The Problem of Artificial Control of Rainfall on the Globe[1]

II. The Coastal Orographic Maxima of Precipitation in Autumn and Winter

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Abstract

The coastal maxima of rainfall during autumn and winter cannot be explained alone by the classical theory of orographic precipitation. Three different *frictional effects*, and one effect leading to *orographically conditioned convergence* at quasi-isophysic flow, are discussed and illustrated by Scandinavian and Dutch rainfall maps of remarkable special cases of maximum coastal precipitation. The rainfall maps over Holland even hint secondary maxima further inland, at zero-level and parallel to the coastal maximum; they might be explained in connection with standing waves in the sense of QUENEY and others. With all these effects a *low condensation level* and an *efficient precipitation release*, by ice-nuclei or in other ways, seem indispensable to cause intense orographic condensation and bring its results promptly down to the earth.

As stated in article I such orographic cloud-systems, if lacking an efficient release, just represent the clouds where artificial seeding might materially increase precipitation, because (1) condensation may for a long time keep intense and stationary, and (2) the clouds may keep releasable but unreleased. This increase, if at all possible, would diminish precipitation inland where it is much more useful. — A better scheme would therefore be trying to overseed coastal cloud-systems in order to prevent their precipitation release, and thereby increasing precipitation inland, provided the overseeding could be avoided there. This overseeding process might also be used for dissipating inland Cunb, but presumably not for dissipating tropical hurricanes.

The generally accepted idea of the *increase of precipitation with height* is often, e.g. in Norway, contradicted by individual cases with a marked decrease from the very coast and upward when moving inland. A rational attack on this problem was hitherto impossible because the complex nature of orographic precipitation (hinted above) was not recognized. — Outside the Tropics *excessive precipitation* needs low cloud formed by an intense updraft at high temperature (= maximum condensation and minimum evaporation) in continual contact with an upper cloud (part) surpassing the $-10°$ C-level, or seeded artificially (= efficient precipitation release). These conditions will be fulfilled in certain orographic clouds discussed above, and within some convective and frontal clouds.

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1 Based partly on a lecture delivered Aug. 25, 1948, at the Meeting of the U. G. G. I. at Oslo, and on a manuscript Report, dated April 24, 1947. — The previous article I, in *Tellus* 1, N:o 1, is for shortness referred to as »I».

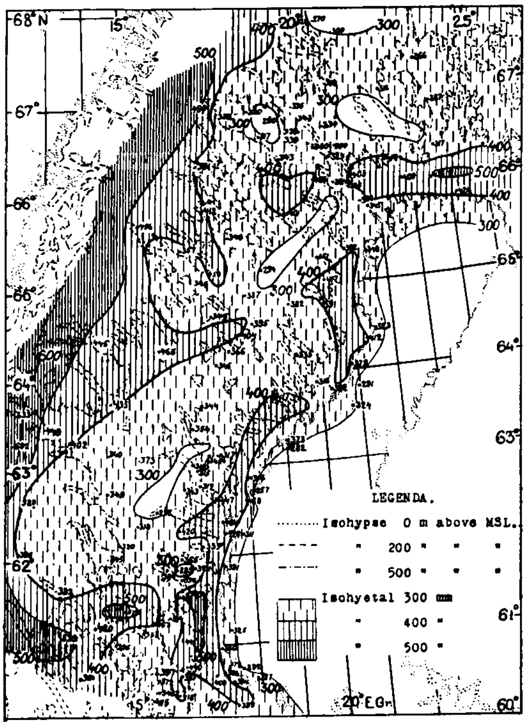


Fig. 1. Average precipitation (1909—1925) during August—April in N. Sweden (excepting the alpine region, the Scandes) showing a marked maximum zone along the Bothnian coast.

1. Rain-fall maps for the winter-half of the year, in temperate and polar regions, show coastal maxima of precipitation which lie even much nearer to the coast than one would expect from the classical theory of orographic precipitation.

(a) This fact is, for instance, revealed by the *rainfall distribution along the Bothnian coast of N. Sweden* in the season August—April, shown in fig. 1 (mean values for the years 1909—1925). E—W-profiles of the country at 61°, 63° and 65° N are seen in fig. 2, showing along the northernmost profile a gradual and small rise of the country from the very coast at 21°10′ E long. to about 16° E long. where the mountains begin. Nevertheless, even along this profile there is a marked zone of maximum precipitation (430 mm) less than 20 km from the coast, and a minimum (300 mm) in the somewhat higher interior of the country. For the two other profiles the corresponding figures are 420 and 290 mm, 510 and 325 respectively, showing an even more pronounced decrease of rainfall inland in spite of a general increase of the elevation of the country. — Most of this coastal precipitation is deposited with the upslope and/or convergent motion associated, in this region, with winds between S and NNE.

Not until near the watershed of the Scandinavian mountain range, the Scandes, and on its W. side, an amount of rainfall considerably greater than the Bothnian maxima is encountered. But then these great amounts are deposited by winds between SW and NW, i.e. during weather types which hardly contribute at all to the maxima along the Bothnian coast.

In the absence of the Scandes the winter precipitation deposited with the above-men-

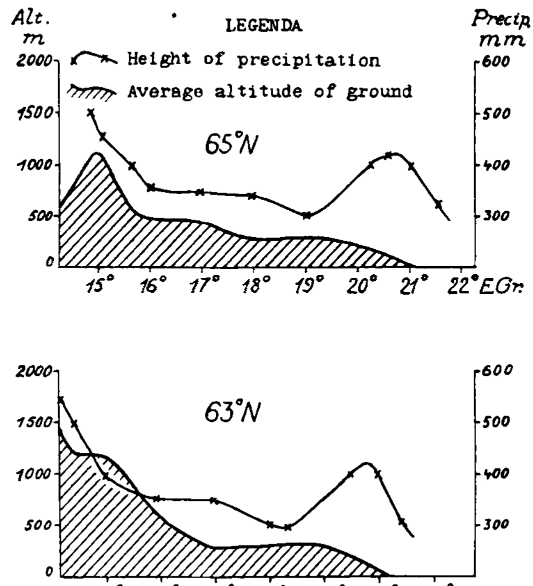


Fig. 2. Profiles of precipitation (from fig. 1) and ground from the Bothnian to the Scandes, along 65°, 63° and 61° N long., showing the marked coastal rainfall maxima.

tioned S to NNE winds over N. Sweden would obviously only show the marked Bothnian maxima of figs 1—2, and then a continued decrease of precipitation across the peninsula. An explanation of this, partly unexpected, distribution will be attempted in 3. But it should be stated already here that the discontinuity of friction, and of direct supply of water vapor into the air from the earth's surface, found along a coast-line evidently favours the formation of a zone of maximum precipitation near this line within air-currents with an on-shore component. If the ground is flat and comparatively dry the amount of precipitation in such currents will decrease more and more inland.

(b) To prove the validity of the above statements more in detail one has to resort to other methods than using only the official rainfall stations, cfr fig. 1, since this network is too sparse, as seen by that figure. Figs 3 A and B show *the snow-depth over the very flat Stockholm-peninsula*, at a map-scale 4 times that of fig. 1, during some well-defined weather-types in the cold winters 1941/42 and 1942/43. In both cases most of the snow fell during one week, without any thawing and with winds between E and N. The Baltic and Bothnian Seas were still mainly ice-free, and the moisture supply into the air, while passing these waters, was considerable. The snow-cover was insignificant at the beginning of each period, and the wind force was generally moderate when the snow fell. Considering that even this flat region in its NE. part is covered by forest to 65 % (excepting the outer skerries in the sea), and that the observers were instructed to measure the snow-depth, if possible, in forest glades, or in similar places, where it had not drifted, we may infer that the observations give at least a good relative measure of the amount of precipitation during these periods. Moreover, the agreement between neighbouring figures, and the close connection between the snow-depth and the orographic features (in this case mainly the distribution of sea and land) gives another, and even better, support to this statement.

The observers were mostly voluntary, and their cooperation was demanded by a broadcast appeal or by telephone calls to unknown people. The number of official rainfall stations in the 1-degree square 59—60° N lat. and 18—19° E Gr. long. is only 12, i.e. $^1/_8$ of the number of snow-depth data (98) within the same square in fig. 3 B. The official stations alone could have given little evidence concerning the problem discussed here, when used for a period of a few days only.

It is striking to notice that the special distribution of snow in fig. 3 A is repeated almost in all details in fig. 3 B, a year later. The weather type was in both cases characterized by a low ice-nucleus level and a low condensation level. The orographic cloud-system was as a whole stratiform, sometimes with a marked inversion above it already at about 1 km height. Owing to the intense heating of the cold air over the open sea, however, the air below the inversion was often unstable, and in reality the cloud-system consisted of very low and untypical, dwarflike, Cunb fused into a more or less continuous cloud deck. In such weather-types even a slight lifting, or an increase of turbulence, will presumably suffice to release convection, and formation of dwarf-Cunb, within the lowest unstable layer, at the coast-line. Farther inland this convection is probably damped or stopped by continental cooling, and in any case the moisture supply from below into the clouds is almost cut off. It is reasonable, then, to claim that any such orographic effects within the region investigated will be more pronounced than otherwise in winter time with an on-shore wind. — In fact, E of 17°30′ long. this region is remarkably flat, the isohypse of 60 m (200 ft) only comprising some very small areas at A, B and C on the maps, see fig. 3 A. Consequently, in this region any orographic effect, lifting the air, orderly or disorderly, considerably above the condensation level in winter, when the thermal convection due to the heating of land surfaces is missing, must be caused or released mainly by the frictional difference mentioned.

(c) A *direct frictional effect*, partly caused by the frictional convergence and lifting within an on-shore wind (BALDIT 1929, ARAKAWA 1936), and partly by the sudden increase of vertical mixing at the coast-line, and affecting only a shallow layer of the atmosphere, needs a low condensation level to produce any cloud at all, and the lower the better. Even the upper limit of such a cloud will generally be low, and in order to get the water which has been condensed within it down to the earth again as

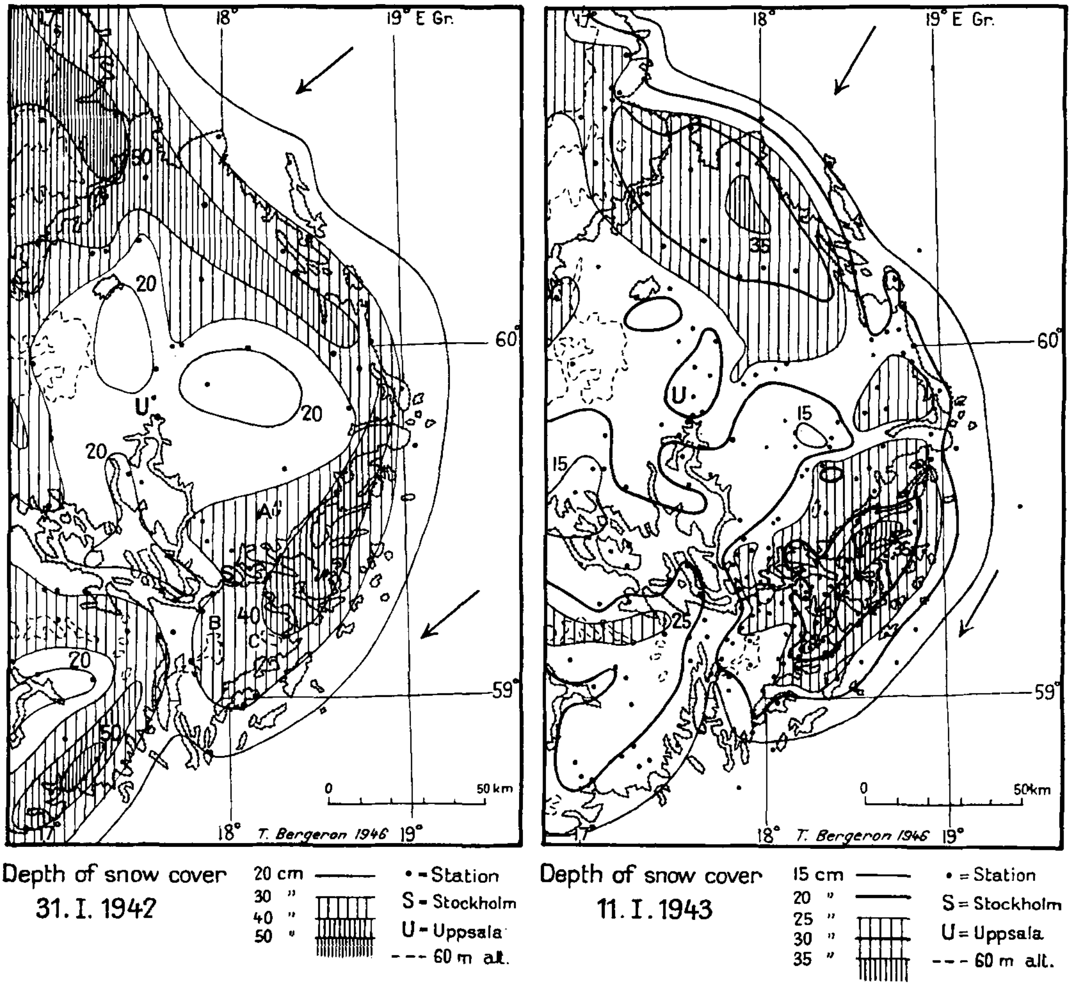
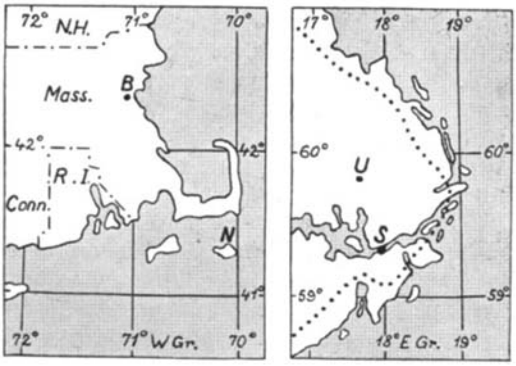


Fig. 3 a.

Fig. 3 b.

Fig. 3. Snow-depth distributions over the Stockholm-peninsula (region Uppland—Södertörn) resulting from snow-fall with NE wind (the arrows) in cold winter weather, showing combined frictional effects on precipitation along a flat coast.

rapidly and completely as possible the cloud must also become physically unstable, e. g. through infection by a suitable number of natural (or artificial) ice-nuclei (cfr 7., in article I). Thus, a low ice-nucleus level will mostly be another necessary condition for getting a marked coastal rainfall maximum along a flat coast, such as the one in figs 1—3, where friction is the main orographic factor. — Let us then state, however, that the winter conditions described by figs 3 A and B could be very little influenced by any artificial seeding, as the natural one was already operating, and probably nearly at an optimum rate. — In similar cases, with a much higher ice-nucleus level, not reaching down to the orographic coastal cloud, the precipitation might be considerably less intense, all other conditions remaining the same, cfr 3. Then, a suitable artificial seeding might increase the precipitation within the coastal zone of maximum condensation, but this would also mean depriving the current of some moisture which otherwise might give precipitation farther inland by a renewed orographic lifting, or by thermal convection.



B = Boston U = Uppsala
N = Nantucket S = Stockholm

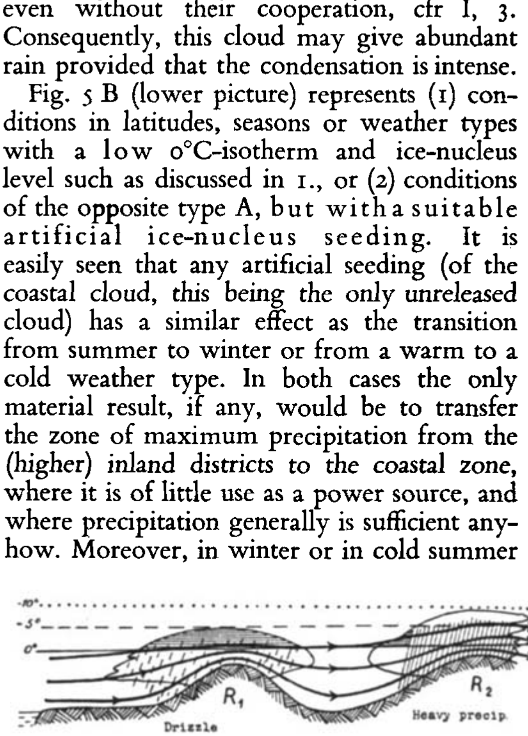
Fig. 4. Dimensions of the region in fig. 3 compared with a region in New England, U. S. A.
.... Central line of zone of maximum snow-depth in fig. 3 B.

The snow distribution in figs 3 A and B will be appraised anew in 3. after having learnt more about the orographic precipitation effects. — Before leaving figs 3 we shall compare the dimensions of their region with a well-known region in the USA: the SE. part of New England shown in fig. 4. Owing to the analogous orographic situation, and the frequent occurrence of blizzards with N-NE wind in New England, very pronounced coastal snow-maxima must sometimes form in this region, although, presumably, the network of rainfall stations will also here not be dense enough to show these maxima.

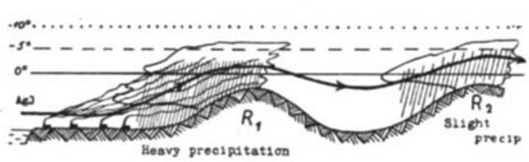
2. *The hydrometeoric reactions of on-shore and cross-mountain air-currents to fundamental types of orography*, partly discussed in 1., are represented schematically in fig. 5, showing land profile, air current, clouds, and precipitation in a vertical section from the sea (or very flat lowland) to the left and landward to the right. — The lefthand ridge R_1 may symbolize (1) a coastal mountain range (such as the Californian) or (2) simply the coastal effect of increased friction etc. discussed in 1., found along a flat coast (such as around Stockholm, or N of 64° N lat. at the Bothnian Sea). In both cases the on-shore wind component produces a cloud system. — The righthand ridge R_2 may symbolize (1) a (higher) inland range (such as the Sierra in California, or the Scandes in an easterly weather type), or (2), in summer, just the effect of increased thermal convection by the gradual heating and instabilization of the air farther inland. In both cases a second cloud system or cloud region may occur.

Fig. 5 A (upper picture) represents conditions in latitudes, seasons or weather types with a high 0°C-isotherm and ice-nucleus level (temperate latitudes in summer, warm spells during colder seasons, lower latitudes all the year), and natural seeding only. The coastal cloud is assumed to surpass the 0°C-isotherm but not to get any efficient precipitation release. It will then give only little precipitation, mainly as drizzle. — The inland cloud will reach the natural ice-nuclei or, within the Tropics, get efficient release even without their cooperation, cfr I, 3. Consequently, this cloud may give abundant rain provided that the condensation is intense.

Fig. 5 B (lower picture) represents (1) conditions in latitudes, seasons or weather types with a low 0°C-isotherm and ice-nucleus level such as discussed in 1., or (2) conditions of the opposite type A, but with a suitable artificial ice-nucleus seeding. It is easily seen that any artificial seeding (of the coastal cloud, this being the only unreleased cloud) has a similar effect as the transition from summer to winter or from a warm to a cold weather type. In both cases the only material result, if any, would be to transfer the zone of maximum precipitation from the (higher) inland districts to the coastal zone, where it is of little use as a power source, and where precipitation generally is sufficient anyhow. Moreover, in winter or in cold summer



A. With only natural ice-nucleus seeding (at R_2)



B. With efficient artificial seeding at R_1 (and R_2)

Fig. 5. Orographic cloud-systems produced in on-shore and cross-mountain flow (schematic vertical sections).
☰ Potential layer of precipitation release, cfr I, fig. 8.

weather an artificial seeding would have no appreciable effect at all.

There is still something to be said about the method to use in these cases for seeding the orographic cloud systems. Their precipitation intensity is small compared with the Cunb precipitation, and rainfall amounts of economical importance are obtained mainly thanks to the vast extent of this kind of cloud-systems and the long duration of their precipitation. The orographic cloud systems are stationary, and a prevailing wind is flowing through them. Consequently, any artificial seeding of them must also be of long duration since the nuclei are constantly brought down to the earth with precipitation elements, or blown out of the cloud-system to the leeward. Moreover, as stated in I, it is important to keep a suitable ratio ν within the cloud to get the effect desired. These two conditions can hardly be fulfilled by dropping CO_2-pellets from air-planes; if practicable, this method would be uneconomic. The *quasi-permanent ice-nuclei* found by LANGMUIR and collaborators (AgJ and other chemical compounds) might possibly be used in this case since such nuclei can be produced at low cost in even a much greater number than those produced by the CO_2-pellets, and since they can be brought up into the clouds from below in the manner indicated in Fig. 5 B. A row of AgJ-factories, erected along a windward coast, are assumed to pollute the air with these nuclei — which can subsist also at temperatures above 0°C — and they are gradually spreading vertically through the whole depth of the air-current in question, and also horizontally, thanks to turbulent vertical and lateral mixing. The great problem, however, would be to keep a suitable ν throughout all the orographic cloud-system, from its windward to its leeward edge, in view of the constantly increasing vertical spreading of the nuclei; cfr BERGERON 1943, p. 271—272.

Here we might, at the same time, see a glimpse of a solution to the main difficulty underlined above: the artificial seeding "stealing" rain from the dry inland instead of rendering more rain to these regions. If it could be possible artificially to keep the coastal cloud-systems more or less continually o v e r s e e d e d [cfr I, 7(b).] their release (by ice-nuclei) then and there might be impeded in all cases where this cloud system did reach the natural ice-nucleus level and otherwise would have rendered a rather abundant precipitation. At the same time more moisture would be left within the current for producing some possible precipitation inland where, as a rule, it is much more needed.

This method of overseeding might then also perhaps be used in some way or other to *prevent the too intense precipitation from, and electric phenomena within, quasistationary Cumulonimbi* by transforming most of their cloud droplets above the 0°C-isotherm into minute ice-crystals. If artificial ice-nuclei were present in the same number as, or in a greater number than, the condensation nuclei ($\nu \leq 1$), and were of the same efficiency as the latter, only sublimation would occur above the 0°C-isotherm, since $E_i < E_w$. Then, any supercooled droplets brought up above this level by the intense updraft in the Cunb would be "consumed" by the crystals in a few seconds, cfr I, 7 (b). Such numerous ice-crystals cannot, any more than the ordinary cloud droplets of a Cu, grow very much by direct sublimation alone as long as they remain within their respective air parcels. Then, they will not acquire any appreciable fall velocity and the cloud will remain physically stable. The final result might be a cloud compound being a water-cloud, a Cumulus, below the 0°C-isotherm, and a kind of Cist above this level, giving no appreciable precipitation, especially no hail, no squall at the ground, and no lightning or icing in its interior — a tamed monster deprived of all its horrors.

The next step, to extend this treatment to the rapidly passing Cumulonimbi within a strong air-current, or to tropical hurricanes, does not seem very promising, in view of their propagation which mostly would make any stationary seeding plants useless. — *The dissipation of extensive storms by artificial seeding with ice-nuclei*, if feasible at all, could probably only be achieved by the aid of quasi-permanent ice-nuclei, as outlined above, and *not by dropping CO_2-pellets from air-planes*, as tried hitherto.

3. Synoptic investigations of certain weather situations, characterized by *excessive orographic precipitation*, carried through already many years ago, have led the writer to the conclusion, that *the pronounced coastal rainfall maxima*,

displayed by most winter-time rainfall maps, *are produced in a number of different ways.*

(a) Such maxima may occur even according to the classical scheme of orographic precipitation (by the orderly lifting of an on-shore and/or cross-mountain current) when the air is so humid that the condensation level, and thereby also the thickest cloud, comes to lie very near the sea, provided that there is an efficient precipitation release operating within this cloud.

(b) Other maxima are mainly conditioned by the direct frictional effects discussed in 1. above.

(c) A most striking case, the main features of which cannot be explained by the processes (a) or (b), is shown in Fig. 6. The general situation was governed by a steady outflow of continental Polar air, and partly also of Arctic air, from the Russian continent in connection with a quasi-stationary anticyclone over N. Scandinavia and N. Russia. A marked and quasistationary frontal zone (not shown in fig. 6) between the *cA* and *cP* to the NE and the *mP* (and partly *mT*) to the SW, extended from the Black Sea over N. Germany and S. Denmark to Scotland and Iceland, giving upslide precipitation on its northern side. The northern limit of this precipitation is represented by a zero-isohyetal running from Stockholm northwestward to Storlien and farther westwards over the Scandic, cfr fig. 6. The frontal precipitation measured during 3 days (24—27 March, 1927) increases from this zero-line towards the front zone and attains an average value over S. Sweden and Denmark of 20 to 30 mm. — A detailed study of the isohyetals reveals several striking deviations, though, from this general distribution, deviations which must be closely connected with the orography. The outstanding feature of the whole map is the narrow and very intense maximum zone along the Norwegian Skagerak coast, culminating at Grimstad, on the very coast, with 201 mm of melted precipitation in 72 hrs. (Most of this precipitation fell as snow or sleet, and in all it continued for about a week, with the effect that this small town, Grimstad, NW of **G** on the map, became literally buried in snow).

A zone of excessive precipitation may sometimes be caused by one giant Cumulonimbus, or by a so-called convective system.

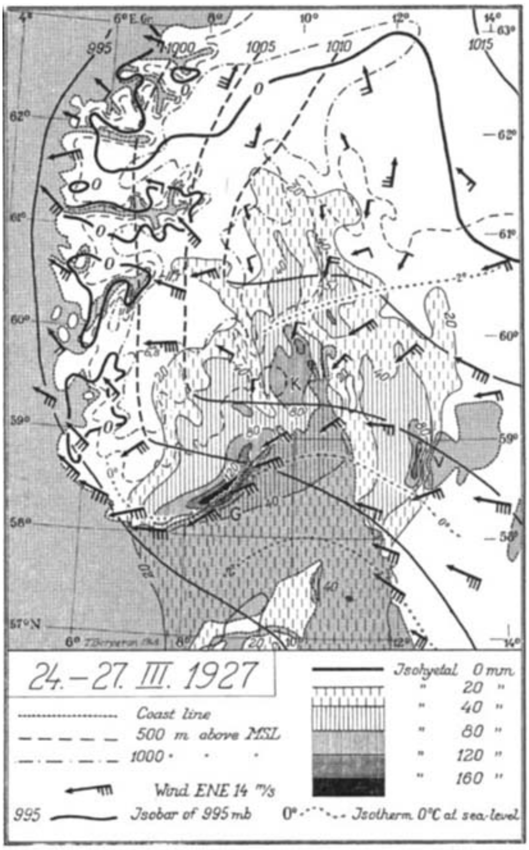


Fig. 6. Distribution of precipitation, wind, pressure and temperature in SW. Scandinavia during the period 24—27 March 1927 (72 hrs), showing marked coastal maxima of precipitation mainly due to orographically conditioned convergence.

In the case of fig. 6 such an interpretation, however, is first of all contradicted by the fact that the season and the general weather type hardly permitted the formation of any Cunb at all, not even of the dwarf-type discussed in 1., much less then of the giant-type sometimes forming inland in the summer-half of the year, and rendering 100—200 mm of rain in passing a region. The general current in lower layers was SE, at the mid-troposphere level presumably around W, and there was certainly rather warm air aloft above the front surface. The clue to the situation, and the final proof that this zone of excessive precipitation was of real orographic origin, is given by three facts:

(1) The same connection between orography

Table 1. Data from Norwegian mountain stations averaged for the period 24.—27. III. 1927 (07^h—07^h GMT).

Station	φ	λ	z(m)	T_z (°C) observed	T_0 (°C) interpolated	γ (°C/km)	DDF
Kutjern	60° 34′ N	10° 33′ E Gr.	496	— 5.1	— 2.5	— 5.2	NNE 4
Svandalsflona	59° 50′ »	6° 59′ » »	1 065	— 6.7	— 3.0	— 4.4	E 9
Slirå	60° 37′ »	7° 23′ » »	1 304	— 10.7	— 3.5	— 5.5	ESE 8

and precipitation is repeated, on a smaller scale, in two other regions of the map, viz. in the region of Kongsberg (**K** in fig. 6, W of Oslofjord), and just to the West of the lake Vänern (at 59°.0—58°.5 N and 12°.5 E Gr., **V** on the map) where a maximum precipitation of 108 mm was actually measured, whereas the precipitation from the same air-current over the Lake itself (at about 59° N, 13° E Gr.) was less than 15 mm.

(2) In these three regions, situated to the W of open water, the country is rising considerably and produces in all places a special wind pattern, treated below, at least within the lowest layers of the atmosphere.

(3) The orographic effects (1) and (2) were even found on every individual day during the period of fig. 6, and also during other analogous autumn and winter periods. Inger Bruun 1944 has several daily rainfall maps showing a quite similar distribution within Norway (cfr below p. 30).

The whole phenomenon is most pronounced in S. Norway, which has a more marked orography than the surroundings of Vänern. The former region, therefore, displays the effect in its typical form. Thanks to the vertical stability of the air over S. Norway during the period of fig. 6, shown by Table 1, the ESE current of the 0.5—1 km nearest to the ground could not surmount the Scandes in this region (where the mountain barrier is on an average 1 000—1 500 m high), but was divided into two branches. A minor branch found its outlet over the lower part of the Scandes near Storlien, flowing slowly upslope (Östersund and Röros 4 Beaufort), but quite rapidly downslope (e.g. up to 8 B West of Trondheim). The main current had to bend SW or even SSW (even Kutjern, at 500 m above s.-l., reports NNE 4 B) and to flow along the Skagerak coast as an increasing NE wind. This increase of the NE wind is due to its converging into the general ESE current coming over Sweden and Denmark, but the $\frac{\partial v}{\partial s}$ is evidently not great enough to compensate for the pure stream-line convergence, i.e. $\mathrm{div}_2\mathbf{v}$ remains < 0: *orographically conditioned convergence.* — The convergence is considerably accentuated by the fact that, in this case, the region of greatest roughness and friction (the land) lies on the high-pressure side of the current, an effect which has been recognized since 1919 both theoretically and empirically by the Bergen School: the *indirect frictional convergence* (cfr Bergeron 1934, fig. 51, p. 70). An intense lifting then must take place within this ENE current, although it is flowing almost parallel to the coast-line and to the general isohypses of the country; and this lifting is evidently reponsible for the excessive coastal snow fall — It should be noted here that these and other features of the wind-field seen in fig. 6 cannot be dismissed as occasional deviations, but are representative and persistent, since this field is constructed by forming the vector mean of 10 individual observations, at the main observation hours, through the whole period. [A number of other interesting features in the wind-field (not discussed here), in the pressure-field, and regarding their interaction, is reserved for future treatment.]

We now return for one moment to the *experimentum crucis*, the conditions along the W. shore of Vänern. Also here an open water surface borders to a rugged country, and the same orographically steered wind-pattern (see Vänersborg, at the southern part of the lake, with ENE wind), frictional difference, convergence, lifting, and cloud-system as at the Skagerak coast is produced, though on a smaller scale. — All the above reasoning does not, however, in itself explain definitely why the precipitation reached such extraordinary amounts just in this March case. Favouring conditions were the strong wind and the negative values of $T - T_s$ over the water surfaces, both increasing the intensity of condensation within the coastal zone of maximum precipitation. — Some October cases, with the same general wind pattern, have also been studied. During the period 20—26 October 1933 the wind velocity was only about $^2/_3$ of that in the March case. On the other hand, T_0 was around $+ 10°$ C, and the condensation level was just as low, implying that the saturation vapour pressure E, and $\frac{dE}{dz}$, in an individual rising air parcel must have been even almost the double of the March values studied here. Nevertheless, in the October cases the greatest amount of precipitation in the coastal maximum zone was only 5—20 mm a day, and the precipitation was mainly drizzle. The latter circumstance helps us to solve the problem.

In fact, a cloud system formed by the orographically conditioned convergence discussed above, along a coast of only 100—500 m height generally does not reach the natural ice-nucleus level (at about — 10°) unless formed entirely within cA (which was not the case here), because as a rule the cloud-system will not extend much higher than the average height of the steering obstacle; above a certain height there will mostly even be a marked divergence, combined with a rapid decrease of the lifting motion and with vertical stability. The average mountain temperatures observed in the March case at the 500, 1 100 and 1 300 m levels (see Table 1 and fig. 6), indicate that even during this cold winter-situation the purely orographic cloud, at least in its southern part, around the sea-level isotherm of 0°C, did not reach the ice-nucleus level.

The processes prevailing during all such easterly weather-types in S. Norway could then be generalized as shown very schematically in fig. 7. The lines of equal values of negative $\text{div}_2\mathbf{v}$ (convergence), of lifting, and of intensity of condensation to the East of the Scandic divide (and their counterpart with opposite signs on the W side) would then nearly coincide, any deviations being due to cross-current and down-stream differences in pressure, temperature and humidity.

In an imaginary case of this kind, without precipitation release, the water content of the

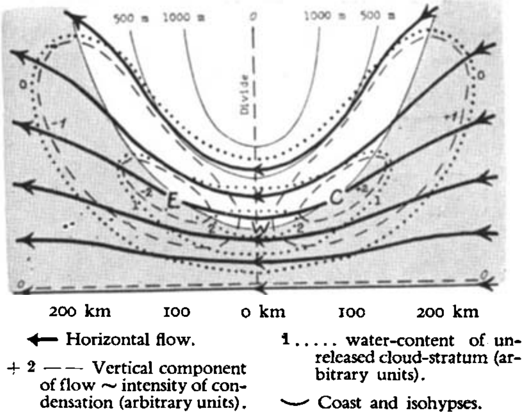


Fig. 7. Schematic map of orographically conditioned convergence, vertical motion, condensation and precipitation produced in a general E wind by a symmetric obstacle similar to S. Norway.

orographic cloud system would be strictly symmetrical with respect to the N—S line of divide — -- – in fig. 7, and could be represented by the dotted isopleths in this fig. — This state would be analogous to that of the stationary and symmetric cloud-cap of fig. 1 in article I, though the vertical axis of that fig., pointing upward, would correspond to the divide-line of fig. 7, pointing downward. Moreover, the horizontal dimensions are 50—100 times greater in fig. 7 than in fig. I, 1. Just as in the latter case, also within the orographic cloud-system of fig. 7 — if it were physically stable (I, 1.) — the individual cloud-droplets would rush through the cloud at high speed, forming and growing within the rising current at the Eastern (windward) side, shrinking and at last dissolving within the sinking current at the Western (leeward) side — and few of them would be deposited on the earth's surface.

In reality, however, there will always be some precipitation release within the cloud-system of fig. 7, thanks to the greater extent of this cloud-mass and the much longer lifetime of each droplet as compared with the local cloud-cap; cfr I, 8 (d). Under conditions such as in the October cases quoted above the release is inefficient and slow, though, so that only a fraction of the water condensed reaches the ground as precipitation; and this will not occur just below the place where the release started, but to the leeward. The

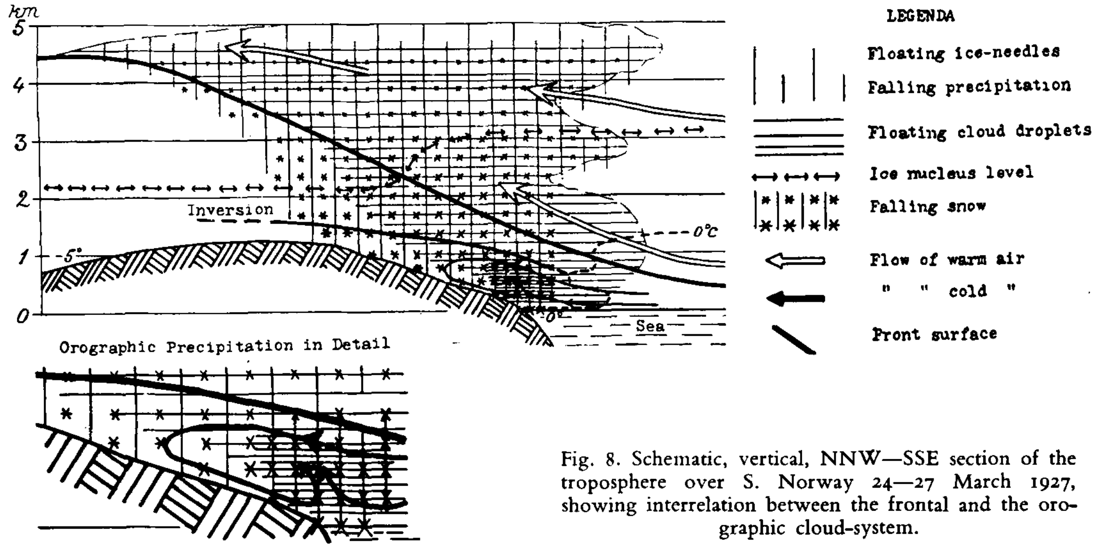


Fig. 8. Schematic, vertical, NNW—SSE section of the troposphere over S. Norway 24—27 March 1927, showing interrelation between the frontal and the orographic cloud-system.

maximum zone will then have a position in between the two positive maxima *C* and *W* in fig. 7, and the precipitation within it will be of modest amount and drizzly character, even if the intensity of condensation in the zone *C* is extraordinarily great.

In the case of 24—27 March 1927, shown in fig. 6, however, the synoptic maps (not reproduced here) clearly show that any low, orographic cloud systems forming within the SE current of Polar air at the SE coasts or SE slopes of S. Scandinavia were overshadowed by a vast and quasistationary shield of Altostratus-Nimbostratus, formed mainly within and above the afore-mentioned frontal zone. From this cloud-system snow fell continuously everywhere in the region between the zero-isohyetal of fig. 6 and the front-line south of Sweden (even in regions having orographic rain-shadow with an E-wind, except in the fjords of W. Norway, where the orographic shelter was too effective). North of the 0°C to + 1°C-isotherm at the ground (see fig. 6) the precipitation reached the ground as snow. Even south of this line snow must have reached down to the 200 or 300 m level, and thereby also to the tops of the orographic cloud systems of S. Sweden and Denmark, although these were not so strongly developed.

The three main zones of excessive orographic precipitation discussed here lie almost entirely within the first-mentioned region, with snow reaching the ground. In these zones the continuous snow-fall from a cloud having its base at 1 000—1 500 m above s.-l., as shown in fig. 8, represents a natural mechanism for ice-nucleus seeding and precipitation release even more effective than the ordinary one operating in supercooled water-clouds at and above the — 10° level. In this case the seeding elements (snow-flakes) were already large and fell at a rapid rate, thus forming a kind of "network" of branched crystals apt to carry down to the earth most of the water condensed in the low cloud within zone *C* of fig. 7, rapidly and almost directly below the spot where the condensation took place. Let us assume the fall velocity of the snow-flakes to be, say, 1 m/s, the centre of the main condensation to lie at 500 m above s.-l. (possibly bordered by an inversion at the upper limit of the ground turbulence and convection within the Polar air), and the average wind to be E 10 m/s through the lowest layer of 1 km depth (there will be a considerable decrease with height of this E wind above 500 m). A snow-flake would then be displaced only $\frac{500 \text{ m}}{1 \text{ m/s}} \cdot 10$ m/s, or 5 km, westward from its position at the level of main condensation, during its fall to the sea-level, a distance hardly discernible in figs 6 and 7. Under the assumptions made, it is thus permissible to claim that the area of maximum precipitation would almost coincide with the area *C* in fig. 7. The shape and position of this area as compared with the area **G** in fig. 6 shows an agreement which is striking and to a certain extent convincing, even if we make allowance for the fact that the position and shape of the area *C* in fig. 7 is constructed only mentally, and qualitatively, from the stream-lines.

It is obvious that the zones **K** (W of Oslo) and **V** (W of Vänern) cannot compete with the zone **G** as to amount of precipitation and typical features, the orographic conditions being so much less pronounced. But they may well serve to confirm the validity of the general reasoning set forth here, because even snow-amounts of 100 mm (melted water) by *one* storm are very rare in Scandinavia. — As to the remaining zones of maximum precipitation during this period (only the one at Skagen is visible on fig. 6), none of them can serve as a further support of the existence of this kind of orographic precipitation since there is nowhere else in the wind field any clear indication of the orographically conditioned coastal convergence. There is also nowhere else any indirect frictional convergence effect acting since the wind nowhere blows with the sea to the left of the current (except just at the Southern coast of Scania).

On the other hand, most of these maximum zones are situated quite near the windward coast, even when the coast is very flat (Denmark, Swedish East coast between 55° and 59° N etc.), indicating that they are favoured or produced mainly by the direct friction effects discussed in 1(c).

4. Returning to the snow maps, figs 3 A—B, we may now state that only NE of Uppsala, where the wind was perpendicular to the coast, was the precipitation mainly produced by the direct friction effects. Within the maxima east and south of Stockholm, where the current was partly parallel to the general coast-line, the high-pressure side friction effect must have cooperated, and possibly also some orographically steered convergence at quasi-isohypsic motion. Only in that manner can we explain why these maximum zones are even more pronounced and their centers lie even nearer the coast than those NE of Uppsala.

It is important, therefore, to study the orographic precipitation in a completely flat region, where frictional differences alone can be made responsible for the distribution of rainfall. The Netherlands offer such an opportunity since the network of rainfall stations is tolerably dense (about 300), and since the NW. part of the country is extremely flat and even mostly depressed below sea-level, excepting the zone of dunes along its NW. sea-shore, see fig. 9. — A preliminary study of the rainfall distribution during individual days in July—October 1945 with extensive, and in part abundant, rain over the country has rendered a striking confirmation of the principles expounded above. This study is based on the 200 rainfall values printed *in extenso* in the Dutch year-book *Regenwaarnemingen.*

(a) Six cases, the 24^h-periods ending 1. VII., 18 ,19 and 24. IX., 24. and 26. X. 1945, with a S—SW wind, fresh to a gale on the coast, and rain from a frontal cloud system, gave in principle the same picture of the rainfall distribution, the map for 26. X. 1945, reproduced as fig. 9, being the most typical one. The outstanding feature of this map is the main maximum zone along all the seashore of Zuidholland and Noordholland, continuing toward NE and E over the Frisian islands, and practically coinciding with the belt of dunes, which forms the border of the country toward the North Sea and represents a very narrow (0—5 km) barrier of an average height of 20 m (5—60 m). Already C. Braak 1933 ascribes the marked maximum of average October precipitation found over Noordholland, well to the E of the dunes (l. c., Plate V), "to the friction above the land, and particularly by the dunes" (l.c., p. 100). In view of the much closer relation between the coast and the maximum zone during the special 24^h-periods investigated here, it is natural to go some steps further and interpret these maxima as analogous to those of figs 3, the one over the mainland forming with an on-shore wind component and corresponding to the northern maximum zone of figs 3, the one over the Frisian islands corresponding to the southern maximum of figs 3.

This Dutch analogy is especially valuable since it occurs with the opposite wind direction (warm-air current from SW) as compared with the Swedish winter cases (cold-air current from NE), but still (1) occurring with the greater friction on the high-pressure side

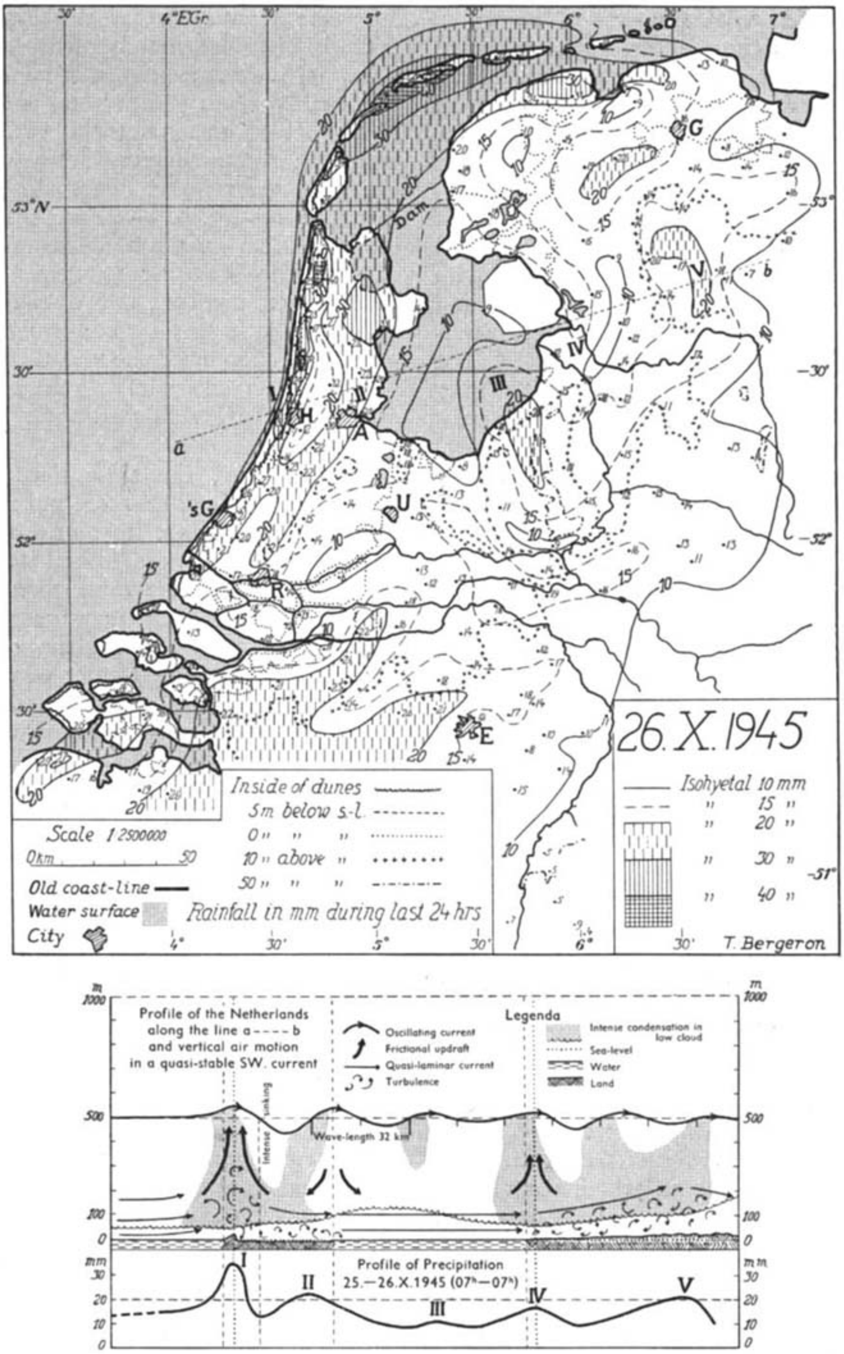


Fig. 9. Distribution of rainfall over the Netherlands, and WSW—ENE profile around 52.5° N lat., during the 24h-period ending 26. X. 1945, 07 GMT.

Map figures show the total rainfall in mm
a - - - b shows the position of the profile
A = Amsterdam 's G = 's Gravenhage
E = Eindhoven H = Haarlem
G = Groningen R = Rotterdam
U = Utrecht

of the current, hinting that this latter condition is a necessary, and even deciding, one for producing a typical and marked coastal maximum. Again, both in the Swedish and Dutch cases (2) the condensation level was low, and (3) the statical stability was pronounced, at least above the turbulence layer, hinting two other necessary conditions. Lastly, in *all* cases (4) the precipitation release was efficient, in the cases of figs 3 thanks to low temperatures at all levels, in the case of fig. 6, and in the Dutch cases, mostly thanks to the precipitation from overlying frontal clouds (cfr fig. 8).

(b) In fact, two other cases of abundant precipitation in the Netherlands from the same year, when one or more of the above conditions were failing, show quite different rainfall distributions. — During the 24^h-period ending 10. VIII. 1945 abundant rain fell over the country in connection with an upslide front to the E, belonging to a small retrograde cyclone over W. Germany, and with low level winds around NE in the province Groningen, but elsewhere with winds between N and WNW on the coast. In this case the main rainfall maximum (about 70 mm) lay near Groningen (coinciding with a seasonal maximum, cfr BRAAK, l. c., plate IV). Another maximum (55 mm) lay on the northern slopes of the Veluwe (max. height 107 m a. s.), in good agreement with the orographic effect to be expected in a WNWly current. — On the coast there was only an ill-defined secondary maximum (35 mm), in the provinces Zuidholland and Zeeland, produced in a Nly—NWly wind by the direct friction effects, cfr 1 (c), but counteracted by the indirect one, factor (1), cfr 3 (c). Moreover the former factors were not pronounced since the Nly current formed a comparatively unstable cold-mass. Only in Zuidholland—Zeeland the direct frictional effects were operating, presumably assisted by efficient release from the overlying frontal cloud, factor (4). — On the 26. X. 1945, some time after midnight (i. e. a few hours before the 24^h-period immediately following the period of the map, fig. 9), a postfrontal unstable cold-mass (mP) invaded the country from WSW (the coastal winds changed from SW'S to WSW), and at 3—8 km height above Uccle the temperatures fell between 4° and 10°C, whereas they remained almost constant in the lowest layers of the region. This implies the failing of the factors (2) and (3) above, whereas the precipitation release (4) may still have been efficient within the convective clouds. The result was a precipitation distribution differing entirely from that of the previous day, without any coastal maxima at all in Holland and Friesland, but with one maximum of 50 mm over the province of Groningen, factors (1) and (4), and another one of 50 mm over the river region.

The map of fig. 9 shows also some other noteworthy features. The m a x i m u m zone I, discussed above, is flanked to the E by a marked m i n i m u m zone at a distance of 6—10 km inland over Noordholland, i.e. over a very flat depression (— 1 to — 5 m), having in some parts only about 25 % of the rainfall of the maximum zone. In Friesland there is not always a clear indication of a minimum over the sea surface between the isles and the mainland — as could be expected. The weak secondary maximum on the N coast of that mainland (Friesland) could be expected from the indirect frictional effect, just as the secondary maximum (15—18 mm) on the E coast of IJsselmeer IV must be due mainly to the direct frictional effects. — A most surprising feature, however, is *the marked secondary maximum II over the E part of the absolutely flat land-surface of Noordholland* (faintly indicated also in Zuidholland). In the profile at the bottom of fig. 9 — drawn along the line a - - - - b in the map, and parallel to the gradient wind — this maximum is explained as caused, or at least supported, by the first f r e e oscillation of the low troposphere after the obstacle formed by the dunes and through the considerable increase of turbulence in the lowest layers set up by them. It is reasonable to compare this effect with the effect of a smooth obstacle in a laminary current of at least 200 m height. According to recent investigations and experiences in connection with soaring flight, such an obstacle may cause marked oscillations several km up in the atmosphere; cfr KÜTTNER, 1939, p. 113, fig. 43 and QUENEY 1948, p. 19, fig. 1. The next maximum (III) is partly conditioned by the Veluwe. It is possible, though, that this updraft, and the updrafts causing the faint Overijssel rainfall maxima (IV and V), as a

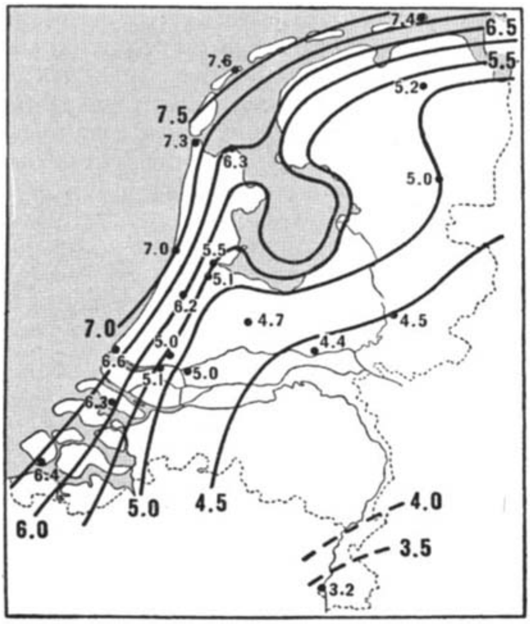


Fig. 10. Average wind velocity (m/s) in the Netherlands in winter (Dec.—Febr.). — From C. BRAAK 1942.

component contain the second, third and fourth free oscillations after the main obstacle at the dunes. Moreover, it seems reasonable to assume that the asymmetric position of maximum II (E. Noordholland) is caused by frictional downdraft at the W. shore of IJsselmeer, see profile of fig. 9. In fact, the climatological wind maps prepared by C. BRAAK 1942, show a very marked influence on the wind even of this flat country (see fig. 10), the average velocity in Dec.—Febr. decreasing from 7 m/s on the W coast to 5 m/s in the interior of Noordholland, and again attaining almost 7 m/s over the IJsselmeer.

Naturally, the question arises to what extent these different maxima are able to leave their marks on the average (normal) rainfall distribution of this region and season. In fact, the Dutch normal rainfall maps edited by C. BRAAK 1933 show one astonishingly pronounced secondary maximum over Noordholland in all the months August to December, whereas it seems to fail entirely in the months March—July: conditions (1) and (3) may fail completely then! As aforesaid, BRAAK attributes the just mentioned maximum to frictional differences. On the other hand, there is no trace, on these normal maps, of double maxima in Noordholland — and it would be unreasonable to expect them. Their intensity and position with respect to the dunes, and more particularly their mutual distance, will vary considerably even with small variations of the direction, velocity, humidity and statical stability of the general S—WSW flow producing them. Consequently, say, during a rainy October month with a southwesterly weather type, two such maxima, even if they coexist as separate maxima during each single day, will overlap so frequently that the average picture will be blurred and only show one single maximum. Moreover, also during such a month there will always be many days with situations like those described in (b) above which will blurr the picture even more.

In this connection the author should like to emphasize the main difficulty felt by all who have tried to study different precipitation distributions and factors: *the period of* 24^h *between two consecutive measurements is too long.* In most cases it is impossible to find — over a region of some extent — a 24^h-period containing only a "one-factor rain". At the beginning or end of the period other factors generally will creep in and disturb the results of the study. The chance of catching a "one-factor rain" over a region would become more than doubled, if the period was cut down to 12^h, as is the case with the stations reporting by telecommunication. Their network, however, is much too sparse for the purpose in view, cfr 1 (b). Consequently, *it would be desirable to introduce twice-daily measurement at all rainfall stations* in some countries, at least during certain months or years.

5. The *effect of artificial seeding* on an orographic cloud system of the types discussed here may now be expressed in short terms.

(a) If a frontal cloud-system is producing a natural seeding of an orographic one, as in the case of March 1927, then an artificial seeding has no chance of increasing its precipitation. The only possible artificial change within the cloud-systems might be achieved by overseeding the frontal cloud system, thereby impeding its precipitation, which in turn would check precipitation from the (coastal) orographic one.

(b) The important points with the orographic cloud-systems are: (1) that a number of them may just surpass the 0°C-isotherm, but not reach the natural ice-nucleus level, (2) that the intensity of condensation may be considerable within them, and (3) that the above conditions may be stationary for hours or days.

(c) In the cases (b), with a slow and inefficient natural release, as in the October cases of 1933, the artificial seeding might evidently bring about a big and steady increase of the coastal precipitation. These cases will mainly occur in spring and autumn in our latitudes. — Cfr, however, what was said in 2. about the little practical use of increasing coastal precipitation.

6. We cannot leave the question of orographic zones of maximum precipitation without mentioning the problem of *"the increase of precipitation with height"*. After having hinted, and partly studied in some detail, in articles I and II, precipitation mechanisms of widely different structure and functioning, it seems futile to lay down rules or to make quite general statistics regarding this assumed "increase" taken as a geographical phenomenon.

Obviously, almost every kind of precipitation mechanism will show an increase of precipitation from the ground up to the condensation level or cloud base of that individual mechanism thanks to the gradual evaporation of the precipitation elements below that level (cfr I, 3. and 12., and FINDEISEN 1939, p. 457). — With mechanisms having a high cloud base, well above all the meteorological stations (or mountains) of a country, such as the pure frontal Ast-Nbst-system or the Cunb, abstracting from any low (orographic) cloud underneath them, precipitation will increase with height, except in the rather frequent cases when these mechanismes themselves deform, weaken, or get impeded in their development or progress also by orographic barriers lying below the cloud base in question. — There is, for instance, much evidence in favour of a decrease also of convective precipitation toward the interior of high plateaus even if they lie near water, have rich vegetation and are snow-free. — With precipitation mechanisms having a low cloud base, the rule of increase with height will only hold good over comparatively low land.

Even greater complications meet in the case of precipitation mechanisms such as those studied in 1.—2., since they do not form or progress into the highland, some of them not even entering the low inland. — Any such statistics, therefore, should only be carried through for separate seasons, and for well defined homologous geographical regions and weather types.

7. It is appropriate to conclude this treatment of orographic precipitation by discussing some earlier monographies and other papers on such rainfall in NW. Europe in the light of the above findings. Most of them, however, treat the problem merely descriptively, without trying to solve the problem physically or to separate the different orographic factors operating. — The first noteworthy work of this kind for Sweden was achieved by C. J. ÖSTMAN 1927, who studied the distribution of cyclonic or frontal precipitation in S. Sweden with the four main wind directions SW, NW, NE and SE. For each wind, his maps show rainfall maxima on the windward slope of the central highland of S. Sweden (up to 370 m a. s.), and of the foothills of the Scandes, beginning at about 60° N lat. — as could be expected. Now we may also state that, with a NE and SE wind, these maxima are mostly located in accordance with the effects discussed above in 3. (cfr l. c., fig. 4 and 5). — For Norway the pioneer work in this field was performed by F. SPINNANGR through a series of papers (in *Naturen* 1925 ff.) on the rainfall distribution in S. Norway at different weather types. The results as to frontal precipitation are summed in his paper 1943. With NE wind below an upslide surface his maps show, over SE. Norway, in principle the same rainfall distribution as fig. 6 in the present paper, with marked coastal maxima and the amount decreasing landinward, the isohyetals being on the whole parallel to the isohypses, but *precipitation decreasing with height* (cfr l. c., p. 457, fig. 7). With S—SW wind, below an upslide surface, the analogous distribution is clearly seen on the Western coast of Norway (e.g. in fig. 8, l. c., p. 461), although the maxima in some cases lie up to 50 km inland from the coast. Also here the precipitation goes down to relatively small

values even far W of the great divide in the Scandes — contrary to any theories of a general increase of precipitation with height. SPINNANGR's results were corroborated as to all essential features, for SE. Norway, by the papers of INGER (HALVORSEN) BRUUN in 1943 and 1944. In the former paper, for the first time, we meet a clear statement of the importance of "the wind field in advance of the front" (i.e., in the terminology used here: the wind direction within the cold wedge below the upslide surface) for determining the rainfall distribution, although without any further explanation. 9 out of her 10 cases published in 1944 show in principle the same wind and rainfall distribution as fig. 6 above; even the bipartition of the marked maximum along the Skagerak coast is clearly seen. INGER BRUUN supposes these cases to represent frontal precipitation at all possible orientations of the front and with widely different weather situations resp. wind directions. In reality, however, the similarity of the rainfall patterns in all these cases hints that the bulk of precipitation fell prefrontally and within an NEly—SEly cold-air current (although this cannot be proved, because of the too great length, 24 hrs, of the period of measurement), essentially of the same structure as in the case of 24—27 March 1927 investigated above. In fact, this is the only weather type giving widespread excessive precipitation on that coast in autumn and winter. — It follows, then, hat when excessive rainfall occurs in connection with warm-fronts, this rainfall will often not be of true frontal or upslide character, but only conditioned by the front: a special low rain mechanism is formed by the cooperation of prefrontal wind-field, orography and the overshadowing frontal cloud (mainly rendering the efficient natural seeding). — In 1947 SV. JOHANSEN delivered the investigation for N. Norway corresponding to those of SPINNANGR and INGER BRUUN. His maps confirm on the whole the action of the same orographic factors as in S. Norway. Because of the scarce network of stations JOHANSENS maps cannot be quite so convincing as those of SPINNANGR and INGER BRUUN. JOHANSEN's fig. 8 a—d (l. c., p. 368—369), though, shows a very marked prefrontal coastal rain maximum (40 mm) ahead of a warm-front, advancing from the NE, between 21° and 29° E Gr. long. where the prefrontal N—NW wind had a chance of flowing with land on its high-pressure side; the opposite was the case to the W of 20° E, and here the coastal maxima no longer were pronounced. With a SW wind parallel to the coast, on the other hand, the coastal maxima in this latter region become very pronounced. — C. L. GODSKE 1947 utilizes a very dense network of rainfall stations, erected for special purposes in Hardanger-fjord and around Bergen, for studying, on the basis of the classical theory, merely the huge differences in rainfall at short distances due to a very marked alpine orography. VEIKKO ROSSI 1948 studies the general effect of the Scandes on the rainfall distribution over all Fennoscandia in connection with fronts advancing from the W. The network of stations used is too scarce and the map-scale too small to permit any conclusions regarding special coastal precipitation effects.

8. Already in 1921 J. BJERKNES and H. SOLBERG made an important contribution to the physical understanding of orographic precipitation: the difference of friction between sea and land might cause convergence, lifting of the air, and precipitation. At the same time, however, they claim (l. c., p. 9) that only mountains of 1 000 m height or more can produce pure orographic rain, a statement which seemingly contradicts the former one.

Further, they discuss the effects of orography on fronts. This line of thought was pursued by T. BERGERON 1934 (l. c., §§ 34—35) and 1937, by investigating the effect of orography also on the field of wind and precipitation (cfr p. 6 above) in different air masses. — We have already quoted C. BRAAK concerning the outstanding importance of friction for explaining the distribution of the autumn and winter rains in the province of Holland. — In 1936 R. M. POULTER studied configuration, air mass and rainfall, and tried to supplement the classical theories for estimating the amounts of orographic rainfall by introducing the concept of the *front* into the calculations. According to his theory a warm-front would, for instance, give about the double amount of rainfall when approaching a hill-slope of the same inclination. We have tried above to show that orography only indirectly increases frontal rain, or *vice versa*, and merely by means of quite special mechanisms the yield of which cannot be calculated in a simple way. — In 1945 L. C. W. BONACINA discussed the global aspects of orographic rainfall and maintained that such rainfall will as a rule have an optimum yield with mountain ranges of about 3 000 m height, but that even hills of 100 m height may cause such rain. Our rainfall maps of Sweden and the Netherlands surely point to much lower limits in both these cases, at least in NW. Europe in autumn and winter. BONACINA also emphasizes the important fact — first mentioned by the Bergen School — that orography may impede the progress of rain-producing mechanisms and thereby increase the rainfall in the mountains, and especially on their windward slopes.

The most important contribution in late years to the field discussed here is due to C. K. M. DOUGLAS and J. GLASSPOOLE 1947. Their paper is really elucidating as to the possible causes of orographic precipitation in certain weather types. Space does not allow us to discuss thoroughly the coincidence and differences between their results and those of the present paper. They have mainly studied orographic precipitation with strong winds between S and W in the rugged country of NW. Great Britain, conditions which differ widely from those represented by figs 6 and 9 above. We shall only quote one of their main findings: the greatest amounts of orographic rainfall often occur with a deep moist layer of tropical air blowing for a long time within a wide warm sector. The discussion in 4. above indicates that this situation may produce, and for a long time maintain, low-level orographic cloud-systems over the mountains in the NW, with intense condensation (high wind and temperature, statical stability, low condensation level, great depth of cloud). In spite of the high temperature such a cloud-system will receive efficient precipitation release from its upper part or from general cyclonic clouds thanks to the great depth of the moist layer. — One cannot think of any other southerly to westerly weather type in Great Britain that so well could fulfil these conditions, corresponding to the factors (1)—(4) in 4. It remains to see, though, how and where excessive orographic rain forms in the British Isles with a northeasterly weather type.

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