

# Macroclimate, microclimate and dune formation along the West European coast

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## Abstract

Extremely important to the climate in any region are the radiation balance and the exchange processes of heat, water vapour and momentum. Most climatological parameters (*e.g.* temperature, humidity, wind speed, cloudiness and precipitation) are the direct or indirect result of the radiation balance and these exchange processes.

The weather of the West European coast from Tarifa (Spain) to Skagen (Denmark) is especially suitable for the formation of dunes. Often a wind is blowing, varying widely in force and direction. The conditions are optimal for the formation of high and wide dune complexes, given a large supply of sand by the sea. The annual precipitation surplus is considerable for most of this coast. This favours the establishment of vegetation, and thereby it enhances dune formation. The short distance to the land-sea border causes strong gradients in several climatological parameters. These gradients lead to mesoscale effects, such as land-sea breezes and coastal fronts. The varying vegetation cover and the presence of slopes in all directions induce a strongly varying microclimate. However, this microclimate is not unique to the coastal dunes. Unique is the interaction with the wide range of ambient weather, which is inherent to the coast.

It is not possible to be conclusive about the effects of climatic change on coastal dunes because climate models are not yet able to predict the changes adequately and because these models supply information on the expected mean climate, but not on the actual weather.

## Introduction

Bare sands are usually affected by the action of the wind. This action is profoundly altering the state of the surface. Several geomorphological structures may appear, like ripples, ridges, small cliffs, isolated hills and extensive complexes of dunes. Geomorphological processes are in one respect governed by properties of the soil. On the other hand vegetation also is an important factor if it has been able to settle. The development of vegetation is

greatly influenced by the weather (mainly rainfall, temperature, wind force, saturation deficit and the intensity of solar radiation), but also by soil properties and geomorphological processes. Weather also affects the geomorphology by controlling the sand flow in dunes. The energy for these sand flows has to be provided mainly by the atmosphere. Inversely, the state of the atmosphere is influenced by geomorphological processes and soil properties. This feed back mechanism can significantly modify micrometeorological parameters. In addition to the

direct action of weather on the mobility of sand and on the quantity of ground water (by wind, precipitation and evaporation), there is also an indirect action of the weather, since also the currents of the sea are dominantly maintained by the weather.

The multitude of processes and the wide range of soils makes one expect that weather induced morphological structures will occur widespread over the sandy soils. A large part of the soils in Europe consists of sand. It is however remarkable that in spite of the fact that complexes of coastal dunes are common, inland dune complexes are relatively scarce. This is mainly due to the source of bare sand on the beach.

The small scale spatial differences with respect to micrometeorological parameters are larger in undulating areas than in flat areas. Coastal dunes are located near a transition zone because of the boundary between sea and land. This location and the effects of sloping surfaces leads to extreme differences within a small area. These local differences are reflected in the nature of the vegetation cover. Hence the extent to which the vegetation cover is able to stabilize blown surfaces is profoundly influenced by the local microclimate, for which the macroclimate is a boundary condition.

On the other hand the atmospheric parameters are profoundly modified by the action of the surface. Enormous differences in the degree of harshness of winters exist between areas which are located on the same latitude but on a different longitude. Compare, for example, Rome ( $41^{\circ}54'N$ ) with a mean January temperature of  $7^{\circ}C$  to Vladivostok ( $43^{\circ}10'N$ ) where the mean January temperature is  $-14^{\circ}C$ . These differences are enforced upon the atmosphere by the surface of the earth. It is hard to overestimate the importance of the interaction between the surface and the atmosphere. This interaction is dominantly governed by exchange processes, such as the exchange of energy (*e.g.* heat), momentum (*e.g.* drag forces) and matter (*e.g.* precipitation and evaporation). Understanding the special nature of coastal dunes requires a basic knowledge of these exchange processes. For a detailed description the reader is referred to the handbooks of micrometeorology, *e.g.* Sutton (1953) and Monteith (1973).

## Energy balance

The energy balance is very important because it determines the temperatures at and near the surface (among other factors) and the rate of evaporation.

The sun is the source of an energy flux which appears as radiation. The part which is not reflected by clouds is hardly absorbed by the atmosphere. Therefore, the free atmosphere is hardly heated by solar radiation (about  $1K/day$ ). A part of the solar radiation is reflected by vegetation, bare soils, water and snow. The rest is absorbed, and converted to heat. Also important, especially during the night is the infrared radiation emitted by the surface and the atmosphere. At daytime a part of the heat gained by radiation penetrates the soil. Another part is transmitted to the air (**sensible heat flux**). The rest is mostly used to evaporate water (**latent heat flux**). Only a very small fraction is used for assimilation by plants. In the energy balance of the earth surface this fraction is less than the uncertainty in the other terms.

The solar radiation load of a surface depends upon the slope of the surface. Southern slopes receive more solar radiation than a flat area, northern slopes receive less. Eastern and western slopes receive an equal quantity of radiation, but western slopes will reach a higher temperature because they face the sun at the warmer part of the day.

Heat is transferred from the surface to the air by direct contact. Heating is causing the air to expand, and so instability is created. In an unstable boundary layer heated parcels of air will rise and the still unheated air will descend. This process is considerably enhanced by wind. This causes for example that the difference in average air temperature between a point situated two meters above the surface of a dune valley and a point two meters above the summit of a dune usually is small during day time, if at least a fair wind is blowing. Even the differences between a northern and a southern slope are negligible at two meters above the surface. However, air closer to the surface and absorbing elements, like plants, will become much warmer on a southern slope. A plant which grows on a southern slope therefore experiences far more extreme temperature differences than a plant

which grows on a northern slope.

The transport of heat into the soil is taken care of by two processes, conduction and distillation (distillation is discussed in the next section).

The ability to conduct heat increases with the soil moisture content. The differences in thermal conductivity are extremely large between a sand which has completely dried out and a sand which is moist after some rain. The thermal conductivity increases only slightly when a moist sand gets soaked (Wijk 1963). So the surface temperature of a moist soil will be lower than that of a dry soil under the same conditions. The warmer soil surface of a dry soil will transmit more heat to the air and the soil heat flux will consequently be reduced.

During the **night time** long wave radiation becomes very important. Every surface, soil, plant or whatsoever radiates heat. The loss of heat by the surface due to long wave radiation increases with temperature. The atmosphere also emits long wave radiation, of which a part is received by the surface. Under a clear sky the received long wave radiation is much less than the emission by the surface because the atmosphere does not radiate as a black body. Therefore the surface can cool down considerably. The free atmosphere is also cooling down slightly by its own radiation. The decrease is about one or two degrees in twenty-four hours. So the surface is cooling at a higher rate than the air above it. Clouds, however, do radiate as a black body. So under a heavily overcast sky the radiation received by the surface from the atmosphere can almost equal the radiation emitted by the surface. Under these conditions the cooling down during the night will be much less.

In general the soil and air gain heat during day time, and lose heat by night. By night the processes in the soil are physically spoken the same as during the day, but their direction is reversed.

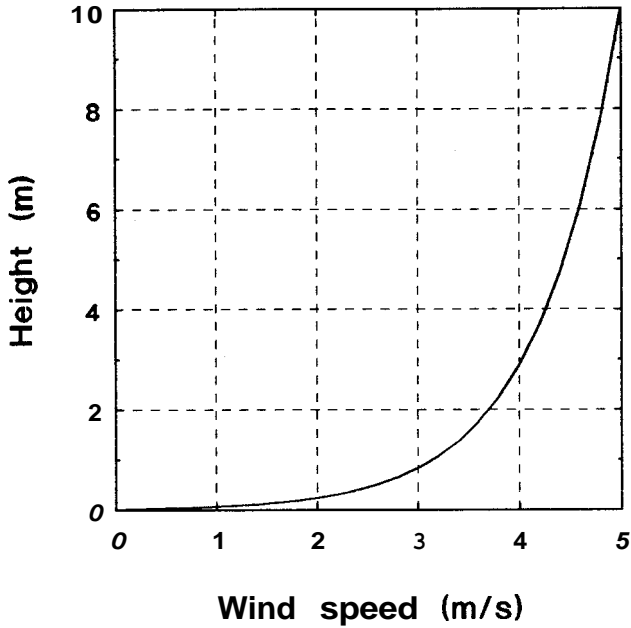
During the night the state of the air is significantly different from the day time situation. The colder air with the highest density is at the lowest possible height (stable stratification). Vertical movements are suppressed. This phenomenon causes enormous vertical temperature differences. If the cooling happens above a slope then the cold air will slide downwards. In this fashion the cold layer in depressions

will grow higher and will get more stable. Between dune crest and dip large differences will arise, even at a height of one or two metres. Because of the small scale character of coastal dunes these differences can be considerable on a short distance, even in the case of some wind. Temperature differences of about ten degrees or more are found at a height of ten centimetres.

The exchange of heat over the sea is not entirely analogous to the exchange over a land surface. In the first place the solar radiation is not absorbed at the surface, but it penetrates the uppermost layer of water. A 99 percent absorption requires at least a layer of ten metres depth. The heat is dispersed over the entire layer and therefore the temperature increase in a 24-hour period is very small. Moreover, vertical mixing increases the depth of the heated layer, leading to even smaller daily temperature changes. For these reasons the daily course of the temperature over sea is negligible and the yearly course is much smaller than over land. Since the dunes are so close to the sea, they are strongly affected by it. Especially the reduced yearly temperature amplitude can be felt many kilometres inland. The micrometeorological differences due to topography, which were discussed before, can be seen as superpositions on this effect.

## Evaporation

From a meteorological point of view water vapour transport is especially important because of its link with the energy balance. The transition of phase requires a tremendous amount of heat called the latent heat of evaporation. Over vegetation covered surfaces sensible heat transport and latent heat transport to the atmosphere usually are of the same order of magnitude. Only if the vegetation is very scarce or if not enough water is available, the evaporation will be lacking. Wind will improve the removal of water vapour from the vicinity of the leaves and so it tends to augment evaporation. It also carries away the heat, which causes the evaporation to decrease. So in the case of closed vegetation or a bare soil the evaporation will be rather unsusceptible to wind, because of the counter effects.



*Fig. 1.* Example of a wind profile near the surface.

However, obstacles behave very differently. The evaporation of a solitary tree or an isolated shrub increases enormously with the wind speed. This dependence gets stronger with the water vapour deficit. Even during the night time the evaporation of an isolated plant can be considerable, although the plant also loses energy through radiation (the emitted radiation will usually exceed the incoming infrared radiation). Evaporation, which occurs in the soil, can not be neglected (Berge 1986), so we shall examine it in a nutshell. It already has been shown that a temperature gradient will arise in the uppermost decimeters of the soil. The air is nearly water saturated almost anywhere in the soil. The vapour pressure therefore is higher if the temperature is higher. Due to this difference distillation will occur. Water vaporizes in the warmest soil masses and condenses in the coldest ones. These distillation related latent heat fluxes can roughly equal the heat fluxes due to conduction. In dune soils usually enough capillaries are air filled to allow the diffusion of water vapour. The actual total thermal conductivity of a soil is therefore very dependent on the temperature. But it decreases if the soil starts to get soaked. The small moist fluxes which enter the rooting zone by distillation may well be crucial for

the survival of plants in the case of huge water deficits.

### Momentum exchange

Air flowing over a surface is retarded due to surface drag (friction). The effects caused by this drag differ fundamentally from the situation when a solid mass is forced to slide over a solid surface. The interaction between two solids is marked by a step change in velocity. On the other hand the interaction between a solid or a liquid and a gas (such as air), is characterized by a velocity gradient. In the atmosphere this gradient is usually referred to as the wind profile, in which the time averaged velocity decreases to zero near the surface (figure 1) (time averaging is necessary because the air flow is turbulent, which causes the wind speed to fluctuate continuously). A part of the momentum of the free flowing air is extracted and at the surface its energy is dissipated as heat due to surface drag.

The layer in which the wind speed is influenced by the underlying surface is called the planetary boundary layer (PBL). The upper limit of this layer is often well defined. The wind direction in the PBL

is changing downwards in a counter clock wise sense, because of the interaction between pressure gradient force, Coriolis force and surface drag. This causes the downward transported momentum to be extracted from the horizontal pressure gradient within a few hours. An equilibrium is established, and the wind profile is roughly constant over an extensive area. This steady state will continue to exist over the period that the weather remains unchanged on macroscale (at most about one hour). At the surface the downward transport of momentum manifests itself as a drag force. This surface drag is of eminent importance to the initiation of grain movement.

One has to realize that the source of momentum is located high up in the free flowing atmosphere. From there momentum is transported downwards. The magnitude of the surface drag determines the rate at which the momentum of a layer is replenished from above. A smaller drag translates into a smaller loss of speed and will therefore result in a higher speed at lower altitudes. An unstable vertical distribution of air masses augments the exchange, so more wind will result from this. The latter is the principal reason why over land the wind is generally blowing stronger during day time than by night. Diurnal changes in wind speed do not occur over sea because of the almost complete absence of daily changes in sea surface temperature.

If air flows from one surface to a surface with another roughness then some time may pass before a new equilibrium is reached. The sea is dragging the air less than a land surface. Therefore the wind will be stronger over sea. The slowing down over the dunes is gradual. At first the wind speed is higher than in the equilibrium situation. Extra momentum is drawn off the flowing air and the drag force is larger than in the equilibrium situation (Blom and Wartena 1969, Kroon 1985). This is called an overshoot in the drag force.

An obstacle raised in the wind forces the air to flow around it. This initiates a very complicated distribution of shearing stresses and whirls. If the vegetation cover is sparse then every solitary plant may be considered as an obstacle, but the crest of a dune may also be seen as such. So beyond a sum-

mit often lee whirls form and between two dune crests extra strong winds may blow.

### Wind and grain movement

The air acts upon the surface by a drag force. This force is acting parallel to the direction of the air flow. If the uppermost solitary sand grains were not bound to others and would lie on a flat surface, they would accelerate. However, sand grains are cemented to each other, *e.g.* by humus, algae, carbonates or water. The surface will remain undisturbed as long as these cementing forces exceed the drag force (also referred to as shearing stress). If the shearing stress exceeds a certain threshold, a grain may be loosened and start rolling over the surface. The rolling grain may hit a small irregularity and rise from the surface. When the grain is airborne it will be accelerated horizontally by the dynamical pressure of the wind. The downwind impact of the grain which has gained momentum and which has fallen back to the surface initiates the rising of more grains from the surface. Saltation, the process of numerous grains jumping up and travelling downwind, has started (see also Bagnold 1984).

The lightest particles, consisting of loam, clay or organic matter are liable to be taken into suspension by the upward branches of turbulent whirls. Dust in suspension is able to travel up to thousands of kilometres.

The heavy particles are very important for the processes which govern the formation of blown structures. These are only moved horizontally and not raised when they are subjected to a bombardment of saltating grains. This mode of transportation is usually referred to as surface creep. It causes accumulation of particles in zones perpendicular to the wind. These zones can very often be observed as ripples on beaches and dunes. The coarsest material accumulates on the crests of the ripples, the finer material is to be found in the depressions between the crests. If the ripples are located in an area with prevailing light winds then they can grow slowly to the height of several decimeters. These large ripples are classified as ridges. Ridges are almost com-

pletely confined to the arid climates. A very strong wind can effectively prevent the formation of ripples. Dispersed shell debris can also suppress ripple formation. This material is able to stabilize an area, which is liable to sand drifts, entirely. Ripples can not grow to be dunes, since in comparison to ripples the vertical distribution of grain sizes in dunes is inverted: the finest grains are on the crests.

Among the three modes of transport (suspension, saltation and surface creep) saltation is the most important for dune formation, because firstly the larger part of the transport is by saltation and secondly saltation greatly enhances suspension and surface creep.

### **Dune formation**

Saltation and surface creep are responsible for ripple formation, but are also vitally important to the creation of dunes. The wind causes grains to get blown away from the source area and it maintains the sand flow by surface creep and saltation. It can also alter the morphology of primary dunes by wind erosion. The velocity of the wind has to exceed a certain threshold, which is related to the texture of the topsoil. If the fetch is sufficiently long an equilibrium will be established between erosion and deposition. The sand load, which can be transported under steady state conditions, will increase progressively with wind velocity. When the surface becomes rougher, the wind velocity near the surface will decrease and the sand load will consequently be reduced. With a given constant wind velocity, however, the sand flow will increase when the surface gets rougher. The solidity of the surface also has a profound effect on the maximum sand load. On a hard surface the descending grains will bounce off with a smaller loss of momentum. On a softer surface a part of the momentum of the saltating grains will be used for surface creep.

Essential to the formation of dunes is the availability of a large sand supply. Very subtle differences may decide if erosion or deposition is to occur. The existence of extensive sand deserts without dunes is due to a lack of sand susceptible to wind erosion.

If the smaller grains are blown away and the courser ones remain then wind erosion may stop entirely. The source area then ceases to exist.

Along the coasts the sea is the main sand source. The sea bottom has to be subjected to erosion, or else the sea has to transport sediment from a retreating coastline. Another possibility is the discharge of sand by a river. A change in the pattern of sea currents or coastlines may divert the main sand flow. The rate of erosion, transport and deposition by the sea depends on the weather. This interaction between sea and weather is most directly influenced by the wind speed, wind direction and the duration of strong winds. During a strong onshore wind the sand deposited on the beach will usually be blown inland with remarkable ease.

A water surface retards the air far less than a land surface. When the wind blows from water onto a land surface a transition zone will develop in which, due to the inertia of the flowing air, the wind speed is too high in comparison to the equilibrium wind speed over a land surface. The air will already be sand saturated having travelled a couple of decameters over a dry surface. When the air moves further inland a new equilibrium will establish with overall reduced wind speeds. This causes an oversaturation of air with sand. Consequently deposition will start.

Deposition of sand will locally lead to slight elevations of the surface, which are called an obstacles in fluid dynamics. In front of and behind obstacles there are usually zones of reduced wind speed and shearing stress (Jacobs and Wartena **1987**). These zones are liable to have accumulation of sand. When sand moving inland meets a dune ridge, deposition as well as transport up the dune slopes may occur. A wind not blowing perpendicular to the dune ridge makes the transport up the dune easier, since the upward slope will be relatively less steep. Extreme angles of inclination, equal to the angle of repose for sand, on the leeward faces of the dunes limit the maximum height of blown structures. During very strong winds it is possible that wind erosion will restart near the top of stabilized dunes. A broadening of the basis of dunes inland will result. Winds with changing force and direction make the formation of extensive and high dune

complexes possible. These occur all along the European coasts of the Atlantic Ocean and the coasts of the North Sea. This is why dunes can be found everywhere along these coasts as long as there is a durable sand source. Local departures are due to the eroding action of rivers and the sea.

Vegetation has a far reaching effect on dune formation. Every plant or part of it will act as an obstacle and favour sand deposition. On West European coastal dunes vegetation often has established. Generally the vegetation in the most seaward dunes is low and scarce, after a short distance inland, the vegetation becomes denser and taller and stabilizes the sand better.

Decay turns dead plant material into water repellent humus. This process is often observed when the colour of the sand changes from yellow to grey. The grey sand is relatively stable to wind erosion due to the binding effect of the humus. The water repellent nature of the humus may quite effectively inhibit infiltration of rain water (Dekker and Jungerius 1990, Jungerius and Jong 1989). This can considerably increase the susceptibility to water erosion due to surface runoff during heavy showers (Jungerius and de Jong 1989). Water erosion is most severe on the steepest (leeward) slopes. The newly exposed yellow sands of the subsoil are easily eroded by the wind. So wind erosion will often restart at the least likely places (from a atmospheric point of view): the leeward slopes. There blowouts can be formed which tend to grow upstream (against the wind) (Jungerius and Meulen 1989). More inland the difference between north oriented slopes and south oriented slopes also is important. The north oriented slopes usually have a well developed vegetation, whilst the vegetation on the south oriented slopes often is scarce due to the unfavourable water balance (much higher potential evaporation due to a higher radiation load and higher temperatures). The scarcer vegetation causes these slopes to be more susceptible to water erosion and consequently to wind erosion.

Blowouts can lead to the formation of secondary dunes. According to Davies (1972) these will be longitudinal dunes if the sand moving winds come from one major direction and parabolic dunes if there is a great variation in approach direction of

the sand moving winds. From the foregoing it can be concluded that extensive and high complexes of coastal dunes can be formed if the sea acts as a durable sand source and if the wind is variable in strength and direction. These conditions are met at many locations at the West European coasts.

### **Macroclimate along the European Atlantic and North Sea coast**

The macroclimate is a boundary condition for the local microclimate and many geomorphological processes. For the following brief discussion of the macroclimate of the west coast of the European main land from Skagen, Denmark (57°44'N) to Tarifa, Spain (36°00'N) weather stations were selected from Wernstedt (1972), which are in most cases situated less than 10km from the coast and at an elevation of less than 30 m.

The yearly mean temperature decreases with latitude (Figure 2). The yearly temperature amplitude shows a tendency to increase with latitude, because the change of the mean July temperatures with latitude is less than the change of the mean January temperatures. More inland the yearly temperature amplitude increases rapidly with the distance to the coast. Another interesting feature is the jump in the July and January temperature near 51°N. It demonstrates the diminished influence of the Atlantic ocean at the Strait of Dover, *i.e.* a greater continentality.

In Figure 3 the yearly sum of precipitation is compared with the yearly potential evaporation, which is the evaporation of a short wet vegetation (e.g. a meadow after rain). This was calculated by Henning and Henning (1980) with the aid of the Penman formula. The evaporation of a dry vegetated surface under nonrestricted conditions is 0.6 to 1.0 times the potential evaporation. The evaporation from a bare soil usually is even less. At most locations shown the yearly precipitation exceeds the yearly potential evaporation. Only the Southern half of Portugal and the Spanish coast South of Portugal have a definite precipitation deficit. The precipitation surplus eases the growth of vegetation and thereby the formation and the fixation of

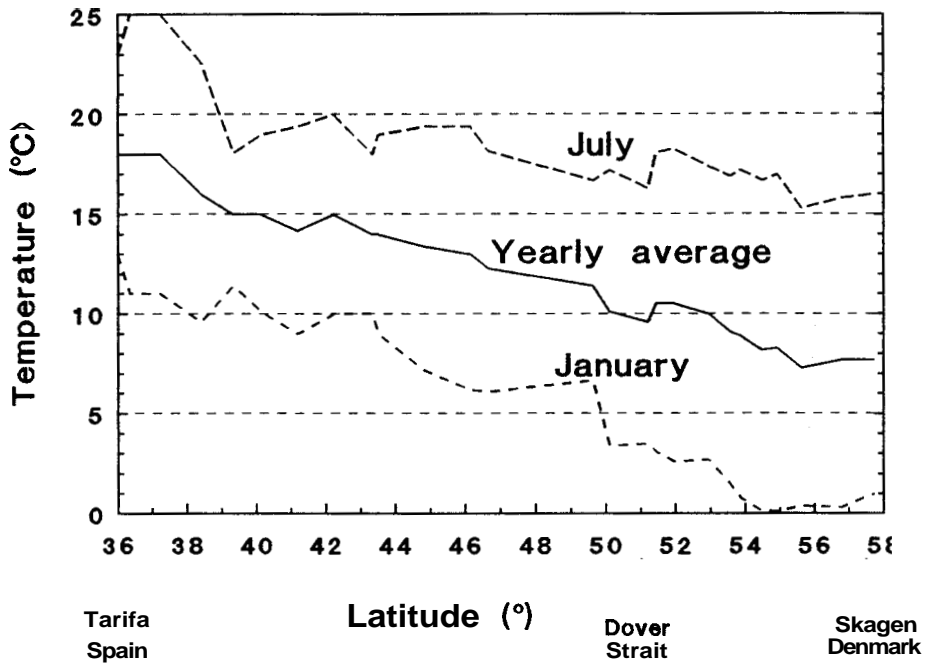


Fig. 2. Temperatures along the European Atlantic and North Sea coast. Data from Wernstedt (1972).

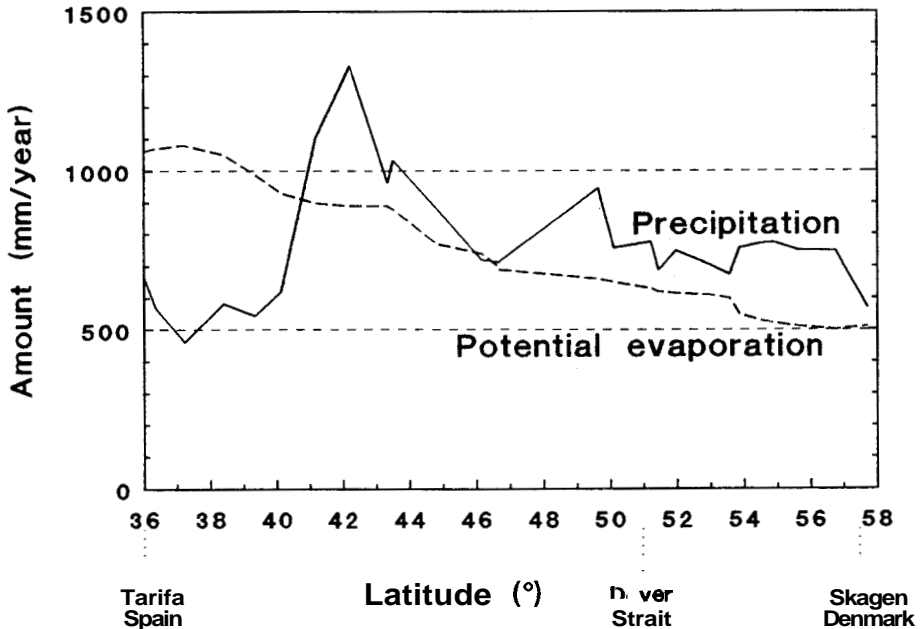


Fig. 3. Precipitation and potential evaporation along the European Atlantic and North Sea coast. Data from Wernstedt (1972) and Henning and Henning (1980).

dunes. Peaks in the precipitation distribution (mainly Northern part of Portugal and Spain, 42° latitude) are due to topography and mesoscale effects.

Wind speed and direction at the West European coast are highly variable (figure 4). There is no prevailing wind direction or prevailing wind speed, as is the case in some parts of the tropics, e.g.

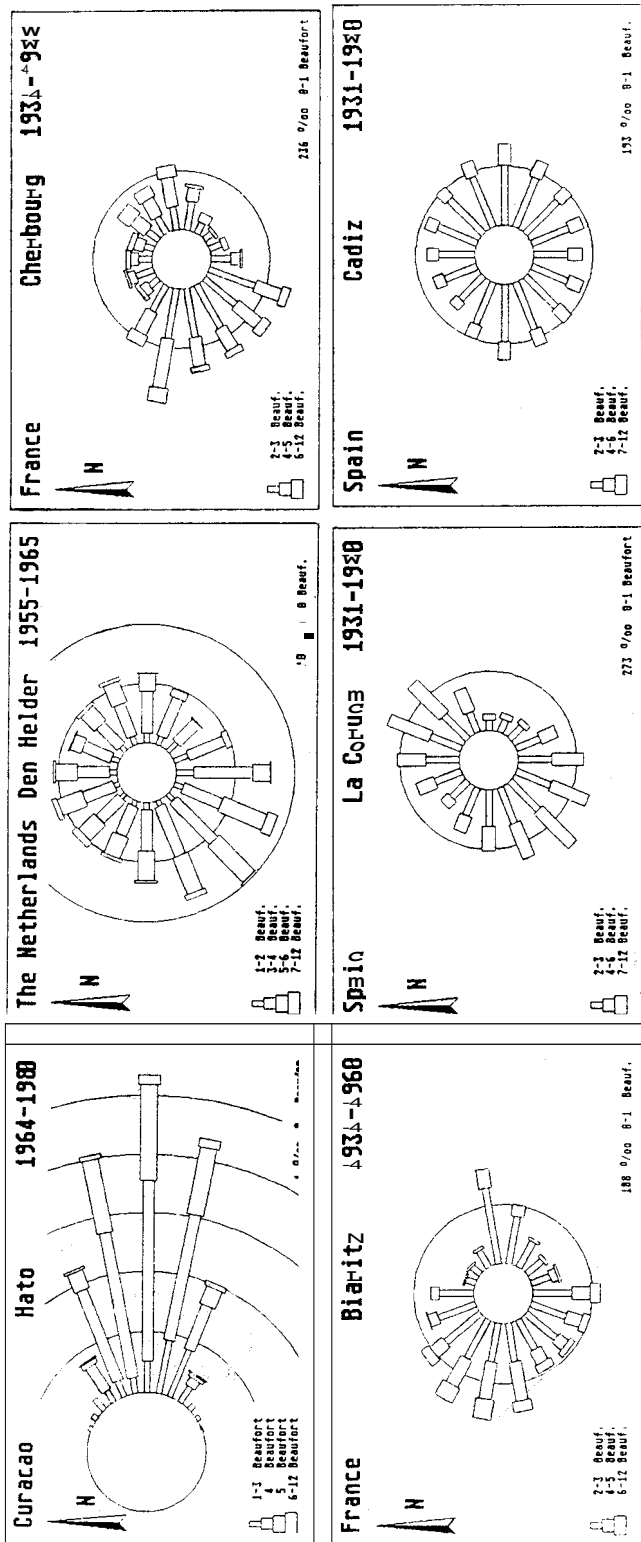


Fig. 4. Distribution of wind speed and direction at various locations. Each circle outside the inner circle represents 5%. Data taken from Anonymous (1972, 1983), Dania (1982) and Bessemoulin (1969). Note that the wind speed scales are different.

Curacao in the Caribbean Sea. At many points along the West European coast the frequency of winds, strong enough to play a role in dune formation, have a much more prevailing direction (SW, W and NW). However, the frequency of strong winds from other directions is still high enough to be in favour of the formation of high dune complexes.

### Mesoscale effects

All mesoscale phenomena which are important to coastal dunes are related to the fact that these dunes are located near the boundary between land and sea. Climatic conditions over sea are completely different from those over land.

A coastal area experiences the weather present over the sea during onshore winds. Inversely, if the wind is offshore, the dunes are influenced by 'continental' weather. Although mesoscale phenomena cause a moderate influence of the sea to reach ten or more kilometres inland, even during offshore winds, one may state that the coastal region alternately experiences maritime and continental weather situations. If the winds are onshore the weather has a far more maritime nature near the coast. The direct maritime influence is felt one hundred kilometres or so inland (Blom and Wartena 1969).

The yearly temperature amplitude over sea is much less than that over land. When moving inland this amplitude increases. Over sea there is hardly any diurnal course in the temperature. The difference with the temperature course over land often causes land-sea breezes in the coastal zone.

Dunes can cause a profound modification of the mesoscale phenomena. Coastal fronts for example will form sooner near coastal dunes than near an artificial sea defence on the edge of a plain. However if the hilly countryside is continuously extending from the shore inland then an increase in the formation of coastal fronts will not occur (Berg 1987).

Wind speeds over sea are higher than those over land. There is an relatively abrupt change in wind speed at the coast, whereas more inland the wind

speed reduces less suddenly (*e.g.* Wieringa 1983).

When the wind direction is onshore the sudden drop in wind speed creates a convergence at the coast, which will lead to a rising motion of the air. This motion often triggers the formation of clouds and precipitation. However this precipitation usually does not fall in the coastal zone itself, but some ten kilometres inland. When the wind is offshore there will be divergence at the coast and descending air, which generates a decrease in cloudiness. Altogether these factors cause the coastal zone to be sunnier and slightly drier than the regions more inland (Schuurmans 1988, Buishand and Velds 1980).

Potential evaporation is higher in coastal regions mainly due to the higher insolation (Buishand and Velds 1980). This is only partially compensated by the higher relative humidity (lower saturation deficit). The higher wind velocities have little effect (see also the section on Evaporation).

### Coastal dunes and microclimate

Although the results of micrometeorological measurements in the dunes are sometimes presented as being unique the micrometeorology of the dunes is very similar to that of any undulating area, as described in the handbooks of micrometeorology (*e.g.* Geiger 1961).

When studying the micrometeorology of the dunes the physical interaction between atmosphere and surface is very important. If one studies meteorology on this scale, it appears that some geomorphological structures and vegetations have a characteristic set of parameters. A multitude of ambient situations is possible, *e.g.* bare soils, soils sparsely covered with grass or moss, a closed cover of herbs, shrubs or woods. The morphology of dunes is a complex of isolated depressions, open or closed valleys, slopes with a varying degree of steepness and with an orientation into almost any direction, crests and elevated flats. The lower areas can be dry as well as moist. All these elements are present at close distance and rather irregularly dispersed.

The effect of slopes on the energy balance and the

resulting surface temperatures has already been discussed. On south oriented slopes the higher radiation load and the higher daytime temperatures also cause the potential evaporation to be higher than on north oriented slopes. Since precipitation is roughly the same on all slopes the water balance is strongly dependent on the direction of the slope. In the depressions the surface runoff from the slopes is an additional water source. Since in most cases the soil in the dunes is highly permeable to water a large part of the precipitation is lost to the ground water. Only in some low areas the ground water table is high enough to be reached by smaller plants.

### Climatic change

Carbon dioxide plays a very important role in the radiation balance of the atmosphere. The  $H_2O$  and  $C_2O$  in the atmosphere are responsible for the greenhouse effect. Without this effect the mean temperature on earth would be approximately 25 K lower. There is little doubt about the increase of atmospheric  $CO_2$  concentrations (and other greenhouse gasses) in the recent past and the effect this has on the absorption and emission of infrared radiation. Over the last 100 years  $CO_2$  concentrations have increased by 25 % (Cohen 1990). Since 1890 the global temperature has risen by about  $0.5^\circ C$  (Vinnikov *et al.* 1990), but within this epoch periods with considerable warming (1910-1940) and cooling (1940-1970), caused a high variance. The recent rise in temperature is still within the normal climatological variability. The climatological models are not yet able to present a clear explanation of the observed fluctuations. Another indication of the inaccuracy of these models is the wide range of the predicted changes in global average temperatures. Even the most sophisticated models give increases which range from 1.5 to 4.5 K during the next century (Schneider 1990, Cohen 1990).

During the past century mean annual precipitation on the continents between  $35^\circ$ - $70^\circ$  N has increased by 6 %, but in Central and South Europe there has been a decrease in precipitation of about 6% (Vinnikov *et al.* 1990). Also these differences

are not confirmed by the present climatological models.

In order to evaluate the value of these models one has to understand the main cause for the meteorological processes, which is the unequal warming of the earth surface, both in space and in time. The atmosphere is like a big heat machine, which tries to smooth temperature differences. But since the differential warming continues, the machine never runs out of fuel. The weather machine uses many processes. Hurricanes, tornados, storm complexes in the tropics, monsoons, frontal depressions, polar lows, stationary high pressure systems, troughs and ridges, all are driven by the same source of energy (differential warming) and all serve the same purpose (smoothing the differences). Most of these systems have a life cycle of a few days up to a few weeks. Therefore current meteorological models cannot predict the weather more than 4 to 7 (at most 10) days in advance.

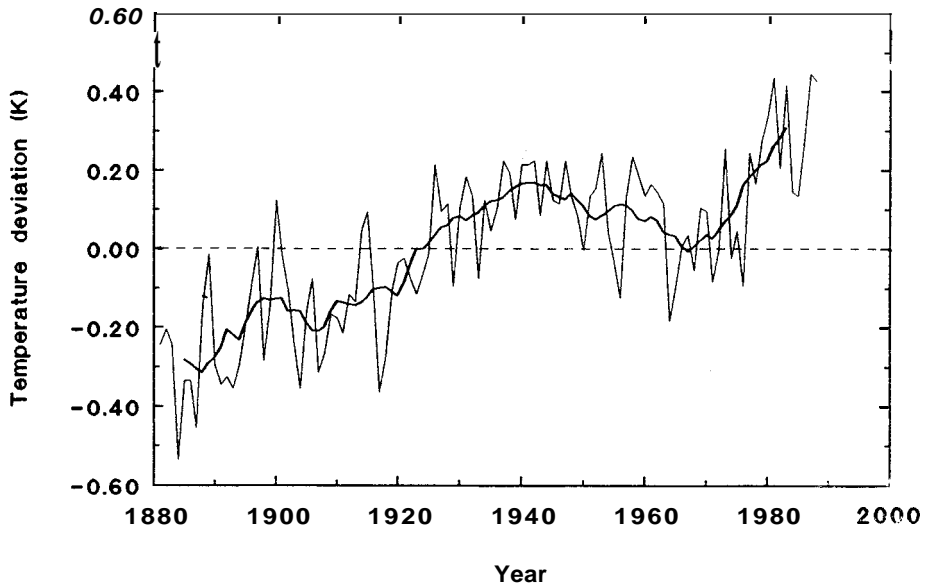
Nevertheless we can predict, on the basis of climatological considerations, that the average temperature of february 1992 in the Netherlands will be less than that of july 1992. This also is based on physical processes, which are studied by physical climatology. Physical climatology, however, describes average situations (averaged over many years) and does not yield information on year to year fluctuations. The actual weather, for which even shorter time scales are important, is not described by the climatological models.

It seems logical that changes in the magnitude of the greenhouse mechanism will have consequences on the weather, because weather systems serve to keep the temperature differences over the earth limited.

Will this be manifested in more blockings and less frontal lows, or only in weaker frontal lows?

If something changes, it must be expected that some areas become warmer and others colder. At some places the summer becomes hotter and the winter a little bit colder. Wind direction histograms will change, but until now, no model is able to give an indication of the most likely modification.

Changes in weather system frequencies and intensities influence the currents of the sea, even without a change in sea level. In the section on dune



**Fig. 5.** Yearly mean global temperatures (thin line) and 10-year running means (bold line) for the period 1881-1989. All values relative to the 1881-1989 average. Data taken from Vinnikov *et al.* (1990).

formation it was discussed that dune formation depends on the sand source (supplied by the sea) and strong onshore winds, combined with strong winds from other directions with sufficient frequency. At the present state of knowledge it is absolutely impossible to predict the likelihood of certain changes in the wind distribution, or the magnitude of these changes.

Figure 5 shows the course of globally averaged mean yearly temperatures and 10-year running means relative to the average for the period 1881-1989 (data from Vinnikov *et al.* 1990). The climatological models do not yield a temperature course which resembles the course of the 10-year running mean. In the eighties the air temperature was rising. However this is nothing abnormal, since a similar rise is seen between 1920 and 1940. The rise of the global mean temperature in the eighties is mainly due to a warming in the tropics, while in the polar regions the temperature stays roughly constant. This is remarkable because climate models predict that the global warming will be strongest in the high latitudes. So the regional distribution of the current warming is not reproduced by the models.

It is clear that from a meteorological point of

view, an impact on the temperatures alone is very unlikely, if not impossible. Weather systems are responsible for cloudiness, insolation, precipitation, temperatures, wind speed and direction, storm frequency and intensity. The weather also causes sea currents and indirectly dune formation and erosion of dunes. So some of these factors could be changed.

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