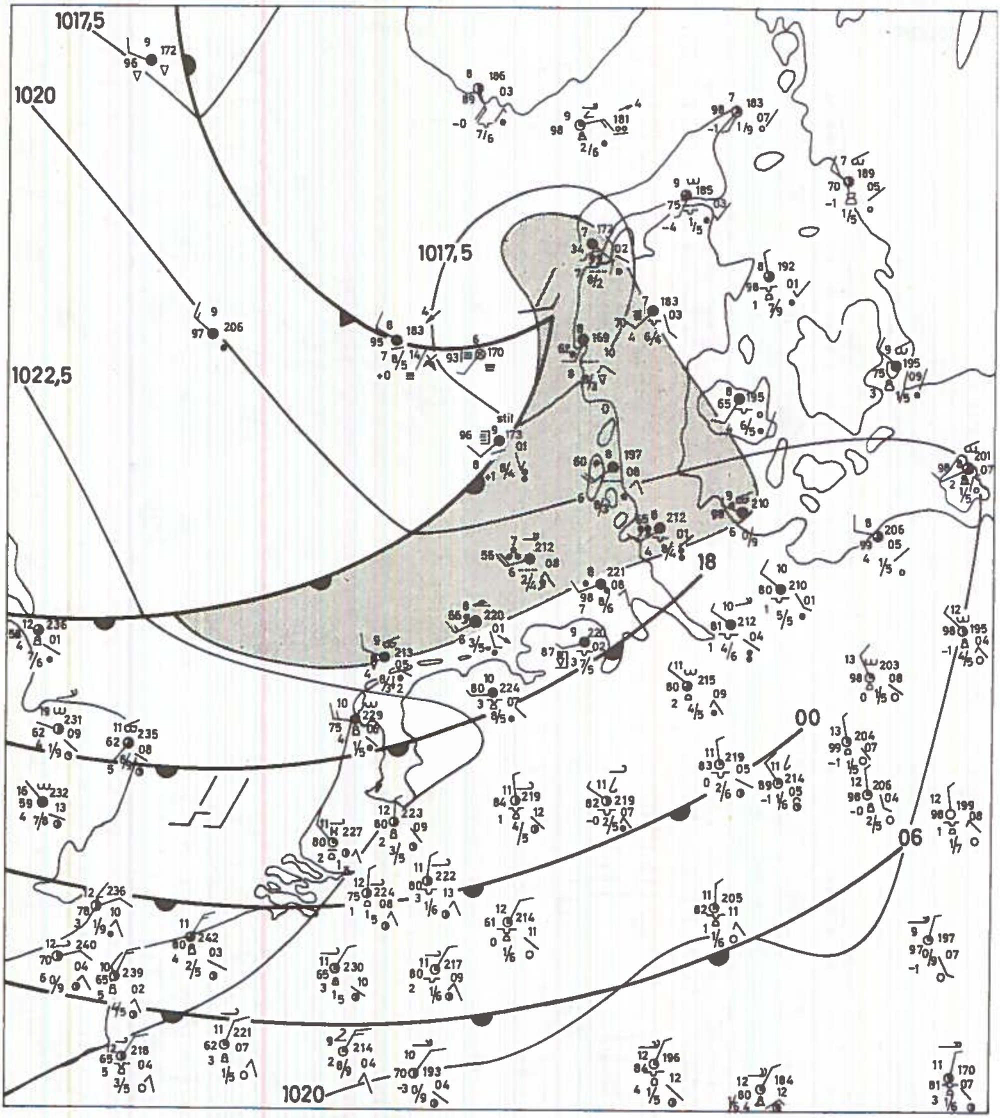


Fig. 34 1 May 1957

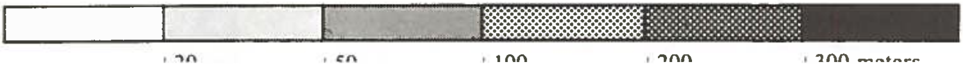
Surface weathermap 1200 z.

▨ rain area

Fig. 35 1 May 1957

Amounts of rain in mm. fallen between 1 May 1957 0840 MET and 2 May 1957 0840 MET

• no rain — isohyets 0,3 mm.



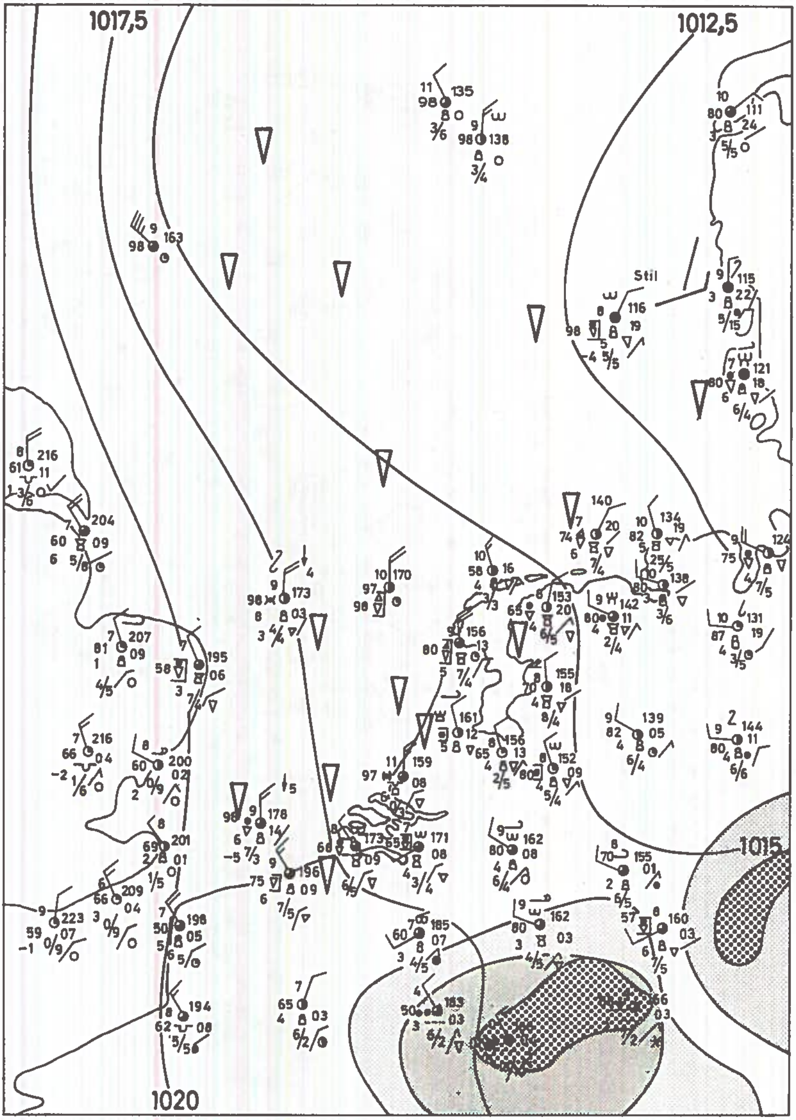


Fig. 36 26 October 1956

Surface weathermap 1200 z.

▨ rain area

□ ▨ ▩

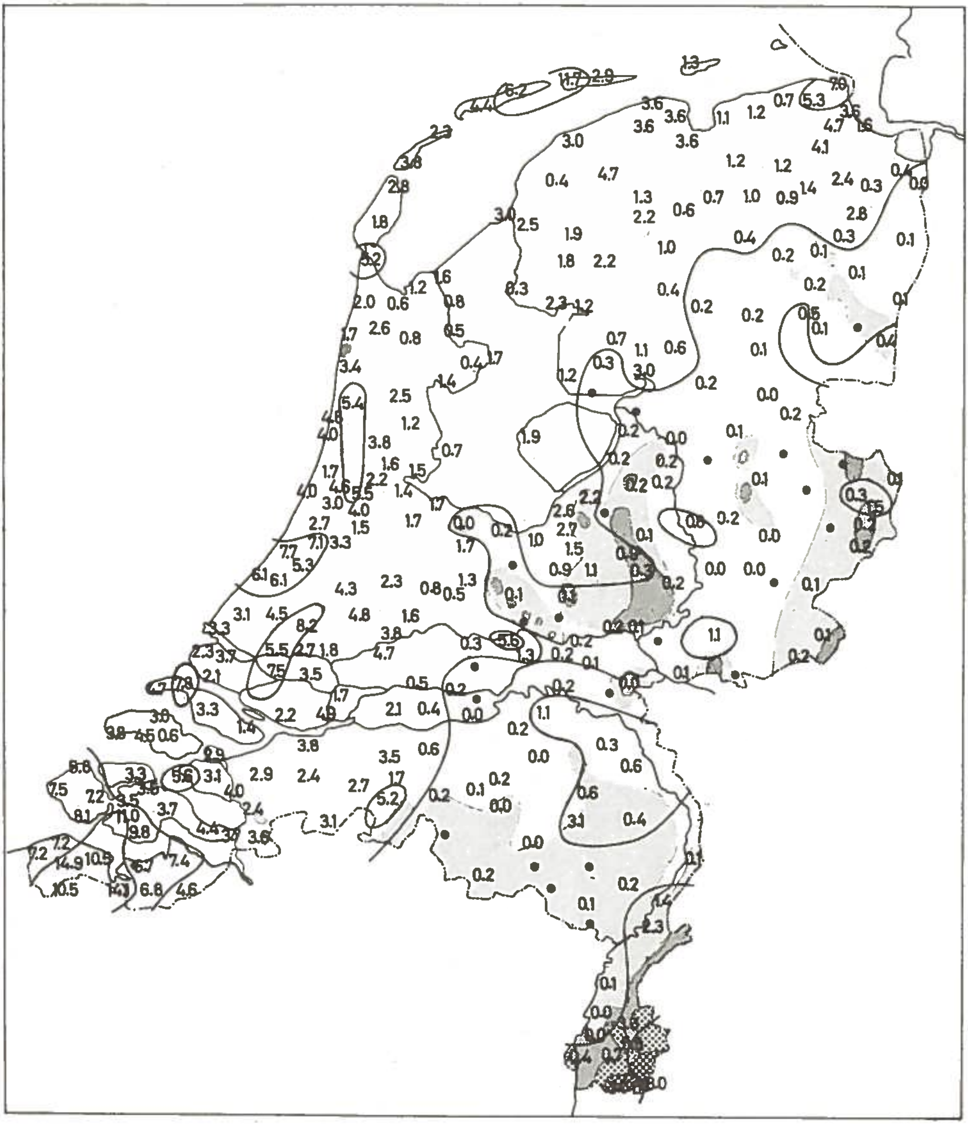


Fig. 37 26 October 1956

Amounts of rain in mm. fallen between 26 October 1956 0840 MET and 27 October 1956 0840 MET

● no rain — isohyets 0,3 mm. and 5,0 mm.

☐	░	▒	▨	▩	■
	+ 20	+ 50	+ 100	+ 200	+ 300