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DIRECTIONAL EFFECTS OF WINDS, WAVES AND CURRENTS ALONG THE DUTCH NORTH SEA COAST

L. M. J. U. VAN STRAATEN [1]

ABSTRACT

As yet very little is known about the movements of sediment along the Dutch North Sea coast. In this paper new data are presented regarding the directions in which sediment transport seems to take place. Some of the main conclusions are as follows.

The directions of Dutch coastal dunes appear to vary with a) the primary orientation of the foredunes and b) the relative effect of winds of moderate strength blowing from angles that differ from those of the stronger but less frequent winds. The magnitude of this effect depends on the width of the wind-formed depressions in the dune areas.

Wave observations show that sand drift must be strong along the northern barrier islands (from west to east), but that its importance must be small along the more south-north directed part of the coast between Katwijk and Texel. This conclusion seems to agree with direct sedimentological evidence.

Comparison of meteorological data with beach measurements between Scheveningen and Bergen reveals that the relatively frequent westerly and south-westerly winds in the second half of the 19th century resulted in an important (temporary) landward shift of the low tide line.

CONTENTS

INTRODUCTION

The chief agencies influencing sediment transport in the Dutch coastal environments are winds, sea currents and waves. These are all vector quantities. To understand the movements of sediment one must therefore be informed, not only about their magnitude, but also about their directions. The primary aim of the present paper is to review some of the old data and to give some new ones, both with regard to these directions and to the consequences on transport and distribution of sediments, especially of the sand.

If the author had limited himself to giving nothing more, he would have had a fairly easy task, and the result would have been a rather short collection of tables and diagrams. But he could not resist the temptation of weaving these data together into a more coherent story. By doing so he often had to deal with topics about which very little or nothing is known. A sceptical reader may therefore be less appreciative of the general texture of this paper than of the data which served as the base for it. Nevertheless, in its present shape it may be useful in stressing once again the great lack of data that still exists concerning these problems, the solution of which is not only higly important from the purely scientific point of view, but also from the standpoint of coastal engineering.

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[1] Geologisch Instituut, Melkweg 1, Groningen, Netherlands.

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DIRECTIONAL EFFECTS OF WINDS

Wind directions during the last decennia

Direct meteorological observations

Winds influence the transportation of sand in direct and in indirect ways. Direct effects are the movements of sand over the subaerial parts of beaches and in dune areas. Indirect effects are produced by wind-generated waves and currents in the sea. The latter will be dealt with in a later section.

It is clear that the mere frequencies with which the winds blow from different directions have no practical value for understanding their effects on the Dutch coast. One must also take into account the velocities of these winds. Van der Stok (1912) and Braak (1942) calculated the average wind directions resulting from vector addition of the frequencies of winds from 16 sectors of the compass (N, NNE, NE, etc.), multiplied with the corresponding average wind forces, expressed in Beaufort numbers, see Table I.

It is seen from this table that the resultant directions at sea and along the coast are in general more closely west-east than those inland, which tend to have lower azimuths. The average of the directions at sea and on the coast is N 249°E. For the stations lying between 5 and 50 kilometres from the coast the average is N 242°E, while for the stations still further inland it is N 234°E. This decrease in azimuth is explained by the increasing friction, exerted by the rough land surface on the moving air, which reduces the deviation due to the earth's rotation. It is true that a few stations do not fit into this general picture, e.g. Hoorn, Avereest and Rottumeroog. Their exceptional character may be caused by rather unsuitable locations with regard to local topography and by insufficient accuracy of the estimates of the wind force.

The azimuths computed by Van der Stok and Braak give only an approximate idea of the directional effects of winds on the coast. For instance, as far as the transport of sand is concerned, this material is not moved at all by gentle winds, which nevertheless make up an important part of all winds blowing in the course of the year. One should therefore know, for each direction, the separate frequencies of winds of succesive velocity classes.

TABLE I

o) IJmuiden (1928—1940)	N 264° E	o) Hoek van Holland (1926—1940)	N 241° E
x) Schouwenbank (1882—1906)	262	o) Vlissingen (1893—1940)	239
x) Haaks (1890—1909)	261	Groningen (1894—1940)	238
Hoorn (1905—1940)	257	Amsterdam (1907—1940)	238
Avereest (1904—1924)	257	Akkrum (1920—1939)	238
x) Terschellingerbank (1884—1908)	255	de Bilt (1897—1940)	236
o) Den Helder (1893—1940)	250	Oudenbosch (1906—1940)	236
o) Katwijk (1893—1927)	250	o) Rottumeroog (1926—1940)	235
o) Vlieland (1926—1940)	245	Maastricht (1893—1940)	231
x) Maas (1891—1910)	244	Winterswijk (1900—1940)	226
x) Noord Hinder (1884—1908)	244	Gemert (1905—1940)	222
o) Naaldwijk (1928—1940)	244		
Rotterdam (1907—1940)	243	x) Lightships o) Stations at or near the coast	

TABLE II: Position of ligthships

	Goeree	Texel	Terschellingerbank
1949	51°52' — 3°38'	53°05' — 4°31'	53°29' — 5°08'
1950	„ — 3°39'	„ — 4°32'	„ — „
„	„ — 3°34'	„ — „	„ — „
1951	„ — „	„ — „	„ — „
„	„ — „	53°06' — 4°30'	53°30' — „
„	51°53' — 3°35'	53°07' — „	„ — „
1952	„ — „	„ — „	„ — „
1953	„ — „	„ — „	„ — „
„	„ — 3°36'	53°08' — 4°32'	53°29' — 5°09'
„	51°52' — 3°34'	53°07' — 4°30'	53°30' — 5°08'
„	51°55' — 3°40'	„ — „	„ — „
1954	„ — „	„ — „	„ — „
„	„ — „	53°02' — 4°21'	„ — „
1955	„ — „	„ — 4°22'	53°29' — 5°07'
1956	51°56' — „	53°01' — „	„ — „
1957	„ — „	„ — „	„ — 5°08'
1958	„ — „	„ — „	„ — „
1959	„ — „	„ — „	„ — „

	Goeree	Texel	Terschellingerbank
Maximum diameter of area occupied by successive positions of lightships	10 km	17 km	2 km
Corresponding variations in depth (below Dutch Ordnance Level)	16—22 m	24—29 m	23—25 m

TABLE III A: Directions of wind resultants for 3 different periods

Lightship	Schouwenbank	Haaks	Terschellingerbank
Position	51°47' — 3°27'	52°58' — 4°18'	53°27' — 4°52'
Period	1882—1906	1890—1909	1884—1908
Beaufort	1—5 6—7 8—12	1—5 6—7 8—12	1—5 6—7 8—12
Azimuth [1]	248° 264° 272°	247° 265° 275°	243° 263° 267°
Lightship	**Schouwenbank**	**Haaks**	**Terschellingerbank**
Position	51°47' — 3°27'	52°58' — 4°18'	
Period	1910-1915; 1921-1934	1910-1914; 1919-1939	'10-'14; '16-'17; '21-'39
Beaufort	1—5 6—7 8—12	1—5 6—7 8—12	1—5 6—7 8—12
Azimuth [2]	212° 242° 259°	228° 246° 255°	239° 250° 258°
Lightship	**Goeree**	**Texel**	**Terschellingerbank**
Position	see Table II	see Table II	see Table II
Period	1949—1959	1949—1959	1949—1959
Beaufort	1—5 6—7 8—12	1—5 6—7 8—12	1—5 6—7 8—12
Azimuth [3]	244° 258° 267°	241° 257° 264°	240° 261° 269°

[1] From data of Van der Stok (1912). [2] From data of Verploegh (1958). [3] This paper.

No such data have been published for stations on land, but they are given for stations at sea, in the vicinity of the coast, by Van der Stock (1912) and Verploegh (1958). These data are based on observations on the lightships Noord Hinder, Schouwenbank, Maas, Haaks and Terschellingerbank. In the following some new information of this kind will be presented concerning the lightships Goeree, Texel and Terschellingerbank (Table II) during the period 1949-1959. In this period observations of wind direction (expressed as one of 36 sectors of the compass) and wind force (Beaufort scale) were made with intervals of 3 hours.

The data were classified in three velocity groups (Beaufort 1-5, 6-7 and 8-12) and according to the four seasons (Dec. + Jan + Febr, March + April + May, June + July + Aug, Sept + Oct + Nov). For each category and for each of the 36 sectories, the total number of observations for the 11-year period (1949-1959) was computed at the Royal Dutch Meteorological Institute at de Bilt. The vectors resulting from these numbers were calculated by the author, whereby differences in wind force within the three velocity groups were left out of account. Corrections were made for the (usually short) times that the ships were not lying at

TABLE III: Wind resultants (1949-1959)

	Goeree				Texel				Terschellingerbank			
Wind force	1—5	6—7	8—12	6—12	1—5	6—7	8—12	6—12	1—5	6—7	8—12	6—12
Winter												
Azimuth	206°	252°	269°	257°	216°	253°	264°	255°	208°	258°	267°	261°
Res. number [1]	1598	518	193	701	1532	636	218	850	1698	510	145	654
Sorting % [2]	27	31	53	35	26	39	59	43	28	34	48	37
Spring												
Azimuth	358°	309°	295°	307°	338°	287°	326°	290°	11°	285°	310°	286°
Res. number	552	184	24	211	230	149	14	160	485	137	26	156
Sorting %	8	27	41	29	3	27	24	26	7	24	42	25
Summer												
Azimuth	286°	254°	254°	254°	272°	259°	249°	258°	289°	260°	255°	259°
Res. number	1812	512	58	570	1889	264	38	302	1666	192	38	234
Sorting %	25	72	88	73	25	60	93	63	22	56	90	61
Fall												
Azimuth	192°	254°	263°	255°	212°	253°	263°	255°	206°	258°	267°	260°
Res. number	948	614	106	717	1163	478	126	605	1267	538	81	611
Sorting %	15	43	57	45	18	36	56	39	19	42	52	42
Year												
Azimuth	244°	258°	267°	260°	241°	257°	264°	258°	240°	261°	269°	263°
Res. number	2964	1754	377	2126	4005	1503	387	1888	3264	1363	283	1641
Sorting %	11	39	56	41	15	38	56	41	12	37	50	39

[1] The "resultant number" is the theoretical number of observations for the resultant direction (length of vector).

[2] The "sorting percentage" gives the proportion of the resultant number to the total number of observations for all directions.

their position. Thus, the resultants are given as they may be expected to be if observations had been made without interruptions, see Table III.

This table gives for each resultant its direction **(azimuth)**, its scalar size **(resultant number)** and the proportion of the resultant number to the total number of observations for all directions, expressed in percentages **(sorting percentage)**. The resultants for the whole period 1949-1959 ("Year") are compared in Table III A with those following from the data of Van der Stok and Verploegh for the earlier periods 1880-1909 and 1910-1939.

Some of the conclusions that can be drawn from Table III are:

1) The sorting percentages show that the resultant directions of the strong winds (Beaufort 6-7, 8-12) are much less scattered over the various points of the compass than those of the weaker ones (Beaufort 1-5), see also Fig. 7.

2) The resultant directions of the weak winds show, for each season separately, greater differences between the three lightvessels, than those of the stronger winds, except in the case of the spring season, where comparatively great differences are found for winds of all three velocity classes.

3) The resultant directions for the whole 11-year period ("year") show, for each velocity class a much closer similarity at the three lightships. In other words, there appears to be little variation in average resultant directions along the coast between Goeree and Terschelling.

4) The average azimuths of the resultant directions along this part of the coast increase in the order of increasing wind velocities: N 242°E for Beaufort strength 1-5, N 259°E for Beaufort 6-7 and N 267°E for Beaufort 8-12.

Directions of trees

In all parts of the Netherlands one notices the influence of the dominating winds on exposed trees. The latter stand in oblique positions, the inclination being generally in easterly directions. Along the coast, where the winds are stronger and the effect of salt spray from the sea is added, the trees are often distinctly hindered in their growth. Apart from the inclined positions they then also have an asymmetrical shape, giving the impression that the branches are shorn off on the windward side.

The direction of inclination or asymmetry of the trees may give additional information about the resultant directions of the winds. It is true that this information is mostly only of a qualitative nature, because among other things, it is not known in what measure the trees are influenced by winds of different strength. But they have the advantage of being distributed over the whole country, so that they may give insight in local or regional variations of wind resultants.

As to the winds, responsible for the asymmetric shape or position of the trees, it is evident that only comparatively strong winds need to be considered. Furthermore, the influence must be much greater during the period of active growth of the trees, than in the remaining parts of the year. Boerboom (1957) supposed that the trees investigated by him in the dunes near Scheveningen (hawthorn and white poplar) were mainly influenced in the spring. Van Steyn (1933) thought the strongest effect to be from May to August.

Up till now the directions of oblique or asymmetric trees had been measured mainly in dune areas, viz. by Runge (1955) and Boerboom (1957). Both investigators found that local topography is a very important factor determining their orientation. Trees on the southern side of dunes have more northerly inclinations than trees on the northern side. The direction of trees in elongate dune pans was often found to be more or less parallel to the long axis of the pans.

In the hope of learning more about the relation between the directions of trees and of winds, at places where the latter are not deflected or otherwise influenced by local relief, the present writer has made a series of measurements in the flat country behind the dunes, at a safe distance from their inner side. Such observations were made e.g. near Schoondijke, Arnemuiden, Hellevoetsluis, Brielle, De Lier, Nootdorp, Oude Wetering, Hoofddorp, Uitgeest, Limmen, Burgervlotbrug, 't Zandt and Ballum, at distances varying between 2 and 15 kilometres from the coast.

The ideal trees for this purpose, of course, are those which are quite isolated and equally exposed on all sides. However, no such cases were found. At most places the writer had to content himself with trees that were planted in rows on dikes, etc. Only trees of a certain height, corresponding to estimated ages of 1 to 5 decennia, were considered.

The result was a little disappointing. Even in the flat polder landscape the trees showed a strong variation in orientation. Most of this variation could be attributed to the mutual sheltering effect of successive trees in rows, or to the deflection of winds by the dikes on which they were standing. Yet, most of the measured azimuths lie between N 75°E and N 100°E.

Comparison of these directions with the wind data obtained on the lightships confirms the obvious conclusion that weak winds have little or no influence on the orientation of trees. It cannot be seen from this comparison whether the trees are influenced in more or less equal degree by strong winds of all seasons, or only by the strong winds of summer and part of the spring (though on other grounds the latter may be more likely). Finally, the variations in azimuth, owing to the effects of local deviations and exposure, are too large to permit conclusions about the regional distribution of resultant wind directions

Dunes

Dune landscapes

Along the Dutch coast one finds both dunes without vegetation and dunes that have become stabilized to a certain degree by plants and shrubs. The former are always of small dimensions and occur mostly on beaches. They will not be dealt with here, since their orientation changes many times a year, owing to changes of the wind. From time to time they many even disappear completely, to be rebuilt later on.

The dunes with vegetation display the same morphological features that are found in other coastal areas of the world where the dunes are predominantly fixed by plants (cf. Van Dieren, 1934; Van Houten, 1939; Faber, 1960). Along the highest part of the backshore a fairly continuous dune ridge is formed: the foredune. The crest of the foredune is usually rather irregular owing to the presence of numerous blow-outs. Landward of the foredune one passes into a landscape, consisting mostly of parabolic dunes, longitudinal ridges and hummocky dunes. The longitudinal ridges are frequently developed out of parabolic dunes, by the gradual wearing away of their front parts during the migration in inland direction. Hummocky dunes are erosion remnants of more or less random shapes. Still more inland one may find relatively high, transverse ridges, probably formed by coalescence of the front parts of adjacent parabolic dunes, the legs of which have gradually become dissipated.

As to the "negative" relief features, distinction can be made between comparatively small shallow, blow-outs with concave bottoms, e.g. those on the foredune, and large "dune pans" with flat bottoms, which have been caved out to a little above the ground water table or to other deflation-resisting levels, such as old soils. These pans have frequently distinctly elongate forms, especially where they are enclosed between the legs of great parabolae or between longitudinal dunes. The largest depressions, or "dune valleys" originate in quite different ways. One possibility is the development as blow-out plains in the wake of whole chains of parabolic dunes. These valleys are normally roughly parallel to, or make small angles with the foredune.

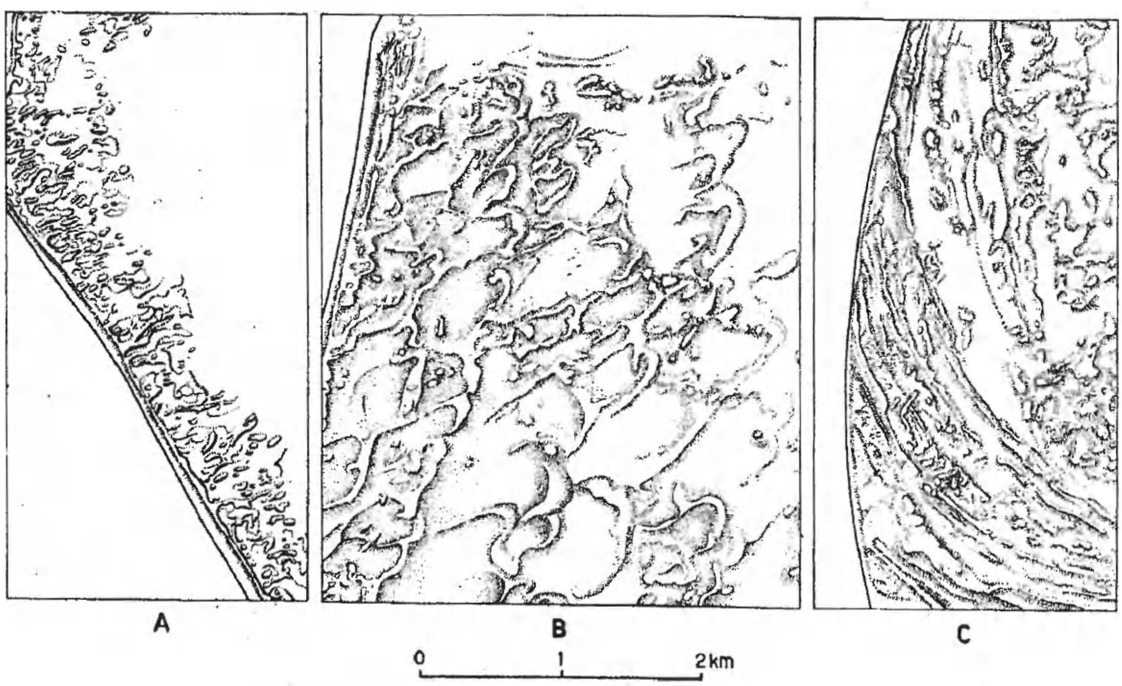

Fig. 1 — Dunes, A on Voorne, B near Zandvoort and C on Texel. From topographic map of the Netherlands 1 : 25.000.

The different dune forms, found over the entire width of the dune belt may represent the accumulations of sand supplied out of one source area only: the open sea beach. Elsewhere other sources, inland of the foredune may have contributed, e.g. chains of older dunes on former beach barriers.

The above morphological features are far from uniformly developed in the various parts of the Dutch coastal dune belt. As a result, strongly different types of dune landscape are encountered. A number of them will be briefly described.

1) In a few areas, e.g. on south-western Texel (Fig. 1 C) one notices several, fairly narrow, but continuous, rather closely spaced and nicely parallel dune ridges. These are without doubt successive foredunes, developed along a prograding shore. At Texel their formation must be very recent, since their original shapes are still so well preserved. Inland of these foredune ridges a much older dune landscape is met with, showing a more irregular relief.

2) On south-western Voorne only one ridge of foredunes is present. Inland of it a comparatively narrow dune area was formed, which is characterized by numerous small, strikingly parallel, parabolic and longitudinal dunes, see Fig. 1A. Their elevations are generally slight, mostly less than 10 metres. The maximum heights occur on the foredunes: 14 to 16 metres.

3) Between Katwijk and Noordwijk the dunes are much higher, up to 20 metres and more, and the ridges and troughs are wider, the distances between adjacent ridges being, in many cases, of the order of 100 metres. But they are still strongly parallel, see Photograph I. The inner side of this dune area is remarkably straight and cuts off the natural forms. It is the result of digging away of sand by man.

4) Between Scheveningen and Wassenaar one notes a type of dune landscape with an apparently very irregular relief of relatively closely spaced, rather high dunes, many of them reaching up to 25 or 30 metres above sea level, see Photograph II. There is one, fairly narrow dune valley and a few large dune pans. This area has been investigated in detail by Van Houten (1939), who found, by stereoscopic examination of aerial photographs, that the landscape is yet essentially composed of parabolae. The latter stand so closely together that they do not appear distinctly on a map.

5) At Zandvoort, IJmuiden and Wijk aan Zee the dune belt is characterized by numerous very large parabolae, together with long, longitudinal ridges, see Fig. 1B and Photograph III. The pans, enclosed between these positive relief features have widths of up to 400 metres.

6) Between Bergen and Schoorl one notices, in the inner part of the dune area, three to four very continuous and very high transverse ridges (heights up to 56 metres). Seaward of them there are few distinct parabolae, but several longitudinal ridges.

It will probably take a long time before each type of dune landscape can be satisfactorily explained. Yet, it is possible to mention already now some of the factors that must be involved, notably with regard to the elevations of the dunes. Thus it could be that the small elevation, and the narrowness of the dune area on south-western Voorne is caused by a very limited supply of sand, possibly in connection with the small width of the fore-lying beach, and with the comparatively recent formation of these dunes (see below). The height of the dunes between Scheveningen and Wassenaar may correspond to a much stronger and often renewed supply of sand.

Regarding the height of the foredunes, it was mentioned already by Pratje (1942) that a steep windward side of these dunes tends to raise the level to which sand is blown up from the beach. This circumstance could account for the rather great elevation of the outer dunes on south-western Schouwen and on the western end of Ameland. The steepness of the windward side is often the result of the preceding formation of dune cliffs, at places where the beach has been strongly eroded by waves and currents.

The state of vegetation must also be of influence, e.g. where the inner dunes are more densely vegetated than the outer ones. In such cases more sand is supplied from the outer dunes than is removed again in landward directions and the level of the inner dunes must be gradually raised. This could perhaps account for the considerable height (and continuity?) of the transverse dune ridges between Bergen and Schoorl.

The original topography of the dune covered areas may also have its effect. It is known that in the top parts of the older (pre-Roman) dunes, soils have formed before they were buried below the much higher, younger, post Roman dunes. These soil layers are more resistant to erosion than normal dune sand, and could in this way determine, at least locally (and temporarily) the base level of deflation. It does not seem impossible that the absence of these older dunes in the area at Castricum, where a large inlet has existed up till Roman times, is at least partly responsible for the generally low level of the dunes pans, as found by Faber (1960). Another factor that may have played a part in producing variations in dune heights is the grain size distribution of the sand (cf. Sokolov, 1894; Bagnold, 1941), though it is not likely that this effect has been very important, considering the relatively small differences that exist in the granulometrical properties of the sand along the Dutch coast.

As to Faber's suggestion (1960) that some of the dissimilarities between the average elevations of dunes in different parts of the dune belt could be due to tectonic movements, this seems

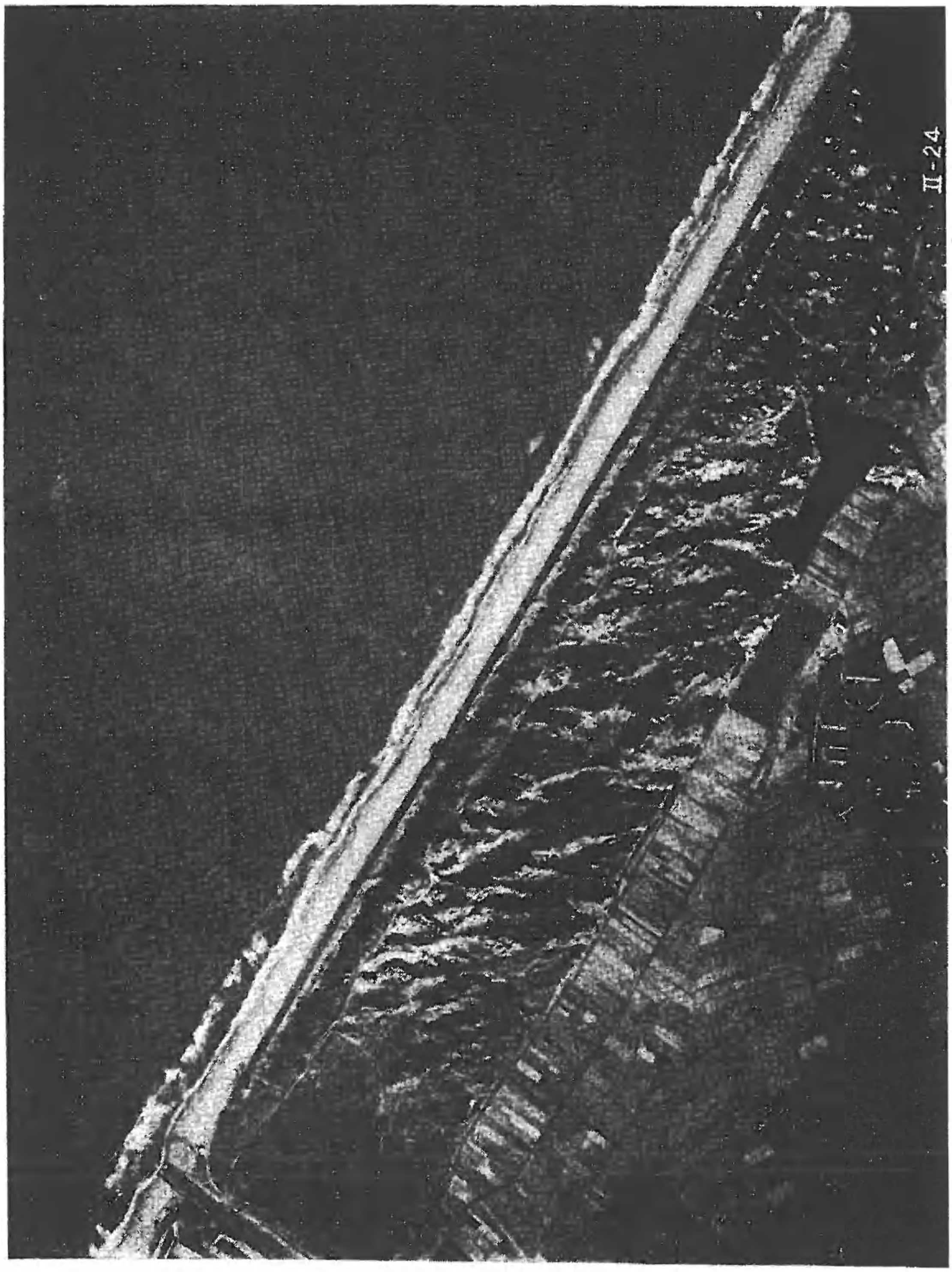

Photo I — Dunes between Katwijk and Noordwijk (scale appr.: 1 : 20.000)

Photo 11 — *Dunes between Scheveningen and Wassenaar (scale appr.: 1 : 26.000)*

improbable because there are no other indications whatsoever for such great movements during the short period that our modern dunes were formed.

Age of dunes

Dune formation has taken place, along the Dutch coast, at various stages. The oldest (pre-Roman, partly Subboreal) dunes are fairly low, normally not higher than some 5 or 6 metres. They have been accumulated on the successive Atlantic (?) and Subboreal beach barriers, and have become partly buried by the more recent, post-Roman dunes (cf. Pannekoek et al. 1956, and many other publications).

The sand of these old dunes is usually decalcified to depths of several metres and the top layer has, at many places, acquired the character of a dark humic soil. Where the old dunes were not covered by the recent ones, they have for a great part been taken away by man. Their original properties can at present be studied in sand quarries and other artificial exposures in the area of the recent dunes, e.g. at IJmuiden, Zandvoort, Bloemendaal and several other places.

The conclusion that most of the high dunes date from post-Roman times is based on the following arguments:

1) The fact that the old Roman writers, in their descriptions of the low countries make no

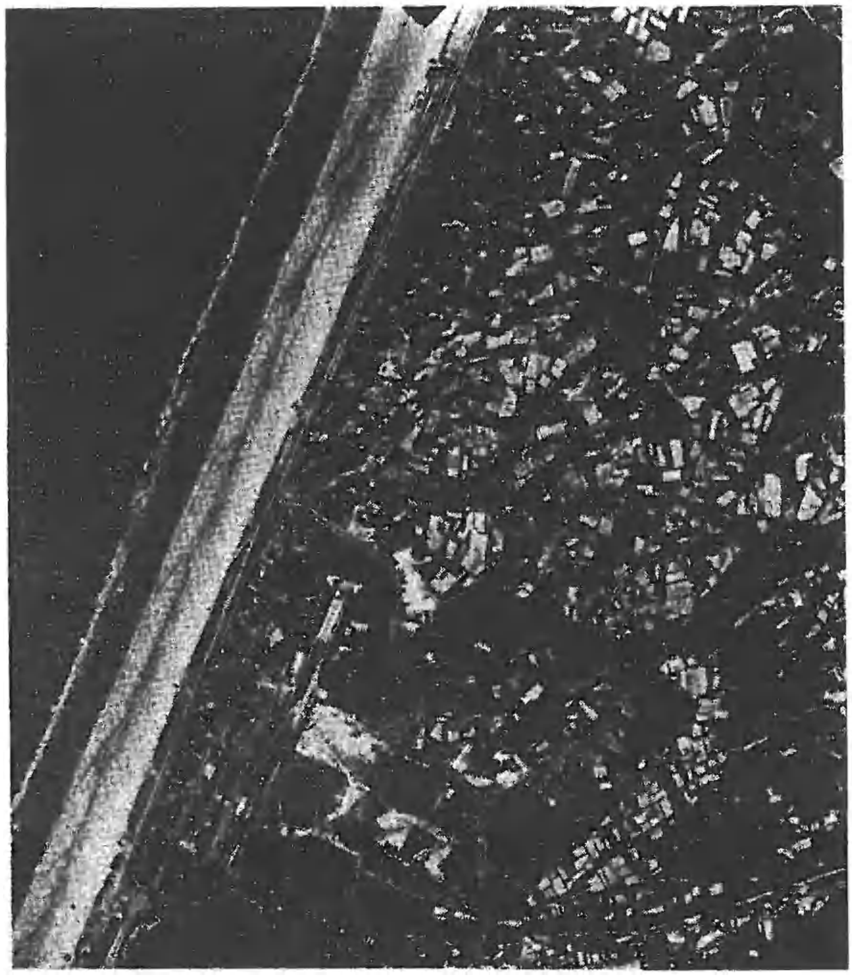

Photo III — Dunes and beach at Zandvoort (scale appr.: 1 : 26.000)

mention of them, which they almost certainly would have done if by that time the dunes had reached their present height and width.

2) The circumstance that pottery remains etc. of Roman and Medieval age have been found below these dune formations, in pans, or in artificial excavations. Such archaeological finds have been made at

a) Walcheren, near Oostkapelle (Trimpe Burger, 1955),
b) Schouwen, at various localities, (Hubregtse, 1927; Van Rummelen, 1959),
c) Goeree, (Van Baren, 1927),
d) Katwijk, (id.),
e) Santpoort (Calkoen, 1958),
f) Castricum (Van Deelen, 1954),
g) Groet (Braat, 1947; Schermer, 1957).

3) The indications that at Castricum inlets have existed in the coastal barrier as recently as about the year 200 (de Roo, 1953; Bennema and Pons, 1957; Pons and Wiggers, 1960), in an area where now a normal dune landscape is found.

On the other hand, it can be seen on the oldest reliable maps, dating from the 16th century, that by that time the distribution of the dunes was at most places the same as at the present day. The bulk of the high dunes thus appears to have been formed in the Middle Ages. It may be remarked that in nearby countries, like Belgium and Denmark, most of the high coastal dunes are also supposed to have originated during this period.

Along some parts of the coast the dunes are much younger. Thus it is known that south-east of Rockanje, on the island of Voorne, they date from after the beginning of the 16th century and between Callantsoog and the former island Huisduinen from after 1610. The dunes between de Koog (Texel) and the former island Eyerland, which now have heights of up to 20 metres, accumulated after 1630. The initial formation of most of these very young dunes was partly artificial. They originated by the trapping of sand by man-made screens of reeds, dead branches etc. This partly artificial origin is still clearly visible in the unnatural straightness of these dune ridges. Although they have grown up to quite appreciable elevations, no dune landscapes of any significance developed on their inland side, presumably because this was prevented by man.

Human intervention was probably also the chief cause of the circumstance that, except at a few places, the inner boundary of the other, older dune areas did not shift significantly in landward directions after about the 16th century. It does not mean, though, that the processes of dune migration within these areas had stopped. On the contrary, historical data prove that in the 16th, 17th and 18th centuries there was still much sand drifting, e.g. between The Hague and Schoorl (see Kops, 1818; Boerboom, 1958) and on Terschelling (Van Dieren, 1934). It was not until the 19th century that this drifting was drastically diminished owing to more serious efforts towards dune fixation.

Dune directions

Looking at aerial photographs of the Dutch coast one is struck by the frequently roughly parallel orientations of the relief features, such as elongate blow-outs, the legs of parabolic dunes, longitudinal ridges, etc. These directions have been measured by Van Dieren and Faber. Van Dieren found by field observations on Terschelling that the long axes of parabolic dunes have azimuths ranging from north-east to south-east. The large differences could be ascribed to the different exposure to the winds. Dunes along the approximately west-east running North Sea shore of the island are much stronger influenced by winds from northerly directions than dunes on the curved, partly south-east—north-west trending shore near the village of West Terschelling. It can only be expected, therefore, that the latter have lower azimuths than the dunes along the northern shore of the island. Both trends converge towards east-west directions in the more central parts of the dune area.

Faber (1960) studied new, detailed topographic maps of the province of North Holland, based on aerial photographs. He also noted a considerable spreading of the directions, and tried to correlate their averages with the resultant wind directions calculated by Labrijn (1945). Since the latter refer only to the frequency distribution of the winds along the different sectors of the compass regardless of their velocities, the results have only a limited value.

The study of dune orientations in connection with the distribution of winds has also been undertaken in other countries. Steenstrup (1894) believed that the long axes of parabolic dunes in Denmark coincides with the direction of maximum frequencies of winds with Beaufort forces 10-12, although he had to admit that certain dune complexes form exceptions to this rule. According to Musset (1923) the relief of the Inner Pomeranian dunes corresponds to the resultant wind direction computed by vector addition of the wind frequencies (from 8 sectors of the compass) multiplied with the relevant Beaufort forces.

Schou (1945) considered that weak winds, although blowing much more frequently, could hardly affect the orientation of dunes. He used the same method as Musset, but left the winds with Beaufort strength smaller than 4 out of account. Landsberg (1956) preferred still another manner of computing the resultant direction of effective winds, based on the experimental data of Bagnold (1941). This latter author found that sand transport by winds exceeding a certain strength (about 10 miles per hour) is proportional to the cube of the wind velocity.

Jennings (1957) investigated the orientation of coastal dunes on King Island, Tasmania, and came to the conclusion that not only the distribution of the winds, but also the exposure of the dunes to the winds is essential. It appeared that, particularly on the leeshore of the island „the relatioship between wind direction and dune orientation was much closer if only the onshore winds were used for the construction of the vector diagram of wind direction" (King, 1959, p. 223).

Finally, it may be mentioned that Hansen (1959) noticed on the North Sea coast of Denmark (Thy area) a slight decrease in dune azimuths from the shore to the interior. He attributed this to the reduction of the wind velocities by friction with the land. The influence must be greater for strong winds than for weak ones. Thus the effect of the latter, which have resultant directions at lower azimuths, would be relatively increased.

The present author has studied the relief of the Dutch coastal dunes as shown by the new topographic maps and by aerial photographs. The results are given in Figs. 2 and 3. In Fig. 3 it is seen that variations in dune orientation exist both parallel to the coast and transversely to it. As to the transverse variations, it appears that the azimuths on the inner side of the dune areas are generally lower than closer to the beach. With regard to the variations parallel to the coast one may distinguish between four regions:

1) the islands Walcheren, Schouwen, Goeree and Voorne (mostly relatively low azimuths),
2) the mainland coast from Monster to Noord-

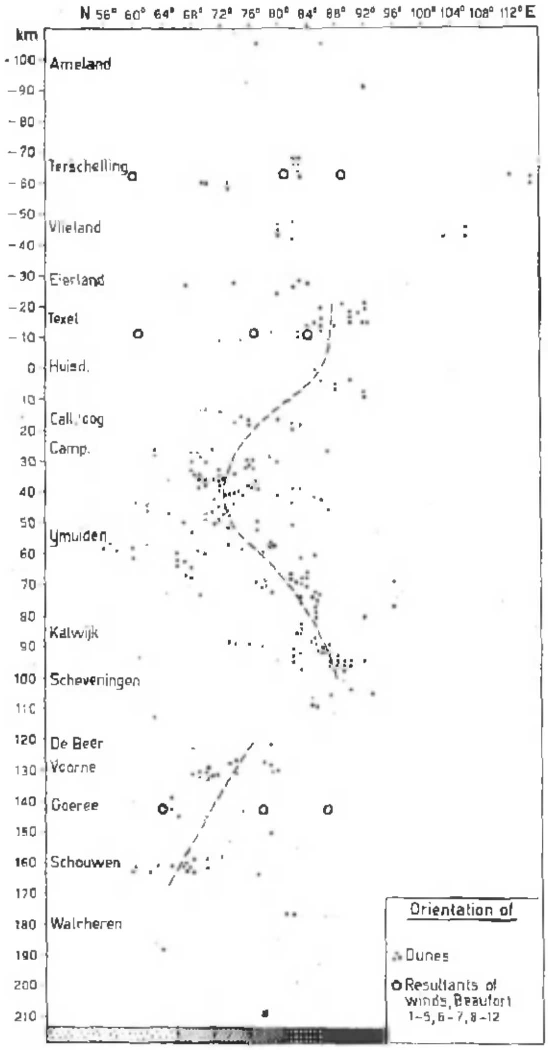

Fig. 2 — Directions of dune topography.

wijk (mostly relatively **high** azimuths),

3) the mainland coast from Noordwijk to Camperduin (mostly relatively **low** azimuths),

4) the coast from Petten to Ameland (mostly relatively **high** azimuths).

Both the differences transversely to the coast and parallel to it may be as large as 20°.

In the following some possible explanations for this phenomenon are considered. In the first place one could think of regional variations in the resultant directions of the winds (leaving aside the influence of local relief). However, the wind data obtained on the lightships show that (at present) no such strong variations in resultant directions exist parallel to the coast. Nor does it seem probable that they occur between the seaward and the landward side of the dune areas. It is true that in the latter sense some difference in the resulting directions of the winds may be expected because of the effect of friction on the force of Coriolis, but it is doubtful that it could attain a value of 20°.

Moreover, apart from the fact that the dune orientations do not fit the picture of the wind directions of the present day, it can be shown that the attempts to correlate the two are theoretically unsound. It was mentioned above that most of the dunes were formed in the Middle Ages, and that the migration of dunes came to a stop at most places in the course of the 19th century.

Now it is known from direct meteorological observations that the resultant directions of the winds (regardless of strength) have changed considerably since about 1700, see fig. 4 E (from Labrijn, 1945). This diagram gives for each year the average values of the 30-year period extending from 15 years earlier to 15 years later. It is seen that the azimuths increased from about

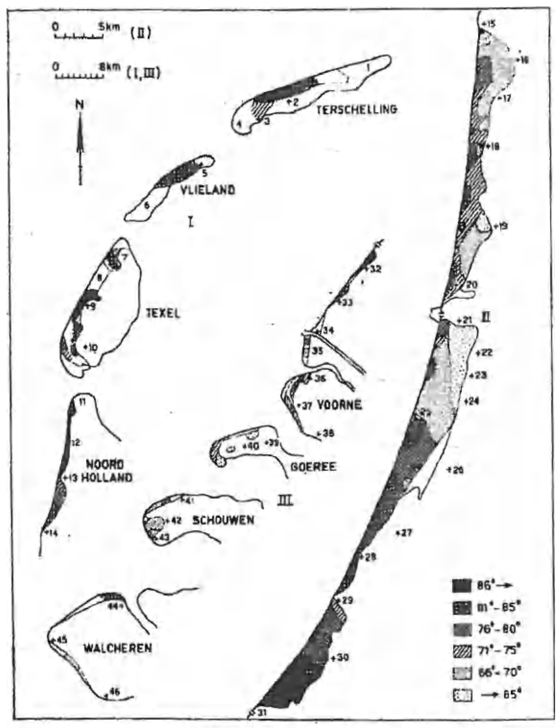

Fig. 3 — Directions of dune topography.

1. Boschplaat
2. Midsland
3. West-Terschelling
4. Noordvaarder
5. Oost-Vlieland
6. Vliehors
7. Eyerland
8. Slufter
9. De Koog
10. Den Hoorn
11. Den Helder-Huisduinen
12. Koegras
13. Callantsoog
14. Petten
15. Camperduin
16. Schoorl
17. Bergen
18. Egmond
19. Castricum
20. Wijk aan Zee
21. IJmuiden
22. Santpoort
23. Bloemendaal
24. Overveen
25. Zandvoort
26. Hillegom
27. Noordwijkerhout
28. Noordwijk
29. Katwijk
30. Wassenaar
31. Scheveningen-Den Haag
32. Kijkduin
33. Monster
34. Hoek van Holland
35. De Beer
36. Oostvoorne
37. Rockanje
38. Hellevoetsluis
39. Goeree
40. Ouddorp
41. Renesse
42. Haamstede
43. Westenschouwen
44. Vrouwenpolder
45. Westkapelle
46. Vlissingen

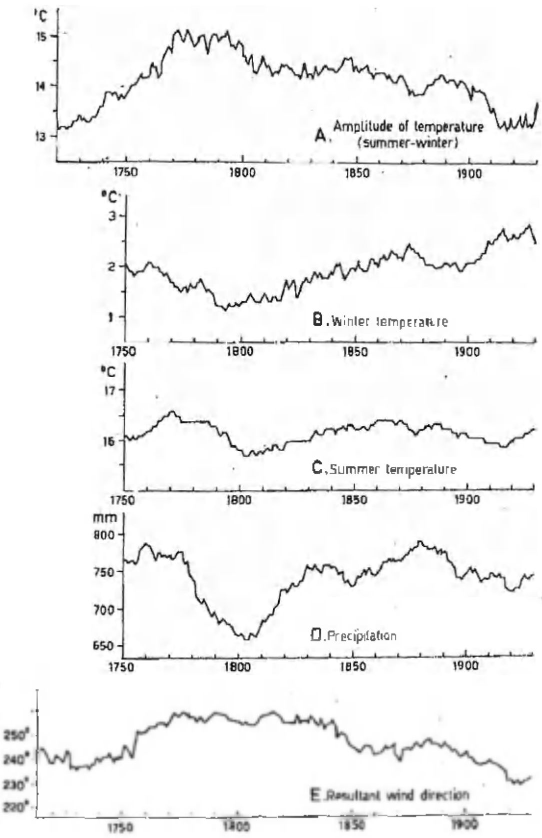

Fig. 4 — Overlapping 30-year-averages of temperature, precipitation and wind direction in the Netherlands (1700-1944). From Labrijn (1945). Temperature: Delft-Zwanenburg-Utrecht-de Bilt. Precipitation: Zwanenburg-Hoofddorp. Wind: Amsterdam.

1710 to 1800 (N 235°E to N 250°E) and then decreased again until 1920 (to N 225°E).

These variations of the wind directions were the consequence of changes of the whole climate. In the course of the 19th century and up into the 20th century it became gradually more oceanic, with increase of the winter temperatures and decrease of the difference between winter- and summer temperatures.

Around 1800 the climate was also much drier than later on.

This was obviously the cause of the fact, mentioned but unexplained by Boerboom (1958), that between The Hague and Katwijk most of the dune pans, which before and after the beginning of the 19th century were filled with water, became temporarily very dry. The ground water table must have been lowered at least a few feet.

As may be expected, this climatic change did not only affect the Netherlands, but also the neighbouring countries, see e.g. Wagner (1940) and Lysgaard (1949). From other data (frequency of marine inundations due to storm surges, the growth and retreat of glaciers etc.) it may be deduced that similar, possibly even greater climatic fluctuations occurred before 1700. The resultant wind directions must have changed concomitantly.

These considerations lead automatically to the supposition that, at least part of the differences in dune orientation correspond to differences in age. Since all dune areas tend to pass, in the course of time, through successive stages of morphological evolution, one could then perhaps expect some kind of correlation between dune orientations and dune landscapes. When comparing these two properties, one immediately notices that the large and wide parabolic dunes have always relatively low azimuths. The high azimuths are limited, at least from Monster northward, to areas with closely spaced dunes. Many of the latter are found on the foredune ridge or in the area immediately behind it, e.g. south and north of Zandvoort, at Wijk aan Zee, and south of Egmond, although between Scheveningen and Wassenaar rather narrowly spaced dunes with high azimuths occupy the whole width of the dune belt.

The large parabolae must in any case be older than the smaller dunes at or near the ridge of the foredunes. The latter are the new-comers, which have not yet had the time to develop into full-grown parabolae. It thus seems tempting to conclude that in the former period, when the large parabolic dunes were formed, the winds had resultant directions of distinctly lower azimuths than later on.

A first difficulty with which the application of this hypothesis meets is the problem how the old parabolae could have retained so well their original orientation during the subsequent periods with different wind distributions. One might try to explain this as the result of their large dimensions. The rate at which a migrating dune can adjust its orientation to a changing wind system diminishes, of course with increase of its volume. Yet, this explanation is not entirely convincing.

A second, much greater difficulty is formed by the directions of the dunes on the islands south-west of Hoek van Holland. For some of them it is known that they have been formed, or remodelled in very recent times. The dunes on south-west Voorne date from after the 16th century, those on Schouwen were migrating until a few decennia ago. Such young dunes surely ought to have high azimuths, according to the above hypothesis. But the contrary is found. Their directions lie mostly between N 65°E and N 70°E. It follows that, even if ancient dune directions are preserved at some places, the differences in age cannot be the only factor involved.

Another factor that must be of considerable importance for the orientation of dune topography is their exposure to winds from different directions. Where the shore, and hence the foredune trends approximately east-west, the winds from the north may have a much greater effect on the directions e.g. of blow-outs, than winds from the west, even though the latter are stronger and more frequent.

It was mentioned, that Van Dieren (1934) recognized this influence when studying the dunes on the island Terschelling. The relief along the curving western shore of this islands, forms, as a matter of fact, a very clear example of this effect, because here a strong variation in directions occurs over a relatively short distance. It seems quite possible that the low azimuths of the dunes along the south-east—north-west running shores of the islands Walcheren, Schouwen; Goeree and Voorne, as compared to the higher azimuths between Monster and Wassenaar, where the coast is almost south-west—north-east, are due to this same factor. The only difficulty here is that along the north-western shores of Schouwen and Goeree the azimuths of the dunes are also comparatively low. This is perhaps the result of a good accessibility of these narrow dune areas to more southerly winds blowing from the landward side.

Obviously, the influence of the trend of the foredune is most pronounced directly along the shore itself. Soon after a blow-out dune has started to migrate towards the interior, it becomes surrounded on all sides by other dunes. Then the only difference in exposure to winds from varying directions is dus to the elongate shape of the blow-out, but this initial direction of elongation must gradually shift to azimuths corresponding to the resultant directions of the winds.

For example, along a south-west—north-east trending shore the initial direction of blow-outs, formed at the present day, may have azimuths of a little more than N 90°E. When these blow-outs move inland, their direction must tend to become more purely east, because the strongest winds blow, on the average, from west to east.

However, further changes in direction may be expected on account of the effect of friction on the force of Coriolis, which tends to reduce the azimuths of the resultant wind directions. Another factor which may significantly change the orientation of the dunes is connected with the following two circumstances. The first one is that the resultant directions of the strongest winds have higher azimuths than those of the weaker, but more frequent winds. It seems likely that similar conditions have existed during earlier periods, when most of the dune landscape was formed, even though these directions themselves have fluctuated.

The other circumstance is the gradual widening of the depressions as they migrate towards the interior. So long as these are still comparatively narrow, the weaker winds, passing obliquely or transversely over them can only be of little effect on the direction in which they are elongated. But as their diameter increases, these weaker but more frequent winds, blowing from more south-westerly directions will have an ever greater influence on their orientation.

Where the trend of the coast is more south-east—north-west, as on the south-western parts of the islands Schouwen, Goeree and Voorne, the depressions have little tendency to turn around during their inward migration, because the initial orientation of the blow-outs on the foredune is already much closer to that of the more frequent south-westerly winds.

The foregoing may be summarized in the following conclusions:

1) It is impossible to correlate the directions of the now largely overgrown coastal dunes with the resultant directions of winds as deduced from recent meteorological observations. Most of the dune orientations date from many decennia ago, while some of the larger features may be already many centuries old.

2) The direction of a dune ridge with regard to the dominating and prevailing winds is a major factor determining the orientation of the dune forms originating out of this ridge. Thus, the dunes that develop out of south-east—north-west trending foredunes have in general distinctly lower azimuths than those generating from south-north or south-west—north-east running foredunes.

3) A relation exists between the directions of elongate dune pans and their widths. With increase in width the directions tend to decrease in azimuth. The relation may be attributed to the difference between the resultant directions of the strongest winds and the more frequent, weaker winds.

to be continued