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AN INVESTIGATION ON SOME ASPECTS OF THE EFFECT OF LAND AND SEA BREEZES

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INTRODUCTION

1. General remarks on the effect of land and sea breezes.

At the coasts of continents and islands the phenomenon of land and sea breezes occurs on days with favourable conditions. This means that in the day-time the wind has a component from the sea, whereas during the night the wind has a component that is offshore. The phenomenon is caused by the greater cooling during the night and the greater heating in the day-time of the air above the land, both compared with the cooling and the heating of the air above the sea.

The phenomenon therefore is furthered by those circumstances in the atmosphere and by those properties of the earth's surface that promote this cooling and heating.

On days of unfavourable circumstances it occurs that the wind varies in a perceptible way, showing a period of 24 hours, without reaching a change of the sign of the wind component perpendicular to the coast.

The textbook of Willett (1944) contains a representative description of the development of the sea breeze in the absence of any prevailing gradient wind on a day of favourable thermal contrast. This description, which has been given for the New England coast, is quoted here.

"During the mid morning hours, after the ground has been considerably heated by the morning sun, the sea breeze starts in the immediate vicinity of the shore as a light breeze only a few hundred feet deep which blows directly onshore. The outflow of air from land to water must already be in progress at upper levels.

As the morning passes into early afternoon, the sea breeze increases in strength and depth extending progressively further inland and further out to sea.

By mid-afternoon, the sea breeze reaches its maximum strength near the coast, with a velocity of 12 or 15 miles/hour, and probably also its maximum depth between 800 and 1200 feet. The top of the sea breeze stratum is usually clearly discernible from above due to opacity produced by light fog or particles of sea salt or industrial smoke haze in the shallow layer of stable air. By this time the influence of the horizontal deflecting force begins to appear in the first deflection of the breeze toward the direction parallel to the shore, the direction such that the observer facing the wind has the land on his right.

By late afternoon the sea breeze reaches its broadest extent, sometimes extending as much as 30 miles inland and 30 miles out the sea. The strength of the breeze diminishes slowly first along the shore, later further inland and further offshore. The wind continues to shift toward the direction which is parallel to the shore line.

During the early night hours the breeze rapidly dies away to a near calm, which may be followed by the appearance of a light land breeze."

After that Willett says:

"On days of light prevailing wind when the thermal conditions are less markedly favorable to the development of the sea breeze, the development follows the same course, but the breeze starts later, it is weaker and much less extensive and it terminates earlier than is indicated above. On some days the sea breeze is only a very light breeze, two or three hundred feet in depth which blows for only a couple of hours during the latter part of the afternoon and extends no more than two or three miles inland.

Even when the prevailing gradient wind is such that the direct sea breeze circulation is not established in the manner that is outlined above, nevertheless when the thermal conditions are favorable the superposition of a considerable sea breeze component on the prevailing gradient wind is clearly indicated. The effect of the sea breeze is to strengthen the gradient wind parallel to the shore."

In the literature more information is given of sea breezes than of land breezes. This must be considered due to the fact that the land breeze in general has a speed that is much smaller than the speed of the sea breeze. Furthermore it is more difficult to observe the land breeze at night than the sea breeze in the day-time, especially for acquiring aerological data. In this investigation also more stress must be laid on the sea breeze.

Not only at the coast periodic wind changes as described above can be noticed. On the sea, at distances from continents and large islands that may exceed 100 miles, a change of the windvector with a period of 24 hours can be observed (Braak — 1929; Visser — 1936), especially in the tropics. It was ascribed by them to the influence of the adjacent coast.

Moreover, far inland a diurnal variation of the wind vector has been detected and described by several authors. Here, however, the investigations do not indicate any influence of a definite coast although the heating and the cooling of the land is considered to be the principal cause of the variation. Möller (1940) divided the effect into a "convective variation" and a "gradient variation", the convective variation being caused by the diurnal variation of the "eddy transfer of momentum" the gradient variation being mainly caused by the diurnal variation of the differential heating of the air in different directions from the place of observation.

In this investigation all periodic changes of the wind, having a period of 24 hours, that are caused by the differential heating of the air above the land and above the sea at a definite coast, will be embraced by the name "land and sea breeze *effects*". A special case of it, viz. the diurnal succession at a coast of a wind with a component from the land from the sea and from the land again, will be called "the *phenomenon* of land and sea breezes".

Analogous periodic wind changes, not caused by the differential heating and cooling at the coast, are not considered to be land and sea breeze effects. These may occur, for instance, owing to the exchange of momentum by turbulence or to the presence of mountains in the neighbourhood of the coast. In the latter case a land and sea breeze effect is accompanied by a mountain and valley wind effect.

If the air as a whole does not move with respect to the earth's surface, i.e. when a general gradient wind does not occur, we shall speak of an undisturbed situation. The diurnal change of the wind vector that then occurs near the coast will be called an undisturbed effect (phenomenon) of land and sea breezes. A general gradient wind in cooperation with a land and sea breeze effect (phenomenon) will be the cause of a diurnal wind variation which is called a disturbed land and sea breeze effect (phenomenon).

It is often difficult to say whether, or to what extent, a change of the wind belongs to the effect of land and sea breezes. This is especially the case when the network of stations is sparce.

The question how large the area of the land must be to give a perceptible effect can be answered by studying the wind at islands. For instance the island of Bawean (16 km x 16 km) in the Malay Archipelago (112° 40′ E.L. — 5° 50′ S.L.) has a system of land and sea breezes of its own. Kimble (1946) mentioned Bawean as being an example of an island which is just large enough to have such a system of land and sea breezes.

Attention must here be paid to the fact that the shape of the land, its vegetation, its latitude, the general gradient wind, etc. are some of the determining factors.

As the phenomenon of heath and forest winds, which is similar to that of land and sea breezes, occurs with rather small woods (Koch — 1935) we may assume that also very small islands (or lakes) will show some effect of land and sea breezes. Under very favourable circumstances we might then even expect the presence of the phenomenon of land and sea breezes, although its intensity might be without any importance. It seems worth while examining whether this assumption is true, but the author has no observations available to verify it. The theory, put forward in chapter II, 1, supports this assumption.

2. *Historical development of observations and of theoretical investigations.*

It is of importance to approach recent discussions on the effect of land and sea breezes via the historical development of the observations and the theoretical considerations on the subject.

Kaiser (1907 a) wrote a survey on this development, stretching from antiquity till 1907. Although his survey is not complete and contains some inaccuracies it gives a good picture. As an introduction to the subject and an extension to Kaiser's survey it is worth while mentioning here the following facts without aiming for completeness.

At many places in the Malay Archipelago the mountain and valley winds, together with the reinforcing land and sea breezes, have got proper names. This shows that these winds have doubtlessly for long been drawing the attention of the inhabitants and are of importance to them (Braak — 1929 a).

Braak (1929 a) also described how Javanese fishermen regulate their work according to the phenomenon of land and sea breezes. At Djakarta (formerly Batavia) the proas sail out with the aid of the land breeze very early in the morning. The vessels are built in such a way that they can only sail before the wind. When against noon the sea breeze rises, the fishermen stop fishing and along the horizon a crowd of full sails appears, approaching the harbour at great speed. This description demonstrates too that at this coast these winds occur with a great steadiness, for the fishermen rely on them for being brought home.

Fontseré (1920) remarked that at the Catalan coast work on the land is ruled by the hour of the day at which the cool sea breeze starts blowing.

It is difficult to trace at what time in history the above mentioned more or less unconscious perceptions were changed into scientific observations and the understanding of the laws governing land and sea breezes. Probably this happened very long ago.

According to Kaiser (1907 a) it was already Herodot who described how the sea breeze was made use of for a sea fight. Krümmel (1893) has quoted Varenius who, in 1650 in his „Geographia Generalis", considered the influence of the tide on land and sea breezes.

About 1700 Dampier in his itineraries gave his description of land and sea breezes at several coasts. His description of the phenomenon was for a long time regarded as a standard example. Especially his description of the approach of the sea breeze from the sea towards the land has for two centuries been of great influence on later studies.

Semeijns (1755) gave a good description of the effect at the coasts of Java, especially at Djakarta (Batavia). He already ascribed the effect to the difference in daily variation of temperature between land and sea.

Whereas the former publications are of a mainly descriptive nature, it was about 1860 that theory was brought to development. Theory then was based on the idea that the sea breeze is caused by the aspiration of the land over which a deficit of air will occur in the lower layers due to the daily heating and expanding of the air. Representatives of this opinion are Maury (1856) Buchan (1860 : 1871) and Mühry (1860).

In 1873 Laughton concluded that the theory prevailing at that time was unsatisfactory and was put forward without being in harmony with the poor observational data then available. According to theory the sea breeze must begin at the coast, extending more and more seaward. Observations pointed out the contrary. Furthermore, according to Laughton, observations at different places on earth would show that the difference in temperature between land and sea is subordinate to others factors. Nowadays it is clear that orographical influences and those caused by a prevailing general wind have led Laughton to his incorrect conception.

To stimulate further observation Laughton gave an explanation of the phenomenon of land and sea breezes which was based on the assumption that the pressure of the water vapour in the atmosphere is the "pushing-power" of the sea breeze. The pressure of the water vapour above the sea must show a diurnal variation that corresponds to the diurnal change of the wind, but this variation would be imperceptible.

This explanation was not accepted. Some years later, however, the development made an important step forward. It was Blanford (1877) who, proceeding from pressure data which were obtained at sea and land stations, pointed out that the difference in the diurnal variation of temperature above the land and above the sea must indeed be the cause of the phenomenon of land and sea breezes.

The following conception, given by Blanford, has been of great importance for later developments of the subject. He pointed out that the greater heating of the air above the land causes a lifting of the isobaric surfaces in the higher layers to a greater extent than above the sea. Consequently an outflow of air in the higher layers from the land to the sea sets in. Only now a pressure gradient, pointing from the sea towards the land, is set up at the surface being the cause of the sea breeze. It may be said for short that during the night the opposite process occurs.

Later on more observations of the difference in pressure at sea and land stations were published, among others, by Kaiser (1907 b) and Grenander (1912) all confirming the results of Blanford.

Although the explanation as given by Blanford has for a long time been the leading thought it soon became clear that it wanted some extension. To explain that the sea breeze starts over the sea Köppen (1884) pointed out that the greater friction above the land at first prevents the sea breeze from blowing near the coast. Seemann (1884) assumed a lateral pressure gradient, caused by the expansion of the heated air, to exist from the land towards the sea preventing the beginning of the sea breeze near the coast. Other explanations of this aspect of the sea breeze were given by others without being accepted.

For a long time the development of theory proceeded slowly but a lot of observational data were gathered throughout the world.

According to Braak (1928) the fact that the sea breeze originates out to sea, as was found by most observers, is caused by the presence of a general gradient wind that has a component from the land. Without such a wind the phenomenon of land and sea breezes has what he calls the "normal" type. Then both the sea breeze and the land breeze begin at the coastline. This normal type, being frequent only in the tropics when and where the monsoons or trade winds are of no importance, seldom occurs at higher latitudes.

Braak also stated that a general gradient wind that has an offshore component will retard the onset of the sea breeze and cause a sudden change of temperature and humidity when it enters, just as many observations show.

Koschmieder (1936) worked out this suggestion. He makes a strong distinction between the cases with and without a general offshore wind in the morning for in the first case he assumes the frontal theory being the basis of the explanation of observations.

In the textbook of Hann and Süring (1937-1942, 5th ed.) the explanation of the so-called "sea breeze of the first kind", being the sea breeze without a general gradient wind, is given according to Blanford. As an example the phenomenon at Djakarta (Batavia), as described by van Bemmelen (1922), is put forward. Referring to Koschmieder's explanation the case with a general offshore wind is treated under the name "sea breeze of the second kind". The names quoted were not introduced by Koschmieder but by Conrad (1936).

Further on in this investigation it is tried to show that the difference between these two cases is not as essential as was put forward by Koschmieder. Therefore the cases will be distinguished here by the names "undisturbed" and "disturbed" effect (phenomenon) of land and sea breezes. Because not only a general wind but also other factors may disturb the normal effect, it will be necessary to mention the disturbing factor if this should not be clear from the foregoing text.

3. *The effect at different geographic latitudes.*

The phenomenon of land and sea breezes is observed at almost all latitudes. Though in the tropics its steadiness at a certain place can be very great, at an adjacent coast it may occur very irregularly because the factors that have an influence on it can show great differences locally. Examples of these factors are for instance the direction of the coastline with respect to the direction of the prevailing general wind and also the density of the vegetation.

According to Braak (1928) both the disturbed and the undisturbed phenomenon, the latter being not so striking as the former, occur in the tropics. At temperate latitudes the undisturbed phenomenon seldom occurs.

It seems that in the tropics the disturbed phenomenon can occur in a more pronounced form than at temperate latitudes. This is suggested by the data of extreme cases published by Bijourdan (1899) for the tropics, in comparison with those published by Koschmieder (1936; 1941) and Hornickel (1942) for the Baltic coast of Germany.

At temperate latitudes the phenomenon of land and sea breezes occurs with a steadiness that as a rule is smaller than in the tropics. Mostly this is considered to be due to the disturbance that is frequently caused by the variations from day to day of the general gradient wind.

One might think that the fall of mean temperature towards the Poles also is a factor contributing to the decrease of steadiness in that direction. In fact several authors put forward the difference of temperature between the air above the land and above the sea as being the primary factor that rules the phenomenon of land and sea breezes. However, the fall of mean temperature towards the Poles is not accompanied by a decrease of the difference of temperature just mentioned. Statistics show that in summer at noon this difference in the tropics is about equal to its value at temperate latitudes and in the extreme cases it is smaller than at temperate latitudes. In chapters II and III it will be made plausible, however, that rather the difference in supply of heat to the atmosphere and not the difference of temperature between land and sea governs the effect of land and sea breezes. Thus a decrease of daily heat supply towards the Poles (the cause of the fall of mean temperature in that direction) indeed will contribute to the decrease of steadiness of land and sea breezes.

Yet the phenomenon can be detected at the Swedish coast (Grenander — 1912) and at the coast of Finland (Witting — 1908). For instance, in the summer of 1909, with the aid of several meteorological stations and a large number of volunteers, Grenander distinguished 27 days out of 123, on which a sea breeze occurred that was preceded and followed by an offshore wind.

Paying attention on the one hand to the fact that the wind at the coast is only counted as a sea breeze if the angle between the direction of the coastal wind and the wind directions further inland and out to sea is 90° or more and on the other hand to the fact that on those 27 days the sea breeze often occurred along only a small part of the coast, Grenander's investigation gives a good picture of the frequency of the phenomenon in Sweden.

Because a special study of the phenomenon of land and sea breezes in Holland has not yet been made, it seemed desirable to investigate the material that was available. The considerations in the following chapters are based on an examination of wind observations gathered at IJmuiden on the Dutch coast of the North-Sea (4° 34′ E.L. — 52° 28′ N.L.). Here the direction of the coastline is N 14° E — S 14° W (fig. 1).

The recording anemometer (type Halliwell — Dines) is placed on the ridge of a single chain of dunes situated directly at the coast 300 m to the south of the "Noordzee-kanaal". The vane has an elevation of 26 m above the level of the sea (effective height 12.5 m). For further instrumental informations may be referred to Braak (1942).

IJmuiden has the advantage of being situated on a straight coast without a broad river in the neighbourhood. Though Flushing is a far better equipped meteorological station, the situation there is less simple.

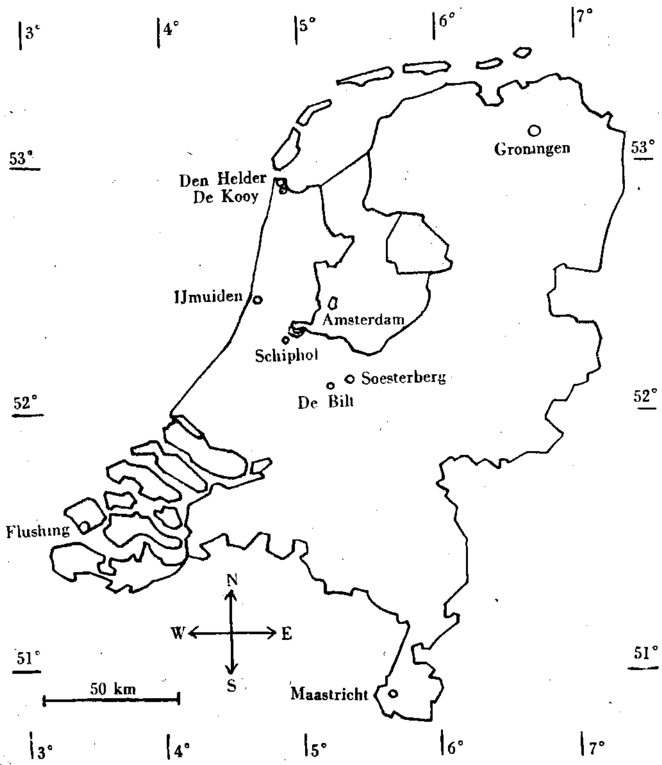


FIGURE 1.

Meteorological stations in the Netherlands to be referred to further on in this investigation.

CHAPTER I

THE ANALYSIS OF OBSERVATIONAL DATA

1. *Climatological survey.*

Starting with the examination of the occurrence of land and sea breezes in Holland, the anemobiagrams from IJmuiden were analysed. At first sight it becomes clear that, especially in the warm months, on several days the wind changes in a way that suggests the occurrence of the phenomenon of land and sea breezes. It is also obvious that a wind from the sea fluctuates less in speed and in direction than an offshore wind.

To get an impression of the mean diurnal change of the wind vector in the several months the anemobiagrams were analysed in the following way. Mean values of wind speed and wind direction were computed for each hour. A period of 10 years was chosen. Because the instrument, which was placed in the year 1919, has not always worked satisfactory the years 1920 — 1926 and 1933 — 1935 were used. Of these periods some months must be dropped too, mainly in winter.

From the hourly mean values of wind speed and wind direction the wind components in the directions N — S and E — W were evaluated (from the N and from the E taken positive). From these the mean hourly values for each month were calculated. The result is given in table 1 and in figure 2.

The numbers 7 and 19, placed along the curves of figure 2, denote the values from 6 — 7 h and 18 — 19 h respectively. The curves are drawn for the first half of the day and dotted for the second half.

Figure 2 shows that:

1° The diurnal change of the mean wind is very small from November till March,

2° The diurnal change of the mean wind rapidly increases from March till June,

3° The diurnal change of the mean wind decreases from June till November,

4° All the curves from March till November are followed in a clockwise direction,

5° The N-component of the wind clearly increases around noon from March till September, which increase is followed by a decrease during the late afternoon.

A large number of factors will contribute to the shape of the curves. Thus it is not allowed to draw a conclusion from them about the effect of land and sea breezes.

Apart from the effect of land and sea breezes there will be the influence of the diurnal variation of the vertical transfer of momentum. Moreover, at IJmuiden winds from directions between SSW and NW are most frequent and will be preponderating in giving the curves both their places with respect to the axes and their shapes, the more so because the strong winds mainly blow from these directions.

To eliminate the influence of the frequency distribution Möller (1940) proposed another way of analysing wind observations. He supposes the diurnal variation of the wind vector to be mainly due to a "gradient variation" (Gradientgang) and to the variation of transfer of momentum or "convective variation" (Konvektionsgang). He also assumes these variations to be equal with all directions of the wind. For these reasons he selects the days according to the octant from which the wind comes at, for instance, 15 h and mean hourly values of the wind components are calculated for each octant. According to Möller the octant values, averaged with equal weight, lead to the "gradient variation". After rotating the octants till they coincide with one of them the octant values are averaged with equal weight again. Now the result is thought to be the "convective variation".

Apart from those factors that may cause a faulty result everywhere, the way of analysing observations as described here is worthless especially at a coast because it is not allowed to assume the "gradient variation" and the "convective variation" to be equal with all directions of the wind. Therefore such an analysis has not been performed for IJmuiden.

It will be of interest to compare the change of the curves in figure 2 with the change of some climatological data throughout the year.

1. The mean daily relative insolations in the periods 1920—1926 and 1933 — 1935 in the several months are recorded here. The values were computed from the observations at De Bilt (57 km from IJmuiden, fig. 1). In a second row the rounded mean values in a period of 43 years at De Bilt are given too.

	J	F	M	A	M	J	J	A	S	O	N	D
1920—1926 and 1933—1935	19	26	34	34	42	40	43	39	38	32	26	14
1904—1946	21	26	33	36	43	41	39	40	39	32	21	17

2 The mean values of daily maximum temperature and of daily minimum temperature at the surface in the several months in a period of 43 years at De Bilt are given below. It appears that the differences between them and the relative insolations in the same period have a quotient that is nearly constant throughout the year.

1904—1946	J	F	M	A	M	J	J	A	S	O	N	D
Mean maximum(°C)	4.6	5.5	8:7	12.1	17.0	19.8	21.5	21.2	18.6	13.6	8.4	5.4
Mean minimum(°C)	-0.1	-0.2	1.6	4.1	7.7	10.7	12.8	12.7	10.2	6.7	3.1	0.9
Difference	4.7	5.7	7.1	8.0	9.3	9.1	8.7	8.5	8.4	6.9	5.3	4.5
Relative insolation(%)	20.8	25.6	32.8	36.4	42.6	40.7	38.9	40.2	39.4	31.5	21.4	16.6
Difference / Relat. insol.	0.23	0.22	0.22	0.22	0.22	0.22	0.22	0.21	0.21	0.22	0.25	0.27

3 The mean temperatures in the months April to August inclusive at the elevations of 0 m, 500 m, 1000 m and 2000 m in the periods 1920 — 1926 and 1933 — 1935 were computed from observations at Soesterberg (fig. 1). From days on which 2 or more observations were available the earliest observation was used. Then 73 % of the observations occurred between sunrise and 8 h. The result is as follows:

	t_0	Δt	t_{500}	Δt	t_{1000}	Δt	t_{2000}	$\Sigma\Delta t$
April	8.06	2.49	5.57	2.97	2.60	5.64	-3.04	11.10
May	12.06	2.43	9.63	2.96	6.67	5.61	1.06	11.00
June	14.42	2.81	11.61	2.82	8.79	4.99	3.80	10.62
July	17.05	2.45	14.60	2.83	11.77	5.17	6.60	10.45
August	15.20	1.73	13.47	2.97	10.50	4.90	5.60	9.60

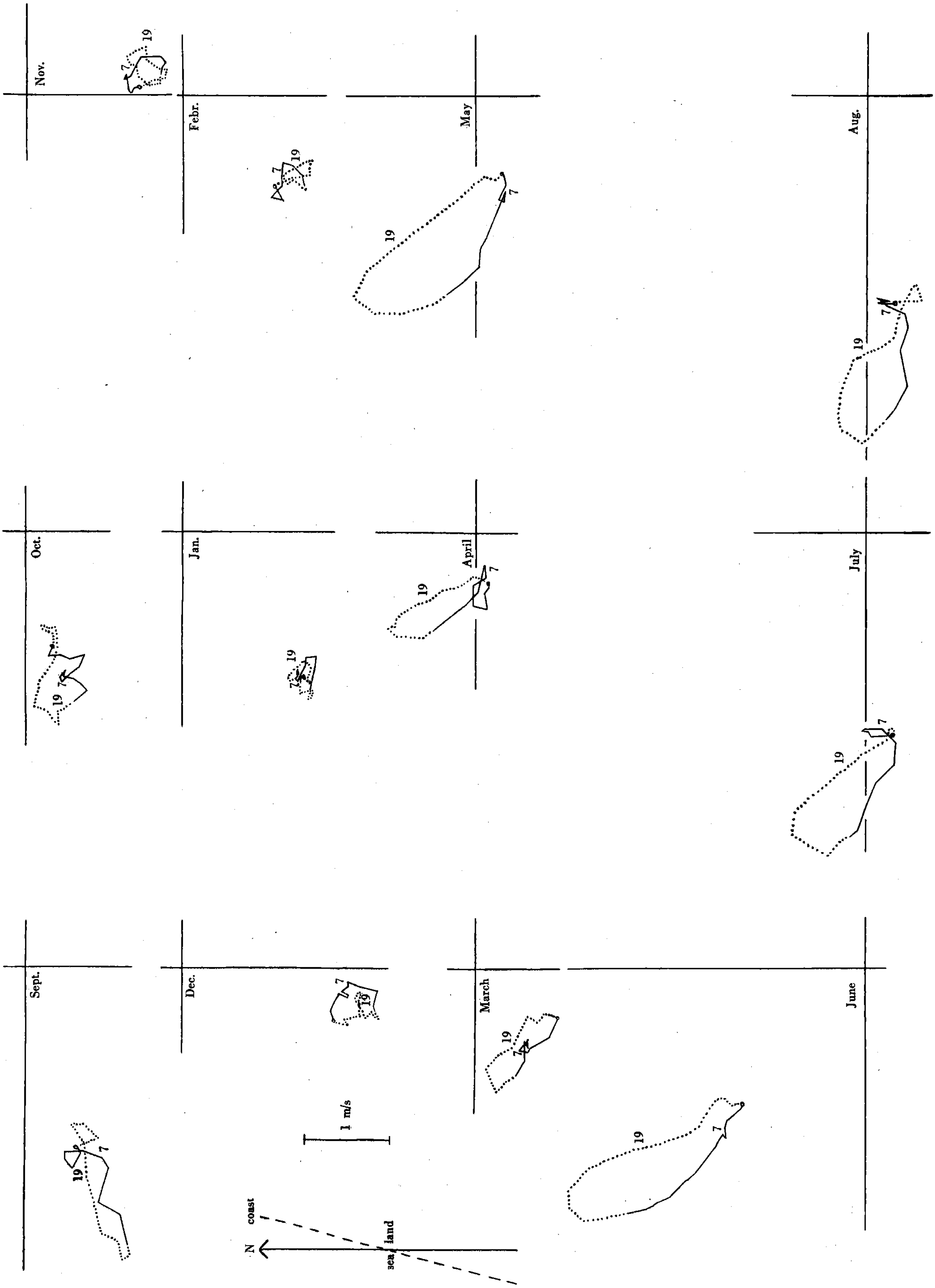


FIGURE 2.

Diurnal variation of mean wind in the months of the year.

Hour of the day	Mean wind components in m/s.											
	January N E	February N E	March N E	April N E	May N E	June N E	July N E	August N E	September N E	October N E	November N E	December N E
1	—1.40—1.66	—1.08—1.06	—0.97—0.56	—0.16—0.58	—0.31—0.89	+1.41—1.58	—0.31—2.31	—0.32—2.37	—0.63—2.06	—0.35—1.32	—1.33+0.08	—1.77—0.60
2	—1.36—1.76	—1.19—1.22	—0.90—0.72	—0.16—0.63	—0.35—1.01	+1.44—1.61	—0.30—2.33	—0.23—2.38	—0.69—2.13	—0.29—1.43	—1.26+0.07	—1.74—0.51
3	—1.37—1.74	—1.15—1.20	—0.87—0.79	—0.10—0.70	—0.32—1.05	+1.58—1.75	—0.07—2.35	—0.11—2.36	—0.58—2.32	—0.37—1.42	—1.24+0.00	—1.81—0.30
4	—1.33—1.59	—1.04—1.18	—0.65—0.93	—0.14—0.89	—0.26—1.18	+1.62—1.85	—0.04—2.29	—0.26—2.37	—0.48—2.20	—0.52—1.46	—1.19+0.06	—1.91—0.34
5	—1.35—1.65	—1.10—1.10	—0.62—0.97	+0.03—0.82	—0.27—1.19	+1.61—1.92	+0.03—2.28	—0.14—2.33	—0.49—2.14	—0.70—1.41	—1.17+0.20	—1.92—0.32
6	—1.31—1.68	—1.16—1.05	—0.53—0.94	+0.03—0.62	—0.32—1.20	+1.60—1.98	—0.04—2.26	—0.13—2.32	—0.71—2.11	—0.62—1.57	—1.16+0.16	—1.85—0.28
7	—1.36—1.73	—1.15—0.90	—0.52—0.94	—0.13—0.52	—0.33—1.09	+1.64—1.94	—0.19—2.26	—0.28—2.41	—0.93—2.20	—0.45—1.73	—1.24+0.23	—1.93—0.22
8	—1.44—1.54	—1.16—0.78	—0.62—0.82	—0.11—0.39	—0.34—1.09	+1.65—1.95	—0.35—2.42	—0.44—2.50	—1.00—2.31	—0.42—1.68	—1.29+0.35	—1.94—0.18
9	—1.44—1.46	—1.28—0.81	—0.64—0.91	—0.09—0.55	—0.23—1.38	+1.75—2.11	—0.32—2.67	—0.47—2.67	—0.89—2.71	—0.50—1.60	—1.33+0.41	—1.93—0.16
10	—1.57—1.44	—1.39—0.91	—0.58—0.85	—0.03—0.67	—0.05—1.76	+1.95—2.37	—0.10—2.88	—0.38—2.91	—1.14—2.84	—0.43—1.65	—1.57+0.43	—2.06—0.21
11	—1.55—1.56	—1.41—1.04	—0.58—1.07	+0.17—0.86	—0.03—1.95	+2.30—2.68	—0.02—3.14	—0.46—3.33	—1.16—2.98	—0.59—1.67	—1.62+0.37	—2.27—0.26
12	—1.51—1.74	—1.42—1.05	—0.47—1.25	+0.36—1.01	+0.14—2.11	+2.58—2.80	+0.10—3.43	—0.30—3.61	—1.20—3.12	—0.75—1.82	—1.59+0.30	—2.23—0.43
13	—1.49—1.91	—1.43—1.09	—0.36—1.30	+0.62—1.20	+0.47—2.36	+2.89—2.85	+0.27—3.55	—0.12—3.81	—1.25—3.30	—0.40—2.07	—1.54+0.12	—2.29—0.57
14	—1.51—1.81	—1.42—1.06	—0.26—1.41	+0.93—1.19	+0.84—2.49	+3.24—2.91	+0.44—3.72	+0.05—3.98	—1.17—3.36	—0.40—2.23	—1.41+0.10	—2.27—0.56
15	—1.37—1.86	—1.30—0.99	—0.22—1.35	+1.01—1.10	+1.17—2.49	+3.40—2.76	+0.63—3.62	+0.29—3.85	—1.12—3.16	—0.26—2.06	—1.32+0.19	—2.23—0.50
16	—1.38—1.69	—1.22—1.01	—0.20—1.32	+0.95—1.08	+1.41—2.31	+3.41—2.56	+0.84—3.47	+0.32—3.70	—0.93—3.07	—0.13—2.01	—1.27+0.32	—2.14—0.57
17	—1.27—1.72	—1.17—0.97	—0.14—1.15	+0.91—0.98	+1.40—2.26	+3.18—2.32	+0.81—3.21	+0.29—3.35	—0.89—2.92	—0.19—1.72	—1.22+0.33	—2.02—0.35
18	—1.24—1.69	—1.18—0.93	—0.28—1.00	+0.77—0.87	+1.27—2.00	+2.96—2.21	+0.63—3.03	+0.15—3.04	—0.85—2.75	—0.35—1.46	—1.19+0.41	—2.09—0.28
19	—1.29—1.61	—1.25—0.88	—0.45—0.90	+0.55—0.79	+0.90—1.70	+2.65—2.10	+0.31—2.76	—0.01—2.95	—0.75—2.42	—0.37—1,28	—1.40+0.52	—2.04—0.36
20	—1.43—1.47	—1.41—0.78	—0.55—0.70	+0.43—0.69	+0.52—1.41	+2.19—1.97	+0.01—2.54	—0.31—2.76	—0.72—2.07	—0.36—1.11	—1.41+0.38	—2.08—0.49
21	—1.53—1.56	—1.52—0.75	—0.62—0.56	+0.21—0.63	+0.24—1.20	+1.90—1.81	—0.17—2.42	—0.39—2.49	—0.57—1.81	—0.29—1.12	—1.54+0.30	—2.10—0.53
22	—1.47—1.67	—1.49—0.80	—0.74—0.61	+0.07—0.55	—0.03—0.97	+1.78—1.62	—0.27—2.36	—0.51—2.23	—0.69—1.81	—0.19—1.09	—1.65+0.29	—1.98—0.59
23	—1.53—1.77	—1.49—0.91	—0.81—0.53	+0.06—0.54	—0.10—0.91	+1.66—1.49	—0.29—2.26	—0.56—2.16	—0.81—1.93	—0.22—1.11	—1.62+0.19	—1.90—0.60
24	—1.48—1.69	—1.44—0.92	—0.89—0.53	—0.13—0.55	—0.22—0.95	+1.52—1.57	—0.30—2.26	—0.62—2.35	—0.88—1.98	—0.36—1.18	—1.64+0.20	—1.92—0.65

TABLE I.

Hourly mean values of the wind components, averaged for the months of the year, in a period of 10 years.

From these data it appears that the mean lapse rate of temperature between 0 m and 2000 m is about constant with a small decrease from April till August. This decrease especially occurs in the lowest 500 m and between 1000 m and 2000 m.

The temperature increases most rapidly from April till May (at all levels up to 2000 m about 4° C). From July till August the temperature at these levels decreases.

Conclusions: Although the amplitude of the diurnal variation of the wind speed clearly changes throughout the year, the mean relative insolation as well as the mean diurnal temperature variation only show a qualitative correlation to that amplitude.

No indication can be found for a simple connection between the stability of the atmosphere and the daily variation of the wind speed.

Because in September and in October the N-S component of the mean wind during the morning does not increase, the diurnal wind change in these months must be ascribed mainly to the influence of the vertical transfer of momentum and for a minor part to the effect of land and sea breezes. This will become clear from chapter II.

2. *The effect of land and sea breezes in connection with the direction of the wind.*

Now the days of observation were classified as follows.

1°. According to the wind direction at sunrise, divided into 8 octants:
from N — NE, denoted by 1,
from NE — E, denoted by 2,
etc.

2°. According to the daily mean value of wind speed, divided into 3 groups:
0— 5 m/s, denoted by 1,
5—10 m/s, denoted by 2 and
10—15 m/s, denoted by 3.

The number of days with a mean wind speed exceeding 15 m/s is too small for giving reliable results.

3°. According to the relative insolation, divided into 4 groups:
0 % — 25 %, denoted by 1,
25 % — 50 %, denoted by 2,
etc.

Thus a day that is indicated by 314 will be characterized by a wind direction at sunrise between E and SE, a mean wind speed between 0 and 5 m/s, while the relative insolation exceeds 75 %.

Days having at sunrise a wind direction just on the boundary between two octants have been counted with half weight to both octants.

Because at IJmuiden no observations of the insolation are performed, those from the Dutch observatory (K.N.M.I.) at De Bilt were used. From September 1923 the data of sunshine from the station in Amsterdam are available too. De Bilt lies at a distance from the coast of 52 km as the crow flies and of 57 km from IJmuiden. For Amsterdam both distances are 25 km.

Comparing the data from De Bilt and Amsterdam, belonging to the period from September 1923 until January 1927, it has been found that out of 367 days in summer (May — August) 265 belong to the same class of insolation for both stations, 100 belong tot two subsequent classes and only 2 days have a difference of 2 in the figure by which they are classified for the insolation. These data and also those for the other seasons can be compared in table 2.

Third numbers of classification for both stations:	Summer	Spring Autumn	Winter
are equal	265 (72 %)	332 (79 %)	349 (83 %)
differ 1	100 (27 %)	86 (20 %)	63 (15 %)
differ 2	2 (1 %)	5 (1 %)	7 (2 %)

TABLE 2.

Data of the difference in insolation at Amsterdam and De Bilt.

Because the numbers in each column show a rapid decrease it will be clear that in summer the number 100 in the table belongs for the greater part to days having only a small difference in insolation at De Bilt and Amsterdam. The same can be said of the numbers 86 (spring-autumn) and 63 (winter). This justifies the way of proceeding as described above.

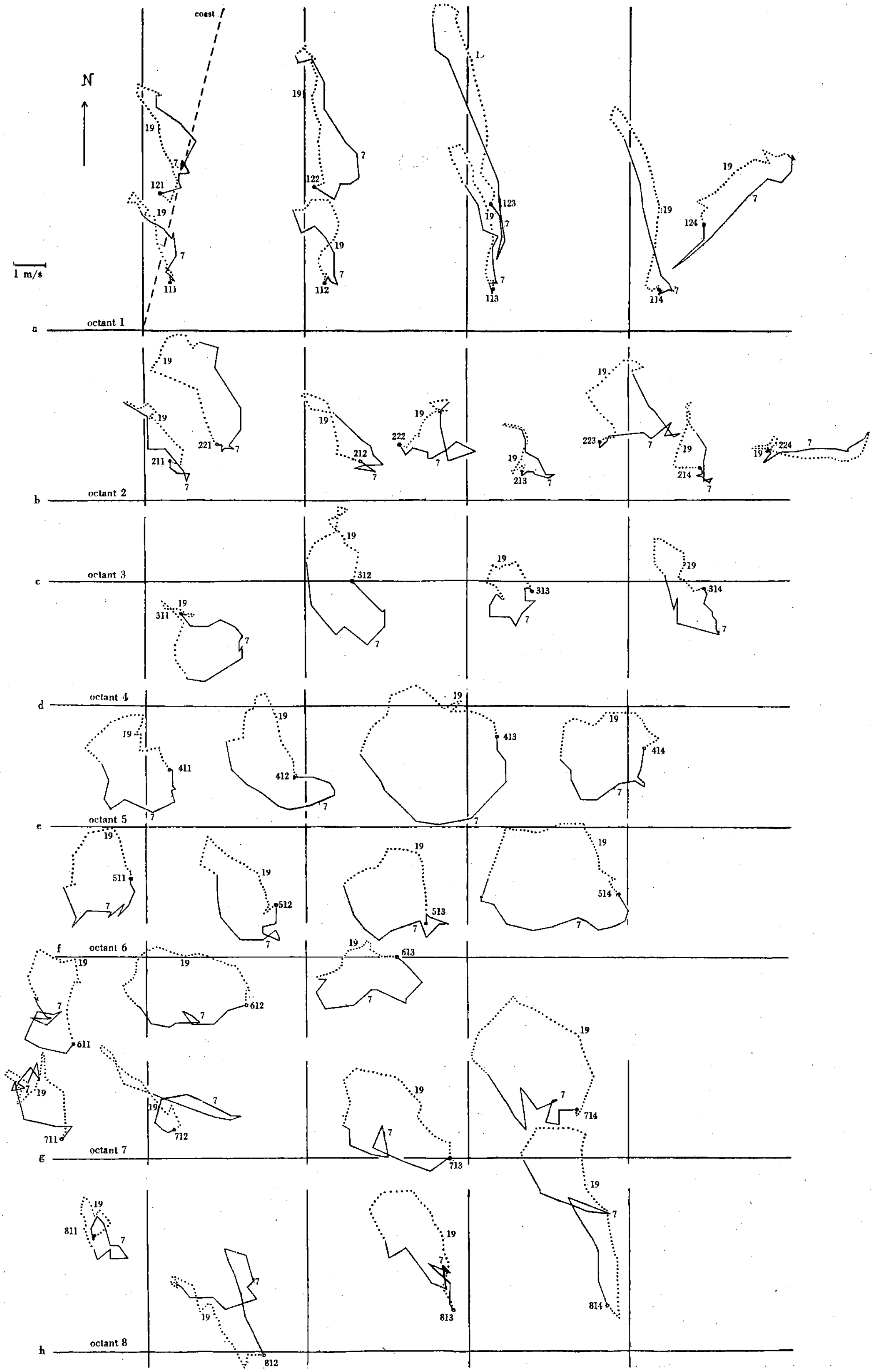
Now the observations of wind components belonging to the same number of classification were combined to 3 groups, viz.:
summer — May, June, July and August;
spring and autumn — March, April, September and October;
winter — November, December, January and February.

The mean values of the wind components in each year were calculated of days belonging to the same group of months. Then the years 1920 — 1924 were combined and also the remaining 5 years in order to have the possibility to get an impression about the reliability of the results by comparing the data for both periods of 5 years.

Finally the corresponding data for these periods were combined, thus mean values were calculated for 10 years.

It appeared now again that the mean diurnal variation of the wind vector in the winter-months is very small or undetectable. The mean diurnal variation of the spring-autumn group of months lies between that of the winter and the summer months. Therefore attention will be paid only to the summer months. The result for the group of summer months is given in table 3 (see page 50) in so far as the cases afterwards seem to be reliable and of any importance. In each column first the component in the direction N — S and next to it that in the direction E — W is placed, both given in m/s. The data in the columns marked N_1, N_2, N and C represent:

N_1 — the number of days belonging to the number of classification that is placed in the first column of that row and occurring in the first period of 5 years;
N_2 — this number in the second period of 5 years;
N — this number in 10 years;



FIGURES 3 a — h

Mean diurnal wind change in summer, for several numbers of classification. In the rows from the left to the right insolation increasing from group 1 to group 4.

C — the conformity between the results from both periods. The conformity has been estimated with the aid of graphs that were drawn for each row in the tables for both periods of 5 years (not given here). It is characterized by the letters g (good), m (moderate) and s (small or absent). Attention may be drawn to the fact that a small conformity can be caused by a small number N_1 or N_2; nevertheless a case denoted by s can be reliable if N is large.

A letter F in the sixth column means that a figure is made for the case in question (fig. 3). The following must be said with regard to this figure.

For getting a better impression of the data of table 3 they were plotted on a chart whose abscissa is the E — W component of the wind vector and whose ordinate is the N — S component. Each classifying number gives 24 points, each point representing the starting point of the mean wind vector that is computed for the corresponding hour (W.E.T.). The end of this wind vector is laid in the origin of the coordinate system. Connecting the 24 points a broken line is formed. This line indicates the diurnal change of the mean wind for the number of classification in question.

It will be clear that the points at which a line begins and ends will generally not coincide. Even when a large number of days are represented the line might show a systematic difference between its first and last point. If this difference exceeds that between other successive nocturnal hours this must be caused by a systematical change of the wind. For instance, a number of classification might mainly occur with a weather situation that often shows a change from an onshore wind during the first towards an offshore wind during the last hours of the day. The direction of the wind during the first and during the last hours of the day have been investigated for several numbers of classification. The result is given in table 4. As examples some curves belonging to numbers of classification out of the second and the third column are given in figure 4.

From the table it becomes clear that a wind that at both times comes from the land or changes from a wind from the sea towards a wind from the land is as a rule accompanied by a great insolation. The transition from sea to land occurs only if the speed of the mean wind is small.

In order to get a clearer impression of the diurnal periodic change of the wind, without being troubled by systematic or unsystematic changes that are not periodical, the curves by which this change is represented have been closed artificially in the following way. The mean total change during the 24 hours of the day is divided into 23 equal parts and each part, considered as being a vector, is 5-fold subtracted from the mean wind vector during the first hour of the day, 4-fold subtracted from the mean wind vector during the second hour of the day, etc., once added to the mean wind vector during the seventh hour, 2-fold added to this vector during the eighth hour, etc. The result is a closed curve. The vector for the sixth hour (5—6 h) is left unchanged because then in all figures the wind directions at sunrise appear to remain in accordance with the number of classification.

Wind during the first hours of the day: from the land		from the sea		
Wind during the last hours of the day from		Wind during the last hours of the day from		
the land	the sea	the land	the sea	
112	111	513	511	713
114	113	514	512	721
124	121	612	521	722
212	122	613	522	723
213	123	711	523	732
214	211	712	524	733
222	221	714	531	811
223	312	724	532	812
224	321	813	611	814
311	322		621	821
313	412		622	822
314	421		623	823
411	422		631	824
413	423		632	831
414	431			

TABLE 4.

Showing the non-periodical diurnal change of the wind vector with regard to the coastline in connection with the number of classification.

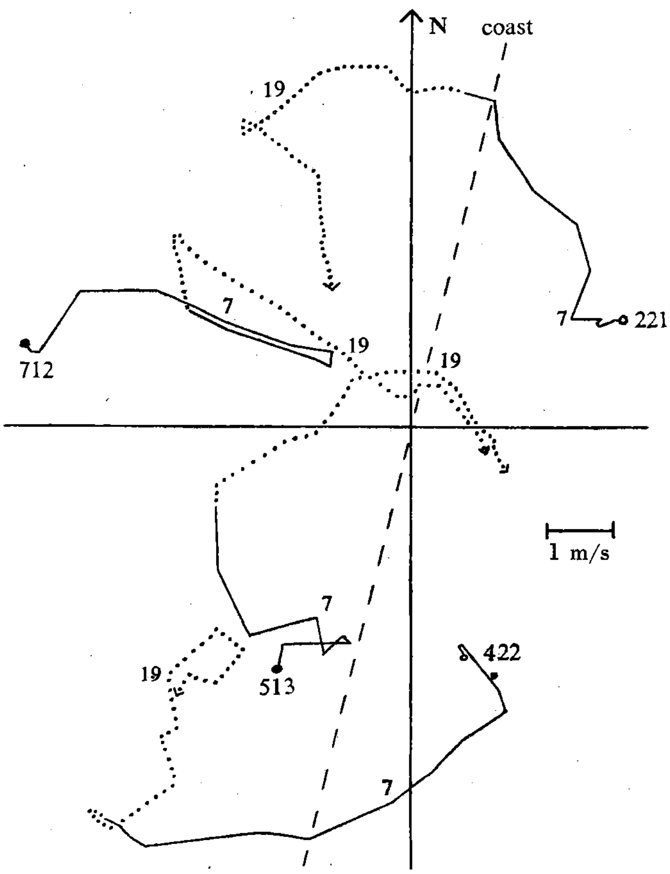


FIGURE 4.

Mean wind in cases 221, 422, 513 and 712, showing a permanent transition from an offshore wind to a wind from the sea or the reverse.

The data in table 3 belong to the uncorrected curves. The curves that have been artificially closed are given in figure 3.

In each curve the point representing the mean wind from 0 h — 1 h is indicated by a small circle and the number of classification. The points that represent the mean wind vector from 6—7 h as well as from 18—19 h are marked by 7 and 19 respectively. The curve is dotted from noon until midnight. Only those curves that will be discussed more in detail are given in figure 3. The other cases have too little importance or give no reliable results.

A speed of 1 m/s is represented by a length as is given in the figure for the first octant.

A superficial examination of the curves shows that in summer in the daytime a component in the direction W—E is added to the mean wind, thus a component from the sea. The cases 124 and 224 are exceptions to this rule. They will be discussed in detail further on in this chapter (section 8).

Also the component in the direction N—S increases in most of the cases. These changes of the components often result in a rotation of the starting point of the mean wind vector along the curve in a clockwise direction. This rotation sometimes occurs only around noon but in most cases during a great part of the day.

Morning winds from the 1st, 2nd or 8th octant as a rule are accompanied by a mean diurnal wind change that shows a great change of the wind speed and only a small change of the wind direction. Morning winds from the other octants are as a rule accompanied by a change of the wind vector that is represented by a more circular line.

The curves 211, 212, 213 and 214, in this sequence of increasing insolation, show a diminishing daily increase of the onshore component in such a way that the mean wind in the cases 213 and 214 even around noon does not become a wind from the sea. The same can be said of the sequence 221, 222, 223 and 224.

These unexpected facts show the necessity of investigating the influence of the factors that are active here. In the first place attention must be paid to the influence of the strength of the wind and of the insolation.

Summarizing it can be said that, apart from some exceptions, in summer with all directions of the morning wind there is a diurnal change of the wind that may suggest the occurrence of a land and sea breeze effect. If the morning wind comes from the 1st, 2nd or 8th octant the diurnal change of the wind is represented by a rather narrow curve, whereas with a morning wind from one of the other octants the curves are more circular. An influence of the insolation, with regard to the variation of the wind speed as well as to the increase of the onshore component of the wind, is obvious especially in the cases of the octants 1, 7 and 8.

3. *Influence of the wind speed on the effect of land and sea breezes.*

From the weather maps those days were selected which had:

a. a very feeble or no general wind (because then one may expect to find days with a sea breeze that is only slightly disturbed), as well as

b. a general wind that is offshore (because only then can it be concluded with some reliability that a sea breeze occurs), and

c. a general wind that during the day shows but a small change in direction and speed, as can be found from the direction and the distance of the isobars on successive weather maps (because otherwise a change of the wind at the coast might be due to a change of the general pressure gradient).

In the period of 10 years over which the investigation extends about 20 of such days were found in the months from April to August inclusive. On all these days at the coast temporarily a wind from the sea occurred, apart from 1 day in April with a very small insolation. About 25 of such days in the winter-months were found but none of them had a temporary transition of the wind over the coastline, although often the relative insolation was large.

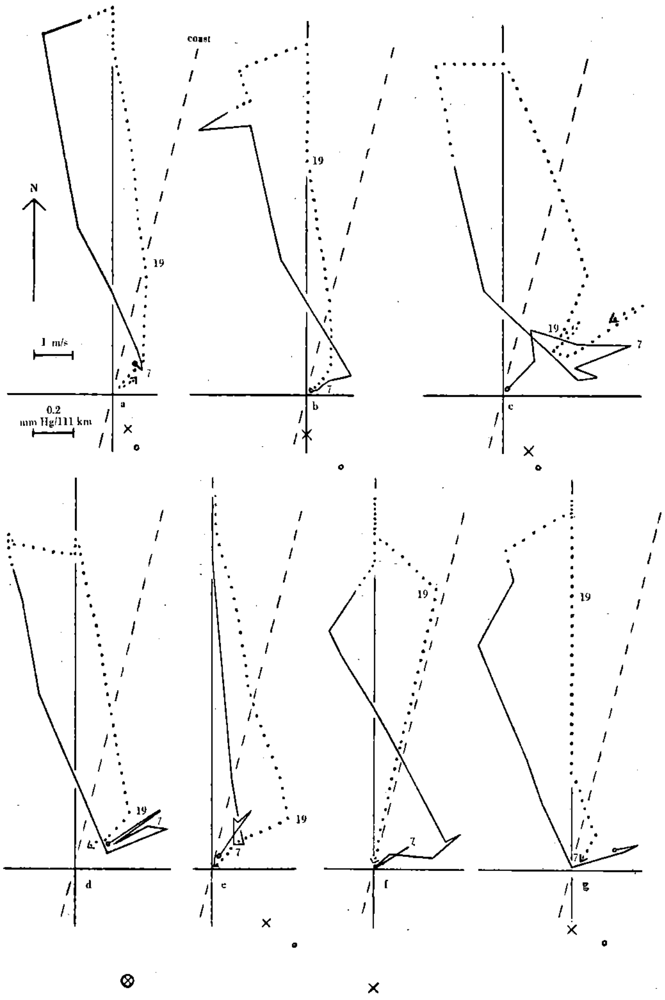


FIGURE 5.

Seven successive days with a sea breeze.

An interesting group of 7 successive days in July with a wind that during the day temporarily came from the sea is given in figure 5. The curves are not closed artificially but represent the real wind. Each day the wind increased from a very feeble offshore wind to a wind from the sea with a speed of about 9 m/s and returned to a feeble offshore wind again. Each curve in figure 5 is accompanied by a small cross and a small circle which represent the ends of the pressure gradient vectors at 7 h and 8 h 30′ respectively. These vectors have their starting points in the origin of the coordinate system and were computed from the weather maps as the mean values for Holland (calculated from pressure observations at Groningen, Den Helder, De Bilt, Flushing and Maastricht; see fig. 1). The pressure field has been assumed to be a linear one. As can be seen from the figure the pressure gradients on the 4th and the 6th day were somewhat larger than on the others. The relative insolations on the days of figure 5 differed only slightly and amounted to about 75 %.

Investigating the occurrence of land and sea breezes when the general wind has a greater speed one meets with some difficulties. Then figure 3 is of no use because days with a wind that at sunrise is offshore more frequently show a transition to a permanent wind from the sea when the daily mean value of the wind speed is larger. Then the change of the general pressure gradient predominates. Thus the curves are not reliable for drawing conclusions about the effect of land and sea breezes. For this reason the cases 32● and 42● were not given in figure 3.

Therefore it will be necessary to investigate separate days. From the anemobiagrams it becomes clear at once that days with a strong offshore wind about perpendicular to the coast never show the phenomenon (page 5) of a sea breeze, even not when the insolation is very large. With a wind (from other directions) having an offshore component that is smaller, the sea breeze occurs more frequently.

For a more thorough investigation it is necessary to know the general wind vector. Here again a difficulty arises. As a matter of fact the general wind as it is on the coast must be known. Here an influence of the effect of land and sea breezes on the wind must be expected, which influence cannot be separated from that of the general pressure gradient. Therefore a moment, some time before the onset of the sea breeze, must be taken as a reference, but it is impossible to say how long this period must be.

To get rid of this influence of the effect of land and sea breezes one might use a mean wind vector from an area that extends more inland (and more over the sea if enough observational data are available). But the mean general wind found over a larger land area may differ considerably from the general wind on the coast.

If the wind at sunrise is used, and if only a small influence of either a land or a sea breeze then would be expected, on days with a sea breeze that starts late the general wind in the meanwhile may have changed considerably. The wind at sunrise still has another disadvantage. During the night and the early morning the vertical transfer of momentum near the surface is generally small but may show great differences from day to day. The wind on days with the same wind vector at sunrise may some hours later differ considerably. This will be especially the case when by the heating of the land the vertical transfer of momentum will become active. Simultaneously the sea breeze effect will influence the wind.

On account of the foregoing remarks first the question will be investigated whether the general wind or the general pressure gradient must be taken as a parameter for classifying the observations.

In the next section it will appear that preference must be given to the use of the pressure gradient. Therefore a further investigation about the influence of the general wind on land and sea breezes has not been performed.

4. *The connection between the wind vector and the gradient vector on the coast about sunrise.*

From the weather maps days were selected which had a general pressure field that only slightly changed in the course of time. These days were divided according to the direction of the pressure gradient and also according to the octant from which the wind blew at about sunrise on the coast. The direction of the pressure gradient was found as the mean of the directions at 7 h and 8 h 30′ (till 25 March 1922 at 7 h and 9 h 30′) which were computed as described in sec. 3. The number of days with a certain direction of the pressure gradient and a certain direction of the wind is given at the corresponding place in table 5.

For instance, with a gradient in a northerly direction the wind on the coast at sunrise mostly comes from the 6th or the 7th octant. It is useless to compare quantitatively the numbers in a column of table 5 because these numbers are influenced by the frequency distribution with regard to the direction of the gradient (for days with a gradient that is about constant).

From table 5 it appears that with the pressure gradient in the directions S, SSW, SW and WSW the wind at sunrise mostly comes from the 2nd octant. On the contrary, with a wind that at sunrise comes from the 2nd octant the direction of the gradient may vary from SSE to W. Also days

Direction of the gradient about sunrise	Number of the octant from which the wind blew at sunrise								Total
	1	2	3	4	5	6	7	8	
N				1	1½	16½	12	2	33
NNE						1	12½	4½	18
NE								10	10
ENE	2½						½	9	12
E	6							5	11
ESE	2								2
SE	3								3
SSE	7	8							15
S	3½	24½							28
SSW	2½	29	3½						35
SW		19	7	1					27
WSW		8½	2½						11
W		1	10	7					18
WNW			2	11	1				14
NW			2	3	8				13
NNW				½	15½	8	2		26
Total	26½	90	27	23½	26	25½	27	30½	276

TABLE 5.

Number of days with a pressure gradient that remained about constant during the day, divided according to the direction of the pressure gradient and to the direction of the wind at sunrise.

with a morning wind from the 1st and the 3rd octant show a rather varying direction of the gradient.

Thus the table leads to the following conclusions. With directions of the gradient between NW and ENE the wind comes from the sea and the direction of the wind on the average is perpendicular to the direction of the gradient. With directions of the gradient between E and SSE the morning wind is offshore and mostly comes from the 1st octant. Thus the angle between the direction of the gradient and the direction towards which the wind blows now is smaller than 90°. This angle decreases still more when the gradient points towards the 5th or 6th octant. Especially with the gradient towards SW and WSW this angle is small (on the average about 25°).

The difference in the friction in the lowest layers of the atmosphere over land and sea will probably be the most important cause of this asymmetry. It is difficult to say to what extent also other factors, for instance a land breeze, have an influence.

Closer investigation shows that with the greatest gradients (in table 5 the gradients vary from 0 to about 2 mb/111 km) the asymmetry is somewhat less pronounced. No influence of the minimum temperature during the preceding night could be found.

If days with a morning wind from, for instance, the 2nd octant are compared their gradients may vary much. It will be obvious, however, that as a result of the heating in the daytime the general wind at the surface will now vary accordingly, due to the vertical transfer of momentum. Days that in section 2 of this chapter were classified as being equal will be comparable no longer.

To avoid the influence of the transfer of momentum on the wind from now on the pressure gradient will be used as a parameter instead of the general wind.

Now again the question arises at what time and at what place this parameter must be computed. The following facts have led to the choice of the pressure gradient near to the coast and at about sunrise.

Braak (1926 b) published data about the diurnal variation of air pressure at several places in Holland. From these the following will be used.

The mean diurnal variation of air pressure in the months from April to August inclusive for the stations Groningen (G), Den Helder (H), De Bilt (B), Flushing (F) and Maastricht (M) (figure 1) is given in figure 6.

The number of years over which the observations extend is not the same for all stations but is at least 10 years. In the figure the daily mean values for the stations are indicated on the ordinate. From their sequence it appears that in Holland westerly winds predominate.

From the curves it will be clear that some collaborating effects contribute to their shape. The nightly minimum for Maastricht nearly equals the daily mean value. The nightly minimum for Den Helder and to a smaller extent for Flushing (both on the coast) is much lower than the daily mean value.

At 15 h the pressure at Maastricht is much smaller than the daily mean value. At that moment the pressure at

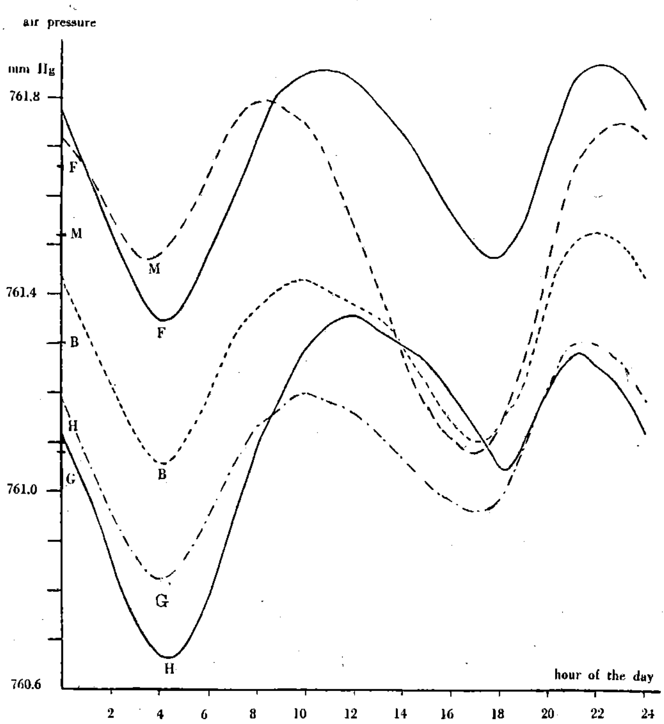


FIGURE 6.

Diurnal variation of air pressure April — August for 5 stations in the Netherlands.

Den Helder is greater than the daily mean value, at Flushing they are equal.

From analogous considerations Braak concluded that, with regard to the pressure variation, Den Helder represents a "coastal type" and Maastricht more or less a "continental type". The other stations are intermediate.

From the pressure values in the coastal triangle Den Helder, De Bilt and Flushing and for the period from April to August inclusive the mean diurnal change of the gradient vector has been computed and is given in figure 7. At about 6 h the gradient starts changing clearly. The change can be represented by a vector that points landward about perpendicular to the coast.

Because on the weather maps the pressure values at 7 h and 8 h 30′ are given they will be put forward in the following. In figure 7 the pressure gradient changes between 7 h and 8 h 30′ with a vector of 0.13 mm Hg/111 km in the direction SE by E.

Examining figure 2 with regard to this fact it is worth while mentioning that in the summer months at about 7 h the hourly wind change starts to increase. This change then can be represented by a wind vector in a direction that nearly equals the direction of the vector that represents the change of the pressure gradient.

This leads to two important conclusions.

1e. At about 7 h on the average no influence of a land breeze on the general wind will occur, rather a small sea breeze effect will be active.

2e. The diurnal change of the wind can be seen as an isallobaric effect with a direction of the isallobaric wind perpendicular to the isallobars. Figure 2 then shows that during the day the vector that represents the hourly change of the mean wind regularly turns

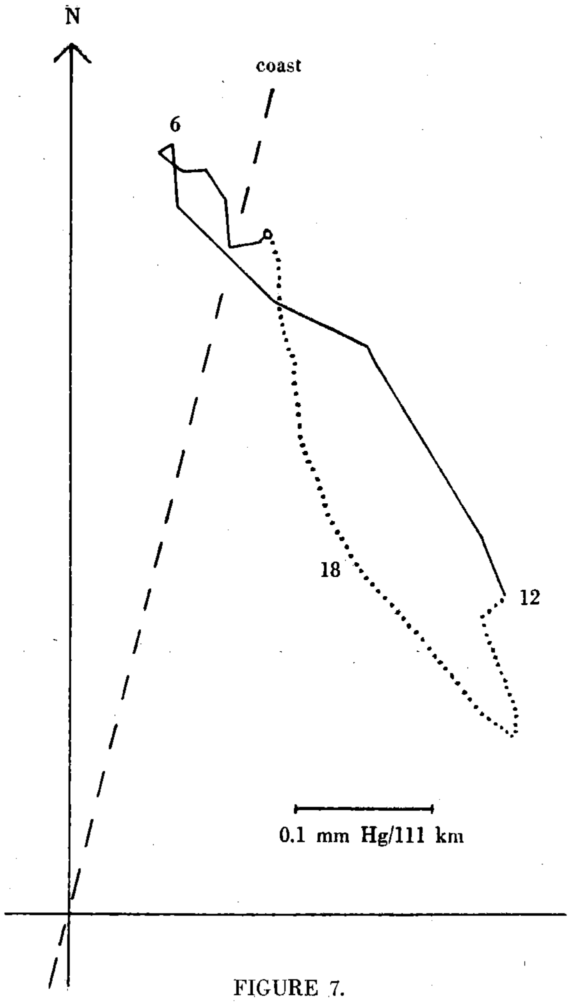


FIGURE 7.

Diurnal change of the mean pressure gradient, averaged for all days in April — August inclusive.

with regard to the isallobars in such a way that it gets the area of rising pressure to the right.

Furthermore it will be of interest to remark that the air pressures at Flushing, Den Helder, De Bilt and Groningen pass their daily mean values at about 7 h 30′.

For these reasons from now on the pressure gradients at the coast at 7 h and 8 h 30′ will be used as a parameter for the general wind. Here one should be aware of the fact that non-linearity of the pressure field on separate days may be the cause of differences between the computed and the real pressure gradient.

5. *Land and sea breeze in connection with the general pressure gradient.*

The following investigation about the connection between the sea breeze effect and the general pressure gradient has found its origin in the fact that Koschmieder (1936) remarked that with a general offshore wind the sea breeze occurs more easily if the general wind blows in a direction more perpendicular to the coast. The result of a superficial examination of the anemobiagrams from IJmuiden has shown the contrary.

The investigation again extends over the months of April to August inclusive. Those days have been used on which the wind at De Bilt (Soesterberg), De Kooy (fig. 1), and in the years 1933 — 1935 also on the airport Schiphol, in the morning and in the afternoon up to an altitude of 2 km had an offshore component with regard to the direction of the coast at IJmuiden. A number of these days had at the coast a temporary wind from the sea. On account of the offshore general wind this wind from the sea most probably must be ascribed to the sea breeze effect, although it is possible that for instance a change of the general wind or non-linear isobars caused the occurrence of a wind from the sea.

To the days now found some were added on which no or only one observation of the upper wind was performed but on which the surface wind at De Bilt, and during the years 1933—1935 also at Schiphol, was offshore all day.

Also days were added which at De Bilt or at Schiphol in the afternoon temporarily had a wind with a direction from the sea (with regard to the direction of the coastline at IJmuiden), provided this was the case within the period during which the wind at IJmuiden came from the sea. These days were denoted with a point of interrogation because with them the chance increases that the wind from the sea was caused by, for instance, a change of the general pressure field.

Days having, at an elevation of 1500 m or 2000 m, a wind direction from the sea, at one station only, were dealt with in the same way.

Of the days, thus selected, the pressure gradients at 7 h have been plotted on a chart. The gradient vector starts in the origin of the coordinate system. Only the end of the vector is denoted, by a dot, the vector itself is not drawn. In the same way the gradient at 8 h 30′ (until 25-3-1922 at 9 h 30′) was dealt with. Between the two points which were found for every day a line was drawn. This line was provided with an arrow that points from the first towards the later observation.

For days at IJmuiden without a wind from the sea full lines were drawn. They were partly dotted if between 7 h and 19 h a wind from the sea occurred. The length dotted denotes the part of the period from 7 h until 19 h in which the wind came from the sea.

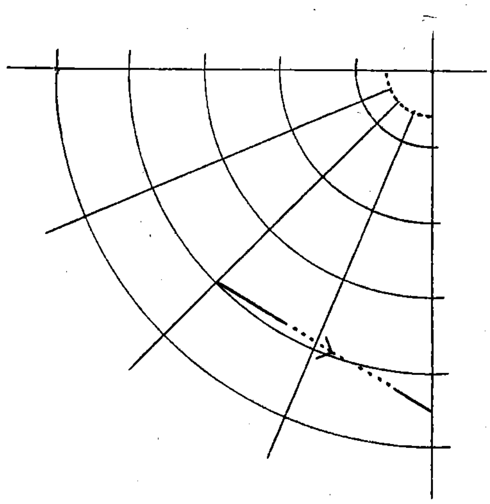


FIGURE 8.

Representation of a day with a wind from the sea.

As an example figure 8 is given. It represents a day with at 7 h a pressure gradient at the coast of 0.4 mb/111 km in the direction SW. At 8 h 30′ (or 9 h 30′) the gradient is 0.45 mb/111 km in the direction S. At IJmuiden the wind came from the sea from about 11 h until about 17 h.

The days for which lines were drawn as just described were divided according to the insolation.

Group I : April with numbers of insolation 1 and 2 (from 0 to 50 %, see page 12), May-August (inclusive) with insolation 1;
Group II : April with insolation 3, May—August 2;
Group III: April with insolation 4, May—August 3;
Group VI: May—August with insolation 4.

This classification is founded on the following considerations. The data about the heat-supply by insolation in the months of the year, as given in Köppen-Geiger, Handbuch d. Klimatologie I B 1936, are not extensive enough for accepting a certain classification as being the best. For our purpose the heat-supply on days with a clear sky may be taken as equal in the months May, June and July. The month of August has a smaller heat-supply. In April and September the heat-supply is smaller than in August. In Holland the length of the day in April, May, June, July and August is 13.9 — 15.7 — 16.6 — 16.2 and 14.7 h respectively. Also the declination of the sun in August on the average is greater than in April. For these reasons August was counted to the summer but April was not.

For each groep of insolations a figure is made (fig. 9a, b, c and d; see next 4 pages).

The days with and without a wind from the sea can be separated by straight lines in a direction N 50° W — S 50° E. If the ends of the gradient vectors at 7 h and 8 h 30′ on a certain day lie above this line probably a sea breeze will occur, unless their connecting line has a great component towards the region below the separating line. If the ends of the gradient vectors lie below the separating line probably no sea breeze will occur, unless their connecting line has a great component towards the region above it.

The separating lines are displaced from the origin in a direction which is perpendicular to them over a distance that for the 4 groups of insolation is as follows:

I uncertain, but probably between 0.25 and 0.50 mb/111 km.
II 0.20 — 0.40 mb/111 km,
III 0.35 — 0.55 mb/111 km,
IV 0.50 — 0.65 mb/111 km.

These distances have especially been found from days having a connection of the ends of their gradient vectors that is about parallel to the separating lines because only such days can give reliable results. They are rather rough estimations because on the one hand the small number of observations in the neighbourhood of the separating lines and on the other hand the deviations which occur prevent an accurate determination.

The separating lines were chosen straight because this leads to a simple picture and because then rather few exceptions occur. It is uncertain which shape the separating lines must have from theoretical considerations. The fact that separating lines can be found must mean that in any case the general pressure gradient and the insolation regulate the sea breeze effect considerably.

It is impossible to find the direction of the separating line in one figure quite accurately. A direction has been chosen that is satisfactory for all the figures. Then it may deviate 5° to both sides.

Of course the separating lines have only a small theoretical value. Their importance for forecasting purposes may be somewhat greater. However, as said before, exceptions occur. They will be dealt with in the next section.

Conclusions. The pressure gradient during the early morning gives a simple but rather rough characteristic for answering the question whether at a certain day with a general offshore wind a sea breeze will occur. Together with this gradient the insolation must be taken into account.

It appears that the onset of a sea breeze meets with the greatest difficulty when the pressure gradient points towards S 40° W, in other words when the general wind is about perpendicular to the coast.

6. *The sea breeze effect in connection with the difference of temperature between land and sea.*

In this section a subject will be discussed which was dealt with before the investigation described in the preceding one was performed. Simultaneously a discussion of the exceptions with regard to the separating lines in the figures 9 will be given.

In the majority of publications about the effect of land and sea breezes the diurnal variation of the difference of air temperature between land and sea has been used as a parameter. For this reason the investigation about the occurrence of a sea breeze in connection with the pressure gradient was performed with as second parameter the difference of air-temperature between land and sea instead of the insolation.

A rather rough estimation of this temperature difference was used because the data of the fireships before the coast were not available directly and because an impression about the results of the investigation was wanted in a short time.

The temperature of the air over the sea was evaluated from the isothermal lines on the weather maps and from the observations of the temperature at 7 h at Flushing and Den Helder (both situated on the coast, fig. 1) on days with a wind from the sea. Thus use was made of the fact that the temperature of the sea slowly changes with time.

Denoting the daily temperature maximum at De Bilt by t_l and the estimated temperature of the air over the sea at 7 h by t_s the following classification was made:

$$t_l - t_s < 5^\circ$$
$$5^\circ \leqq t_l - t_s < 10^\circ$$
$$10^\circ \leqq t_l - t_s < 15^\circ$$
$$15^\circ \leqq t_l - t_s.$$

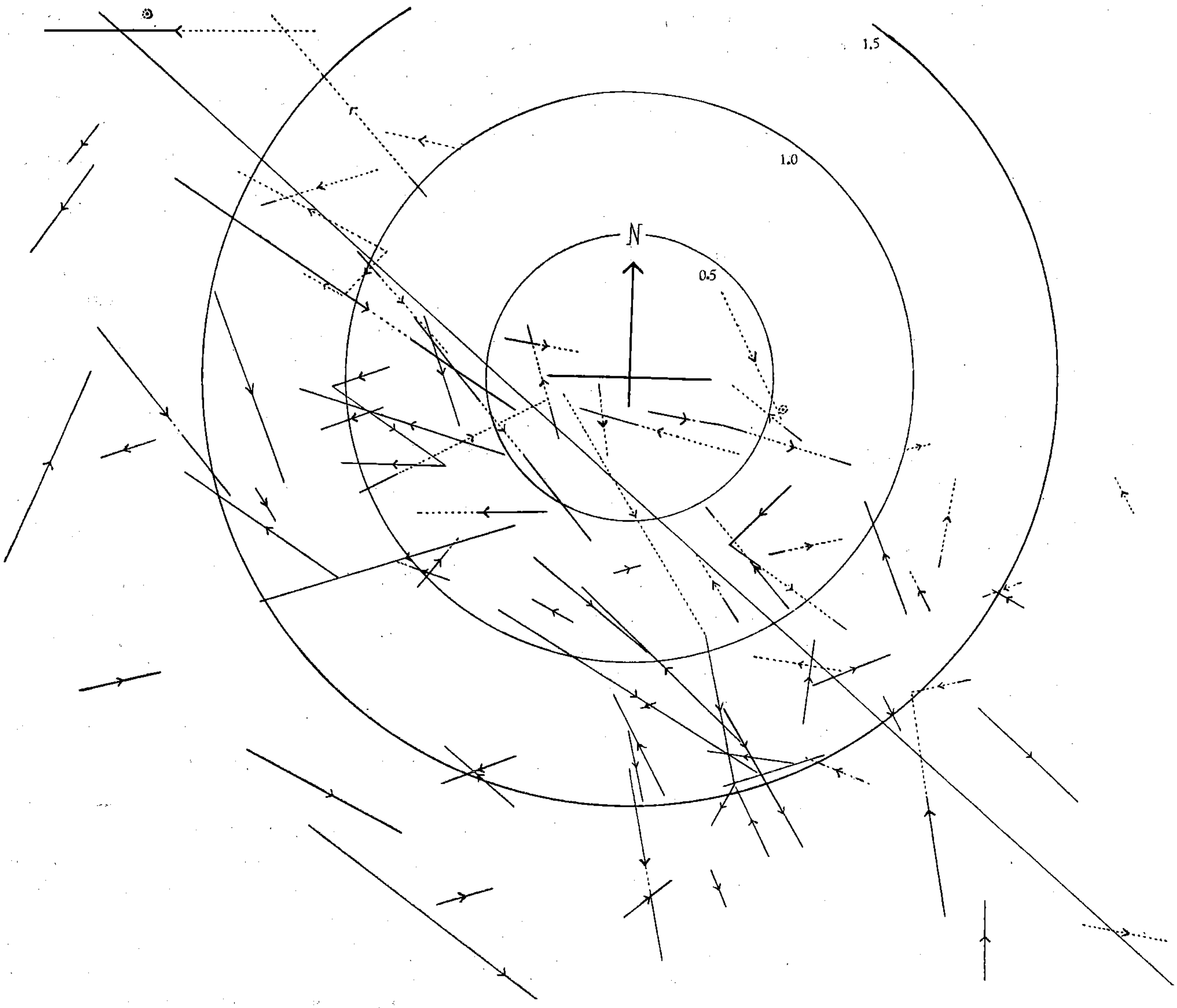


FIGURE 9 a

Pressure change between 7 h and 8 h 30′ (or 9 h 30′) on days with an offshore general wind. Insolation Group I.

Figures like figures 9 were made for the days which have been described in the foregoing section, i.e. days with a general offshore wind. In these figures (not given here) also lines could be drawn that separate days with and without a sea breeze.

With these lines also exceptions occur. Days with the ends of the gradient vectors above the separating lines, but without a wind from the sea or with a wind from the sea that lasts a short time, will be denoted as days with "too little" sea breeze. Days which are represented below the separating lines, but with a wind from the sea that lasts rather long, will be denoted as days with "too much" sea breeze.

It is striking to see that most cases with "far too much" sea breeze have a rather small temperature maximum at De Bilt (t_l) but a great insolation. On the other hand days with "far too little" sea breeze mostly have a rather great t_l and a small insolation. This might indicate that probably days with "too much" have a small stability of the lower layers of the atmosphere and days with "too little" a greater stability.

For a closer investigation the days that deviate much were brought together in table 6. In the 3rd and 4th row of this table days occur which in the figures are represented in the neighbourhood of the separating lines but, if compared, show "too much" or "too little" sea breeze. The table contains columns for:

1. number of days,
2. character with regard to sea breeze,
3. mean value of t_l — t_s (page 19),
4. mean relative insolation,
5. t_0 — t_{500}, with t_{500} and t_0 the mean temperature at Soesterberg about sunrise at an elevation of 500 m and at the surface respectively (this difference is not known for every day).
6. t_{500} — t_{1000},
7. t_{1000} — t_{2000},
8. the difference between the estimated temperature of the air above the sea (t_s) and the minimum temperature at De Bilt in the preceding night ($_m t_l$).

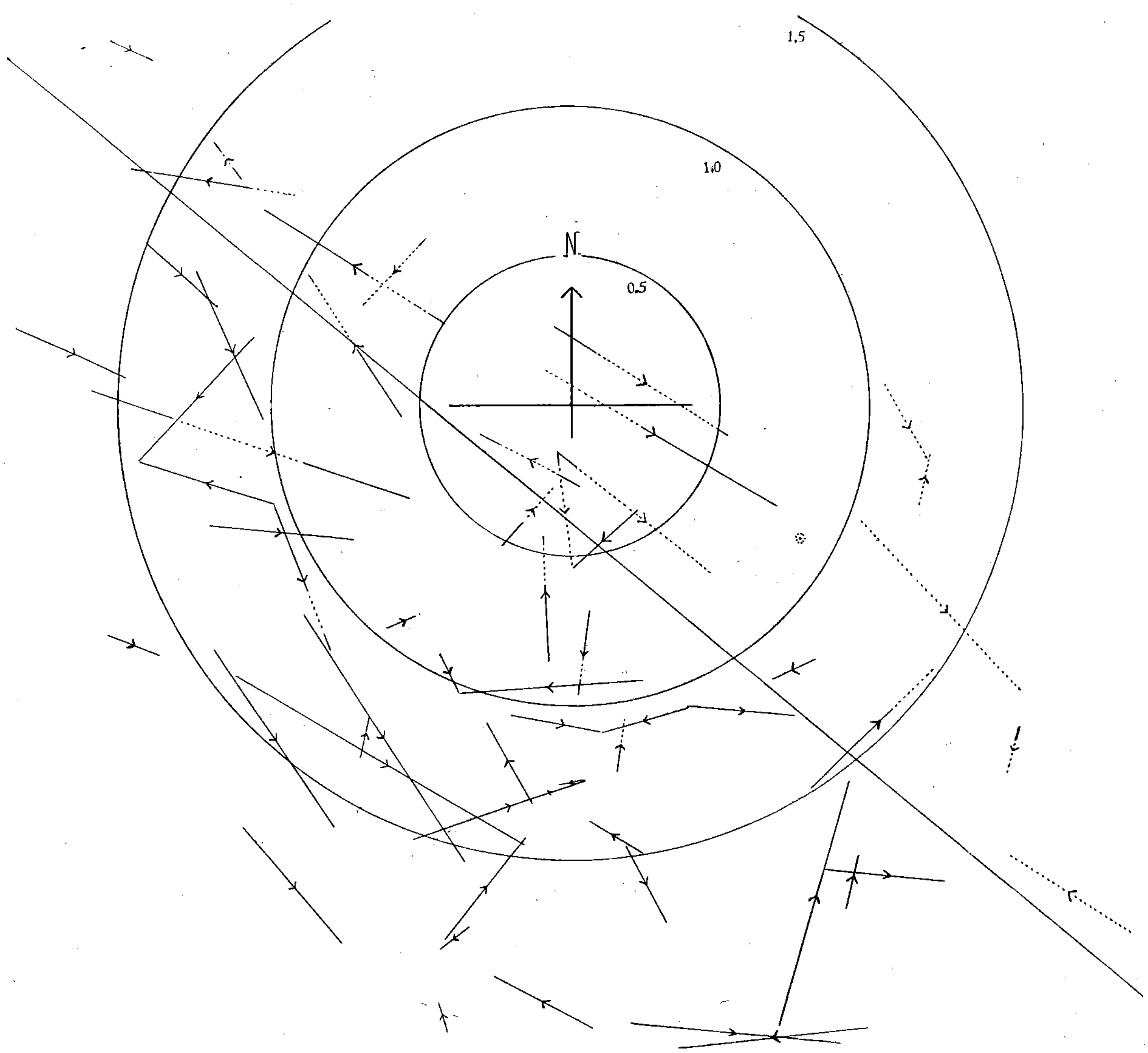


FIGURE 9 b

Insolation Group II.

Number of days	sea breeze	$t_l - t_s$	relative insolation	vertical lapse rate of temperature some hours after sunrise t_0-t_{500}	t_{500}-t_{1000}	t_{1000}-t_{2000}	$t_s - {}_mt_l$
6	far too much	8.0	78 %	0.9	2.3	5.0	5.7
10	far too little	9.5	32 %	0.5	3.6	5.8	1.2
13	too much	11.2	65 %	1.2	1.8	5.5	2.8
13	too little	10.3	67 %	1.5	3.7	5.3	2.4

TABLE 6.

Several data, concerning days with "too much" and "too little" sea breeze.

The supposition that here the stability of the atmosphere is active is not clearly confirmed. Paying attention to the layer between 500 m and 1000 m and to the layer between 1000 m and 2000 m this may be seen in the 1st and 2nd rows and for the layer between 500 m and 1000 m also in the 3rd and 4th rows.

Another possibility is that $t_l - t_s$ in the first row is smaller than must be expected from the value of the insolation because during the day colder air is advected by the offshore general wind. Then, however, "too much" sea breeze is improbable. An analogous way of reasoning can be followed in the case of "far too little" sea breeze.

It is to be expected that a change of the general pressure gradient during the day will contribute much in causing exceptions. Therefore it will be of interest to remark that from the exceptions given in table 6 several belong to days with a general pressure gradient that is about constant during the day.

Also the fact that the pressure gradient has been computed with the supposition that the pressure field is linear may lead to an incorrect value of the pressure gradient on the coast:

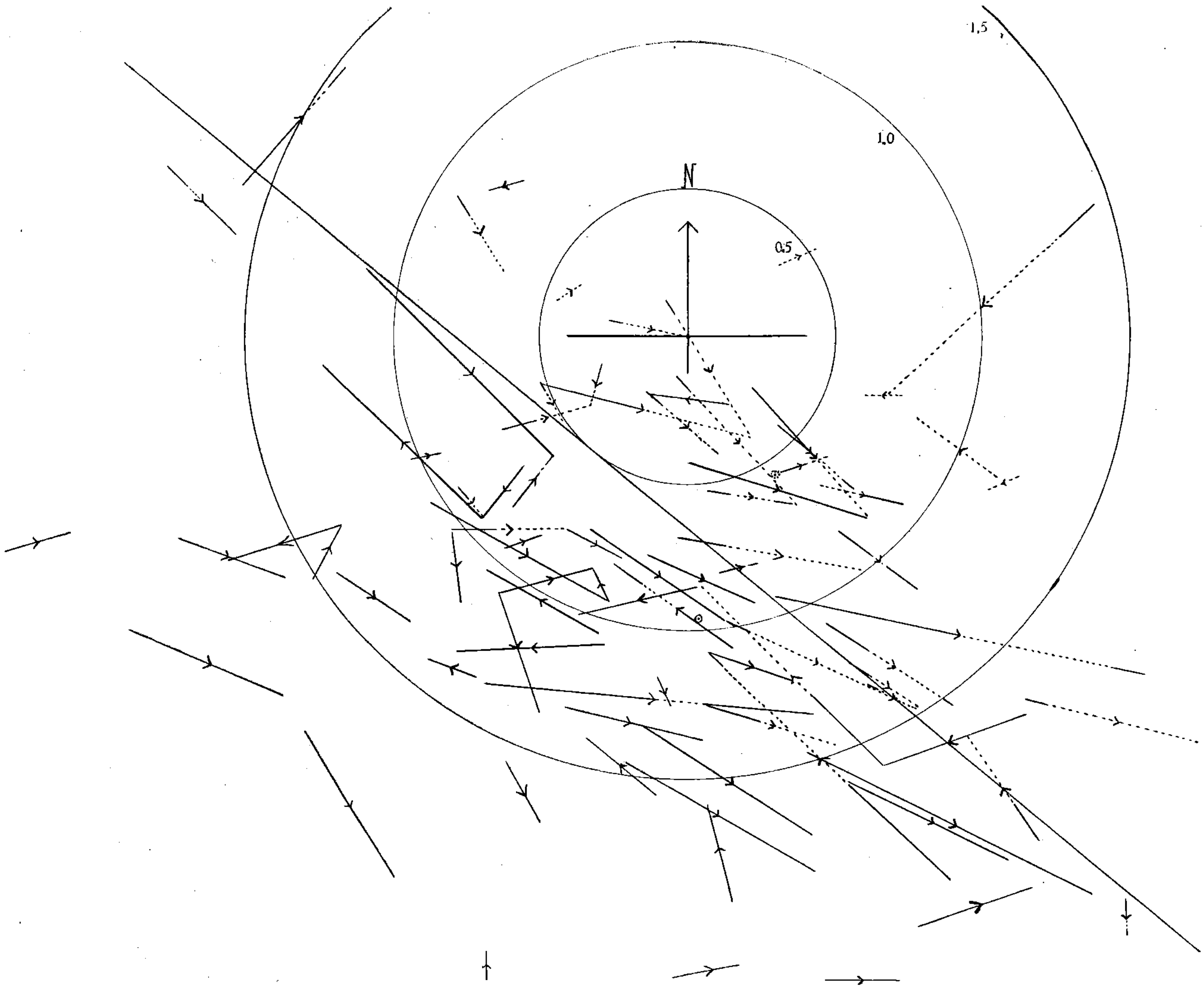


FIGURE 9 c
Insolation Group III.

a. when the isobars are curved,
b. when the isobars are not equidistant.

From the weather maps it became clear that these possibilities indeed sometimes can have been the cause of an exception in figures 9. In other cases, however, a day which in a figure 9 is represented on the wrong side of the separating line would come on a still larger distance from this line if the real pressure gradient on the coast could be taken into account.

From table 6 it appears rather clearly that the great insolations on the days represented in the 1st row are not accompanied by a great mean value of $t_l - t_s$ because during the preceding night the temperature above the land was relatively low. The contrary can be said of the days in the second row. This will indeed contribute to "too much" or "too little" sea breeze if not $(t_l - t_s)$ but the heat supply (the insolation) regulates the sea breeze effect.

For this reason the investigation has been repeated in the way that has been described in the preceding section. Then indeed there are fewer and smaller exceptions. It will not be surprising that exceptions still occur.

Another fact may now be the cause of exceptions. An insolation that, for instance, is denoted by the number 2 (between 25 % and 50 %) can belong to:

a. a day with sunshine only during the morning,
b. a day with sunshine only during the afternoon,
c. a day with intermediate periods of sunshine.

A division of days according to these possibilities has not been performed because then the number of comparable days would decrease so much that conclusions from a comparison would become uncertain. Furthermore the influence of this factor can be diminished for forecasting purposes by paying special attention to the insolation that is to be expected during the morning.

Conclusions. An indication has been found that the insolation (heat supply) rather than the difference of air temperature between land and sea regulates the sea breeze effect. The use of the figures 9 for forecasting purposes leads to a only rough estimation of the chance that a sea breeze will occur because a great number of factors reduce their reliability.

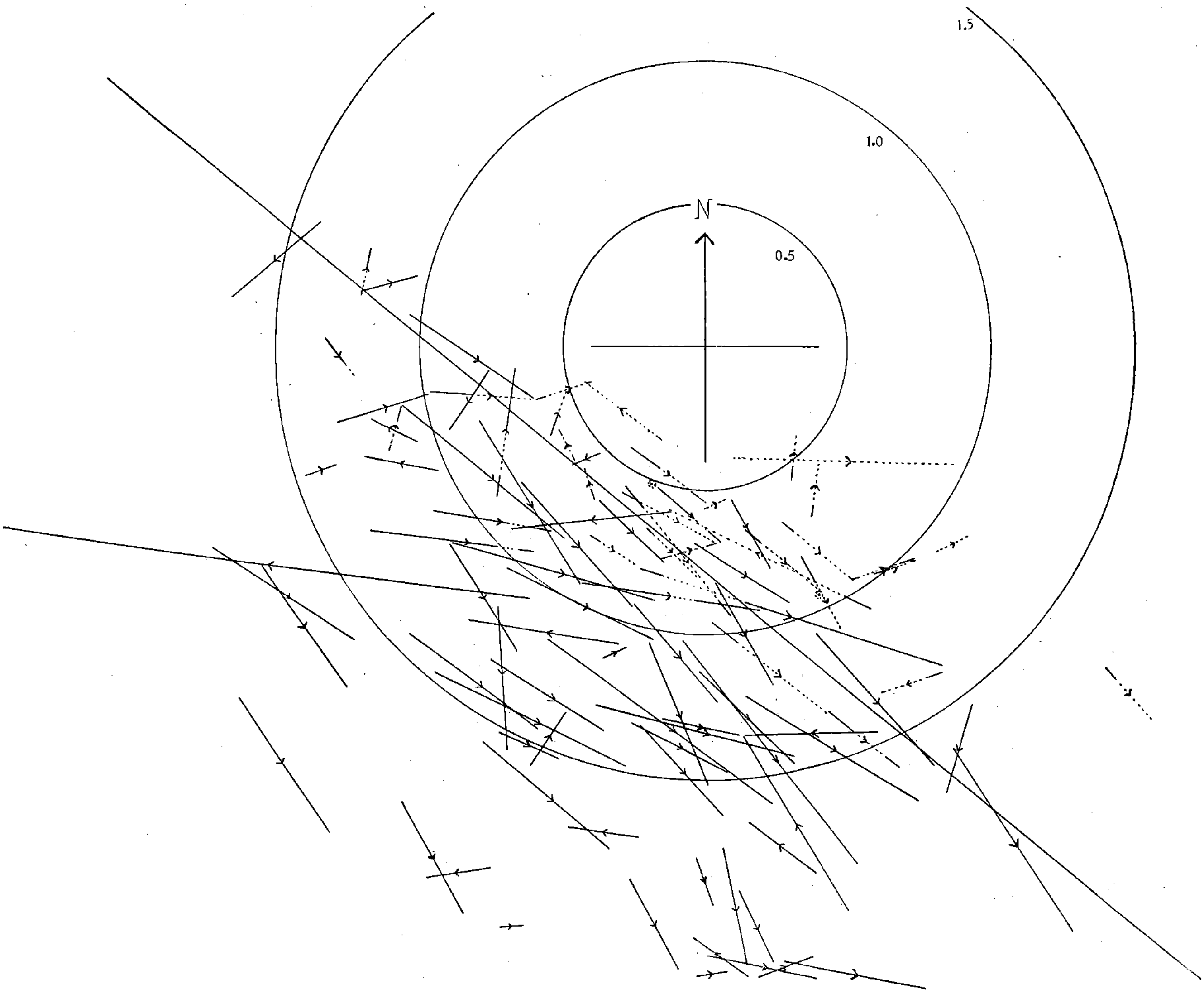


FIGURE 9 d
Insolation Group IV.

7. *The change of the pressure gradient vector some hours after sunrise.*

From the arrows of figures 9 it appears that the pressure gradient between 7 h and 8 h 30′ (or 9 h 30′), i.e. for some hours after sunrise, in 203 out of 350 cases changed in a way that can be described as the adding of an onshore component to it. On the other hand 106 out of 350 cases showed an adding of an offshore component to the pressure gradient vector. In 34 cases the arrows point in a direction along the coast, 21 out of these 34 point towards N, 13 towards S. In 7 cases the gradient did not change. The number 34 is small because attention has been paid especially to the change in the directions perpendicular to the coast. Then only 34 cases remain with no or an indistinct change in that direction.

The numbers given here were divided according to the insolation. The result is given in table 7.

From this table it appears clearly that with a great insolation an onshore component is added more often to the pressure gradient than with a small insolation. This shows that the heating of the land during the first hours after sunrise will be the cause of the change of the pressure gradient.

A closer investigation will be described now. First figure 6 (page 17) shows that between 7 h and 8 h 30′ the mean value of the air pressure for all days of April to August inclusive increases. This increase is small at Maastricht (0.05 mm Hg) and large at Den Helder (0.20 mm Hg) and Flushing (0.18 mm Hg). De Bilt (0.09 mm Hg) and Groningen (0.10 mm Hg) show an intermediate pressure change.

The change of the mean pressure between 7 h and 8 h 30′ has also been computed for the days of April to August inclusive which have a general offshore wind all day (the days which were used for the investigation described in section 5). The pressure data for these days are given on next page and are represented in figure 10.

Group of insolations	Number of days with an increase of the pressure gradient between 7h and 9h 30′ (or 8h 30′) towards					Total
	E	W	N	S	nihil	
I	38 (41.3 %)	44 (47.8 %)	5 (5.4 %)	3 (3.3 %)	2 (2.2 %)	92 (100 %)
II	32 (50.8 %)	22 (34.9 %)	5 (7.9 %)	3 (4.8 %)	1 (1.6 %)	63 (100 %)
III	58 (63.7 %)	24 (26.4 %)	4 (4.4 %)	3 (3.3 %)	2 (2.2 %)	91 (100 %)
IV	75 (72.1 %)	16 (15.4 %)	7 (6.7 %)	4 (3.8%)	2 (1.9 %)	104 (100 %)
Total	203 (58.0%)	106 (30.3 %)	21 (6.0 %)	13 (3.7 %)	7 (2.0 %)	350 (100 %)

TABLE 7.

Number of days with a general offshore wind, divided according to the change of the pressure gradient after sunrise and according to the insolation.

Mean air pressure on days with an offshore general wind, group of insolations I.

a. Wind on the coast temporarily from the sea, thus a feeble mean general wind (47 days).

	G(roningen)	H(elder)	B(ilt)	F(lushing)	M(aastricht)
7h	759.27	758.98	758.87	758.75	759.12
8h 30′	759.32	759.07	758.93	758.81	759.03
increase	+0.05	+0.09	+0.06	+0.06	—0.09

b. Wind on the coast offshore all day, thus a stronger mean general wind (50 days).

	G	H	B	F	M
7h	760.61	759.87	759.25	758.57	758.85
8h 30′	760.53	759.82	759.18	758.49	758.67
increase	—0.08	—0.05	—0.07	—0.08	—0.18

Group of insolations II.

a. Wind on the coast temporarily from the sea (23 days).

	G	H	B	F	M
7h	760.32	760.04	759.80	759.72	759.96
8h 30′	760.51	760.27	759.96	759.94	760.06
increase	+0.19	+0.23	+0.16	+0.22	+0.10

b. Wind on the coast offshore all day (35 days).

	G	H	B	F	M
7h	762.11	761.37	760.69	759.85	760.25
8h 30′	762.10	761.36	760.61	759.79	760.16
increase	—0.01	—0.01	—0.08	—0.06	—0.09

Group of insolations III.

a. Wind on the coast temporarily from the sea (46 days).

	G	H	B	F	M
7h	764.69	764.49	764.03	763.84	763.73
8h 30′	764.75	764.60	764.08	763.99	763.82
increase	+0.06	+0.11	+0.05	+0.15	+0.09

b. Wind on the coast offshore all day (49 days).

	G	H	B	F	M
7h	764.33	763.53	762.75	761.82	762.09
8h 30′	764.32	763.60	762.73	761.86	762.00
increase	—0.01	+0.07	—0.02	+0.04	—0.09

Group of insolations IV.

a. Wind on the coast temporarily from the sea (38 days).

	G	H	B	F	M
7h	767.18	766.96	766.57	766.17	766.39
8h 30′	767.16	767.00	766.54	766.25	766.31
increase	—0.02	+0.04	—0.03	+0.08	—0.08

b. Wind on the coast offshore all day (62 days).

	G	H	B	F	M
7h	766.99	766.29	765.61	764.68	764.98
8h 30′	766.93	766.32	765.49	764.58	764.77
increase	—0.06	+0.03	—0.12	—0.10	—0.21

From these data and from figure 10 the following appears.

1° The pressure at Groningen always exceeds the pressure at the other stations. Either the pressure at Flushing or that at Maastricht is the lowest. This agrees with the fact that the data are concerned only with days with an offshore general wind.

2° The differences between the stations are small when a sea breeze occurs. This agrees with the result of figures 9, namely that on such days in general the pressure gradient must be small.

3° With a small insolation the mean pressure is low as compared with the mean pressure on days with a great insolation. This will not need further explanation.

4° On days with a sea breeze (perhaps better: a temporary wind from the sea), i.e. on days with a feeble offshore general wind, the stations on the coast always show a pressure rise. Groningen and De Bilt have a smaller pressure rise and with very great insolations even a pressure fall. Maastricht has, with one exception, a pressure fall or the smallest pressure rise.

5° On days without a wind from the sea, i.e. on days with on the average a stronger offshore general wind, all stations show a pressure fall which is greatest at Maastricht. Only Den Helder in 2 cases (with large insolations) still shows a pressure rise.

6° Combining all days with an offshore general wind, the mean pressure rises on the coast, decreases slightly at Groningen and De Bilt and decreases more at Maastricht.

From 4°, 5° and 6° the following conclusions may be drawn. When the general wind is offshore all stations show a more continental character with regard to the

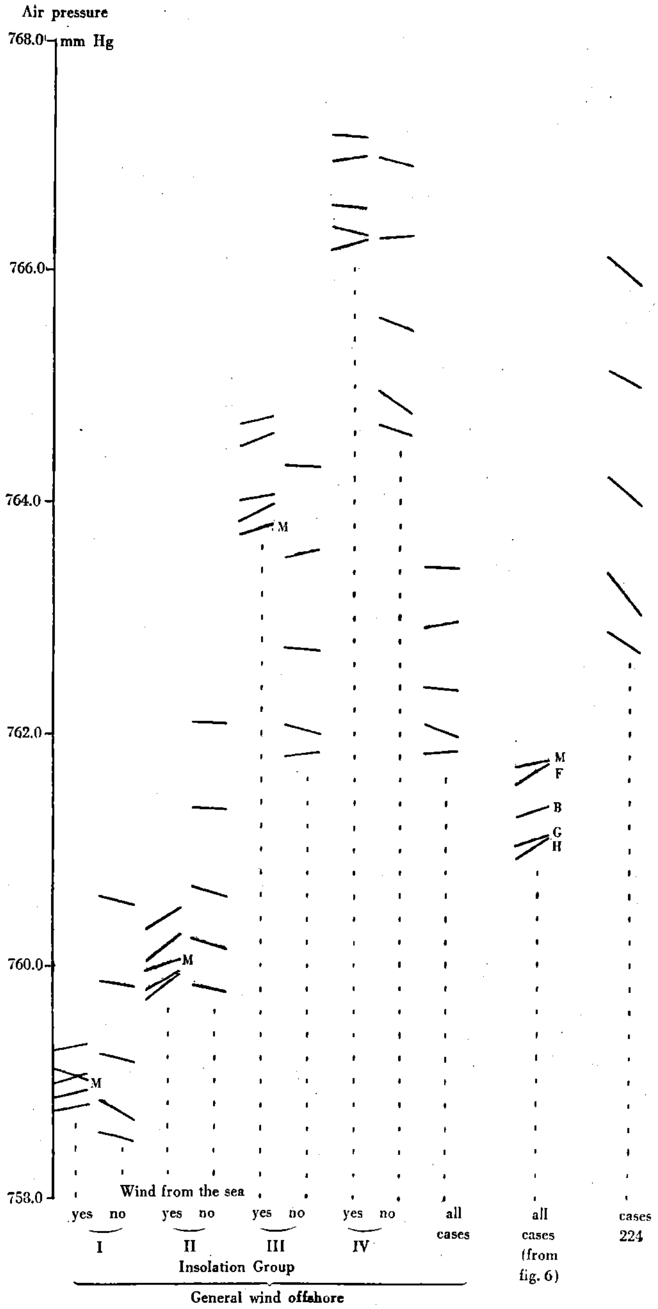


FIGURE 10.

Pressure changes from 7 h to 8 h 30′. Sequence from high to low: G, H, B, M, F unless denoted otherwise.

change of air pressure. This is more pronounced when the general wind is stronger.

A confirmation of this conclusion is given by the following fact. Investigating the 16 cases with the number of classification 224 (section 2 of this chapter: morning wind from the 2nd octant, daily mean value of wind speed between 5 and 10 m/s, insolation exceeding 75%) it is found that on these days, having a permanent offshore wind without an exception, the pressure data are:

	G	H	B	F	M
7h	766.14	765.16	764.25	762.91	763.42
8h 30′	765.87	765.00	763.98	762.73	763.06
increase	—0.27	—0.16	—0.27	—0.18	—0.36

The decrease of the air pressure is now much greater.

7° The mean pressure gradient, computed from the pressure data for the days with an offshore general wind, is larger with greater insolations. For instance, in the western triangle of Holland (Den Helder, De Bilt and Flushing), supposing the isobars to be rectilinear, the pressure gradient appears to point about along the coast southward and to have the values (in mm Hg/111 km):

Group of insolations	I	II	III	IV
7h	0.55	0.73	0.86	0.90
8h 30′	0.58	0.77	0.90	0.96

This may be explained as follows. A greater speed of the offshore general wind will be the cause of a greater advection of continental air, which will be accompanied by a large relative insolation.

When a distinction is made between days with and without a temporary wind from the sea qualitatively the same effect is found. The differences between the groups of insolations are still greater with the days that temporarily have a wind from the sea. This doubtless must be ascribed to the fact that with great insolations also days are used which have such a great pressure gradient that it would not let a sea breeze set in when the insolation is small.

8° The vector that represents the difference of the gradient vectors at 7 h and 8 h 30′ (in mm Hg/111 km):

with insolation group	I	II	III	IV
points	southward	about SE	about SE	about SE
and amounts to	0.03	0.08	0.10	0.14

Thus, between 7 h and 8 h 30′, the change of the mean pressure gradient for days with an offshore general wind is similar to that change for all days in the months of April to August inclusive (while the pressure gradients themselves are in opposite directions, cf. p. 18, fig. 7). For this reason the change of the mean wind from midnight till noon has also been computed for all days with an offshore general wind.

The wind components are given here. First the wind component N-S is given, next to it the component E-W (in m/s). The wind is represented in figure 11.

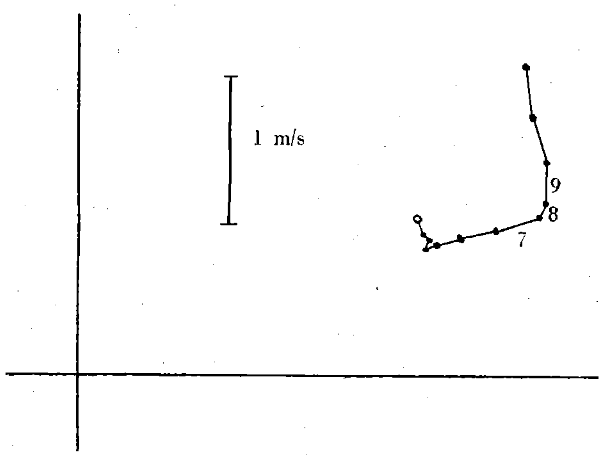


FIGURE 11.

Wind from midnight till noon on days with an offshore general wind (April — August inclusive).

0—1		1—2		2—3		3—4		4—5		5—6	
1.05	2.25	0.93	2.29	0.90	2.35	0.84	2.30	0.88	2.37	0.92	2.53
6—7		7—8		8—9		9—10		10—11		11—12	
0.97	2.77	1.07	3.07	1.15	3.12	1.43	3.11	1.74	3.02	2.07	2.98

These data show that now the wind again (page 17) changes qualitatively as if this change is due to an isallobaric effect with the isallobaric wind perpendicular to the isallobars. The increase of the E-W component is followed by an increase of the N-S component. This may be explained by assuming that the increase of the vertical transfer of momentum preceeds the sea breeze effect.

On the days with the number of classification 224 (see 6°, page 25) the mean pressure gradient in the western triangle of Holland between 7 h and 8 h 30′ changes by the addition of a vector in the direction SE which amounts to 0.11 mb/111 km. The mean wind on these days is represented in fig. 3b. From 9 h until noon only a small increase of the N-S component occurs. Here other factors predominate over the sea breeze effect (see next column).

Summarizing it can be said that the pressure field near the coast, in so far as this is caused by the differential heating of land and sea, is displaced seaward by an offshore general wind. The rather great change of the pressure gradient near the coast, that occurs some hours after sunrise, is the cause of a wind change that can be described as an isallobaric wind perpendicular to the isallobars. This wind change is not found if the pressure field is displaced more by a stronger offshore wind. Then other factors predominate over the sea breeze effect.

Days with a greater speed of the offshore general wind on the average have a greater insolation.

8. *Closer investigation of figure 3 with regard to the influence of the insolation on the effect of land and sea breezes.*

Whereas an influence of the insolation on the sea breeze effect has been clearly found in section 5 of this chapter, in figures 3a, b, c, and d such an influence could not be found by any means. Rather the contrary appeared.

These figures represent days with a morning wind from the 1st, 2nd, 3rd and 4th octant. With these figures a forecasting of a sea breeze on account of the insolation that must be expected seems impossible.

For instance the curve for the number of classification 124 (morning wind from the 1st octant, daily mean value of wind speed between 0 and 5 m/s and a great insolation) does not show a wind from the sea. It appeared that out of 4½ cases 124 only 1 day got a wind from the sea, in the morning. On this day the pressure gradient at 7 h was about southward and amounted to 0.45 mb/111 km. During the morning the general pressure gradient changed and at the coast it became easterly, 1.1 mb/111 km. The other 3½ cases (4 days) had a pressure gradient pointing southward, amounting to about 2 mb/111 km. Such a gradient prevents the development of a sea breeze. Indeed figure 3a shows that case 124 clearly had a greater offshore component of the mean wind about sunrise than the other cases 12• (days with a morning wind from the 1st octant but with a smaller insolation).

With a morning wind from the 2nd octant and a small daily mean value of wind speed (i.e. the cases 21• in fig. 3b) the wind also shows a decreasing inclination to come from the sea in the day-time when the insolation is greater. Here the offshore component of the wind about sunrise is again greater when the insolation is greater. The same is valid for the curves 22• (i.e. with a morning wind from the 2nd octant and a greater daily mean value of the wind speed).

The larger wind speed at sunrise when the insolation is greater is in agreement with the fact that with greater insolation the pressure gradient is larger (page 25 — 7°). This will be the cause of the discrepancy between the expectations and the observations about the influence of the insolation suggested by figure 3.

Investigating the change of the wind on the separate days, divided according to the several possibilities, the results of table 8 are obtained. The possibilities are:

a. the wind is offshore all day,
b. the wind becomes a wind from the sea by a backing through N,
c. the wind becomes a wind from the sea by a veering through S,
d. the wind becomes a wind from the sea via a calm.

In table 8 the number of days on which the wind from the sea turned to be an offshore wind again is given between brackets.

From table 8 it appears that with a greater insolation the number of days with a permanent offshore wind is indeed relatively larger.

Closer investigation has shown that the number of days on which the wind became a wind from the sea by a change of the general pressure gradient is larger with smaller insolations. This is in accordance with the explanation of table 4 (page 14).

Furthermore, on days with a permanent offshore wind, the wind speed increases during the morning and decreases during the afternoon (fig. 12).

For all these reasons it will not be surprising anymore that figure 3b shows a wrong influence of the insolation on the sea breeze effect.

The mean wind on days with the numbers of classification 21· and 22·, in so far as they had a permanent offshore wind, is represented in figure 12. Influence of the insolation cannot be clearly found. Braak (1926 b) on this point remarked that with an easterly wind in Holland (De Bilt) the diurnal change of the wind speed is smaller than with westerly winds. This would be caused by the smaller increase of wind speed and a greater wind shift with increasing height if the wind is easterly compared with the circumstances with westerly winds. Also an opposing effect of the sea breeze would be active here. On the coast the latter factor will be more important than further inland.

Together with the increase and the subsequent decrease of the vertical transfer of momentum during the day another factor will also contribute to the shape of the

Diurnal change of the wind		Number of classification							
		211	212	213	214	221	222	223	224
Offshore all day		6	5	16	30	1½	8	10	16
Towards a wind from the sea	through N	7 (3)	9 (7)	13 (9)	17 (17)	4 (2)	3 (—)	2 (2)	—
	through S	3 (3)	5½ (4½)	5 (2)	5 (1)	—	1½ (1)	1 (—)	—
	uncertain	4 (2)	—	3 (3)	5 (—)	—	—	—	—
Total		20	19½	37	57	5½	12½	13	16

TABLE 8.

Number of days belonging to the numbers of classification 21· and 22· divided according to the possible diurnal changes of the wind.

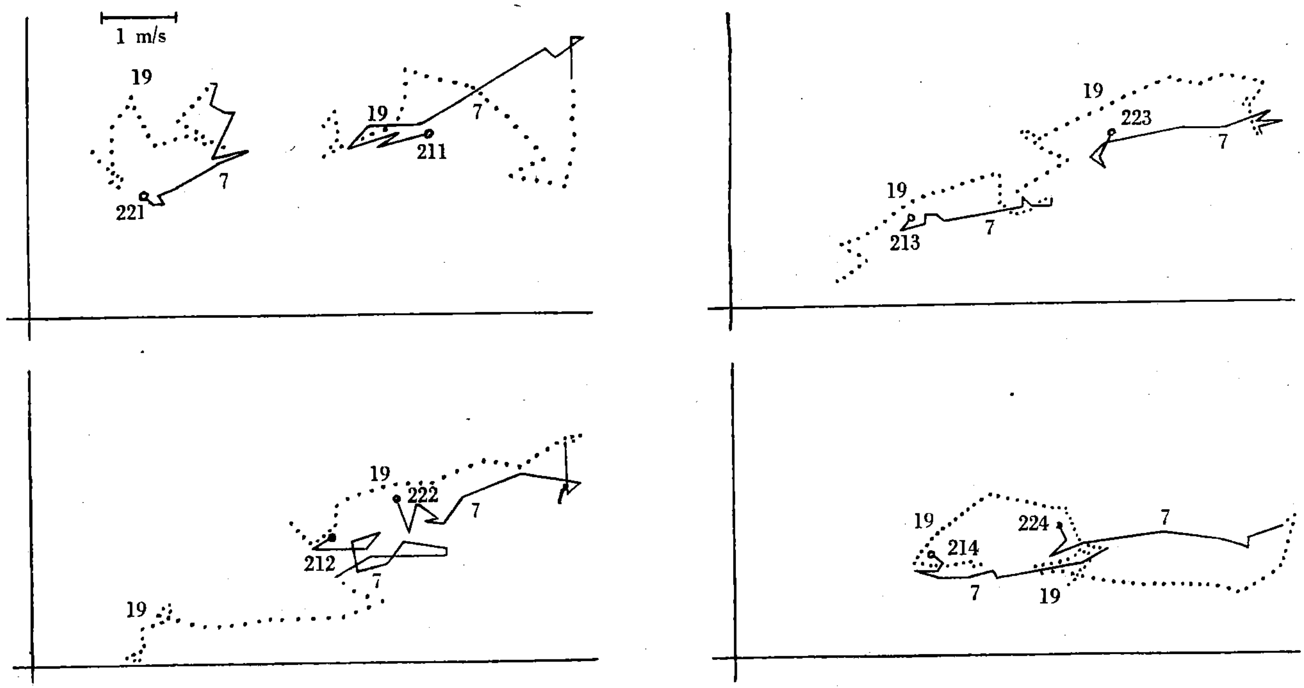


FIGURE 12.

Days with a morning wind from 2nd octant and wind remaining offshore all the day.

curves in figure 12. Bleeker (1936) found that in Holland on days with a great insolation the wind vector changes with increasing height in such a way that this wind change may be due to a thermal low which is formed about SE of Holland. This will contribute to the wind change at the surface. It is impossible to conclude to what extent the vertical transfer of momentum, the sea breeze effect and the influence of a thermal low more inland contribute to the shape of the curves in figure 12, because the number of days represented is too small

In connection with these facts it is of interest to consider again the change of the pressure gradient in the western triangle of Holland (fig. 7, page 18) some hours after sunrise.

Then a component in the direction SE is added to the pressure gradient. This may mean that in Holland, due to its position with regard to the continent and with a W- and a N-coast, the pressure gradient indeed is changed by the heating of the continent. Such a large-scale effect should oppose the sea breeze.

With a morning wind from the 3rd and the 4th octant (fig. 3c and 3d) the wind speed about sunrise is not systematically greater with greater insolations. For these cases table 8 is repeated in table 9. The possibilities are now extended to:

a. the wind is offshore all day (on one day the wind became a wind from the sea after sunset),

Change of the wind	Number of classification															Total for insolation:			
	311	312	313	314	411	412	413	414	321	322	323	324	421	422	423	1	2	3	4
a	1	3½	3½	5	—	—	—	1½	—	—	1	1½	½	2	1	1½	5½	5½	8
b	1	1	2½	2	—	—	1	—	—	1	3	—	1	—	—	2	2	6½	2
c	5	½	1	½	4½	3½	2½	1	2	1	—	—	3½	7½	—	15	12½	3½	1½
d	2	3	2	½	1	2	1	4	8	4	1½	2	7	5½	5	18	14½	9½	6½
e	—	1	1	—	2	2	3	1	1	1½	1	1	1	2½	—	4	7	5	2
f	½	7½	4	6½	4½	7½	7½	8½	1	—	—	—	1	1	—	7	16	11½	15
Total	9½	16½	14	14½	12	15	15	16	12	7½	6½	4½	14	18½	6	47½	57½	41½	35

TABLE 9.

Number of days belonging to the numbers of classification at the top of the table, divided according to the diurnal changes of the wind.

b. the wind becomes a wind from the sea by backing,

c. the wind becomes a wind from the sea via S and turns via S to be an offshore wind again,

d. the wind becomes a wind from the sea via S and at the beginning of the following day is still in the 5th or 6th octant,

e. the wind becomes a wind from the sea via S and at the beginning of the following day comes from the 7th or 8th octant,

f. the wind becomes a wind from the sea via S and turns via W and N to be an offshore wind again.

One day from each of the cases 311, 412 and 414 has been omitted because it is uncertain to which row these days must be counted.

From table 9 it appears that the number of comparable days is very small. It seems that cases a and f are favoured by a great insolation. The cases c and d are favoured by a small insolation. This may mean that here the same factors cause the wrong influence of the insolation on the diurnal change of the mean wind as were discussed in the cases with a morning wind from the 2nd octant.

Finally it is worth while remarking that the investigation confirms the fact, found by Kaiser (1907 b), that the diurnal wind variation on the coast on a day with a temporary wind from the sea can consist of:

a. a veering to a wind from the sea, followed by a backing to an offshore wind again, or

b. a continual veering via a wind from the sea to an offshore wind again, or

c. a backing to a wind from the sea, followed by a veering to an offshore wind again.

According to Kaiser a continuous backing via a wind from the sea to an offshore wind again never or perhaps seldom occurs at the Baltic coast of Germany. In the rare cases of such a wind change a change of the general pressure gradient will probably be responsible. At IJmuiden the same has been found.

Summarizing it can be said that at IJmuiden the diurnal wind change is influenced by several factors. Therefore it is difficult to forecast the occurrence of a sea breeze on a certain day in case the general wind vector about sunrise is taken into account. In section 5 of this chapter it has been shown that the use of the general pressure gradient about sunrise gives results that are more reliable.

9. *The transition from an offshore wind to a wind from the sea and the reverse.*

At first sight the anemobiagrams from IJmuiden clearly show that often during the morning the offshore wind rather suddenly changes to a stronger onshore wind. Often this change is followed by a sudden transition to a feeble offshore wind again in the afternoon or after sunset. This is most striking when the transitions take place between the 1st and the 8th octant.

Then the anemobiagrams look like figure 13. In this figure the change of the wind is also represented in a coordinate system.

Sometimes the phenomenon is repeated once or more times in 24 hours. It occurs also during the night.

It looks as if the transition is accompanied by the passage of a front. Postma and Bleeker (1944) have drawn attention to this fact. They called it the passage of a "pseudo-front". According to them this front must run along the coastline and by some cause or other move to and fro across the coast.

From the anemobiagrams of IJmuiden all cases where either the wind direction or the wind speed or both clearly and suddenly changed were selected in the months of April to August inclusive. Changes with a wind speed smaller than 1 m/s before the transition were omitted to avoid instrumental faults. It appeared that the phenomenon more frequently occurs with a transition via N in the daytime and with a great insolation than with a transition via S and during the night. Nevertheless it occurs that a

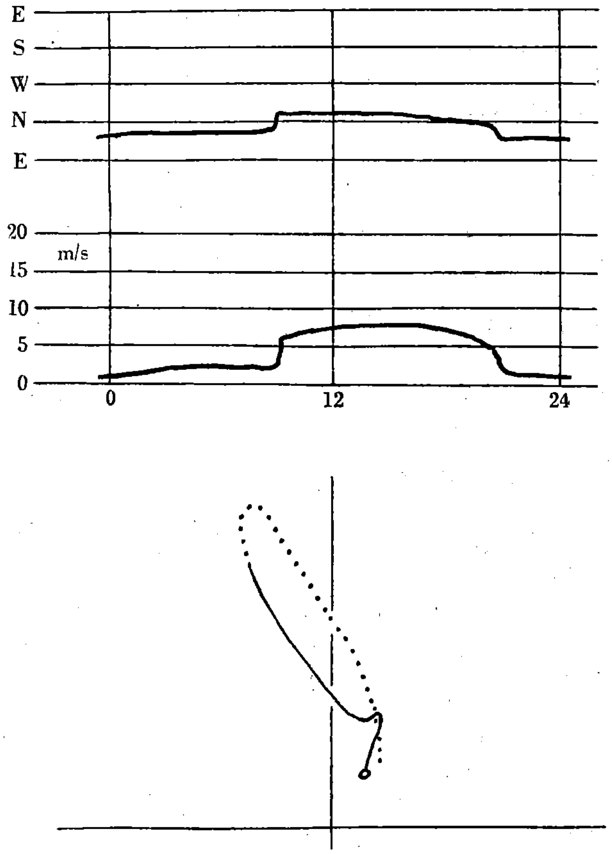


FIGURE 13.
Sudden transitions of the wind across the coast.

"front" passes the coastline during the night or on days with a small insolation. In chapter II it will be tried to give an explanation (p. 34).

Summarizing it can be said that the onset of the sea breeze often has the character of a front passage. At IJmuiden this is more frequently and more markedly the case with a northerly wind.

10. *The influence of the stability of the atmosphere on the effect of land and sea breezes.*

Until now some attempts to find an influence of the stability of the atmosphere on the effect of land and sea breezes have been described in this chapter. They are brought together in this section.

In section 1 the mean diurnal variation of the wind vector has been given for the months of the year. Also a survey of the mean temperature in the warm months at several levels can be found there. No obvious correlation could be detected. Therefore the stability of the atmosphere will be a subordinate factor.

In section 3 days were described with a feeble and nearly constant general wind. The number of days belonging to the same group of insolations is so small that a subdivision according to the stability of the atmosphere cannot lead to reliable results. Therefore this part of the investigation has been omitted in section 3. No information at all about an influence of the stability could be found.

In section 6 (table 6, p. 21, days with "too much" and "too little" sea breeze) also no clear indication could be found about an influence of the stability of the atmosphere.

Because the diurnal variation of the wind vector on the coast is influenced by several factors it is difficult to trace the effect of one of them. For this purpose a number of days must be selected having the same conditions with regard to the other factors but showing differences in the factor under observation. This means that for subordinate factors the investigation must extend over a long period. Therefore a further investigation about the influence of the stability of the atmosphere has not been performed.

Summarizing it can be said that no influence of the stability of the atmosphere on the effect of land and sea breezes could be found. It should be emphasized, however, that attention was paid only to the lowest layers of the atmosphere (up to 2 km).

CHAPTER II

THEORETICAL INVESTIGATIONS

1. The work of W. Bleeker, partly in collaboration with M. J. Andre.

In order to be able to compare the results of observation with the theory the present state of theoretical investigation will be dealt with by discussing some recent publications.

In the first place we shall deal with the work of Bleeker (1949) and that of Bleeker and Andre (1950 a) since their starting-point will, after some extension, be used as a basis for further considerations.

In 1949 Bleeker discussed the formation of a circulation system over a coast near a snow-covered land surface. According to him, the fact that the heating is non-linear in a direction perpendicular to the coast results in the formation of a high pressure ridge on the land and a low pressure trough at sea. The circulation system thus created is then further dealt with.

As already stated by Bleeker this picture also applies to the effect of land and sea breezes, in the daytime a high pressure ridge forming on the sea and a low pressure trough on the land, however. A front forms in the area of convergence in the low pressure trough over the land. When this front passes to and fro the coast this is attended with phenomena already described by Postma and Bleeker (1944), which are particularly marked by a sudden backing of the wind.

The publication of Bleeker and Andre (1950 a) contains further comments. Their paper will be discussed here in so far as it may elucidate the phenomenon of land and sea breezes.

The authors discuss the influence of the supply of heat to the atmosphere on the formation of a convective circulation. After explaining how the present conception of this point has been arrived they deal with the formation of a thermal low. The local additional heat-supply to the atmosphere causes an additional lifting of the isobaric surfaces, which gradually extends into an increasingly thickening layer. The outflow of air in the higher levels results in a change of the pressure at the surface and thus brings about the formation of a circulation system.

The pressure field below will be more marked when the friction changes more with altitude and also when the heating increases more rapidly with time. When the supply of heat becomes constant Bleeker and Andre expect a quasi-constant circulation. When the supply of heat stops the energy of the pressure field will be converted into kinetic energy which, in its turn, changes into heat. The pressure field will flatten out then.

The shape of the pressure field at the surface is deduced for a heated strip in the y-direction. A symmetrical function of x is assumed to represent the supply of heat (Q; a function also of the time). It is then explained why, as a first approximation, the pressure field on the ground may be represented by $\partial^2 Q/\partial x^2$. Their way of reasoning is as follows. The shape of the isobaric surfaces in and over the heated area will be similar to the shape of Q. The velocity of the air there will be determined by $\partial Q/\partial x$, the convergence or the divergence by $\partial^2 Q/\partial x^2$, however. But the convergence or the divergence determines the increase or the decrease of the pressure at the surface.

Proceeding from a logical supposition about the shape of Q the pressure field on the ground must consist of a trough of low pressure under the central line of maximum supply of heat. This trough is accompanied by a ridge of high pressure on either side. On account of these ridges of high pressure a convective circulation need not be closed.

Moreover the land and sea breeze effect is considered from the point of view of Bleeker's working hypothesis referred to above. The existence of the depicted pressure field at the surface, in this case in the daytime consisting of a trough of low pressure over the land and a ridge of high pressure over the sea along the coast, was in an analogous case found by Suckstorff (1939), viz. at the border of a cold and a warm sea-current. With the land and sea breeze effect too it must be expected that the circulation over the coast is not closed.

We assume at a coast a heating-function that is represented in figure 14 by the line Q, running horizontally to the left of AA′ and to the right of BB′. It cannot be said with certainty where in this figure the coast-line must be indicated. It is obvious that the coast-line must be situated somewhere near the point C (below the point of inflection in the curve Q). However, the exact location of the coast-line is not of importance for what follows.

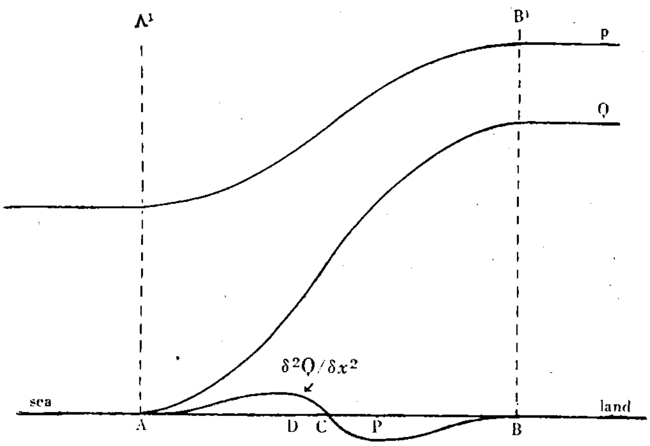


FIGURE 14.

Heating-function on a coast at a certain moment and its second derivative, also a higher isobaric surface.

The shape of an isobaric surface at a greater height is shown in figure 14 by the line p. Moreover, $\partial^2 Q/\partial x^2$ is given to represent the pressure field at the earth's surface. Also p and $\partial^2 Q/\partial x^2$ run horizontally to the left of AA′ and to the right of BB′.

The flow that will now occur near the earth's surface will have an axis of convergence at P. This axis will run parallel to the coast. Here the sea breeze and the (moving) land-air meet. As a rule it is observed that the border between the onshore and the offshore wind shifts landward. This has not been discussed by Bleeker and Andre since they specially focussed their attention on phenomena with clouds.

An increasing heat-supply will deepen the trough of low pressure. Attended with a mowing of P towards B this must result in a larger increase of the pressure gradient between B and P than between C and P. This has not been found in reality, for a corresponding change of the wind field has never been described.

That, in spite of the deepening of the low-pressure trough and the shifting of P, the pressure-gradient between P and B does not increase more than that between B and C may be ascribed to a corresponding change of the heating function in the course of the time. However, this strikes us as unsatisfactory in comparison with an extension of Bleeker's picture to be elucidated now. Anyhow the solution will have to be that not only the point P but also the line BB′ shifts landward. That BB′ shifts landward owing to a change of the heating function is not excluded for the sea breeze effect will change the heating function. However, this change is likely to be so complicated that it would be senseless still to use the line of thought followed.

As already remarked above it is possible, however, to extend Bleeker's starting-point a little. Owing to this the large number of possibilities for explaining various phenomena, already given by Bleeker and Andre, is likewise extended without ascribing special properties to the heating function. The following working-hypothesis will make this clear.

If an isobaric surface at a greater height is, at a certain moment, represented by the line p in figure 15 the seaward flowing air will also reach the area to the left of AA′ owing to the inertia of the air. The divergence in the higher levels immediately to the left of B′ will have as its consequence that, in addition to a current from below, air will be supplied there from the area to the right of BB′. Therefore the isobaric surface will get the shape shown by the line p'.

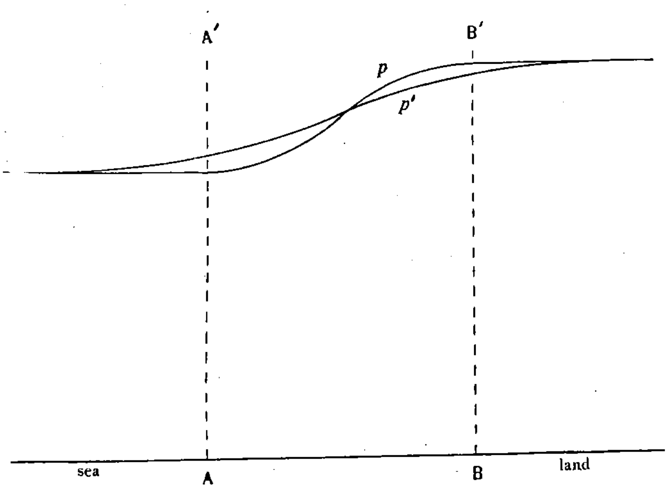


FIGURE 15.

Change of a higher isobaric surface in the course of time.

The surface pressure field will now change in a way that is dependent on the shape of p'. Even if the heating function remains the same, yet an isobaric surface near the earth's surface will now deviate from the horizontal position outside the area where Q shows a gradient, i.e. outside AB. If the heating continues, the influence of $\partial^2 Q/\partial x^2$ will be active in addition to this extension (and flattening) of the extra pressure field on the ground.

The following may be adduced as an argument for the correctness of the extension of the picture of Bleeker and Andre. With a great value of $\partial Q/\partial t$ (t = time) $\partial p/\partial t$ on the earth's surface will, in the first instance, be determined by $\partial^2 Q/\partial x^2$ since the extension (and flattening) of the surface pressure field will play a minor part in its change owing to the rapidly increasing heating. In this case the shifting of P (fig. 14) will not be of importance, provided the shape and the location of the heating function remain unchanged. The displacement of P will, on the other hand, be more rapid when the heating increases less rapidly with time and when the gradient of the isobaric surfaces at higher levels has become greater before, i.e. when the supply of heat has been greater before.

If we identify point P (fig. 14) with the place of the front line of the sea breeze, it must be expected that the front line moves slowly until a few hours before noon. After this $\partial Q/\partial t$ will become smaller and after noon even negative, which causes an increase of the speed of displacement of the front line. Now in his table 1 Koschmieder (1936) published the sea-breeze days found by him, stating also the speed of the sea breeze front. Of the 27 days 9 had a start before 11 h 30′ with a mean front speed of 1.1 m/s, 8 a start between 11 h 30′ and 14 h 30′ with a mean front speed of 2.5 m/s, and on 10 days the sea breeze set in after 14 h 30′ with a mean front speed of 2.3 m/s. In the cases having a start before 11 h 30′ the front speed was not very small owing to a small speed of the sea breeze. The latter averaged 3.8 m/s before 11 h 30′, 4.4 m/s between 11 h 30′ and 14 h 30′, and 4.1 m/s at 14 h 30′ and later.

Moreover, Hornickel (1942) mentioned a number of cases in which the sea breeze, setting in early, did not penetrate far over the land and was often pushed back again to sea. These cases with a practically stationary front were not given in Koschmieder's table because their front velocities cannot be calculated, the sea breeze not reaching the land station situated at 3.5 km from the coast. As a rule the sea breeze front gets a clearly landward movement round about noon. A very striking example is that of 31 — 5 — '34. In the course of the morning *the temperature over the land rose conspicuously rapidly.* At 10 h 30′ the first sea breeze push reached the coast, but the wind became offshore again *in spite of a strong heating.* At 10 h 45′ and at 12 h 30′ again a sea breeze push reached the coast. At 13 h 11′ the sea breeze set in anew and penetrated over the land. These days, too, for which no further data were given, may serve to show that, if circumstances are favourable for sea breezes, the frontal surface of the sea breeze is not given an opportunity to shift until about noon. This has been expressly stated by Koschmieder (1936) and Hornickel (1942) as a result of their observations. However, they explain this fact by holding the instability of the land-air at about noon responsible for the landward displacement of the sea breeze front.

In this respect the observations of Bijourdan (1897) are important too. At Joal on the coast of Senegambia he found very markedly onsetting sea breezes. In 15 exceptional cases the mean temperature-drop on the passage of the sea breeze front is 8.9° C. The insolation being great near the equator, yet Bijourdan emphatically remarked that the sea breeze penetrated over the land very little and extended very slowly only.

Without a special form of the heating function being supposed, this remarkable feature of the extension of the sea breeze landward may consequently be looked upon as a result of the broadening of the extra pressure field on the ground. It will also be clear that the pressure gradient between P and B need not increase for line BB^1 (fig. 14) shifts landward. It seems that the proposed extension of the picture given by Bleeker and Andre may be of importance elsewhere. Thus this extension might be given a better foundation.[1])

The picture given by Bleeker and Andre also lends itself eminently to the description of the sea breeze effect with an offshore general wind. With an offshore wind it may, in the first instance, be expected that the extra pressure field ($\partial^2 Q/\partial x^2$) shifts seaward (see also page 26). If the influence of this pressure field on the wind is taken to be an isallobaric effect (see page 17) the offshore wind will, as regards the component perpendicular to the coast, exhibit a retarded movement between P and D (fig. 14). Now the wind field must be taken to be the superposition of a general wind and a sea breeze circulation. When the pressure gradients of the pressure field of the sea breeze become sufficiently large at a certain moment the velocity component perpendicular to the coast will be zero near D. The further development of the pressure field will really result in a sea breeze starting to blow landward, at first at sea. The convergence before the sea breeze causes the onflowing land-air to get over the sea breeze. The land-air moves on and partly mixes with the sea breeze on top of and, in the area of divergence, behind the sea breeze. The sea breeze can now extend to P. The further extension takes place as explained on page 31.

With a strong offshore wind even point P of the extra pressure field is likely to be shifted to over the sea. An almost stationary front at sea may then be expected. Thus the existence of such a front, which by Koschmieder has been adduced as the conclusive argument for his view, fits in the starting-point chosen by the auther.

Now that Bleeker's line of thought has been given, elaborated and extended as to its application to the land and sea breeze effect, some particulars are added.

a. The height of the sea breeze.

It will be perfectly clear that, if the surface pressure field shows larger gradients, this pressure field will make itself felt up to a greater height. This explains at once the following properties of the sea breeze, which were especially emphasized by Koschmieder (1941) and Hornickel (1942) (the following figures apply to the area near Dantzic).

1°. A sea breeze that sets in early has a maximum height of 200 m. A sea breeze setting in later in the day (the sea breeze then certainly being attended with a front) is higher, maximum 500 — 700 m.

2°. The higher the sea breeze, the greater the speed of the sea breeze at the surface.

b. The moments on which the sea breeze sets in at the surface and at greater heights.

The larger the offshore component of the general wind the later the sea breeze front will, ceteris paribus, pass the coast. This fact has been mentioned by many authors and it has never been contradicted. Furthermore, it may be expected that, if a general offshore wind is blowing, the offshore wind is stronger at a greater height because of the smaller influence of friction. However, the extra pressure field will be less pronounced there. This must bring in its train the later occurrence of the sea breeze at a greater height. When the extra pressure field flattens in the afternoon the friction will cause the sea breeze to weaken more rapidly at the earth's surface than at a greater height. Thus the velocity-wave of the sea breeze at a greater height will lag behind in phase with that at the ground. This has been found in reality and has been clearly stated, among others, by Van Bemmelen (1922). He holds the temperature-wave, which extends upward in the course of the day, responsible for this aspect. In consequence of our conception it might partly be brought about by the reduction of the friction at increasing heights.

More recent observation-data on this point have been supplied by Craig (1945). Straight away after the onset of the sea breeze he found at its front a vertical tongue of moist air and behind the latter a downward tongue of air the degree of humidity of which is comparatively low as compared with the entire surroundings. He proposed two explanations of this phenomenon. In the first place this dry air might have travelled to sea as an offshore dry wind a short time before the onset of the sea breeze. The second possibility consists in the flowing away of dry land-air over the sea breeze, the land-air being taken up in the sea breeze circulation farther out to sea and then flowing rapidly landward in the upper layer of the sea breeze. Both these explanations fit in our picture.

The observations of Koschmieder (1941) and Hornickel (1942) about the shape of the frontal surface when the sea breeze penetrates over the land may give an indication here. With a sea breeze setting in late the result of their observation is as follows.

The frontal surface, existing for a long time already, is approximately vertical up to a certain height, which means that the sea breeze sets in practically simultaneously

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[1]) For instance, the fact that with a cumulonimbus the anvil projects from the cloud is to be understood as an outflow over the heated area extending in horizontal direction outside that area (as part of the "indirect circulation "according to Bleeker (1950 b)). A similar outflow may be expected with a cumulus congestus. Thus at the surface the area of convergence under the cloud may shift beyond the cloud. Hence the rising air-movement beside the cumulus congestus might come into being (with or without the co-operation of other causes).

up to that height. Generally, though not always, the sea breeze becomes a little higher still in course of time. This result indicates that the second possibility proposed by Craig most probably will be correct.

c. The change of the front at the arrival over the land.

Owing to the convergence near P (fig. 14) a frontal surface will arise. This will show increasing differences on either side in course of time, especially when the sea breeze forms at sea. When this front comes over the land it becomes weaker because the sea-air is rapidly warmed up over the land. This has been expressly stated by Hornickel (1942) and Ramdas (1931) as a result of their observations.

Over the sea the front will have a velocity that is smaller than the component of the sea breeze velocity perpendicular to the front. On the coast near Dantzic Koschmieder (1936) found a mean value of $f/w_n =$ 0.62 in 24 cases (f represents the front velocity and w_n the component of the sea breeze vector perpendicular to the front [1]). Over the land f/w_n must be expected to be smaller than 1 as well. It is not known from observations whether the front velocity changes or not at the arrival over the land. If it should appear that the front velocity does not change then, this might be taken as an argument for the conception that the front velocity will be determined by processes at a higher level (see page 31). Hornickel has tried to prove from his observations that the front velocity is constant from the coast to a distance of only 3.5 km inland (see for a further discussion of his reasoning page 39).

But even if, in the first instance, processes going on at higher levels determine the front velocity, it may be expected that the front velocity will change on passing the coast:

1°. at the surface because of the greater friction which the sea breeze is now going to experience; this will be attended by a change of the slope of the frontal surface;

2°. throughout the layer in which the frontal surface occurs, on the one hand by changes that have arisen in the meantime in the pressure field just through the sea breeze circulation, existing for a longer time already, and on the other hand by the change which the vertical temperature gradient of the land-air will have undergone in course of time.

As for the latter point it may be assumed in Bleeker's line of thought that, in case the land-air becomes indifferent or unstable, the surface of the earth will add more heat to the land-air per unit of time. This will result in a deepening of the low-pressure trough to the right of P (fig. 14) and thus will cause a more rapid landward displacement of P. The formation of clouds will promote this process.

Indeed Koschmieder's observations clearly show that the instability of the land-air will cause the front to travel more rapidly. This observation can therefore be used as an important argument in favour of Bleeker's line of thought. In section 2 of this chapter we shall discuss Koschmieder's view that a frontal surface, arisen from an accumulation of cold air over the sea, will start moving only if the land-air is unstable.

d. The phenomenon of the "Windstreit" (Swedish: vindträta).

It may be interesting to discuss here a possible explanation of the so-called "Windstreit" as mentioned in some publications (Appleton 1892, Grenander 1912 and Koschmieder 1936). The name "Windstreit" has been given by them to the sharp transition that on the sea occurs between two directions of wind. The separating line practically does not shift and can often be recognized from the appearance of the sea-surface. "Windstreit" is said to occur in particular with comparatively great wind speeds on either side of the separating line.

Koschmieder has been the first who tried to explain this phenomenon. He looks upon it as a stationary front belonging to a thick layer of accumulating cold air.

However, if we proceed from figure 14, we may think of a seaward shifting of the extra pressure field by a strong offshore general wind. If the line of convergence (P) is in one part of the coast over the land and in another over the sea, because the general wind is stronger there or the general wind has a greater offshore component there because of a different trend of the coast, the sea breeze will not penetrate over the land in the latter part of the coast. Then the wind field entirely resembles that which is called "Windstreit" by the authors in question. That such a situation occurs especially with a rather strong general wind is even conditio sine qua non for the explanation given here.

Appleton and Grenander gave some examples of "Windstreit". The figure 16, in which the broken line indicates the front of the "Windstreit", has been copied from Appleton's publication. He remarked that at a certain coast the phenomenon preferably presents itself with a certain direction of the general wind. For instance, at the part of the New England coast of figure 16, "Windstreit" is said to occur approximately three or four times a year and exclusively with a general wind between S and SW, mostly between S and SSW.

Because of the trend of the coast the sea breeze will, with this direction of the wind, arise more easily on the coast in the Southern part of the figure than in the part where the coast recedes to the West. This may account for the front-line given by Appleton. Also Grenander's descriptions seem to fit in this explanation although they are not enough extensive to verify this.

e. Front phenomena during the night.

On the Dutch coast wind-changes can be found which

[1]) It should be emphasized that not too much value must be attached to this figure. For it appears from Hornickel's publication (1942) that Koschmieder takes the sea breeze speed as the average of the observations of three stations, whereas Hornickel uses one station only. Owing to the difference in the value used for w_n it then appears, according to 8 days mentioned in the two publications, that great differences may occur.

Koschmieder	0.56	0.70	0.58	0.50	0.72	0.84	0.39	0.88
Hornickel	0.47	0.58	0.97	0.57	0.79	0.70	0.40	0.69

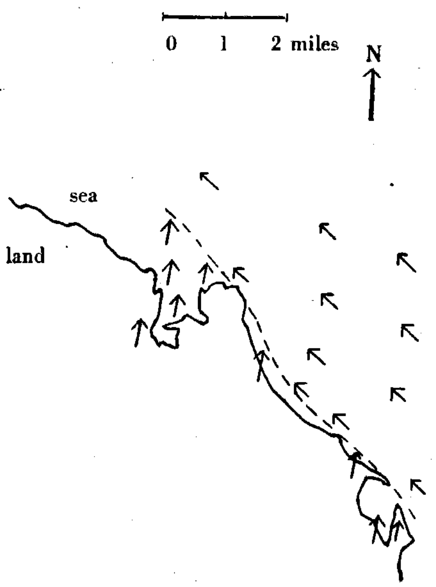

FIGURE 16.

Situation with "Windstreit".

suggest the passage of a front (page 28). Such changes have already been described by Postma and Bleeker (1944). They called them "pseudo-fronts". They, too, remarked that such a front may occur during the night and ascribed it to a convergence due to friction. In the daytime these changes may mostly be ascribed to the onset of a sea breeze.

However, one may expect to occur near the coast during the night a pressure field as represented in figure 14 but with the ridge of high pressure over the land and the trough of low pressure over the sea. The convergence in this pressure field may be the cause of a frontal layer which may be more or less stationary and may shift to and fro over the coastline.

A further investigation of these phenomena will be of importance, especially with regard to the circumstances under which they appear. However, such an inquiry would be so extensive that it has not been performed.

Summarizing we may say that Bleeker's conception of convective phenomena in the atmosphere offers a logical and satisfactory starting-point for the understanding of the many aspects that present themselves with sea breezes. As an extension the author only introduced a widening (and flattening) of the extra pressure field near the coast.

2. *The work of H. Koschmieder and K. Hornickel.*

The publications of Koschmieder (1936, 1941) and that of Hornickel (1942) will be discussed in detail for the following reasons.

1°. They contain much observation-material which has already been used in the preceding section and which will also be used further on.

2°. They contain a first, extensive, treatise on the onset of a sea breeze with front phenomena which treatise differs entirely from the one given in the preceding section.

3°. The investigation made at IJmuiden gives a result that is different from Koschmieder's views.

Koschmieder (1936) investigated the sea breeze phenomenon at Dantzic because markedly onsetting sea breezes of uncommon strength would present themselves there. An investigation of separate days was made because the front character of the sea breeze would be left out of the picture in a statistical investigation. The investigation was based on data obtained in four summers.

During three of them aerological observations were made. Of the seven observation-posts two were situated on the coast and three inland at distances of about 2 km, 3.5 km and 7 km from the coast. Incidentally two ships were used a few kilometers from the coast. The seven stations were never used simultaneously. Fig. 17 shows the lay-out of these stations.

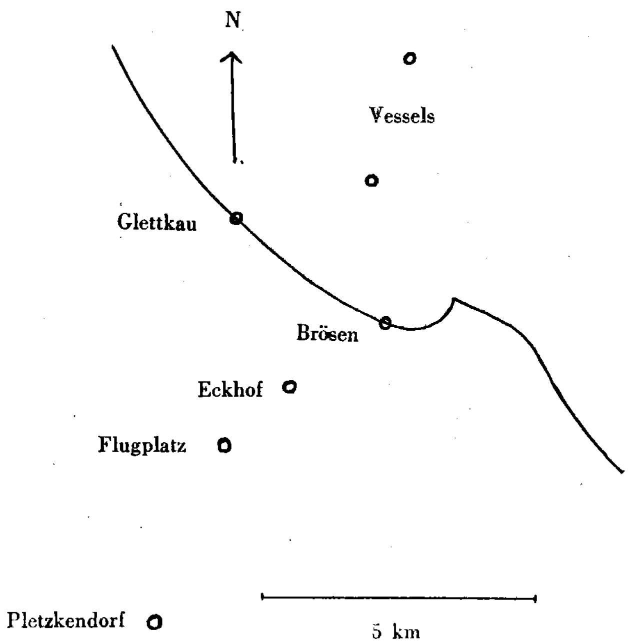

FIGURE 17.

Situation near Dantzic.

Observations on wind direction, wind speed, temperature and relative humidity, on the surface and in the higher layers, were the main points.

The characteristics of the sea breeze were chosen as follows for being certain that a sea breeze was present:

a. The sea breeze only occurs in a narrow strip along the coast,

b. The sea breeze must set in earlier on the coast than farther inland.

c. The onset of the sea breeze must yield either a decrease in temperature-rise when the onset is early or a markedly temperature-fall when the onset is late.

d. The onset of the sea breeze must be attended with an increase of the relative humidity.

e. An offshore wind must precede and follow the sea breeze.

f. Over the sea breeze the wind must be offshore.

Koschmieder considers the sudden onset of the sea breeze to be the passage of a front. He calculated the direction and the speed of displacement of the front-line from the moments of the onset at three stations lying in the angular points of a triangle. On comparing the component of the sea breeze vector perpendicular to the front (w_n) with the speed of the front-line (f) it appeared that f/w_n is smaller than 1, viz. 0.62 on the average in 24 cases (see the note on page 33).

From the fact that f/w_n is smaller than 1 the conclusion was drawn that not only does the land-air rise before the front but that also the air on the sea-side of the front moves upward along the frontal surface. Thus over the sea breeze layer there must be air coming from the sea breeze and flowing back to sea together with the land-air.

Koschmieder expressly stated that, without a general wind, the sea breeze will form direct on the coast soon after sunrise without causing discontinuities. With an offshore general wind the outflow of air at higher levels, according to Koschmieder, will cause an onshore pressure gradient in the sea-air (air that has been over the sea for a long time already). The land-air, when moving out to sea, will at first be cooled only in the lower layers. The isobaric surfaces at greater heights therefore will slope down only slightly to a large distance from the coast. Thus only a small onshore pressure gradient will appear at the surface. The land-air will therefore not revert its direction of movement. Convergence is said to increase at the surface with a diminishing offshore component of the wind velocity at an increasing distance from the coast. The land-air is said to rise over the colder sea-air and, on account of the smaller stability of the land-air, to impart its movement to a thin layer of more stable sea-air. This would result in a constant thickening of the layer of cold air. A front is said to form that is becoming steeper and steeper and that is stationary because of the equilibrium establishing itself between the sea breeze gradient force and the force of friction which the land-air exercises on the sea-air. The cold air, accumulated thus, now yields a sufficiently great pressure gradient to cause the whole system to become unstable, thus enabling the frontal surface between cold and warm air to start moving onshore as soon as the land-air has become indifferent or unstable in course of time. This is said to be the case about noon, owing to which the sea breeze sets in on the coast, as a rule, after noon and sometimes not before evening. According to Koschmieder the sea breeze at Dantzic sets in at 13 h 19′ on an average.

The picture given by Koschmieder must serve to give an explanation of the start of the sea breeze at sea and of its late onset on the coast.

It may be remarked here that the convergence over the sea would at once be counteracted by an accumulation of cold air in consequence of the positive pressure tendency that must be attended with it. Moreover, the supposition that a *stationary* front can arise by a further accumulation of air seems highly improbable. All Koschmieder's arguments were derived from the coastal observations of frontal surfaces of the sea breeze, for which an explanation has already been given in the preceding section. However, the existence of a frontal surface on the coast is on no account a proof of the correctness of Koschmieder's conception of the way in which this frontal surface will be formed out to sea.

Koschmieder also introduced a pressure field, created by the daily heating near the coast, that would be superimposed on the general pressure field. Figure 18 shows his pressure field. He placed the point that agrees with point C of figure 14 on the coast-line also when the general wind is offshore. The aim of this part of his investigation was to show that in the case of an offshore general wind the sea breeze will arise more readily when the angle, which the isobars of the general pressure field form with the coast-line, comes nearer to 90°. He argued that the isobars of the general pressure field will be most distorted by the superposition of the pressure field of figure 18 in case they are perpendicular to the coast.

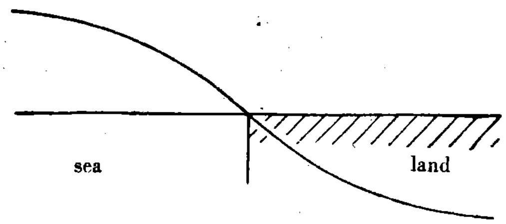

FIGURE 18.
Extra pressure field of the sea breeze on the surface according to Koschmieder.

To show this he compared two cases:

a. the (straight) isobars of the general pressure field are perpendicular to the coast;
b. the (straight) isobars run parallel to the coast, assuming the area of higher pressure to lie over the land.

In case *a* the heating in the daytime is said to bring about a transport of air in the higher layers from land to sea. Owing to this the isobars at the earth's surface show a sharp bend. There would no longer be an equilibrium between the gradient force and the Coriolis force. This would result in great extra force components from sea to land, the more so because the isobars over the coast-line now come closer to one another. Since the direction of the general pressure gradient at Dantzic often belongs to case *a* and then is generally attended with fine weather this would explain why it is just at Dantzic that the sea breeze makes so marked an appearance and occurs so frequently. According to Koschmieder, under these circumstances a sea breeze might be forecast with rather great certainty at pressure gradients up to approx. 1 mb/111 km. For instance, in the period from 1932 to 1935 inclusive, sea breezes have presented themselves on 43 days with an offshore general wind which was clearly offshore, as compared with 5 days with the general wind approximately parallel to the coast. This great difference is, of course, due to the fact that Koschmieder considered only sea breezes setting in with a front-character.

In case *b*, on the other hand, the isobars at a great height over the coast will, according to Koschmieder, come closer together because the air over the land is lifted by heating. The isobars will remain rectilinear. The general wind at a great height would thus become stronger and might get only a small component from land to sea by the disturbance of the equilibrium between gradient force and Coriolis force. Owing to this outflow of air in the higher layers the isobars on the surface will separate. Thus the horizontal pressure gradient at the surface will become smaller, the wind will become weaker, and owing to the disturbance of the equilibrium only a small transport of air from sea to land will arise.

Koschmieder added the statement that case *b*, but now with the area of high pressure over the sea, leads to the same result, as far as the transport of air above and at the earth's surface is concerned.

It will be clear that, if Koschmieder's explanation is correct, it must not only hold good for the coast near Dantzic but also in a general way. But then this would have led to observation-results at IJmuiden different from those given in chapter I.

That Koschmieder's explanation cannot satisfy may appear from what follows. The following cases are represented in the figures 19 a, b and c: *a* isobars perpendicular to the coast, *b* almost parallel to the coast and, facing the offshore wind, the land to the left, *c* almost parallel to the coast but, facing the wind, the land to the right.

In them the extra pressure field as indicated in figure 14 by the line $\partial^2 Q/\partial x^2$ (page 30) has been used. The distance of the original isobars as well as the extra pressure field are taken to be the same in the three cases. This pressure field is separately represented in the lower part of figure 19 a.

The distortion of the original isobars (broken lines) is greater when the extra pressure field shows larger gradients. Or else, with a certain extra pressure field the distortion is greater when the distance between the original isobars is larger. The isobars, as developed after the heating, are represented by full lines.

From figure 19 b it appears that Koschmieder's conception is incorrect. In this figure the isobars show the clearest sharp bends, i.e. in case the general wind is offshore about parallel to the coast and, facing the wind, with the land to the left.

However, if Koschmieder's conception is not accepted, it is still imperative to state here why at Dantzic most cases of a sea breeze setting in with a front occur with a general wind about perpendicular to the coast and even, with a rather strong general wind, exclusively from that direction. It is of importance first to consider what Koschmieder and also Kaiser (1907 b) have said with regard to this.

In connection with his observations of land and sea breeze phenomena Koschmieder has paid special attention to the front character of the transition from a gradient wind to a sea breeze and vice versa. It is small wonder that at Dantzic, just as anywhere else, the occurence of this front character is promoted by an offshore wind, which comes from an approximately SW-direction there. Therefore it is unsatisfactory that Koschmieder has not mentioned with what frequency days occur having a sea breeze that is not accompanied by front-phenomena. He remarked that with an offshore wind the sea breeze not only sets in in the most marked manner, but that it is also more frequent than in the case of a wind direction more parallel to the coast.

Kaiser observed that at Neufahrwasser (near Dantzic) the sea breeze is less frequent than on the German coast of the Baltic. He suggested that the sea breeze near Dantzic probably arises as a continuation of the sea breeze on the coast of the Baltic. This sea breeze would then penetrate over the Bight near Dantzic, thereby even being retarded by the "Putziger Nehrung". Owing to this the sea breeze would arrive at Neufahrwasser on an average two hours later than at the stations on the coast of the Baltic. Koschmieder, too, remarked that a Dantzic the sea breeze sets in remarkably late (page 35) but he suggested as an explanation a continual accumulation of cold air together with an increasing instability of the land-air about noon. However, it does not appear from his work why the sea breeze sets in earlier elsewhere on the coast of the Baltic.

If, indeed, the sea breeze at Dantzic can be caused by the influence of the sea breeze on the coast of the Baltic, it is not astonishing, on the contrary it is even obvious, that an approximate SW-wind is most favourable for the onset of a sea breeze at Dantzic. This will be clear from the investigation at IJmuiden which shows that with that wind direction a sea breeze must easily form on the coast of the Baltic. On this point Koschmieder (1941) said that it is only in very special cases, in which the sea breeze mostly sets in late or has a relatively great height, that the coast of the Baltic makes its influence felt.

Koschmieder's observations contain an indication, not mentioned by him, for the existence of an influence of the Baltic coast. The coast-line in the area of observation has the direction N 34° W — S 34° E (fig. 17). According to his conception the sea breeze front will be directed about N — S if a general wind blows from the W and about E — W if a general wind blows from a southern direction. Now attention must be paid to the arrangement of Koschmieder's sea breeze days given in table 10 [1]). In it a division occurs according to the direction and to the strenghth of the gradient wind. The figures in the table denote the direction of that normal at the front which points to the sea. The table does not contain those cases of sea breezes at Dantzic which, according to Koschmieder, must be looked upon as a continuation of the sea breeze on the coast of the Baltic.

It appears from the table:

1°. that the front mostly runs in about an E—W direction (this direction of the front occurs with all directions of the gradient wind, also with gradient winds from W- and WSW-directions with which this front direction is not obvious),

2°. that, indeed, with gradient winds from W- and WSW-directions there are some cases with a front running almost N—S,

[1]) According to Hornickel (1942) Koschmieder made a mistake in the indication of the location of one of the stations. However, this error is said not to have affected the calculation of the front direction.

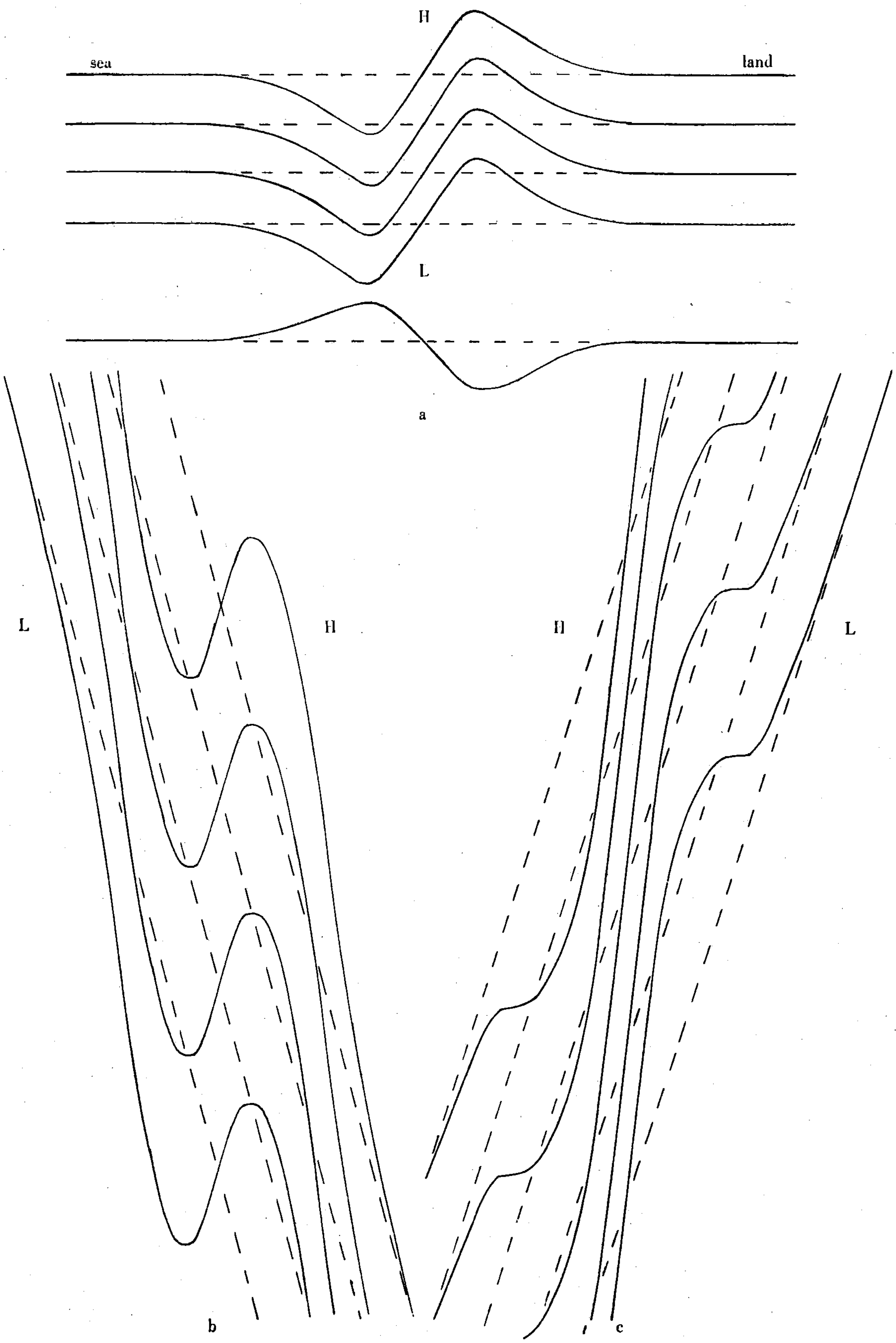

FIGURE 19.

Influence of the extra pressure field represented in figure a *on the shape of the isobars with different directions of the latter.*

Speed of gradient wind Beaufort	Direction of gradient wind						
	W	WSW	SW	SSW	S	SSE	SE
1							N18°W N27°E
2	N32°E	N 5°W N82°E	N19°E				N 1°W
3	N 1°E N13°E N65°E N68°E	N 5°W N N16°E N51°E N59°E N92°E	N 3°W N 4°E	N 8°W	N16°W N22°E		
4		N10°E N15°E N27°E					
5		N20°W					
Mean:	N36°E	N27°E	N 7°E	N 8°W	N 3°E		N 9°E

TABLE 10.

Days with a sea breeze, given by Koschmieder, divided according to speed and direction of the general offshore wind. The direction of the normal at the front is stated.

3°. that with W- and WSW-directions of the gradient winds there are 11 cases with an E—W or ESE—WNW front direction,

4°. that with a direction of the gradient wind about S there are no cases with a front in a N—S direction.

This points to an influence of the coast of the Baltic because this influence must lead to a more or less E—W sea breeze front. This influence is all the more probable because only this front direction occurs with a strong offshore wind approximately perpendicular to the coast in which case, according to chapter I, a sea breeze forms with difficulty only. With W- and WSW-directions of the general wind, however, a sea breeze will, according to the investigation at IJmuiden, easily occur on the coast of the Baltic. In this connection one looks in vain in Koschmieder's work for an explanation of the proposed accumulation of cold air in case an approximately E—W front between cold and warm air occurs while the general wind is westerly.

The difference between Kaiser and Koschmieder with regard to the mean frequency of sea breeze days must still be explained. Most probably it must be ascribed to a difference in the characteristics used to determine whether a day is a sea breeze day or not. Koschmieder especially attended to the frontal character of the onset of the sea breeze (page 34). Kaiser has taken a day to be a sea breeze day when an onshore wind is preceded and followed by an offshore wind while the pressure gradient must be small, the prevailing wind weak and cloudiness slight. This difference causes that the frequencies, given by them for the different places on the coast of the Baltic, are not comparable because they will be considerably affected by the frequencies with which in those places, having a different direction of the coast, the general wind will clearly be offshore.

Let us now continue the discussion of Koschmieder's first publication. He remarked that the energy of the sea breeze is not only supplied from the potential energy of the adjacent quantities of air of different temperatures but also from the unstable layer of land-air in the daytime. This must explain that the front changes from stationary into moving late in the day and with a wind-push which, for 3 — 10 minutes, is 2 to 4 m/s more rapid than the after-flowing sea-air. This wind-push is supposed to be caused by the rapid rising of the land-air that has become unstable.

According to Koschmieder the energy of the pressure field at the earth's surface, formed by the outflow of air at greater altitudes from land to sea, would at greater latitudes have practically no importance because there the supply of heat to the air extends over a small height only.

If this would be correct, a remarkable conclusion would be arrived at. If on a certain day a heating of the land for a few hours after sunrise has caused, at a higher level, a certain outflow of air from land to sea and the insolation then becomes zero, the convergence, which has presented itself over the sea in the meantime, might cause a further accumulation of cold air and thus might bring about the formation of a frontal surface.

In his next publication on the sea breeze Koschmieder (1941) dealt with the wind observations in the higher layers. The balloons used had a small vertical speed so as to be able to investigate the lower layers of the atmosphere all the more accurately. They were followed by a theodolite and a telemeter. Five cases in 1935 were dealt with in detail.

From the observations conclusions were drawn as to the motion of the air before and behind the sea breeze front, the height of the sea breeze, the height of the layer of sea-air flowing back over the sea breeze and the shape of the front.

In general the results confirm Koschmieder's theory in so far that they show that the *penetration* of the cold air takes place in the way explained by him. The formation of a front by the accumulation of cold air is by no means proved, however.

Hornickel (1942) went further into the material collected by Koschmieder, especially as regards the connection between the wind vectors and the temperatures of the land-air and the sea-air on the one hand and the altitude on the other hand. He only dealt with the year 1934.

Some of the facts stated by him have already been used before in this investigation as arguments for Bleeker's conception. None of his results prove the correctness of Koschmieder's conception of the formation of a stationary sea breeze front out to sea.

It is worth while discussing the following subject from Hornickel's publication. From the moments of onset of the sea breeze at four different stations the front direction and the front speed were calculated from four combinations each including three stations. However, of the four stations three are practically in line. Because the results appeared to be equal the calculated values were taken to be constant in the area under consideration. Because in 1934 the time of onset could seldom be determined accurately at one of the stations, the calculation was made for 8 days.

On 3 days for which the calculation could be made for a larger area (15 km of coast-length, 3.5 km inland) Hornickel found entirely different values for the front speed and for the front direction in comparison with those found for 8 days in a small area (3 km of coast-length, 3.5 km inland). This difference was ascribed by him to the difference in shape of the ground.

The fact that the speed of the front has been found by Hornickel to be constant between the 3 stations that are situated in line must mean, if the front changes its speed on passing the coast, either that the front speed adapts itself very rapidly to the circumstances or that the change takes place so slowly that this cannot be detected in a narrow strip along the coast. In the first case the direction of the front very probably will change on passing a bent coast or, on passing a rectilinear coast, when the front and the coast are not parallel. If the speed of the front changes very slowly the calculation of the front direction still depends on the supposition that the front is rectilinear and maintains its direction. Whether this supposition is correct cannot be proved from the observation of the moment of onset of the sea breeze at the 4th (the other coastal) station used by Hornickel.

In fact its correctness may be doubted on the basis of the following reasoning. Hornickel's remark that, when three stations lying farther apart were used, the front had by no means a constant direction and speed will now be interpreted in another way. In the case of a coast like that at Dantzic a sea breeze will, with a southerly general wind, form most easily in the part of the coast running in a more northerly direction because it is there that of the offshore component of the wind is smallest. The sea breeze will then set in first at Glettkau (fig. 17, page 34). Cases of sea breezes reaching Glettkau first are characterized in table 10 by a direction of the normal to the front that has backed with reference to the direction N 56° E. Indeed, with a general wind from SW to SE only such cases occur.

With a westerly general wind the sea breeze will be able to form first in the part of the coast which runs more E—W and consequently will first appear at Brösen. These cases are characterized in table 10 by a direction of the normal to the front which has veered with reference to the direction N 56° E. Indeed, they exclusively occur with this direction of the general wind. That other cases occur as well has already been ascribed to an influence of the coast of the Baltic.

It is likely that on this bent coast the front will not be constant as to direction and speed. With a southerly general wind the sea breeze will already have reached the part of the coast directed more N—S whereas the front in its southern part (running about E—W) will still be vague, all the more vague where it lies farther out to sea. The front will be curved at intermediate places. If the heating is maintained the southern part of the front will move about southward. The northern part of the front, existing for a longer time already, will move westward. The displacements of the two parts of the front can occur at different speeds. Hence the front, as observed near the coast, will as a rule change its direction in the course of time.

Owing to this it may very well be expected that the front direction, as calculated by Koschmieder from the observations at three stations, is accompanied by a sea breeze which points to the sea-air. As a matter of fact, Koschmieder found three of such cases.

Finally another argument against Koschmieder's theory will be deduced from his own observations. He described a number of cases with a very feeble offshore wind yet having a sea breeze setting in with front-character and sometimes even having a strong sea breeze. The instances of table 11 are copied from the wind registrograms in the publications of Koschmieder and Hornickel. In addition to these data Hornickel mentioned a few similar cases that have not been further described. Therefore this phenomenon cannot be said to be very rare.

Date	Wind speed (m/s) averaged for some hours before the onset of sea breeze				Moment of onset of the sea breeze	Sea wind speed (m/s)
	Brösen on the coast	Glettkau on the coast	Eckhof 2 km inland	Airport 3.5 km inland		
19-6-'32	0.5	1.5		2.0	13 h 15′	5.0
21-6-'32	0.5	1.0		2.0	11 h 45′	5.2
28-6-'32	0	0.5		—	6 h 30′	<2
13-8-'32	0.5	1.0		1.5	10 h 15′	3.6
14-8-'32	0.5	0.5		2.0	10 h 27′	2.9
15-8-'32	1.0	2.0		2.0	14 h 30′	2.9
1-6-'34	1.0	1.0	2.0		11 h 21′	4.3

TABLE 11.

Days with a feeble offshore general wind on which the sea breeze set in with front-phenomena.

It is not clear how the feeble offshore wind can lead to the accumulation of cold air, suggested by Koschmieder, which accumulation must even be well developed as can be seen from the large values of the speed of the sea breeze.

If the registrograms published are reliable as to the reading of the wind speed, there appears to occur a clear convergence in the land-air before the sea breeze front in most cases. This must mean that the accumulation of cold air occurs in the immediate neighbourhood of the coast. This can hardly be accepted.

The explanation by means of the pressure field of figure 14 is much more natural. A front-line near the coast, with a strong sea breeze and immediately before it a feeble offshore wind and a slowly moving front, is very well possible.

Also in cases of a well-developed sea breeze, setting in early, a marked accumulation of cold air can hardly be expected. However, if the heating increases rapidly after sunrise, a circulation can already develop well in a few hours, the frontal zone between sea breeze and general wind assuming more and more a front-character. Koschmieder described some cases of this type.

Summarizing we may say that the observations of Koschmieder and Hornickel supply very extensive material which primarily provides data to answer the question how the sea breeze moves landward. As far as the conclusions, drawn by Koschmieder from the observations, are concerned we may say that it is unlikely that the sea breeze forms at sea owing to an accumulation of cold air with a stationary front which would move under the influence of the weight of the formed thick layer of cold air.

It is disappointing that the observation-ships, used by Koschmieder, yielded so few results. In fact, observations at sea are necessary to check properly Koschmieder's view.

His extra pressure field (fig. 18, page 35) must be considered to be too simple.

The starting point of the conception that the sea breeze preferably occurs with an offshore general wind, i.e. the thought that the isobars of the general pressure field are most distorted by the extra pressure field when those isobars are perpendicular to the coast, is incorrect.

At Dantzic influence exercised by the coast of the Baltic is likely.

Several facts, deduced from Koschmieder's observations, are rather in favour of Bleeker's starting point than of that of Koschmieder.

3. *The investigation of F. H. Schmidt.*

Starting from a chosen temperature-distribution Schmidt (1947) calculated some characteristics of the sea breeze.

He has taken into account the acceleration-terms of the equations of motion as well as the compressibility of the air. This had not yet been done before. He separately investigated the influence of the rotation of the earth. For the sake of simplicity he assumed that there is no general pressure gradient. Further the influence of the wind field on the temperature-distribution has not been taken into account. This is why he calls his theory an elementary one.

According to Schmidt the temperature-distribution is represented by:

$$\Theta_z = \Theta_0 - \gamma z + \tfrac{1}{2}\tau_0 e^{-az}\left(1 + \sin\frac{\pi x}{\lambda}\right)\sin \omega t.$$

The symbols have the following meanings:

- Θ_z temperature at the height z,
- Θ_0 temperature on the earth's surface at the moment when it is held to be equal everywhere ($t = 0$),
- γ mean lapse rate of temperature,
- z height,
- τ_0 amplitude of the diurnal variation of temperature on the surface, landward far from the coast,
- a a parameter representing the decrease of the temperature amplitude with height,
- t time measured from moment of uniform temperature,
- ω angular velocity of the rotation of the earth,
- x horizontal distance from the coast, the inland direction being positive,
- λ the smallest value of x for which the diurnal temperature wave reaches the full amplitude (τ_0).

Schmidt himself mentioned some shortcomings of the temperature-distribution adopted, viz. the omission of a phase difference between the temperature waves at different heights and the assumed equality of the temperature rise in the daytime and the temperature fall during the night.

The temperature-distribution implies a diurnal variation of the distribution of density. In the absence of local pressure changes the local density change would be:

$$\frac{\partial \rho}{\partial t} = -\frac{\rho}{\Theta}\frac{\partial \Theta}{\partial t} = -\frac{\rho_0}{\Theta_0} e^{-bz}\frac{\partial \Theta}{\partial t} = -\frac{\delta_0}{\tau_0}\frac{\partial \Theta}{\partial t} e^{-bz},$$

in which ρ represents the density, ρ_0 the density at the surface, and δ_0 the amplitude of the diurnal density change. The factor e^{-bz} is due to the fact that ρ/Θ decreases with increasing height in accordance with $\rho/\Theta = (\rho_0/\Theta_0)e^{-bz}$. Then b will be a function of the mean temperature. Schmidt awards the value $(10^4 \text{ m})^{-1}$ to b.

If the condition is imposed that, in spite of the expansion due to heating and the contraction due to cooling, $\int_0^\infty \frac{\partial \rho}{\partial t}\, dz = 0$, then $\frac{\partial \rho}{\partial t}$ would follow from:

$$\frac{\partial \rho}{\partial t} = -\tfrac{1}{2}\delta_0 \omega e^{-(a+b)z}\left\{1-(a+b)z\right\}\left(1+\sin\frac{\pi x}{\lambda}\right)\cos \omega t.$$

At the equator the horizontal motion will have to satisfy $\frac{du}{dt} = \frac{1}{\rho}\frac{\partial p}{\partial x} - K(x, z)$, in which u represents the component of the velocity in the x-direction, p the pressure, and $K(x, z)$ the friction per unit of mass. $K(x, z)$ is taken to be equal to $c(z).\,u$. On the coast $\frac{\partial u}{\partial x}$ is neglected so that $\frac{du}{dt} = \frac{\partial u}{\partial t}$. Taking into account the compressibility of the air we get the following equation of motion:

$$\frac{\partial^2 \rho u}{\partial t^2} = g\int_0^z \frac{\partial^2 \rho}{\partial t\,\partial x}\, d\xi + g e^{-fz}\int_0^\infty \frac{\partial^2 \rho u}{\partial x^2}\, d\xi - c\,\frac{\partial \rho u}{\partial t}.$$

In this equation $1/f$ represents the height of the level at which the influence of the divergence on the pressure has decreased to e^{-1} times its value on the surface, which decrease with increasing height is a consequence of the compressibility of the air. In the equation $\frac{\partial \rho}{\partial t}$ has been neglected with reference to $\frac{\partial u}{\partial t}$.

U is written for $\int_0^\infty \rho\, u\, d\xi$, and the equation in U, which is obtained by integrating the preceding one to z, is solved.

In $U = V \sin(\omega t + \beta) \cos \frac{\pi x}{\lambda}$, in which U will represent the landward mass flux through a vertical plane of unit width parallel to the coast per second, $\bar{\beta}$ must be approximately 90° and the maximum mass flux, through a vertical plane containing the coast-line, must be equal to

$$V = -f \lambda \delta_0 / T (a+b)^2.$$

In these calculations, too, a few approximations have been made, among others $\cos \bar{\beta} = 0$.

Furthermore Schmidt deduced for the velocity in the *x-direction:*

$$u = u_m \sin(\omega t + \beta) \cos \frac{\pi x}{\lambda},$$

with $\beta = \text{arc tan } (-\omega/c)$

$$\text{and } u_m = -\frac{\pi^2 g \delta_0 \alpha_0}{\lambda T (\omega c \cos \beta - \omega^2 \sin\beta)} \times$$

$$\left\{ z \, e^{\{h-(a+b)\} z} - \frac{f}{(a+b)^2} e^{(h-f) z} \right\}$$

Here $\frac{1}{\rho}$ has been replaced by $\alpha_0 e^{hz}$.

Then Schmidt discussed the conclusions drawn from this deduction.

1°. The onset of the sea breeze comes later at a greater height because the friction decreases with increasing height. In addition to this the cause indicated by Van Bemmelen (1922), i.e. the gradual vertical extension of the heating, will play a part.

2°. By the proper selection of the parameters a good agreement can be obtained between the observations at Djakarta (Batavia) by Van Bemmelen and the theory. This selection was based on the change of the moment of onset of the sea breeze with varying heights and on the change of the maximum speed of the sea breeze with altitude. Then he found 1.5 $(10^4 \text{ s})^{-1}$ for c_0 in $c = c_0 e^{-rz}$, and $(10^3 \text{ m})^{-1}$ for r. For a $(10^3 \text{ m})^{-1}$ has been taken in the daytime and 2. $(10^3 \text{ m})^{-1}$ during the night. If the height of the sea breeze is fixed at 1000 m, f must be equal to $(10^3 \text{ m})^{-1}$. For τ_0 5.5° C and for λ 200 km were used.

Schmidt also calculated the maximum value of the vertical component of the wind speed as a function of the height. However, the vertical speed found over Djakarta is greater. This he ascribed to rising air-bubbles in the lower unstable layers of the atmosphere.

By subsequently adding the terms for the Coriolis force to the equations of motion u_x and u_y were calculated, the results revealing that the sea breeze does not blow perpendicular to the coast at the moment of its maximum development, but has veered with reference to that direction on the N-hemisphere. The end of the wind vector on the ground moves along an oval line in the course of 24 hours.

The countercurrent over the sea breeze will also veer in course of time. Finally Schmidt says that this veering of the countercurrent may account for the fact that the S-component of the wind in the higher layers over the Netherlands increases in the afternoon, which has been shown by Bleeker (1936).

We subjoin some remarks on Schmidt's work.

1°. Schmidt's starting point is fundamentally different from Bleeker's. To make this clear it must be said here that Bleeker and Andre remarked that the isobaric surfaces will also be lifted above the area where the supply of heat takes place. Thus an outflow of air will appear there likewise. They call this part of the circulation "thermally indirect", in contradistinction to the circulation in and under the heated area which they call "thermally direct". Bleeker has given a further elucidation of these terms (1950 b).

Schmidt considered the change of the density field which appears owing to the lifting of the isobaric surfaces during heating. The influence of the resulting change of the temperature distribution has not been taken into account. This may be held to be the most serious objection to Schmidt's elementary theory (negligence of the influence of the sea breeze circulation on the temperature field).

2°. Schmidt's calculation does not allow of drawing a conclusion as to the influence of a general wind. If, with a general wind, the temperature distribution would not change fundamentally, the drawback of the negligence of the influence of the sea breeze circulation as a whole on the temperature field will at once be apparent. For it will then be impossible to derive from the calculation the front character of the sea breeze observed in this case. This again stresses the fact that an elementary theory of necessity lacks the right starting point.

3°. Of the simplifying suppositions introduced by Schmidt we should not pass by the one according to which he puts $\partial u / \partial x$ on the coast equal to zero. This supposition does not fit in Bleeker's line of thought. For, according to the temperature-distribution assumed by Schmidt, point C of figure 14 must, in the absence of a general wind, be exactly on the coast. This would also hold good if he had started for the temperature-distribution from a tanh x he himself considered to be better. However, according to Bleeker then the landward directed gradient of the pressure field will be maximum on the coast so that the air will be positively accelerated there. Schmidt probably arrived at the simplification in question by basing himself on Bjerknes' circulation-theorem which requires the circulation over the coast to be maximum.

Even if it should follow from the observations that $\partial u / \partial x$ is about zero over the coast, this will not mean that Schmidt's supposition is permissible. Such an observation would rather impose the necessity of introducing a friction that is different over land and sea, whereas Schmidt supposed no difference to occur.

4°. Schmidt's calculation allows of drawing a conclusion as to the influence of the stability of the atmosphere on the land and sea breeze effect. The elaboration required will be given in chapter III. The importance of this conclusion is, of course, adversely affected by the foregoing three remarks.

5°. It may be called an advantage that on days without a general wind Schmidt's calculation supplies a very direct result as regards the diurnal variation of the wind vector

As a rule it has been observed that, in case the sea breeze sets in with front character (i.e. when an offshore general wind is present) the variation of the wind deviates from that calculated by Schmidt. However, the mean of diurnal variations of the wind for a large number of days with a general wind shows qualitatively the same picture as that given by Schmidt for a day without a general wind. A further elaboration of the formulae given by Schmidt for u_x and u_y shows that the end of the wind vector moves, theoretically, along an ellipse with the long axis not perpendicular to the coast. This result has also been found by Haurwitz (1947) (see next section). This equal result is due to the fact that both authors started from the same equations of motion and only used a different temperature-distribution.

Though Bleeker's picture qualitatively leads to the same result yet an elaboration of his theory will have to shed further light, because then separate days with a general wind can probably be included.

6°. A few other points will be discussed at the end of the next section, so as to compare Schmidt's work with that of Haurwitz.

4. *The investigation of B. Haurwitz.*

Concurrently with Schmidt B. Haurwitz published an investigation on land and sea breezes (1947). It can be split into three parts.

1st part. Here the circulation-theorem of Bjerknes has been taken as the starting point. If the friction is not taken into account this means that in the day-time the circulation increases till the moment on which the temperature difference between land and sea has again fallen to zero. Haurwitz introduced the friction and then calculated the moment on which the sea breeze reaches its maximum speed.

He started from the equations:

$$\frac{du}{dt} + k\,u = -\frac{1}{\rho}\frac{\partial p}{\partial x} \text{ and } \frac{dw}{dt} + k\,w = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g,$$

and from the equation for the circulation

$$\frac{dC}{dt} = \oint \left(\frac{du}{dt}dx + \frac{dw}{dt}dz\right).$$

The symbols have the following meanings:

- u velocity in the x-direction, i.e. in the direction perpendicular to the coast,
- w velocity in the z-direction, i.e. in the vertical direction,
- t time,
- k a friction-factor held to be constant,
- ρ density,
- g acceleration due to gravity,
- C circulation along a closed curve in the sea breeze area.

The Coriolis force has not been taken into account.

The curve of integration has been chosen along an isobar in the x-direction with the pressure p_o, a vertical line with the mean temperature $\overline{T}_b$, an isobar with the pressure p_1, and a vertical line with the mean temperature $\overline{T}_a$. The circulation is taken as $\overline{v}\ L$ in which $\overline{v}$ represents the mean speed along the curve of integration and L the length of the curve of integration.

We thus get: $\frac{d\overline{v}}{dt} + k\,\overline{v} = \left(\overline{T}_a - \overline{T}_b\right)\frac{R}{L}\ln\frac{p_o}{p_1}$ in which R represents the gas constant for 1 gram of air. It is now assumed that the right-hand term can be replaced by $A\cos\omega t$ in which A is a constant and ω the angular velocity of the rotation of the earth. So the time is reckoned from the moment at which $\overline{T}_a - \overline{T}_b$ is maximum.

The solution of the equation yields:

$$\overline{v} = c\ e^{-kt} + A\ (k^2 + \omega^2)^{-\frac{1}{2}} \cos\ (\omega t - \chi)$$

or, with the condition

$$v = 0 \text{ if } A = 0,\ \overline{v} = A\ (k^2+\omega^2)^{-\frac{1}{2}} \cos\ (\omega t - \chi)$$

with $\chi = \arctan\frac{\omega}{k}$.

Then the connection between χ and k is as follows:

k. $(10^5\ s)^{-1}$	0	2	4	6	8	10	12
χ in h	6	5	4.1	3.4	2.8	2.4	2.1

From the observation of the angle between the pressure gradient and the direction to which the wind blows, this angle being represented by $\arctan\frac{2\,\omega\sin\varphi}{k}$ (with φ the geographical latitude), Haurwitz arrived for New England at a value of k between $2.(10^5\ s)^{-1}$ and $8.(10^5\ s)^{-1}$ The moment of the maximum velocity of the sea breeze would then be about three hours later than that at which $\overline{T}_a - \overline{T}_b$ is maximum. Experience is said to show that this difference in time is practically nil. As reasons that may have led to the poor correspondence between observation and theory Haurwitz mentioned: the restrictive supposition made in the deduction, the fact that k is a function of the hour of the day on account of the varying atmospheric stability and the influence which the sea breeze exercises on the difference in temperature between land and sea.

2nd part. The speed and the direction of the sea breeze, being functions of the time and the temperature difference between land and sea, were now calculated in the following way.

The Coriolis force has thereby been taken into account. Haurwitz supposed, however, that the wind causes a permanent equilibrium to exist between the gradient force of the general pressure field, the pressure gradient force caused by the difference in temperature between land and sea, the Coriolis force and the force of friction. For this reason the theory developed here has been called an equilibrium theory. The acceleration forces have not been considered. Haurwitz remarked beforehand that the equilibrium theory will not satisfy because observations show that the Coriolis force must be taken into account whereas the acceleration forces are not negligible with reference to the Coriolis force.

Yet the result of the calculation was given as an introduction to the third part of the investigation so as to enable us to gain a better understanding of its conclusions.

The starting-point of the second part consists of the following two equations:

$-lv + ku = F_x - F\ (t)$ and $lu + kv = F_y$ in which

$l = 2\omega \sin \varphi$, u and v are the velocity-components in the x-direction and the y-direction, F_x and F_y are the components of the general pressure gradient force and $F(t)$ is a pressure gradient force in the x-direction (perpendicular to the coast). $F(t)$ will change periodically as a function of the time, owing to the change of the difference in temperature between land and sea. For $F(t)$ he introduced $F(t) = \frac{A}{\pi} + \frac{1}{2} A \cos \omega t$ representing the first two terms of the Fourrier series for $G(t)$, a function that is equal to $A \cos \omega t$ in the interval $-\frac{1}{2}\pi \leqslant \omega t \leqslant \frac{1}{2}\pi$ and zero in the other half of the period.

The results are:

1°. The end of the wind vector, starting from the origin of the coordinate system, shifts along a straight line in course of time. This line is called a "hodograph" by Haurwitz.

2°. This line makes an angle with the x-direction equal to arc tan $(-2\omega \sin \varphi / k)$.

3°. In the absence of a general pressure gradient this line passes through the origin. A general pressure gradient causes the hodograph to shift from the origin over a distance equal to the speed of the general wind and in its direction.

4°. It stands to reason that there is no phase-difference now between the velocity-wave and the temperature-wave.

3rd part.

Since the observed hodographs have rather the shapes of ellipses, Haurwitz introduced the Eulerian acceleration terms (dynamic theory). The velocity was held to be equal everywhere as a function of the time only. Differences in vertical direction and the compressibility of the air were neglected. Whilst adding the acceleration terms to the equations of motion used in the second part, retaining $F(t) = \frac{A}{\pi} + \frac{1}{2} A \cos \omega t$, a solution has been obtained that can be represented in rather indistinct formulae for u and v.

The hodograph derived from these formulae is an ellipse, its large axis making an angle with the x-axis equal to arc tan $\left(-\frac{2\omega \cos \varphi}{k}\right)$. The length of the large axis is smaller when k is greater. The eccentricity of the ellipse increases with increasing k. In the absence of a general pressure gradient one of the foci is in the origin of the coordinate system but this focus (and the ellipse) is shifted by a general wind in the direction towards which this wind blows and over a distance that is equal to its speed. A phase difference now occurs between the velocity-wave and the temperature-wave. The hodograph is followed clockwise on the N-hemisphere though the wind itself need not always turn clockwise in case of a hodograph shifted from the origin.

According to Haurwitz a comparison between some observation-facts and the theoretical results shows a distinct correspondence. Some drawbacks of the theory, that prevent the agreement from being perfect, were mentioned by Haurwitz himself. They are: the change of the general pressure gradient in the course of the day, the irregular change of the difference in temperature between land and sea, and also the considerable influence which the degree of stability of the air will have on the development of the sea breeze. Haurwitz considered the observational data available to be insufficient for a further investigation with regard to this.

Observations would, according to Haurwitz, show that a WSW-wind is least favourable to the appearance of a sea breeze on the coast of New England. Indeed theory indicates a W-wind for this. Observations also show that the wind on the onset of the sea breeze changes through S in case the general surface wind has a rather large component from S and changes through N if the wind has a component from N or a small component from S. These and similar observations can be explained by the theory in broad outline.

Finally Haurwitz remarked that the following facts must either be starting points for theory or must result from theory in order to obtain a quantitative correspondence between observations and theory.

1°. The sea breeze circulation prevails in a narrow strip on either side of the coast only.

2°. The sea breeze decreases in strength with increasing height and even changes its sign.

3°. The difference in temperature between land and sea and also u and v are not only functions of the time but also of the coordinates of space.

4°. The turbulence and its change with the varying atmospheric stability must be taken into account.

5°. The influence of the circulation itself on the temperature difference between land and sea must be taken into account.

Haurwitz' theory requires a gradual change of the wind, also when an offshore general wind is present, owing to the fact that he has taken the extra pressure gradient to be uniform over a large area on either side of the coast. If a limitation of the area in which the sea breeze circulation occurs would be used in theory its result must be that the onset of the sea breeze is not gradual when an offshore general wind is present. Thus the omission of this limitation indeed must lead to an incorrect result (sea further page 45).

The 1st and the 5th remarks on the work of Schmidt (page 41) are valid for Haurwitz' work too. In connection with the 3rd remark (page 41) attention is drawn to the fact that Haurwitz used a friction factor which is assumed to be equal not only over land and sea but equal also for vertical and horizontal motions and independent of altitude.

For a comparison of the results of Schmidt and those of Haurwitz, which comparison will also be extended to the observations at IJmuiden, the following points are added.

1°. The phase difference.

Schmidt found the phase difference (β) between the sea breeze speed and the temperature wave from β=arc tan $(-\omega/c)$ if the Coriolis force was not taken into account. If this force is introduced in theory the phase differences for the x- and the y-component of the wind

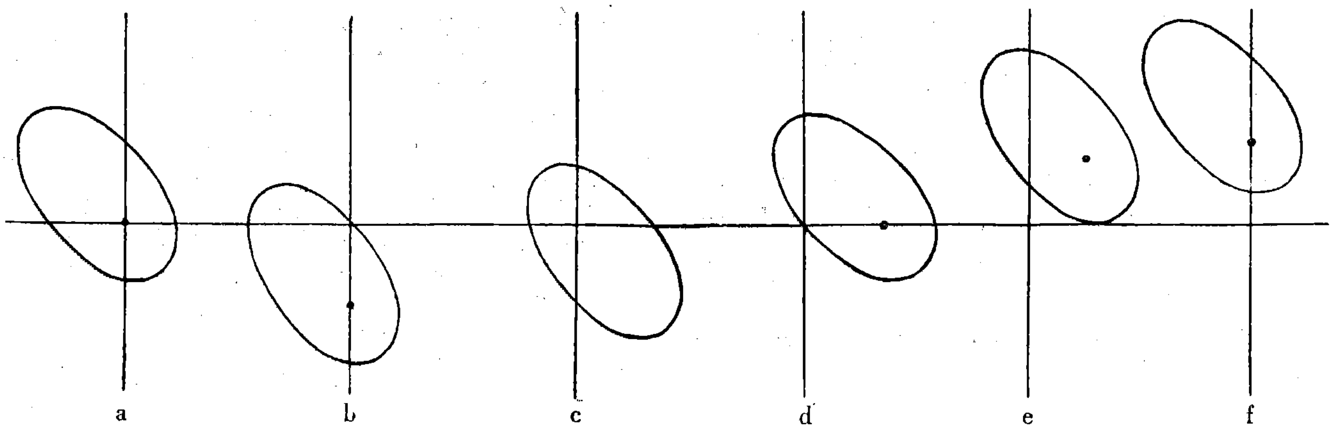

FIGURE 20.

Hodographs according to Haurwitz; a. no general wind, b., c., d., e. and f. general wind from S, SE, E, NE and N respectively.

are not equal and can be derived from a more complicated formula in which the geographical latitude figures as a parameter. Apart from the misprint in Schmidt's formula (3.14), in which AT instead AT^2 occurs, Schmidt and Haurwitz found the same value for the phase difference between wind speed and temperature. This is due to the fact that they started from the same equations of motion.

Owing to a friction factor that is 2.5 times as large as that used by Haurwitz, Schmidt found a small phase difference of approx. 1.5 hours. With the friction factor used by Haurwitz a phase difference of approx. 3 hours has been found. However, from observations of the sea breeze on the coast of New England he found a phase difference that is practically nil. He gave some reasons (see page 42) to account for the discrepancy between the observed and the theoretical phase difference.

From the observations at IJmuiden we at once see, without making an exhaustive inquiry, that the phase difference is very small. To fix our minds we may say that it will not surpass one hour.

This may be expected according to Bleeker's line of thought. When the supply of heat starts decreasing the pressure field on the ground will soon flatten. However, an exact calculation from this starting point will be necessary to verify this opinion.

2°. The transition from an offshore wind to a sea breeze.

a. In the absence of a general wind.

Haurwitz' theory indicates that the end of the wind vector, which vector begins in the origin, passes through an ellipse in the course of 24 hours. As already remarked on page 42 a further elaboration of the final formulae of Schmidt shows that he also arrived at the same result. Since the temperature distribution adopted by both authors will not satisfy during the night a clear correspondence between observation and theory then need not be expected. In the daytime both investigators found a good agreement between theory and observation, though the investigations cover but a few days.

b. A general wind occurs.

It is only Haurwitz who dealt with the influence of a general wind. The hodograph is said to be simply displaced in the direction of the general wind over a distance equal to its speed (if the starting points of the wind vectors are laid in the origin).

It is interesting to compare this with the result of the IJmuiden observations, as stated on page 19. According to Haurwitz, with different directions of the general wind its velocity must invariably have the same component perpendicular to the coast for precisely preventing the appearance of a sea breeze. If the direction towards which the wind blows makes an angle of 60° with the direction of the pressure gradient (according to the figure-example of Haurwitz) and if the wind speed is taken to be proportional to the pressure gradient, the latter then must have its end on a straight line making an angle of 60° with the coast-line. At IJmuiden 64° was found for this angle. However, on the ground of what has been said, not much theoretical value should be set on this.

We shall now investigate whether the offshore wind will change into a sea breeze through the South or through the North. We can use figure 20 for the purpose, in which Haurwitz' conclusions have been applied to the direction of the coast at IJmuiden and in which the ends of the wind vectors have been laid in the origin.

With a general wind from between S and SE, no matter what its strength is, the sea breeze will, according to Haurwitz, invariably arise via S. An E-wind must be rather strong for having a sea breeze setting in via N.

A further investigation of 37 cases at IJmuiden, with an offshore general wind and a sea breeze in the daytime and the general pressure gradient changing very little in the course of the day, shows that the critical direction of the general wind for the passage either through N or through S lies between E and SE.

With a general wind that at sunrise comes from about this direction the upper wind seems to have a considerable influence on the behaviour of the surface wind. In those cases in which the upper wind has backed with reference to the surface wind the passage is through N. This may be explained by assuming as the consequences of the diurnal heating, on the one hand, the appearance of the sea breeze and, on the other hand, the increasing vertical transfer of momentum in the atmosphere (see also page 26).

Thus the critical direction for the passage either through N or through S is in agreement with the calculation of Haurwitz. However, it has appeared that at IJmuiden the sea breeze also arises through N with a feeble E-wind. This points to it either that the hodograph is narrow in comparison with the one drawn or that the veering of the wind is not clearly maintained during the night, i.e. that the hodograph then deviates from an ellipse. For the matter of that Haurwitz also found, in the observation material at his disposal, approximately linear hodographs which he looks upon as highly eccentric ellipses.

The 37 cases referred to above allow of a further comparison. According to Haurwitz the wind speed will, in the event of a passage through N, have to decrease gradually previously and to increase again after this (see fig. 20 e and f). With a very late passage either through N or through S (fig. 20 d) the wind speed must decrease before the onset of the sea breeze and increase soon after that. With a late passage through S (fig. 20 c) the wind speed must decrease before the onset and after that decrease also. With an early passage through S (fig. 20 a and b) the wind speed will remain equal a little before the onset to decrease after that. From the 37 cases those were taken together in which occured a passage through N and also those in which the passage was through S. Then the mean wind speeds (in m/s) during the 3rd hour before, the 2nd hour before, the 1st hour before, the 1st hour after, the 2nd hour after and the 3rd hour after the onset of the sea breeze, were calculated. The following figures were obtained.

	Before the onset			After the onset		
	3rd hour,	2nd hour,	1st hour,	1st hour,	2nd hour,	3rd hour
through N	1.8	1.9	1.8	5.4	6.9	7.4
through S	3.9	4.0	3.8	3.3	2.8	2.7

Qualitatively these data exhibit a good agreement with the figures 20. Yet the velocity-jump before and after the onset of the sea breeze is strikingly great in the case of a passage through N. It is here that the front character of the passage appears.

This front character has been neglected in Haurwitz' theory (see page 43). The following is directly connected with this. Fundamentally the observations at IJmuiden yield a hodograph which can be taken as an ellipse. It is striking, however, that its shape is different for the passage of the sea breeze through N and through S. On the passage through N the curve is narrow and on the passage through S it is much rounder than the instances calculated by Haurwitz. Figures 19 b and c (page 37) can elucidate this. On the passage through N the wind velocity in the extra pressure field near the coast will increase in the S-direction owing to the large gradient prevailing there. On account of this the air that reaches the land as a sea breeze will have travelled a relatively long distance over the sea. Thus the front will become sharp and strong, the change of the wind direction will be slight, and the sea breeze will have a great speed. This accounts for the length and the narrowness of the hodograph and for the often distinct front character of the onset of the sea breeze.

On the passage through S the pressure gradient is small in the area in which the velocity component perpendicular to the coast starts pointing from seaward to landward. Here the air will move slowly. Owing to this the change of the wind direction on the onset of the sea breeze will be greater. The fact that then front phenomena present themselves less often and especially less distinctly can be ascribed to 2 causes. *a.* To the fact that the air has travelled a shorter distance over the sea. *b.* To the fact that the heating, which causes the sea breeze to appear, at the same time causes the vertical transfer of momentum to increase, owing to which the general wind at the surface over the land will, as a rule, veer. On the other hand this effect will more clearly mark the front character of the passage through N because then it increases the difference between the direction of the sea breeze and that of the surface wind over the land (see also page 28).

Summarizing it can be said that the theoretical results of Schmidt and Haurwitz agree rather badly with the observations on separate days, in particular as to the front character of the onset of the sea breeze i.e. on days with an offshore general wind. However, this front character does not come out in the mean of the diurnal wind variations on several days. Thus it is obvious why there is a rather good agreement in so far as mean values of wind velocity are concerned, also for days with an offshore general wind.

CHAPTER III

THEORETICAL CONSIDERATIONS CONCERNING THE INFLUENCE OF THE STABILITY OF THE ATMOSPHERE ON THE LAND AND SEA BREEZE EFFECT

Because the observations at IJmuiden do not allow of positive conclusions as to the influence of the stability of the atmosphere on the land and sea breeze effect it is of importance to discuss the subject from theoretical considerations.

The diurnal variation of the temperature difference between the air over the land and that over the sea has usually been taken as the starting point for calculations about the effect. Generally the lapse rate of temperature has also been taken into account so that a mean temperature difference, mean for a certain height, has been taken to be decisive. This is more correct, indeed, since it must be expected that conditions in the higher layers also influence the effect in the layers near the earth's surface.

From chapter II it may be obvious that the land and sea breeze effect originates in the diurnal variation of the differential heat supply to the atmosphere, which heat supply is greater over the land than over the sea in the day-time and greater over the sea than over the land during the night. Owing to this the difference in potential energy of an air column of unit cross section over the land and over the sea will change continuously. This change brings about the phenomenon of land and sea breezes.

However, with a certain diurnal variation of the heat supply the diurnal variation of the temperature difference at the surface between the air over the land and over the sea will be greater with a stable atmosphere than with a less stable atmosphere. Hence the temperature difference at the surface will no longer be decisive for the effect.

That the heat supply is decisive for the increase of the potential energy of the atmosphere appears from what follows. When we imagine an atmosphere with horizontal isobaric and isothermal surfaces the potential energy and the internal energy in a vertical air column of unit cross section, having the height h, will be connected by $P = -p_h h + (\lambda - 1)\, I$. The symbols have the following meanings (see B. Haurwitz. Dynamic Meteorology, 1st edition, 1941, page 241): P is the potential energy of the air column expressed in mechanical units $(= \int_o^h g\, z\, \rho\, dz)$, I is the internal energy of the air column expressed in mechanical units $(= \int_{p_h}^{p_o} \frac{J c_v}{g}\, T dp$, with J for the mechanical equivalent of heat), $\lambda = c_p/c_v$, p_o is the surface pressure and p_h the pressure on top of the air column. The latent heat of condensation has not been taken into account.

When the column extends over the entire height of the atmosphere then $P = (\lambda - 1)\, I$. With an atmosphere having a permanent horizontal uniformity no flow will appear owing to a supply of heat. This is imperative for the validity of the equation. Since the equation is valid independent of the stability of the atmosphere the increase in potential energy will, with a certain heat supply, be independent of the stability.

On investigating the influence of the stability one must compare cases in which, before the heating begins, the surface temperatures are equal over land and sea and in which the lapse rate of temperature over land and sea on the one hand are equal but small and on the other hand are equal but large. If, with the same surface temperatures, the lapse rates of temperature over land and sea would differ, this alone should already result in a flow in horizontal direction, also when there is no supply of heat.

Now, if a supply of heat occurs only over the land, the temperature far from the coast will change, as indicated in figure 21, from a broken line, representing the temperature before heating, to a full line indicating the temperature after heating.

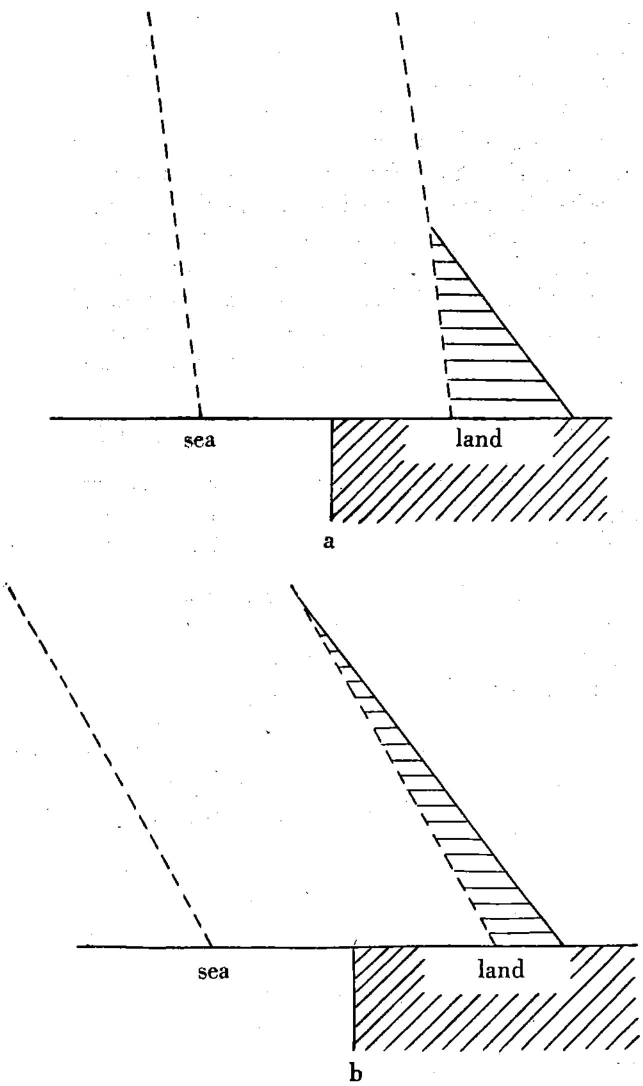

FIGURE 21

Lapse rate of temperature before and after the heating of the land; a. stable, b. less stable atmosphere.

If no flow in horizontal direction would occur through heating, then the same increase in potential energy would appear over the land in the cases *a* and *b* of figure 21, having an equal supply of heat. However, this increase in potential energy will in case a for a greater part belong to the lower layers than in case b. This may be seen at once by considering that the supply of heat in the higher layers has no influence on the potential energy of the subjacent layers.

In reality heating over the land will yield a mass flux to sea. This must have its maximum at a smaller height in case a than in case b. However, it cannot be seen at once if this mass flux in case a will be different from that in case b.

The sea breeze, which will form a circulation with the outflow occuring in the higher layers, will appear in a layer that is thicker in case b than in case a. In this circulation the supplied energy partly changes into kinetic energy. It cannot be said whether, with the same difference in potential energy between land and sea but with a smaller sea breeze height, the speed of the sea breeze at the surface in case a will differ from that in case b. In the first place this cannot be said because the net mass flux in the two cases cannot be compared and in the second place because the sea breeze in case a experiences a greater influence of the friction in a thinner layer on the surface than in case b.

It will be useful to know what the publications under review teach us concerning this point.

Though Schmidt (1947) did not deal with the influence of the stability on the velocity of the sea breeze, yet his calculation can lead to conclusions with regard to that.

We may expect that in figure 21 a, in comparison with figure 21 b, (see page 40 for the meaning of the figures):

a is greater,

b is practically equal (in addition, according to Schmidt, b is one order of magnitude smaller than a),

δ_0 is greater.

As to f it cannot be said at once how its value is connected with the stability of the atmosphere but according to Schmidt f may probably be considered constant since he has taken f to be equal during the night and during the day.

δ_0 will practically be proportional to τ_0. But with equal insolation (heat supply) a will practically be proportional to τ_0 as well.

From this the following appears:

1°. From the equation for u_m (page 41) it follows that the level at which the sea breeze passes into the outflow existing over it is determined by:

$$z\, e^{[h - (a+b)]z} = \{f / (a+b)^2\} e^{(h-f)z}.$$

If b and f are constant $\partial z/\partial a$ is negative. Thus with a more stable atmosphere the layer in which the sea breeze occurs is less high than with a less stable atmosphere. This has already been derived direct from figure 21.

2°. The net mass flux through a vertical plane of unit width parallel to the coast-line is maximum on the coast. It has the amplitude $f\, \lambda\, \delta_0 / T\, (a+b)^2$ there ($T =$ 24 hours). This means that with a more stable atmosphere a smaller net mass flux must occur.

This result will have to be understood in the following way. If the heating reaches higher into the atmosphere, so that the upper air increases relatively more in potential energy, the lifting of the higher isobaric surfaces will have to be greater than with a more stable atmosphere. Owing to this the net mass flux can yet be greater in spite of the smaller density of the air above.

At first sight it seems unsatisfactory that the friction factor does not occur in Schmidt's formula for the net mass flux for it may be expected that this factor affects the flux. Since the friction factor will also be a function of the stability of the atmosphere the stability would have its influence on the flux also by means of the friction factor.

However, if Schmidt's approximation, viz. $\cos \overline{\beta} = 0$, is not used it appears that a greater friction does reduce the mass flux but that its influence must be slight.

3°. As regards the horizontal velocity component in the direction from the sea to the land, called u, it is not at all certain that with a certain insolation and with a stable atmosphere, i.e. with a smaller net mass flux, the sea breeze will have a greater surface speed than with a less stable atmosphere. A greater speed might probably be expected because with a stable atmosphere the diurnal variation of temperature and the diurnal density variation at the land surface are relatively great and also because then the net mass flux must lead to a sea breeze having a relatively small height.

The surface value of u, calculated from Schmidt's formula in case $z = 0$, follows from:

$$u = \frac{\pi^2\, g\, \delta_0\, \alpha_0\, f}{\lambda\, T\, (\omega\, c_0 \cos \beta - \omega^2 \sin \beta)\, (a+b)^2} \times$$

$$\sin (\omega t + \beta) \cos \frac{\pi x}{\lambda}, \text{ with } \beta = \text{arc tan } (-\omega / c).$$

Then

$$u_{\max} = \pi^2\, g\, \delta_0\, \alpha_0\, f\, c_0 / \lambda\, T\, (a+b)^2\, \omega \cos \beta\, (c_0^2 + \omega^2),$$

with c_0, the surface friction factor, being determined by $c = c_0\, e^{-rz}$.

When c decreases $|\beta|$ increases. Schmidt looks upon this as a cause for the increase of β with altitude (already said before on page 41). Van Bemmelen (1922) ascribed this increase of β to the fact that the heating gradually extends over a greater height. Therefore the moment of the maximum temperature difference between land and sea will occur later when a higher level is considered. This has not been taken into account in the temperature field proposed by Schmidt so that he could only find the influence of c on β. By supposing that it is indeed only c that affects β he could, by extrapolation from the observations up to 800 m at Djakarta (Van Bemmelen, 1922), arrive at the values $c_0 = 1.5\, (10^4 \text{ s})^{-1}$ and $r = (10^3 \text{ m})^{-1}$.

It is satisfactory that, as it does in its phase, the friction factor also occurs in the amplitude of u, so that a greater friction yields a smaller speed of the sea breeze.

It has been shown that, with an equal insolation, δ_0 and a are approximately proportional to τ_0. With a more stable atmosphere δ_0 and a thus are greater than with a less stable atmosphere. Since α_0 is approximately proportional to the absolute temperature, α_0 will change much less than proportional to τ_0. If we take f constant and, with a stable atmosphere, we take c_0 greater, i.e. $|\beta|$ smaller, than with a less stable atmosphere then u_{max} at the surface will be smaller with a more stable atmosphere than with a less stable atmosphere.

The introduction of the Coriolis force in Schmidt's calculation does not alter the conclusions we have just drawn.

Summarizing it can be said that Schmidt's calculation shows that the stability of the atmosphere probably acts in such a way that a smaller stability and a stronger sea breeze coincide, in particular because then the outflow of air in the higher layers from land to sea would be greater. The reliability of this deduction from Schmidt's formulae is much reduced by point 1 of the criticism on his work (page 41).

The most important point is, however, that Schmidt's calculation proves that the sea breeze speed is not determined by the diurnal variation of temperature but rather by the differential heat supply over land and sea.

As for the work of Haurwitz we might restrict ourselves here to the statement that he remarked that the stability of the atmosphere must have a considerable influence on the sea breeze speed. However, he did not indicate whether this influence must, for instance with a stable atmosphere, bring about a greater or a smaller sea breeze speed.

Yet his work is instructive for the problem under review. In the first part of his investigation the circulation theorem of Bjerknes has been taken as the starting point. Then the integration, along the line mentioned on page 42, results in the mean wind speed along the line of integration being proportional to $\frac{\overline{Ta} - \overline{Tb}}{L} \ln p_0/p_1$, i.e. to $\frac{\overline{Ta} - \overline{Tb}}{L} \int_o^z \frac{1}{T}\, dz$. The meanings of the symbols have been given on page 42. If we take T independent of z the speed is determined by $(\overline{Ta} - \overline{Tb})\ h$, in which h represents approximately the height for which Ta and Tb are averaged. This formula also shows that the insolation is more important than the surface temperature difference.

If the circulation theorem of Bjerkness is applied to the observations at Djakarta (Van Bemmelen, 1922) at the moment of maximum sea breeze speed at the surface, while this speed still increases at greater heights, the circulation will decrease for a line of integration in the sea breeze. Since $\overline{Ta} - \overline{Tb}$ is still positive now this means that the friction, which renders dC/dt negative, is more important than the influence of $\overline{Ta} - \overline{Tb}$, a positive temperature difference making dC/dt positive. In this case it will be clear that the calculation of the sea breeze speed, as a mean value along and in the direction of the line of intergration, is inadmissible. Moreover this favours Schmidt's view, and that of the author (page 32), that the change of the friction with altitude has a great influence on the increasing phase difference with increasing height.

It must be said here that Haurwitz did not use the calculated amplitude of the wind speed, as calculated from the circulation theorem of Bjerkness, for drawing conclusions. The theorem has only been employed for the calculation of the surface phase difference between the wind speed on the one hand and the temperature difference between land and sea on the other hand.

In the 2nd and 3rd parts of Haurwitz' publication a pressure gradient perpendicular to the coast has been assumed, which gradient is a function of the time. Here it cannot directly be seen whether the temperature difference between land and sea or the heat supply to the air has been taken as a parameter for this extra pressure gradient. However, as Haurwitz gave a figure-example, this can be found because he has taken this gradient proportional to $z \frac{\partial T}{\partial x}$ and has chosen for $\partial T/\partial x$ 3° per 60 km, being the gradient of the mean temperatures in the lower 300 m layer, and for z the height of 300 m. Here 300 m has been taken as the height at which the pressure in a horizontal plane is the same all over. Then $z \frac{\partial T}{\partial x}$ is rather a measure for the heat-supply to the lower layers of the atmosphere than for the temperature difference between land and sea.

But then it follows by no means immediately from the equation of Haurwitz what influence the stability of the atmosphere will have on the sea breeze speed.

Bleeker and Andre (1950 a) dealt especially with the circulation that appears owing to cloud formation, i.e. owing to the liberation of heat at a certain height in the atmosphere. They are positive in stating that it must be expected that the circulation as a whole will be intensified by a smaller stability of the atmosphere. However, this view cannot simply be extended to the land and sea breeze effect.

Since they had in view a heating somewhere in the atmosphere their opinion must mean that, with two clouds developing at the same level but the one in a stable and the other in a less stable atmosphere, the horizontal velocity in the lower part of the circulation is greater with a less stable atmosphere, even when the heat supply is equal in both cases.

On the other hand the pressure field directly below the heated area makes its influence felt as far as the earth's surface. Now, if the same supply of heat occurs at a smaller and at a greater height, an as intense vertical motion and also an as intense horizontal motion in and over the heated area will be possible while yet the horizontal motion below the lowest level of the heated area will be slower in the case of a heating at greater height because this motion now extends over a thicker layer.

For this reason the view of Bleeker and Andre, referred to above, cannot be applied straight away to the land and sea breeze effect. With an unstable atmosphere, in comparison with a stable atmosphere, the same supply of heat from the ground to the air will, on an average, occur at a higher level and give a more intense circulation but also will place a thicker layer at the disposal of the horizontal motion near the surface. Therefore the horizontal surface speed will, with a supply of equal quantities of heat to a stable and to a less stable atmosphere, not have to be greater with the les stable atmosphere. Thus it may be clear that from the picture of Bleeker and Andre we cannot simply infer the influence of the stability on the speed of the sea breeze.

It is worth while remarking here that a quantitative deduction from Bleeker's picture of the "indirect" circulation will need the influence of the stability of the higher layers of the atmosphere to be taken into account (Bleeker, 1950 b).

Hornickel is of opinion that the penetration over the land of a sea breeze that is accompanied by front phenomena requires at least an approximately dry-adiabatic lapse rate of temperature in the air over the land. In those cases in which such a sea breeze penetrates over the land whereas the land-air is stable the sea breeze is supposed to set in late and to be admitted by a decrease of the offshore general wind speed towards the evening. However, such cases are held to be exceptions.

For only two of such days with stable land-air the sea breeze speeds have been given by Hornickel viz. 3.1 m/s and 3.7 m/s as means for all the stations (in the second case 4.5 m/s at one of the stations). The amount of data available is too small to allow of conclusions as to the sea breeze speed being influenced by the stability of the atmosphere (in 27 cases with an unstable atmosphere over the land the sea breeze speed was on an average 4.1 m/s for all stations).

The condition imposed by Hornickel on the land-air for the appearance of a sea breeze, i.e. its being unstable or indifferent, must be seen as a condition that must have been fulfilled in order to cause the front to move landward. That this circumstance of the land-air is favourable in this respect can also be understood from the picture presented by Bleeker and Andre as has already been said on page 33. Nothing positive is therefore to be found with Hornickel about the sea breeze speed in connection with the stability of the atmosphere.

Summarizing chapter III, it may be said that mainly the differential daily variation of the heat supply to the atmosphere over the land and over the sea must be held to be decisive for the land and sea breeze effect and not the differential daily variation of the temperature difference near the surface.

In this connection it is of importance to remark that in the tropics, where the daily variation of the temperature difference between land and sea is of the same order of magnitude as at the temperate latitudes, the land and sea breeze effect will come out so much clearly owing to the greater insolation. In addition an important part will, of course, also be played by the fact that the general pressure gradient in the tropics is usually small so that it is more readily considerably disturbed by the gradient appearing near the coast as a consequence of the difference in heating and cooling between land and sea (Braak, 1929 a).

In spite of the importance of the insolation that is argued here it should not pass unnoticed that the insolation is not invariably the best measure for the appreciation of the heat supplied to the atmosphere. One and the same insolation will with, for instance, a different water content of the soil not supply the same amount of heat to the atmosphere. A difference in vegetation in the various seasons will also bring about a difference in this respect. Therefore in practice the daily variation of the temperature difference between the air over land and sea, but then taken as a mean for a sufficiently great height, will be a better measure for the effect to be expected.

An influence of the stability of the atmosphere on the sea breeze speed does not come out clearly, neither from the theory nor from the observations.

According to theory the landward extension of the sea breeze seems to be promoted by a smaller stability of the air over the land. The investigation at IJmuiden, situated direct on the coast, cannot supply further data on this point. Koschmieder's observations agree with theory on this point.

SUMMARY

After a brief introduction an investigation of the land and sea breeze effect, in particular of the sea breeze effect, has been described. The investigation was based on wind observations at IJmuiden. It appears that here a change of the general wind in the course of the day often wrongly suggests the appearance of the sea breeze phenomenon. It has been discussed how this may lead to it that, from a statistical investigation, the impression may be suggested that the phenomenon manifests itself less clearly with a greater insolation. Also the fact that in the Netherlands, on days with an offshore general wind, the wind speed on an average is greater with greater insolations will contribute to this wrong impression. The latter cause has been ascribed to the trend of the Dutch coast and to its location with reference to the hinterland.

An important result is that the appearance of the sea breeze is opposed more when the offshore component of the general wind is larger. Data have been given with a view to the forecast of the sea breeze. An indication has been found that the insolation is more decisive for the occurence of the sea breeze than the surface temperature difference between the air over land and over sea.

In a discussion of a few recent publications on the subject an extension of the view given by Bleeker has been proposed. It has been developed as a starting point for further discussions.

A comparison with the work of Koschmieder showed that his observations fit in the picture given by Bleeker, while Koschmieder's theoretical considerations have been criticized. This criticism was especially directed against his view of the formation of a sea breeze front, out to sea, by an accumulation of cold air.

A comparison of the observations at IJmuiden and the theory of Haurwitz and of Schmidt showed that, apart from the front character of the onset of the sea breeze, there is a good agreement in so far as mean values for several days are used.

It has been discussed that the elaborated conception of Bleeker is very suitable for explaining the front character of the onset of the sea breeze.

In a last chapter the influence of the stability of the atmosphere on the sea breeze is dealt with. Theoretical considerations on this point have been given, in particular by way of extension of the calculation of the sea breeze effect given by Schmidt.

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Number of classification	N1	N2	N	C	F	0—1	1—2	2—3	3—4	4—5	5—6	6—7	7—8	8—9	9—1
111	13	14	27	g	F	+1.9+1.1	+1.7+1.0	+1.8+1.0	+1.7+1.0	+1.9+0.7	+1.8+0.7	+2.2+0.9	+2.8+0.8	+2.6+0.7	+2.8+
112	6	5½	11½	m	F	+1.7+0.6	+1.8+0.7	+1.8+0.7	+1.7+0.7	+1.5+0.8	+1.4+1.0	+1.6+0.9	+2.3+0.9	+2.8+0.6	+3.0+
113	5½	16½	22	g	F	+1.4+1.0	+1.3+1.0	+1.6+0.8	+1.6+0.8	+1.5+0.7	+1.5+0.9	+1.6+0.9	+2.1+0.7	+2.5+0.7	+2.8+
114	6	11	17	g	F	+1.4+0.8	+1.2+0.8	+1.3+0.9	+1.3+0.9	+1.2+0.9	+1.2+1.0	+1.3+1.3	+1.5+1.2	+1.7+1.1	+2.9+
121	7	14½	21½	g	F	+3.8+0.9	+4.0+1.4	+4.3+1.3	+4.6+1.3	+4.7+1.5	+5.2+1.2	+5.0+1.0	+5.4+1.1	+6.0+1.4	+6.6+
122	4½	11	15½	g	F	+3.9+0.6	+3.6+1.2	+3.7+1.1	+4.3+1.2	+4.4+1.5	+4.7+1.7	+5.5+1.5	+6.0+1.1	+7.1+0.4	+8.0+
123	4	5	9	g	F	+4.6+0.9	+4.0+1.2	+4.6+1.2	+3.0+1.1	+2.3+0.9	+2.8+1.2	+3.0+1.1	+4.4+0.8	+6.0+0.1	+7.8—
124	2	2½	4½	m	F	+3.2+2.3	+2.7+2.3	+2.3+1.8	+1.8+1.3	+2.3+1.8	+3.0+2.6	+4.3+3.8	+4.8+4.3	+4.7+4.7	+5.1+
211	8½	11½	20	m	F	+1.1+1.1	+0.9+1.0	+0.7+1.3	+0.8+1.3	+0.8+1.3	+0.8+1.4	+0.6+1.2	+0.9+1.1	+1.1+0.9	+1.7+
212	11	8½	19½	s	F	+1.5+2.1	+1.4+2.0	+1.1+2.4	+1.0+2.2	+1.1+1.6	+1.1+1.8	+1.0+2.1	+1.0+2.2	+1.2+1.9	+1.5+
213	20½	16½	37	g	F	+1.0+2.0	+0.9+2.0	+0.9+2.1	+0.9+2.1	+0.8+2.2	+0.8+2.1	+0.7+2.4	+0.8+2.6	+0.8+2.2	+1.2+
214	27½	29½	57	m	F	+1.0+2.3	+0.9+2.4	+0.8+2.3	+0.8+2.3	+0.8+2.1	+0.8+2.3	+0.6+2.5	+0.7+2.6	+0.6+2.3	+1.1+
221	4½	1	5½	s	F	+1.6+3.1	+1.6+3.0	+1.6+3.0	+1.5+2.8	+1.6+2.7	+1.6+2.8	+1.6+2.4	+2.2+2.6	+3.0+2.4	+3.5+
222	4½	8	12½	s	F	+1.6+3.4	+1.3+3.5	+1.6+3.6	+1.5+4.0	+1.3+3.9	+1.3+3.9	+1.5+4.2	+1.8+4.5	+1.5+5.0	+1.3+
223	1	12	13	s	F	+2.0+4.6	+1.8+4.5	+1.8+4.5	+1.9+4.5	+2.0+4.5	+2.1+5.4	+1.9+5.6	+2.3+6.1	+1.9+5.8	+1.9+
224	7½	8½	16	g	F	+1.7+4.3	+1.7+4.3	+1.5+4.4	+1.3+4.2	+1.5+4.7	+1.5+4.9	+1.6+5.7	+1.5+6.4	+1.4+6.8	+1.5+
311	4½	6	10½	s	F	—0.9+1.5	—1.3+1.7	—1.3+2,1	—1.2+2.4	—1.4+2.9	—1.7+3.0	—1.9+2.8	—2.2+2.8	—2.1+2.7	—2.5+
312	7½	9	16½	g	F	+0.1+1.9	—0.3+2.2	—0.9+2.7	—1.1+2.6	—0.9+2.5	—1.4+2.4	—1.7+2.0	—2.0+1.7	—1.9+1.3	—1.5+
313	6	8	14	g	F	—0.4+2.3	—0.3+2.1	—0.3+2.0	—0.6+1.9	—0.6+2.2	—0.8+1.9	—1.0+1.6	—1.4+1.4	—1.0+1.1	—1.0+
314	4	10½	14½	m	F	—0.5+2.2	—0.6+2.3	—0.8+2.2	—1.0+2.5	—1.1+2.6	—1.2+2.7	—1.5+2.7	—1.5+2.8	—1.4+2.4	—1.1+
321	9	3	12	m		—1.3+1.9	—1.6+2.3	—1.3+2.4	—1.1+2.8	—1.6+2.1	—2.4+2.7	—3.5+1.6	—3.6+0.7	—4.2—0.4	—4.8—
322	4½	3	7½	m		—0.9+1.0	—0.6+2.2	—0.8+2.8	—1.5+3.4	—1.6+4.0	—1.8+3.7	—2.1+3.9	—3.9+1.1	—1.9—1.1	—1.5—
323	2½	4	6½	s		+0.1+3.1	—0.5+3.9	—0.8+4.5	—1.7+4.4	—2.0+4.5	—2.5+4.4	—2.9+4.3	—3.4+2.9	—3.5+3.1	—3.3+
324	4½	—	4½	—		—2.7+1.5	—1.6+1.9	—1.5+1.7	—0.9+1.9	—0.9+1.8	—0.4+2.0	—1.0+3.1	—1.6+3.7	—1.4+3.0	—1.3+
411	5½	6½	12	g	F	—2.6+0.7	—2.5+0.8	—2.8+0.8	—2.8+0.9	—2.7+0.8	—3.0+0.9	—3.2+0.2	—2.8—0.4	—2.6—0.7	—2.7—
412	8	8	16	m	F	—2.6+0.4	—2.5+0.2	—2.6+0.8	—2.8+0.9	—2.9+0.9	—3.0+0.4	—3.0+0.1	—3.0—0.5	—2.9—0.9	—2.4—
413	7½	7½	15	g	F	—1.3+0.7	—1.7+0.8	—1.9+1.1	—2.5+1.1	—2.8+0.8	—3.0+0.6	—3.4+0.1	—3.6—0.8	—3.4—1.5	—2.9—
414	7	10	17	g	F	—1.5+0.5	—2.2+0.4	—2.3+0.3	—2.5+0.5	—2.5+0.5	—2.3+0.2	—2.4—0.3	—2.8—1.0	—2.8—1.5	—2.2—
421	9½	4½	14	m		—4.3+0.4	—4.7+0.4	—4.5+0.9	—4.8+1.0	—4.5+1.0	—4.2+0.5	—4.1—0.4	—4.9—1.1	—4.9—1.6	—5.1—
422	9½	9	18½	g		—3.4+0.8	—3.3+0.7	—3.9+1.3	—4.2+1.4	—4.7+0.7	—5.1+0.3	—5.6—0.3	—6.1—1.5	—6.0—2.2	—6.1—
423	4	2	6	m		—3.7——	—3.0+0.7	—3.2+0.8	—3.3+1.4	—3.7+1.6	—3.6+1.6	—4.2+0.5	—4.5—1.5	—3.2—2.0	—3.5—
511	6	9½	15½	m	F	—2.1—0.6	—2.2—0.6	—2.3—0.5	—2.7—0.6	—2.9—0.9	—2.4—0.7	—2.7—1.2	—2.5—1.0	—2.4—1.1	—2.2—
512	7½	4	11½	s	F	—2.3—1.1	—3.0—1.1	—3.1—1.4	—3.3—1.4	—3.5—0.9	—3.2—1.0	—3.3—1.0	—3.5—1.4	—3.5—2.1	—2.8—
513	7	4½	11½	g	F	—3.6—2.0	—3.2—1.9	—3.2—1.6	—3.2—0.9	—3.1—1.0	—3.4—1.3	—2.8—1.4	—3.0—2.1	—3.1—2.4	—2.7—
514	7	1	8	g	F	—2.6—0.8	—3.0—0.4	—3.2—0.4	—3.3—0.7	—3.3—1.0	—2.9—1.3	—2.7—1.5	—2.9—2.2	—2.9—2.7	—2.6—
611	3½	6	9½	m	F	—3.1—2.7	—3.3—2.8	—3.0—3.6	—2.8—4.0	—1.8—3.5	—1.8—2.9	—1.6—2.6	—1.9—2.9	—1.7—3.4	—1.6—
612	3	6	9	g	F	—1.8—3.0	—2.0—3.4	—2.3—3.5	—2.2—4.0	—1.8—4.1	—2.0—3.4	—2.0—3.1	—2.0—3.1	—1.9—3.5	—1.9—
613	5	2	7	m	F	—0.1—3.1	—0.8—2.1	—1.3—2.4	—1.4—2.3	—1.0—3.0	—1.0—3.0	—1.1—2.9	—1.5—3.1	—1.6—3.9	—1.1—
711	3½	3	6½	m	F	+0.8—3.5	+1.1—3.1	+1.1—3.4	+1.3—4.2	+2.4—4.4	+2.1—4.3	+2.2—3.7	+2.2—3.9	+2.7—3.2	+2.3—
712	4½	5	9½	m	F	+1.2—5.7	+1.1—5.6	+1.1—5.5	+1.2—5.4	+2.0—4.9	+2.0—3.8	+1.5—2.7	+1.2—1.8	+1.1—1.2	+0.9—
713	7	3½	10½	g	F	+0.1—0.8	—0.3—1.3	——2.2	+0.3—3.1	+1.0—2.7	+1.0—2.8	+0.8—2.7	——2.4	——2.9	+0.1—
714	4	—	4	—	F	+1.4—2.6	+1.4—2.6	+1.5—2.8	+1.0—2.6	+1.1—2.8	+1.8—2.4	+1.8—2.1	+1.5—2.5	+2.2—2.8	+1.0—
811	6½	5½	12	g	F	+4.4—2.0	+4.2—1.9	+4.3—2.0	+4.5—1.7	+4.2—1.5	+3.3—1.2	+3.1—0.8	+2.6—0.5	+2.4—1.0	+2.5—
812	3½	3	6½	m	F	—0.4—1.6	+0.5—2.1	+1.6—2.2	+3.1—2.7	+2.9—1.9	+2.5—1.8	+2.3—1.7	+2.1—1.8	+1.8—1.5	+1.6—
813	5½	3½	9	m	F	+1.7—0.8	+1.7—0.9	+2.3—0.8	+2.8—1.4	+2.7—1.0	+2.4—0.6	+2.5—0.7	+1.8—0.6	+1.9—1.0	+2.6—
814	1	2	3	g	F	+1.4—0.9	+1.6—1.0	+2.2—1.1	+3.0—1.1	+3.4—1.1	+4.7—1.9	+4.2—0.6	+4.3—0.8	+4.3—1.2	+4.6—

TA

Diurnal variation of mean wind in sur

HOUR OF THE DAY

10—11	11—12	12—13	13—14	14—15	15—16	16—17	17—18	18—19	19—20	20—21	21—22	22—23	23—24
+2.9—0.1	+3.0—0.4	+3.3—0.6	+3.3—1.0	+3.4—0.9	+3.4—0.9	+2.8—0.5	+2.5—0.7	+2.5—0.5	+1.5—0.4	+0.9—0.2	+0.6—0.2	+0.4—0.2	——0.2
+2.8—0.1	+3.3—0.3	+3.4—0.3	+3.4—0.2	+3.4——	+3.6+0.3	+3.6+0.8	+2.9+1.1	+2.2+0.9	+1.9+0.6	+1.5+0.5	+1.1+0.8	+1.0+0.9	+0.8+0.8
+3.0+0.3	+3.7——	+4.3—0.4	+5.2—0.8	+5.4—1.0	+5.4—0.6	+4.8—0.4	+4.2—0.3	+3.3+0.2	+2.3+0.2	+1.4——	+1.1——	+1.1+0.1	+0.8——
+4.5+0.4	+5.1+0.2	+5.8—0.1	+6.4—0.4	+6.8—0.3	+6.5——	+5.9+0.3	+5.2+0.7	+3.6+1.1	+1.9+1.0	+1.2+0.8	+1.1+1.0	+1.2+1.2	+1.0+1.2
+7.0+0.3	+7.3—0.1	+7.8—0.2	+7.8—0.1	+7.9—0.1	+8.3—1.0	+8.4—1.0	+8.1—1.2	+7.4—0.7	+6.6—0.5	+6.4—0.4	+5.7—0.2	+5.2—0.6	+5.5—1.0
+8.8—0.2	+8.8—0.6	+9.1—0.8	+9.5—0.6	+9.4—0.6	+9.3—0.4	+9.3—0.6	+9.0—0.4	+8.4—0.7	+7.7—0.5	+7.3—0.7	+6.6—0.6	+6.2—0.6	+6.2—1.0
+7.9—1.2	+8.2—1.2	+8.7—1.4	+8.9—1.3	+8.8—1.2	+8.9—0.9	+8.3—0.7	+7.9—0.8	+6.6—0.4	+4.0—0.1	+2.8—0.1	+2.4+0.1	+1.9+0.3	+1.5——
+5.5+5.0	+5.5+5.1	+5.7+4.8	+5.6+4.5	+5.6+4.5	+5.9+4.1	+5.5+4.3	+5.6+3.8	+5.2+3.2	+4.7+2.7	+4.4+2.1	+4.2+2.4	+4.0+2.2	+3.8+2.3
+1.7—0.2	+2.7—0.3	+3.1—1.1	+3.0—0.8	+3.0—0.8	+3.2—0.5	+2.9—0.4	+2.7—0.6	+2.9—0.6	+2.6—0.4	+2.2—0.1	+1.8+0.2	+1.4——	+1.6—0.3
+1.6+1.3	+2.1+0.7	+2.3+0.4	+2.4—0.4	+2.7—0.7	+2.7—0.9	+2.7—0.8	+2.4—0.2	+1.9—0.2	+1.1—0.1	+0.7—0.1	+0.6—0.2	+0.4+0.1	+0.2+0.3
+1.4+1.4	+1.8+1.4	+2.1+1.2	+2.2+0.5	+2.2+0.5	+2.1+0.6	+2.0+0.9	+1.6+0.9	+1.1+0.8	+0.6+0.4	+0.7+0.3	+0.7+0.5	+0.8+0.6	+0.6+0.4
+1.6+2.3	+1.9+2.1	+2.1+2.0	+2.6+1.7	+2.8+1.7	+3.0+1.8	+2.9+1.7	+2.6+1.7	+1.7+1.4	+1.1+1.2	+0.9+1.3	+0.9+1.7	+0.9+1.9	+0.9+2.0
+4.2+1.3	+4.8+1.2	+5.0+0.4	+4.9——	+5.3—0.4	+5.3—0.9	+5.2—1.4	+4.8—1.8	+4.6—2.1	+4.3—2.5	+4.5—2.5	+3.7—1.4	+2.8—1.3	+2.0—1.2
+2.4+3.7	+2.9+3.6	+3.1+3.7	+3.2+3.6	+3.1+3.0	+3.0+3.1	+3.0+3.3	+3.0+2.8	+2.7+2.4	+2.2+2.1	+2.2+1.9	+2.1+1.7	+1.9+1.4	+2.0+1.1
+1.8+6.0	+2.6+5.1	+3.6+4.5	+3.6+4.4	+3.7+4.6	+3.9+4.3	+3.8+4.0	+3.8+3.7	+3.2+3.1	+2.8+2.5	+2.6+2.4	+1.9+2.8	+1.2+3.1	+1.0+2.5
+1.6+7.1	+1.7+7.3	+1.8+7.4	+1.4+7.3	+1.1+7.2	+0.8+6.7	+0.9+6.4	+0.9+5.5	+1.1+4.3	+1.1+3.9	+1.2+4.4	+1.4+4.6	+1.3+4.7	+0.9+4.4
—3.2+1.4	—3.1+0.9	—3.0+0.8	—2.6+0.3	—2.1+0.2	—1.4+0.5	—0.8—0.3	—1.0—0.3	—1.2+0.1	—1.4+0.1	—1.3+0.4	—1.4+0.1	—1.2+0.2	—1.4—0.2
—1.8+0.4	—0.9—0.4	+0.6—0.7	+1.0—0.5	+1.3—0.1	+2.1—0.1	+2.0+0.1	+1.7—0.6	+1.0—0.2	+0.9—0.3	+0.6——	——0.2	—0.2—0.3	—0.4—0.6
—0.7+0.4	—0.3+0.6	—0.5+0.7	—0.1+0.5	+0.2+0.1	+0.7+0.2	+0.6+0.4	+0.7+0.4	+0.7+0.4	+0.8+0.7	+0.4+1.0	+0.2+1.0	+0.2+1.0	——+1.0
—0.3+1.6	—0.6+1.5	+0.5+1.3	+1.0+1.0	+1.5+1.0	+1.8+1.0	+1.7+1.5	+1.4+2.0	+1.1+2.0	+0.9+1.9	+0.8+1.9	+0.7+2.1	+0.5+2.4	+0.6+2.8
—4.9—2.7	—4.9—3.1	—4.7—3.9	—3.7—4.6	—3.2—5.0	—3.1—5.5	—3.2—5.4	—2.8—5.6	—2.6—5.4	—2.1—5.7	—3.0—5.1	—2.9—4.7	—2.4—5.2	—2.1—5.0
—1.6—2.9	—1.6—4.6	—1.8—5.8	—2.1—6.5	—2.4—6.7	—2.6—6.8	—2.0—6.0	—2.7—6.3	—3.2—6.7	—2.7—6.2	—2.4—5.3	—2.1—5.4	—2.3—5.6	—1.9—5.4
—3.4+3.9	—2.9+3.5	—1.9+1.2	—0.7+0.2	——0.1	+0.1—0.3	+0.1—0.6	+0.4—1.2	+1.4—1.4	+1.6—1.2	+0.9—1.2	+1.3—1.7	+1.6—2.0	+2.8—2.1
—1.2+0.9	—1.0+0.6	—1.2+0.8	—1.0+0.8	—1.0+0.2	—1.1—0.6	—0.4—2.2	—0.3—1.8	—0.5—0.2	—0.6—0.1	—0.2—1.4	—0.6—0.7	—0.8—0.5	—1.6—1.3
—2.3—1.3	—1.6—1.2	—1.0—1.4	—0.4—1.9	+0.5—1.1	+0.9—0.6	+1.0—0.1	+0.9—0.1	+0.6—0.3	+0.7—0.2	+0.3—0.2	+0.5+0.4	+0.3+0.5	——+0.7
—1.9—2.0	—1.5—2.3	—0.5—2.5	—0.4—2.0	+0.5—1.9	+0.8—1.6	+1.2—1.6	+1.4—1.3	+0.8—1.0	——0.8	—0.5—0.4	—0.7—0.4	—0.8—0.2	—0.8—0.3
—2.3—2.4	—1.9—2.5	—1.0—3.1	—0.2—2.8	+0.3—2.2	+0.9—2.1	+1.3—1.3	+0.7—0.3	+1.0+0.2	+0.8——	+0.8—0.1	+0.8+0.6	+0.6+1.3	+0.1+1.4
—2.1—1.8	—1.8—1.8	—1.4—2.1	—1.1—2.1	—0.3—2.0	——1.7	—0.2—1.1	+0.3—0.7	+0.3—0.5	+0.3+0.1	+0.1+0.5	——+0.5	—0.4+0.9	—0.7+0.4
—4.9—3.8	—4.9—4.2	—5.1—4.2	—4.9—4.4	—4.3—4.6	—4.3—4.6	—4.0—4.3	—3.9—4.2	—4.1—4.1	—3.9—4.2	—3.3—4.2	—3.7—3.9	—3.5—4.3	—3.2—4.4
—6.2—3.9	—5.9—4.3	—5.7—4.7	—5.9—4.4	—5.5—3.8	—5.3—3.5	—4.6—3.7	—4.5—3.5	—3.7—3.6	—3.0—2.9	—3.3—2.5	—3.8—2.9	—3.7—3.3	—4.0—3.5
—3.9—4.1	—3.9—4.8	—3.7—4.4	—3.4—4.9	—3.3—4.6	—4.2—4.7	—4.4—4.5	—5.0—4.8	—5.0—4.1	—3.9—4.1	—3.1—4.1	—2.2—4.8	—2.1—5.0	—2.2—7.6
—2.6—2.2	—2.2—2.1	—1.3—2.5	—1.1—2.1	—0.9—2.2	——2.1	+0.8—1.6	+1.0—1.1	+1.2—0.7	+0.8—0.5	+0.4—0.4	+0.2—0.3	+0.1—0.1	——0.2
—2.1—2.7	—2.6—2.7	—1.5—2.7	—1.2—3.2	—0.3—3.0	—0.8—2.4	—1.1—1.9	—1.2—1.7	—1.5—1.3	—2.1—1.1	—2.4—0.9	—2.7—1.1	—2.5—0.8	—2.4—0.7
—2.1—2.9	—1.4—2.9	—0.9—2.9	—0.5—2.3	—0.2—1.8	—0.1—1.4	+0.7—0.9	+0.8—0.3	+0.8+0.3	+0.5+0.7	+0.2+0.8	—0.1+1.1	—0.3+1.2	—0.7+1.4
—1.9—3.7	—1.7—4.0	—1.0—3.8	+0.1—3.3	+0.8—3.0	+0.7—1.9	+1.1—1.1	+1.2—0.3	+0.4+0.2	——+0.4	—0.2+1.0	—0.1+1.1	—0.1+1.0	—0.4+1.4
—1.4—2.8	—0.8—3.0	—0.8—2.8	—0.1—3.1	+0.3—2.9	+1.0—2.6	+0.8—1.8	+0.8—1.7	+0.9—1.2	+0.3—1.0	+0.4—1.1	—0.4—1.2	—0.3—1.2	—1.2—0.9
—1.8—3.8	—1.2—3.9	—1.0—3.8	—0.4—4.0	—0.1—3.5	+0.5—3.2	+0.8—2.8	+1.1—2.1	+0.9—1.0	+1.1—0.4	+0.7+1.0	+0.1—1.6	+0.2+1.7	—0.2+1.9
—0.9—3.7	—0.6—3.3	—0.6—3.3	—0.5—3.3	—0.4—2.6	—0.2—2.1	——2.0	+0.3—1.6	+0.4—1.0	+0.6—0.6	+0.6—0.3	+0.4—0.2	+0.2+0.3	+0.2+1.0
+2.8—2.6	+2.6—2.7	+2.1—2.6	+2.4—3.0	+2.3—3.0	+1.8—2.3	+1.4—2.2	+1.7—1.5	+2.0—1.3	+2.9—0.9	+2.0—0.6	+1.6——	+0.2+0.3	+0.1+0.4
+1.0—1.4	+1.4—2.6	+1.5—2.8	+1.8—3.3	+2.7—3.5	+2.8—3.5	+2.5—3.2	+1.7—1.9	+0.8—0.8	+0.4—0.2	+0.6+0.1	+0.6+0.4	—0.2+1.0	—0.4+1.1
+0.3—3.5	+0.8—3.5	+0.9—3.7	+1.6—3.5	+2.2—3.6	+2.6—3.2	+2.5—2.8	+2.3—1.9	+1.8—1.4	+1.5—1.1	+1.0—1.1	+0.4—0.6	+0.2—0.1	—0.3—0.1
+1.1—2.3	+1.4—2.5	+2.7—3.1	+3.2—3.4	+4.0—3.0	+5.2—1.7	+5.0—1.3	+4.8—0.6	+4.0—0.9	+2.7+1.6	+1.6+1.3	+1.5+1.3	+1.7+1.6	+1.7+1.8
+2.1—1.3	+1.9—1.3	+2.0—1.3	+2.5—1.6	+2.7—1.5	+2.7—1.5	+3.0—1.4	+2.7—1.2	+2.1—1.0	+2.1—0.7	+1.6—0.4	+1.2—0.5	+0.9—0.6	+0.7—0.7
+2.0—2.8	+2.1—3.5	+2.6—3.8	+2.7—4.0	+2.6—3.7	+2.9—3.9	+2.8—3.2	+2.1—2.9	+2.4—2.6	+1.4—2.0	+0.5—1.4	+0.9—1.3	+1.0—1.2	+1.1—0.6
+2.8—1.7	+2.5—2.1	+2.9—2.1	+3.8—2.6	+4.3—2.1	+4.3—1.1	+3.5—0.5	+3.1—0.3	+2.8——	+1.7+0.2	+0.9+0.2	+0.4+0.4	+0.3+0.5	——+0.7
+4.9—2.6	+5.0—2.6	+5.9—3.0	+6.1—3.1	+6.9—2.5	+6.9—1.5	+6.7—1.0	+6.3—1.0	+5.1—0.9	+4.3—0.2	+2.9+0.2	+1.0+0.3	+1.2+0.2	+1.4——

E 3.

er for several numbers of classification