FORECASTING NORTH-WEST GALES IN THE SKAGER RACK

(A SYNOPTIC-STATISTICAL STUDY)

BY

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I. Introductory Note.

Weather forecasting is today for a very great part a matter of experience. Our general experience has been put down in rules, as far as this has been possible. In the book of *Chromow*[1]) not less than 14 pages with general rules are given, and more may be added. It takes, however, several years of practice to become familiar with such rules, and even an experienced forecaster is apt to make severe local blunders if given a new forecastingdistrict. But to put down local experience in words seems to be a very difficult task. We have seen several meteorologists leave the weather service at Oslo and take their personal experience in gale forecasting with them. And so the young forecasters have to participate in the daily service and make more or less distinct local rules for themselves. At the start of his career a forecaster doesn't even know what to look for on the map, and so rules, which may seem commonplace to the more experienced forecaster, will be usefull. In the hope of making the start easier for new meteorologists in the weather service for Eastern Norway, I have begun a search for local statistical rules. Even though the work has been limited to NW-gales in Skager Rack, it is so great that it should have been carried out by a team of collaborators, rather then by a single, occupied forecaster. In fact, the subject has only been touched, but I am publishing the preliminary results in the hope that the methods used will have some general interest.

II. Material and Definitions.

As material the weather maps of the weather service at Oslo for 8, 14 and 19 M. E. T. have been used. The available series cover 20 years, from 1922 to 1939 and from June 1945 to May 1947. Only the 8, 14 and 19 maps exist for the whole period, and so they were made the base for the research. Most wind force observations have been estimated after the Beaufortscale. The maximum wind force between the hours of observation are also given, but they are probably not quite trustworthy, especially not during the night—as every sound sleeping person will admit. It therefore seemed practical to use only the mentioned maps. Some cases of gale situations are perhaps lost in this way, but it is of course impossible to make such an examination as this a really exact one.

The meteorological stations which have been used as basic stations during tho whole period, are given in fig. 1. Practically no ships observations have been available. Gale warnings for Skager Rack and the Norwegian Skager Rack coast are sent out from Oslo, west of Lindesnes the warnings are given from Bergen. Gale warnings are issued if the maximum wind force is expected to reach 7 up to 8 Beaufort, storm war-

[1]) *F. P. Chromow.* "Einführung in die Synoptische Wetteranalyse", deutsch bearbeitet von *Gustav Swoboda*, Wien 1940.

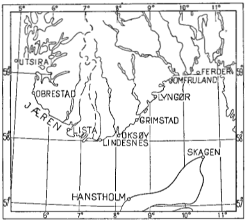

Fig. 1.

nings if it is expected to reach 9 Beaufort or more.

In order to pick out the gale maps (storm maps) it is necessary to define the lower limit of a gale map, and the following definition has been adopted: If one of the Danish stations (fig. 1) or one of the Norwegian stations east of Lindesnes reports as much as 7 Beaufort, we have a gale map. Even 6 Beaufort at one of the mentioned stations is counted as a gale map, if it is at the same time blowing at least 7 Beaufort along the coast of Jæren. There is no upper limit, as we do not in this respect distinguish between gale and storm.

A gale or storm may last for shorter or longer time and so we may speak of a *gale period*. To measure the length of a gale period we must here count the number of successive gale maps. In the middle of a period one single map was allowed to drop below the defined border, but two successive maps which didn't reach the limit, would break the period.

These definitions of the strength of the wind made it very easy to determine the gale situations, as it was necessary to look only for the maximum wind force among the stations.

As to the direction of the wind every direction between W and N was allowed. In some cases it was, however, difficult for westerly gales to say if it belonged to the north westerly or the southwesterly gales, and the choice was to some degree arbitrary, especially in such cases where some stations had a wind direction south of west, and others north of west. Gales from due North were on the contrary so seldom, that a choice between NW and NE generally was very easy.

III. Frequency and Duration of the NW Gales.

Before beginning this statistical research, I interviewed my collegues and tried to sum up what we knew of NW gales. The result was not encouraging. Because the stations along the Norwegian Skager Rack coast are sheltered by the mountains in NW, it has always been thought, that the wind force by NW gales is less at the coast than in the Skager Rack, a fact which later has been confirmed statistically by *Spinnangr.*[1]) To get a gale at the coast itself, the pressure gradient must be very strong, at least stronger than a gale gradient on the open sea. This is the only *local* forecasting rule for the NW gales which had ever been heared of by any forecasters at the Meteorological Institute in Oslo.

At first some climatological research work was made, which will be treated in this chapter. The results are perhaps not of much forecasting value, but may serve as a first orientation.

In the following we shall distinguish between the Skager Rack coast, i.e. the Norwegian Skager Rack coast, and the open Skager Rack itself. As we have no ship observations from these waters, we must let the Danish stations Hanstholm and Skagen represent the open sea, although there is reason to believe that the wind force is still a little stronger on the open sea than at the Danish coastal stations.

In the weather forecasting we sometimes distinguish between the inner and outer part of Skager Rack. If we let Skagen represent the inner part and Hanstholm the outer part, an examination showed more gales at the outer than at the inner part, but we shall in the following treat Skager Rack as a whole, as we are only looking for main features.

To begin with the number of gale periods during the examined 20 years was determined. A total of 268 periods were found. Some of the periods were so short, that they appeared only on one single map. The maximum length of the periods was 9 consecutive maps. In table 1 the periods are arranged according to their length expressed in number of consecutive maps.

[1]) *F. Spinnangr:* On the Influence of the Orography on the Winds in Southern Norway. Bergens Museums Årbok 1942. Naturvitensk. rekke. Nr. 3.

Table 1.

Length of period (number of consecutive gale maps)	Number of periods	Number of maps
1	84	84
2	70	140
3	48	144
4	19	76
5	23	115
6	16	96
7	4	28
8	2	16
9	2	18
Sum	268	717

Mean length of all periods 717 : 268 = 2.7 maps.

Only 8 of the 268 periods (3 %) have lasted more than 6 consecutive maps. 202 periods (75 %) lasted from 1 to 3 maps. Mostly the NW gales are shortliving phenomena. The longer periods are generally due to more than one cyclone passing from W to E north of Skager Rack.

On the whole we have 21912 weather maps for 8, 14 and 19 M. E. T. in the examined 20 years, and 717 showed NW gales. We have in other words NW gales in the Skager Rack (according to our definition) in nearly 3 % of the cases. On the Skager Rack coast itself the NW gales are far more infrequent, as will be seen later.

Sometimes several gale periods will occur within the same month, but it is seldom that two periods are separated by as little as two consecutive maps. The number of periods within a single year differs much from year to year. In 1932 only 4 gale periods were observed, in 1938 as many as 24. The longest interval between two consecutive periods was found in 1932, when there were no NW gales from March till October, i.e. in 8 months.

In order to examine the annual march of the *number of periods*, we may arrange the periods according to the wind force both at the Norwegian and at the Danish stations. As we are most interested in the maximum wind force, we shall compare the maximum wind force within each period at the Norwegian and at the Danish stations. Only in 5 of the 268 observed periods (about

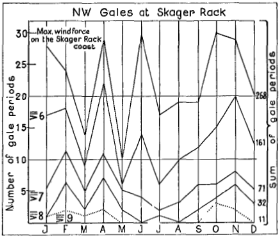

Fig. 2.

2 %) a higher wind force was observed at the Norwegian Skager Rack coast than at the Danish stations, 20 periods showed an equal maximum wind force, and the rest of the periods showed at least one degree Beaufort more at the Danish than at the Norwegian stations. In fig. 2 we have classified the gale periods according to the greatest wind force at the Skager Rack coast during the whole period. The uppermost curve shows how all the 268 periods are distributed on the different months. The next curve gives only the cases (161), where the maximum wind force at the Skager Rack coast is 6 Beaufort or more within the periods. By the 3 lowest curves the lowest maximum wind force is 7, 8 or 9 Beaufort, and the number of cases 71, 34 and 11 respectively. The uppermost curve shows no marked annual march, but the lower curves, where the lower wind forces have been omitted, show that the highest wind force occurs more frequently in winter than in summer. The curves are irregular. Perhaps 20 years will not suffice to smooth them. This is especially true for the lowest curve, which is constructed from 11 periods only.

We notice that 8 Beaufort (or more) has not been observed in June and in August, and 9 Beaufort (or more) not in May—September. The greatest observed wind force on the 8, 14 and 19 maps was 10, which has occured only once. We see that NW storms occur very seldom at the Norwegian coastal Skager Rack stations.

In fig. 3 the number of periods are arranged according to the maximum wind force within each period at the Danish stations. Storm can occur

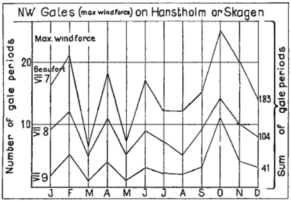

Fig. 3.

any month but is relatively rare. The storm maximum in October is noteworthy. But even this maximum consists only of 11 cases, i.e. not more than about one storm period in October every second year. Such a maximum can hardly make any impression on the memory of a forecaster, it must be found statistically. Apart from this maximum we find no marked annual march.

Fig. 2 and fig. 3 give the number of gale periods. Perhaps it is not a far-fetched idea to think that we might find other frequency curves if we use the number of *gale maps* instead of gale periods.

Table 2.

	J	F	M	A	M	J	J	A	S	O	N	D
Number of gale maps .	65	68	34	71	27	72	53	54	53	80	77	58
Number of consecutive maps in one period	2,3	2,8	2,4	2,4	2,7	2,4	3,1	2,8	2,8	2,7	2,7	2,9

Table 2 gives the number of gale maps within each month. We find, however, the same main features in the upper line in table 2 and the uppermost curve in fig. 2, as a comparison will show.

The lower line in table 2 gives the mean length of the periods for each month expressed in number of consecutive maps. Contrary to what I expected beforehand, the length of the gale periods are not longer in winter than in summer. But in winter the wind force is generally greater.

It is a common assumption that unstable air will cross a mountain ridge easier than stable air. The wind force at the Norwegian coastal stations may therefore perhaps be related to the stability of the air mass. Unfortunately the upper air data are too scarce to allow an examination. Assuming that the air currents by NW gales are crossing the mountains in South-Norway, we might try to find a Foehn effect by comparing the temperatures on each side of the mountains. No sure indications of a Foehn effect were, however, found from the ground temperatures. An observation of the temperature differences between the temperatures on both sides of the mountains therefore seems to be of no interest in this connection.

By gales blowing from due north-west we should of course expect a relation between the maximum wind force on the Skager Rack coast and the pressure difference between Oksøy and Ferder. But as the NW wind generally is gusty, we cannot expect that the maximum wind force at one of the sheltered coastal stations shall vary completely in accordance with the said pressure difference. To take an example: Three consecutive maps beginning with 2/1 1922, 14 o'clock gave as maximum wind forces 6, 4 and 5 Beaufort, all straight from NW, and pressure differences 6,4, 7,3 and 5,3 mb respectively. The agreement between the two magnitudes is not very striking in this case. Although we may find examples with a far better agreement, a more complete examination of the pressure difference between Oksøy and Ferder was dropped, as the matter was thought to be of little forecasting value.

IV. Forecasting Rules for NW Gales in the Skager Rack derived from Cyclone Paths.

It is often difficult to forecast the direction and speed of a moving cyclone, but the forecaster must make a decision, and from this decision on the path of the cyclone, he may then draw certain conclusions.

On the basis of the cyclone paths, we may divide the cyclones into the following types:

a) Retrograde cyclones
b) Polar Sea »
c) Norwegian »
d) Danish »
e) German »

In addition tho these types we may add two more:

f) Reinforcement of an existing NW air current.

g) Indefinite cases.

Below follows a discussion of the different types.

a) Retrograde Cyclones.

Cyclones moving straight towards the north or the south will be classified as belonging to this type, and of course every cyclone with a path pointing more or less toward the west. The westgoing movement, however, is generally slight. Cyclones of this type are rare; only 18 cases of passably distinct cyclones have been noted during 20 years, and none of them have given more than 6 Beaufort on the Skager Rack coast. At Skager Rack (i.e. Hanstholm and Skagen) 8 Beaufort is reported in one single case, 7 Beaufort in 4 cases and the rest didn't reach as much as 7 Beaufort. Generally these cyclones are therefore not much to be feared. The cyclones which have given 7 or 8 Beaufort, originated in Poland or East-Prussia and went afterwards towards NNW. No retrograde cyclones have occured in the winter months December—February.

b) Polar Sea Cyclones.

Within the type b) are included all the cyclones passing north of Norway. (Cyclones north of Spitsbergen cannot be followed on our maps). There have been numerous cases in the examined 20 years, but only one single cyclone (on 8/10 1925) has given a gale situation in Skager Rack, and that was moreover a border-line case, as the maximum wind force was only 7 Beaufort. Generally we may therefore say that Polar Sea cyclones will not give NW gales at Skager Rack. When the cyclones are small and weak, this rule is of course a commonplace one.

c) Norwegian Cyclones.

These cyclones are generally crossing Norway south of the North Cape and north of the Skager Rack coast. The crossing is taking place in many ways, as the different cyclones will cross with different speed and direction, sometimes with one single center, sometimes with the center split up, and in relatively few cases the center will not cross at all, but die west of the Norwegian coast. If a NW gale shall occur, the center must, however, die north of Stadt. Even the highest mountains in Sout-Norway are sometimes crossed, seemingly without great difficulty.

The NW gales are of course combined with the rear of the cyclones and will generally begin as the cold front or the cold occlusion passes the Skager Rack. The center must then as a rule be situated north of a line Stadt-Iceland, when the cold front is passing the Skager Rack. If it lies south of this line—line C E, fig. 4—the cold front

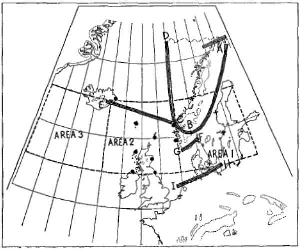

Fig. 4.

will be followed by SW instead of NW. This is a forecasting rule of some value, especially for cyclones coming from SW with their cyclone path W of Norway. Compare the examples in fig. 6 and fig. 7. But even if the center is north of the said line, the cold front may be followed by winds from the southwest. To obtain a direction north of west, the front must be strong with distinct falling areas before and rising areas behind, and an abrubt bend in the isobars. Generally the center will lie within the line ABCDA, fig. 4, when the cold front is passing the Skager Rack, but this is rather a rough rule.

Of the 268 gale periods mentioned in table 1, not less than 188 or 70 % belong to the Norwegian cyclones. Of the 71 periods, which have given 7 Beaufort or more on the Skager Rack coast (compare fig. 2), 63 or 89 % belonged to this type, and of the 34 periods which have given 8 Beaufort or more, 32 or 94 % were Norwegian cyclones. And every period covering 6 consecutive maps or more is of this type. Especially the Norwegian cyclones are therefore to be feared. But they must of course be strong to give NW gales.

An undertype of the Norwegian cyclones is treated in chapter VI in connection with the directions of the air currents.

d) Danish Cyclones.

To this type belong cyclones moving eastward between the Skager Rack coast and the coast of Germany (between the lines FG ang HI, fig. 4). They have all degrees of intensities, and many small ones have passed without giving NW gales at all. 31 cyclones have given NW gales during the examined 20 years. An extremely strong cyclone (9/10 1930) gave NW 9 Beaufort at Oksøy, and one gave 7 Beaufort on the Skager Rack coast, but apart from these two cases, these cyclones have not given more than 6 Beaufort at the Norwegian coastal stations. Generally they are therefore not much to be feared as far as the sheltered coast is concerned, but they may give very strong winds in the outer part of Skager Rack. In accordance with this fact, Hanstholm mostly reports stronger winds than Skagen. Only in a few cases has the maximum wind force been as strong at Skagen as at Hanstholm, but not a single case is reported, where the maximum wind force during the gale period has been stronger at Skagen than at Hanstholm.

The Danish cyclones will give only short living NW gales. Only once a period has lasted more than 3 consecutive maps. 13 periods have shown up only on one single map, 11 lasted two and 6 three consecutive maps.

The Danish cyclones are most frequent in the autumn. Of the 31 gale periods 20 appeared in the months August—November and of these not less than 9 in October. They will often give NE gales on their foreside even if there is no NW gale connected with their rear, but that is a fact which shall not be dealt with here.

e) German Cyclones.

These cyclones are passing between the German coast in the north (line HI, fig. 4) and the Alps in the south. Generally they are not very strong. They may occasionally give NE gales in the Skager Rack, but NW gales have never been found in connection with these cyclones during the examined 20 years. This last fact may serve as a forecasting rule.

f) Reinforcement of an Existing NW-Stream.

Sometimes a NW stream covering the Skager Rack is too weak to give NW gales. But such a stream may gradually increase in strength. The reinforcement must, however, be caused by falling or rising areas and not by moving cyclones (with closed isobars), if they shall belong to type f). Moreover, we demand that the stream shall exist at least 18 hours before a NW gale is formed. The stream ifself may begin at the rear of a weak cyclone, which has passed north of the Skager Rack.

We have found 30 of these cases and one of them gave 8 Beaufort on the Skager Rack coast, four gave 7 Beaufort. They may therefore occassionally be dangerous even on the coast. A close watching of the falling and rising areas is necessary in order to forecast such gales.

g) Indefinite Cases.

14 cases have been found, which couldn't be classified in the foregoing types, mostly because the form of the lows were so irregular. They have, however, all been border-line cases, not giving more than 7 Beaufort at Skager Rack. Most of them were weak and shortliving phenomena, and such irregular cases are therefore not much to be feared.

V. The «Chessboard Method».

A forecaster must of course try to issue a galewarning or stormwarning as soon as possible, but generally it is difficult—at least in Norway—to send out a good warning more than 18 hours in advance of the first gale map in the gale period. As the map 18 hours in advance of the first gale map obviously has led up to the gale itself, it is of special interest to examine it closely, and these maps were therefore made the base of the following investigation. In the previous chapters we have seen that cyclones, moving along very different cyclone paths, may give NW gales at the Skager Rack, and we may therefore expect that maps of even very different appearance may give a NW gale within the following 18 hours.

Now the question arises: Can we classify the maps 18 hours in advance of the first gale map by pointing out common features? Of course it is not easy to find a good and practical method for classification, as the history of meteorology shows. Here an attempt will be made to pick out common features which to the best of my knowledge has not been tried before. It has just been slightly touched in a previous article.[1] The method is called the "chessboard method", because the map is divided into squares as a chessboard, and as pieces in the play we introduce the area means of the meteorological elements within each square.

For practical reasons we shall use "squares" limited by latitude and longitude circles on the map. The size of the squares is arbitrary, but if we use too great squares, too many details will disappear. On the other hand, if we use small squares, we must have many of them in order to cover the map, and then the number of data will increase with the number of squares. After some experiments a size of the squares was adopted, which is indicated in fig. 4. And the research was limited to the two squares described as area 1 and area 2. As to the meteorological elements only the mean geostrophic wind—or mean pressure gradient—and the barometric tendencies were examined to some extent.

VI. Forecasting Rules derived from the Mean Pressure Gradient.

In another paper[2] is described how to use the length of the isobars as an expression for the mean pressure gradient—or mean geostrophic wind force—of a definite area, and how to determine the mean direction of the geostrophic wind by projecting the isobars on the two axes of a carthesian system. In this chapter only the length of the isobars shall be investigated. The length of the isobars of area 1 and area 2 are called L_1 and L_2 respectively, and for practical reasons we use one half of one degree of latitude (or 55 km) as a measure of length. This measure is used in tables 3 and 4. L_1 and L_2 were determined for each map 18 hours in advance of the first gale map of every gale period[1]), and also for many maps that had a "suspicious" look, but which were not followed by any NW gale. It was found that a NW gale would not occur within 18 hours if the sum of L_1 and L_2 was too small. The lower limit was determined statistically, but turned out to be different for each month of the year. The result is given in table 3.

Table 3.

Lower limit of $L_1 + L_2$.

	J	F	M	A	M	J	J	A	S	O	N	D
$L_1 + L_2$ . . .	220	200	190	170	170	135	125	140	150	160	200	200

If $L_1 + L_2$ is smaller than the numbers in table 3, a NW gale will as a rule not occur within 18 hours.

In table 4 is given the mean values of $L_1 + L_2$ for all the maps 18 hours in advance of the first map of the gale periods.

Table 4.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
$L_1 + L_2$	260	244	220	199	175	155	151	169	181	211	224	241	206
Number of cases	28	24	13	27	9	29	17	18	18	29	25	17	254

As some maps couldn't be measured accurately, owing to the incompleteness of observations in the beginning and end of the war, only 254 cases of the 268 gale periods are used.

If $L_1 + L_2$ lies between the numbers in table 3 and table 4, a NW gale is possible, if $L_1 + L_2$ is greater than the numbers in table 4, a NW gale is probable at the Skager Rack. This rule

[1]) *Sigurd Evjen:* En studie over nedbørhyppigheten i Oslo. „Fra Fysikkens Verden." Hefte 2, 1946.

[2]) *Sigurd Evjen:* Statistische Untersuchungen an Druck- und Temperaturfeldern uber Süd-Skandinavien. Geof. Publ. Vol. XVI, No. 9.

[1]) As we are using only the 08, 14 and 19 maps, the interval of time between the measured map and the first gale map may vary with several hours, especially if the gale begins during the night. In some cases—when the first gale map occured at 19 M.E.T.—we had to take the map 12 or 24 hours before the first gale map in the period.

must, however, be seen in relation to the wind directions which are treated in the next chapter.

Gale periods giving 7 Beaufort or more on the Norwegian Skager Rack coast were in 71 % of the cases found to have a value of $L_1 + L_2$ equal to or greater than the numbers in table 4.

In order to use the above results in practice, it is necessary to measure the length of the isobars by means of a "curvemeasurer", and compare the length with the numbers in tables 3 and 4. The determination of $L_1 + L_2$ and of the mean direction of the geostrophic wind takes only a few minutes.

By a calm weather situation, i.e. small pressure gradients everywhere, a weather forecaster is not very likely to send out a gale warning; but as the gradient increases, it will be the task of the forecaster to judge when the situation becomes critical. The method given here is only putting this customary judgement a little more into system. That the critical "degree of calmness" has an annual march, was at first a surprise. It must be due, I think, to the different cooling or heating of land and sea at the Skager Rack coast during the year.

VII. Forecasting Rules derived from the Mean Direction of the Geostrophic Wind.

The probability of NW gales by the cyclone type c) is greatly influenced by the mean direction of the geostrophic wind over area 1 and area 2. As the types a) and d) seem to be much influenced also by the areas south of the mentioned ones, we shall limit the examination of the wind directions to the cyclone type c). The Norwegian cyclones are, as already mentioned, the most numerous and generally the most dangerous ones.

As in the foregoing chapter, the statistics is, as a rule, based on the maps 18 hours in advance of the first map in the gale period.

The measured maps generally show a mean geostrophic wind with a westerly component over area 1 and area 2. Using only the 8 main wind directions, we may say as a rule that SW, W or NW will precede NW gales caused by *Norwegian cyclones*. As this rule is valid both for area 1 and area 2, we have the following 9 combinations where the numbers indicate the areas: SW_1—SW_2, SW_1—W_2, SW_1—NW_2, W_1—SW_2, W_1—W_2, W_1—NW_2, NW_1—SW_2, NW_1—W_2, NW_1—NW_2. The combination SW_1—SW_2 occurs seldom, the combination W_1—W_2 is most frequent. The frequency of the different combinations is found in table 6, next chapter, although the numbers given here comprise all the cases, not only the Norwegian cyclones.

We may express the rule about the westerly components in a negative way:

Winds with an easterly component over area 1 will prevent a NW gale from arriving within 18 hours. Of the 188 NW gales caused by Norwegian cyclones, only two cases showed a mean geostrophic wind with an easterly component over area 1. The same rule is valid for area 2, but is here not quite so good, as the number of exceptions has been 5. Unfortunately we cannot make much use of the last rule for area 1, as the wind generally has a westerly component in advance of a Norwegian cyclone. But yet the rule may sometimes be useful.

Wind directions which are not straight from the north or the south often have a distinct component towards the east and the west, so that we can divide such cases in easterly and westerly winds. But sometimes the wind is so straigth from the north or the south that a choice is not possible. It happens relatively often in advance of the Danish cyclones that the wind over area 1 is from the south and over area 2 from the north. But we have also some cases of cyclones coming from the south west and passing so near the Skager Rack coast, that it is extremely difficult to say beforehand if we have to do with a Danish or a Norwegian cyclone. We may here speak of an undertype of cyclones, which we may call Danish-Norwegian cyclones. The effect on the wind of the Skager Rack coast is opposite for the Danish and the Danish Norwegian cyclones, as the Danish cyclones will give easterly winds, the Danish-Norwegian cyclones will give westerly winds, when the center is at or near the Skager Rack. 15 cases of Danish-Norwegian cyclones have been noted, and it is well to remember, that in such cases we may occasionally have S wind over area 1 and N wind over area 2 in advance of the NW gale. The Danish-Norwegian cyclones have occurred in the summer and autumn, i.e. before the land is cooled or covered with snow. A cool land favours a cyclone path south instead of north of the Skager Rack coast in the here mentioned border-line cases. If the cyclone is coming from the west and most likely will pass well N of the Skager Rack coast, a straight N wind over area 2 or a straight S wind over area 1 will not favour a NW gale, and a warning ought not to be sent out in this case without very good reasons.

From the foregoing it is evident that we must look out for a NW gale especially if we have a mean geostrophic wind with a westerly component over areas 1 and 2 in connection with a Norwegian cyclone. But this must be seen together with the rule about the magnitude of the gradient or the size of $L_1 + L_2$ given in the foregoing chapter. As a rule we have no gales even with Norwegian cyclones and westerly winds over areas 1 and 2 if $L_1 + L_2$ is too weak. Neither do we get gales if we have a great value of $L_1 + L_2$, but a wrong wind direction. The value of $L_1 + L_2$ and the wind direction must work together to form a NW gale.

Sometimes the isobars over the given areas are so curved, that we cannot at all speak of a mean direction of the geostrophic wind. Such cases must go out of the statistics, but in order to do this consistantly, quantitativly, we have introduced *the rectilinearity of the isobars* (l.c.). Calling the length of the isobars L and that of their resultant R, we define the rectilinearity by the relation $R : L$. When $R : L < 0.5$, the cases have been omitted, but the choice of this limit is of course arbitrary. Fortunately the number of cases left out is relatively small, about 7 %, and it has never occurred that $R : L$ is smaller than 0.5 for both area 1 and area 2 at the same time. For the area, whose rectilinearity is greater than 0.5, the rules of the wind directions may be employed.

Although systematic measurements have not been made for area 3 (see fig. 4), some special situations have been investigated. It was found that the rule about westerly winds over areas 1 and 2 have one exception, which we may express in the following way: If we have a mean geostrophic wind from SW both over areas 2 and 3, no NW gale will occur at the Skager Rack within 18 hours. The reason for this is that the cyclone center will then lie so far toward the west that the cold front cannot reach the Skager Rack within so short an interval of time.

VIII. The Barometric Tendencies.

As the falling and rising areas can both weaken and strengthen the air streams, we cannot expect to find rules of much forecasting value by examining the tendencies detached from the gradient. However, when $L_1 + L_2$ was determined, the 3 hour tendencies were noted for some stations on the same maps, and some results are given here, even though they are of minor interest. The chosen stations are marked with a circle on area 2 and with a cross on area 1 (see fig. 4). They were picked out in a rather haphazard way, and stations near the eastern border of area 1 had to be omitted, as we had no observations there for many years.

Adding the tendencies of all 15 stations without regard to their sign, we find a pronounced annual march. It must be born in mind that we have picked out only the maps 18 hours in advance of the first gale map in the gale periods.

Table 5.

Mean sum of positive and negative tendencies.

J	F	M	A	M	J	J	A	S	O	N	D	Year
32	26	24	26	21	18	14	18	21	30	27	30	21

The numbers are not adjusted for the different lengths of the months, but the annual march is obvious, although a little irregular.

The size of the tendencies will also as a rule vary appreciably with the direction of the air streams. An already existing NW-stream, having nearly the strength of a gale, may need quite small tendencies in order to exceed the gale limit. On the other hand, if we have SW winds both over areas 1 and 2, we must have quite strong tendencies, or else the field of pressure can not be altered enough to let a NW gale break in during an interval of 18 hours. These obvious conclusions are corroborated by the statistics given in table 6. The tendencies are greater with SW wind over area 1 than with NW. And we may add that if we regard the cases of type f) alone, they have a mean value of only 15.

Table 6.

Sum of barometric tendencies 18 hours in advance of the first gale map in the gale periods.

Mean geostrophic wind direction		Number of cases	Sum of tendencies of 15 stations regardless of sign
Area 2	Area 1		
SW_2	SW_1	9	28
W_2	SW_1	25	32
NW_2	SW_1	30	29
SW_2	W_1	10	27
W_2	W_1	50	23
NW_2	W_1	24	26
SW_2	NW_1	5	26
W_2	NW_1	35	23
NW_2	NW_1	12	19
		Sum: 200	

The mean tendencies are greatest by SW_1. SW_2 occurs relatively seldom.

These results are not, as already said, of much forecasting value. May be a closer examination of the tendencies might reveal some new statistical forecasting rules, but we must bear in mind that the size and movement of the falling and rising areas can vary very much within 18 hourse, and so it would perhaps be necessary to try a shorter interval of time and use smaller areas for another investigation. The tendencies outside areas 1 and 2 may sometimes play a great role too. And at sea great variations may take place which can not be followed at all for lack of observations. But a good forecast can not be made without considering the tendencies, and therefore a more thorough investigation would be desirable.

IX. NW Gales.

Main Results of the Foregoing Chapters.

1. The NW gales in the Skager Rack are generally of short duration. 75 % of them have not exceeded 24 hours, only 3 % have lasted more than 48 hours, and none of the gale periods have lasted more than 9 consecutive maps (i.e. 08, 14 and 19 maps).
2. On the Norwegian Skager Rack coast a wind force of 8 Beaufort (or more) has not been observed in June and August, 9 Beaufort has not been observed in the 5 months May—September, 10 Beaufort has been observed only once in 20 years.
3. A wind force of 9 Beaufort or more may appear at the Skager Rack in any month of the year, although it happens relatively seldom.
4. Polar Sea cyclones and German cyclones will not give NW gales in the Skager Rack.
5. Retrograde cyclones occur seldom, and even the strongest are relatively weak and will only represent border-line cases (7 Beaufort) in the Skager Rack. They have never given gales at the Norwegian coastal stations.
6. Danish cyclones generally will not give more than 6 Beaufort on the Skager Rack coast, but may be very strong in the Skager Rack, especially in the outer part.
7. The Norwegian cyclones are the most frequent type, and most of the NW gales and NW storms on the coast itself have been caused by them. But if a Norwegian cyclone shall cause a NW gale, rule 10 and 11 ought to be fulfilled.
8. If the cyclone center lies south of a line Stadt-Iceland when its cold front passes the Skager Rack, the front is followed by SW, not NW.
9. If a cold front (or cold occlusion) passing the Skager Rack shall be followed by a wind north of west, it must be strong with distinct falling areas before and rising areas behind, and have an abrubt bend in the isobars. Generally the wind just behind the front will be from WNW, not NW. The center must lay north of a line Stadt—Iceland when the front passes the Skager Rack (compare the foregoing rule).
10. The length of the isobars of areas 1 and 2 must be compared with the numbers in tables 3 and 4. (The 18 hours interval must be remembered, see chapter V.)
11. If an advancing *Norwegian* cyclone shall cause a NW gale in the Skager Rack, areas 1 and 2 must have westerly components of the mean geostrophic wind. An exception from this rule occurs when both areas 2 and 3 have SW wind; then no NW gale will occur

within 18 hours (but may occasionally occur later).

12. The mean value of the barometric tendencies over areas 1 and 2 are influenced by the wind directions. By SW winds we generally must expect greater tendencies than by NW winds 18 hours before a NW gale, and generally greater tendencies in winter than in summer. The tendencies must at any rate favour the building of a NW stream, not work against it.

These rules shall not replace the old ones, they are only meant as a help in addition to them. As nearly every NW gale in the Skager Rack is caused by moving cyclones, it is of the greatest interest to follow the life history of the cyclones, especially to watch whether they are deepening or filling. A rapid deepening cyclone can alter the length of the isobars so fast, that rule 10 must be used with great caution. In fact, the above rules are just rules, not laws. They shall only help to facilitate the decision: Gale or no gale from NW. As to the determination of the coming maximum wind force, they are but of limited help, as the wind force may increase gradually after the gale has begun. A close watch of the size and movement of the rising and falling areas from map to map is necessary. And as each gale is a new, individual case, we can not expect that statistical rules based upon rather rough mean values of a few meteorological elements shall give us all the wanted help.

In the next chapter some examples are given, which will illustrate the use of the above rules. I should like to point out that the rules 10 and 11, working together in the case of a Norwegian cyclone, in most cases will cause a NW gale, at least 7 Beaufort in the outer part of the Skager Rack.

X. Examples.

1.

When I went trough the material for the first time during this investigation, I looked at each map and asked myself whether I would have given a warning for NW gale in the Skager Rack or not. Coming to the morning map of 2/3 1922 (fig. 5), I didn't know what to do. Probably

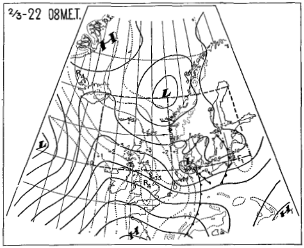

Fig. 5.

we would get no gale at the Skager Rack coast or in the inner part of Skager Rack, as circulation was rather weak and the small cyclone center over Denmark was occluded. But we had quite a strong rising area stretching from England to Greenland, which could strengthen the wind in the North Sea, and we had indeed already NW 7 Beaufort on the German North Sea coast. NW 7 Beaufort at the outer part of the Skager Rack was therefore a possibility as far as I could see. But was the probability more or less than 50 %? I could not tell, although I had been in the weather service at Oslo for more than 10 years. After the statistical rules had been worked out, I measured the length of $L_1 + L_2$ and found a value of 162, which is far below the minimum value of 190 given in table 3 for the month of March. After this the probability of a NW gale was at least less than 50 %, and a warning ought not to be given.

The 3 following maps are not reproduced, but the wind force at the Norwegian and Danish coastal stations did not exceed 4 Beaufort.

2.

Fig. 6 a gives the weather map of 2/11 1947, 14 M. E. T. It might be expected that the strong cold front over Ireland would pass the Skager Rack. The weather service at Bergen gave a warning for NW gale along the coast of Jæren. I was in charge of the service at Oslo and had to decide which direction of the wind should be chosen for the Skager Rack. The low west of

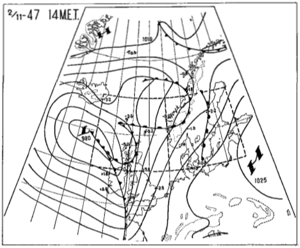

Fig. 6 a.

Scotland was apparently moving towards NE, but it had a longish form from SE to NW, which prevented it from moving fast towards NE, and this, together with the tendencies in front of the low, made it probable that the center wouldn't pass the line Stadt—Iceland within 18 hours. Judging the velocity of the cold front and using rule 8, I found it more probable that the front would be followed by SW, than by NW.

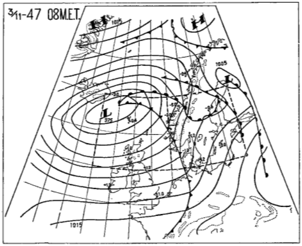

Fig. 6 b.

Fig. 6 b gives the situation 18 hours later. The cold front has passed Jæren and is followed by SW.

We may use this last map to give a further illustration of the use of the 3 main forecasting rules: 7, 10 and 11. A mere glance tells us that the wind is of a southwesterly direction both over areas 1 and 2. In so far rule 11 is satisfied. The length of $L_1 + L_2$ was found to be 224, just the number of table 4. The mean gradient therefore is great enough to allow a gale (rule 10). As to rule 7, we must keep in mind that we are always asking what will happen within 18 hours. The rules are not worked out for a longer interval. We have then to ask if the cyclone can move fast enough to arrive north of Stadt within 18 hours. At first sight this may seem possible on account of the great negative tendencies over Mid-Norway. But the cyclone must soon occlude and, as it has an old, deep center, it is more of the central type, which will move slowly and give the fronts a tendency to circle around the center and thus push the falling areas northwards. Positive tendencies are, moreover, showing up south of the center, and will try to push it more northwards than eastwards. It is therefore unlikely that we have to do with a Norwegian cyclone according to our definition. Rule 7 then is working against a NW gale. And that is just the point by the use of this rules: If a single rule plainly works against a NW gale, it will be wise to think twice before sending out a gale warning.

The following maps are not given here, but the center lies only 200 km more towards ENE 24 hours afterwards and the SW wind in the Skager Rack therefore continued.

A forecaster might object that all these rules are superfluous, at least as far as the last example is concerned. For the NW can not set in before the wind in the rear of the center reaches the Skager Rack, and as these winds still are west of area 2, they will not probably reach us within 18 hours. But in my opinion that is just what rule 7 expresses.

3.

Fig. 7 a gives the morning map of 22/9 1947. The forecaster in charge at Oslo had issued a forecast for SW 6 to 7 Beaufort both at the Skager Rack and on the Skager Rack coast, valid until next afternoon. The weather situation was discussed by the forecasters and upon my question if a NW gale was thought of, I got the answer that NW was unlikely to occur within the forecasting period. However, the wind direction was, as will be seen at a glance, SW over area 2. Area 1 had a mean direction from W,

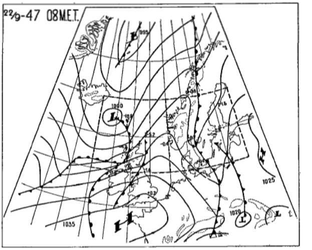

Fig. 7 a

although the rectilinearity of the isobars was less than 0.5. But at any rate the direction didn't work against rule 11. $L_1 + L_2$ had a value of 198, which is greater than the number given in table 4. Rule 10 therefore also indicated a NW gale. It was more doubtful whether the cyclone, centered near the Faeroes, would arrive north of Stadt within 18 hours. But the tendency at Thorshavn was as high as 10,8 mb, and as the pressure was rising a little in South-England, the air stream over area 2 would increase rapidly and push the cyclone fast toward the east. The situation would at any rate be dangerous after 18 hours had passed, as the three main rules, 7, 10 and 11 were working together and, as already said, the forecast was valid for more than 30 hours reckoned from the mentioned morning map.

Fig. 7 b gives the situation 18 hours later,

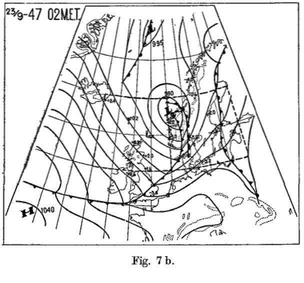

Fig. 7 b.

and it will be seen that a NW gale already is entering the outer part of the Skager Rack.

I should like to point out that the statistical base for the rules ended with May 1947, so that the last example is falling outside the examined 20 years.

4.

In fig. 8 a, which gives the evening map of 1/11 1922, we have a strong cyclone over the North Sea. The arrow indicates the cyclone path

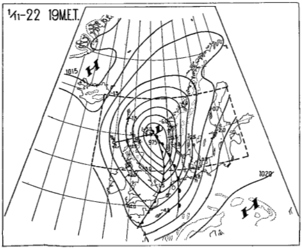

Fig. 8 a.

for the last 24 hours. As the negative tendencies east of the center are very large, I must confess that at first glance I thought this a serious case. We had seemingly a cyclone of the Norwegian type, and $L_1 + L_2$ was as high as 326. But a measurement of the wind directions showed straight N over area 2, and that will not favour a NW gale in the Skager Rack, (see chapter 6).

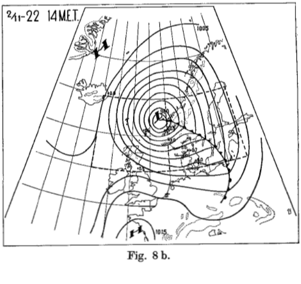

Fig. 8 b.

Fig. 8 b shows the weather situation next noon. We have WSW at the Skager Rack, and as the occlusion already has passed, and the center isn't north of Stadt, we have another example of rule 8. The center is later mowing only slowly towards NE, and as the tendencies are small and the pressure rise is as great south of the center as west of it, no NW gale showed up on the following maps.

5.

Looking at the map of 2/11 1929, 19 M.E.T., fig. 9 a, we can at once decide, that a NW gale at the Skager Rack is most unlikely according to rule 4. Then the cyclone north of Iceland can not possibly cross Norway against the broad S stream E of the center, and we have therefore a Polar Sea cyclone. Moreover, $L_1 + L_2$ is only $= 189$, and this is even less than the minimum value of table 3. Rule 10 therefore also indicates no gale.

Fig. 9 b, the map of 3/11 1929, 14 M.E.T., gives the development. We have only WSW 4 Beaufort at the Skager Rack.

6.

Fig. 10 a, 19/1 1923, 14 M.E.T., gives an example where the 3 main rules 7, 10 and 11 are working together. We have a Norwegian cyclone, $L_1 + L_2 = 319$, area 1 has WSW, area 2 W. Fig. 10 b shows the morning map the next day. The NW gale has begun at the Skager Rack, but Skagen has yet W wind. Later the wind is increasing and turning towards NW also in Denmark.

It may be added that the weather service at Oslo gave a forecast for W, not NW.

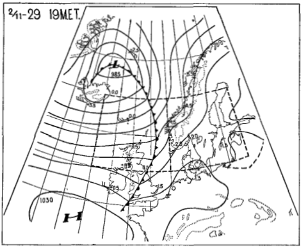

Fig. 9 a.

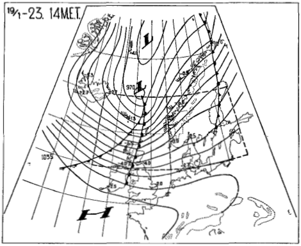

Fig. 10 a.

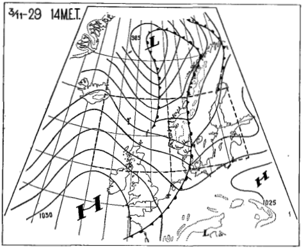

Fig. 9 b.

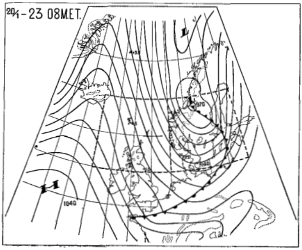

Fig. 10 b.

7.

Fig. 11 a gives the weather situation of 12/11 1930, 14 M.E.T. It is likely that the cyclone south of Jan Mayen belongs to the Norwegian type, i.e. it will pass south of the North Cape. We can not tell how great the tendencies are over the open sea, but they are at any rate great near Stadt, and the wind in the warm sector and in the false warm sector is from the west. These facts indicate that the center is not likely to move much towards the north. $L_1 + L_2 = 287$, which is greater than the number given in table 4, area 1 has NW wind, area 2 W wind. The rules 7, 10 and 11 are working together and a NW gale is likely at the Skager Rack. On the base of this map, the weather service at Oslo issued a warning for SW, valid until evening of the next day.

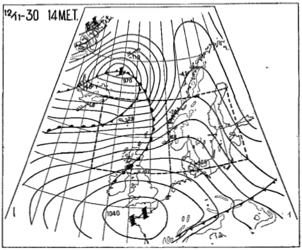

Fig. 11 a.

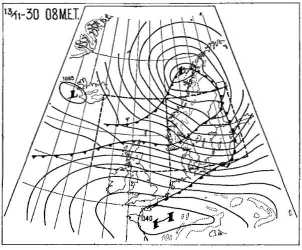

Fig. 11 b.

However, from fig. 11 b it is evident that a NW storm is beginning at the Skager Rack the next morning.

8.

As a last example we shall take a very exceptionale case, where the mean gradient over areas 1 and 2 was extremely weak, and yet a gale occurred against rule 10. See the morning map of 12/12 1947, fig. 12 a. The length of $L_1 + L_2$

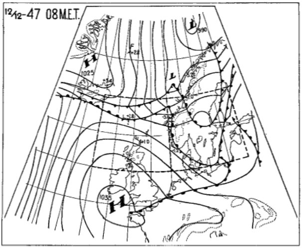

Fig. 12 a.

was only 157, which is even less than the value for December in table 3. The mean geostrophic wind over area 1 was W and over area 2 WNW. So far rule 11 is satisfied and the same is the case with rule 7, as a cyclone center evidently is developing N of Stadt, which will cross Norway on its way towards the east. The barometer is falling rapidly over Mid-Norway and rising over Iceland, and the NW stream between the rising and falling areas must increase in a very pronounced way. The cold front then must reach the Skager Rack within 18 hours. We also have a double warm sector and, as far as my experience goes, we must then in most cases be prepared for a strong deepening of the cyclone. The value of $L_1 + L_2$ must be rapidly increasing and we therefore must look upon rule 10 with suspicion. As all the other indications in this case are clearly pointing in the same direction, a gale warning for NW must be considered, notwithstanding rule 10.

Fig. 12 b gives the situation 12 hours later.

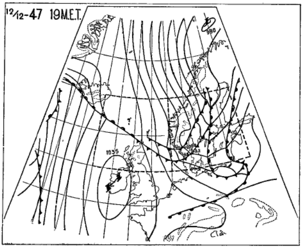

Fig. 12 b.

We have got NW 8 Beaufort at Hanstholm, i.e. a NW gale in the outer part of the Skager Rack, but no gale at the Norwegian coastal stations, and neither did the coast get a gale on the following maps.

A similar situation hasn't occurred during the examined 20 years, which ended with May 1947, so that the case is falling outside that interval. This tells us that an interval of 20 years can not give us examples of all sorts of weather situations and that even the best statistical rules based on 20 years' material occasionally may be broken. But if better rules as to the tendencies had been worked out, the last situation might, perhaps, have been picked out at once as a special one.

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