A literature survey on the wind energy potential in the Sahel

A LITERATURE SURVEY ON THE WIND ENERGY POTENTIAL IN THE SAHEL

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Abstract

This literature study on the wind potential in the Sahel consists of two parts:

1) A survey of the climate and in particular of the wind regime in the Sahelian region in Africa and the major factors by which the climate is determined.
The so-called Inter Tropical Convergence Zone shows to be the major meteorological phenomenon: its annual passage over the region results in strong seasonal patterns in precipitation, temperature, cloudiness, atmospheric moisture and the wind regime.

2) A study of the availability and reliability of the wind data for the Sahel and the build-up of a wind data base.
Very few unprocessed data could be found for Mali, Burkina Faso and Chad. For the other countries (Niger, Senegal and Mauretania) it appeared to be difficult to find hourly measurements of wind speed and direction. Hourly data are only available for station Chikal, Niger. These data were processed into diurnal and seasonal patterns and compared to accepted wind maps.
It is probable that at least some of the data in the data base are unreliable; definite conclusions, however, cannot be drawn because of a lack of information about the measuring station and its surroundings.

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Introduction

This study proposed by CWD (Consultancy services Wind energy Developing countries) aims to examine the wind potential for water pumping in the Sahelian region. This region in West Africa suddenly came into the centre of publicity during the severe drought in the early seventies of this century.

In literature, there appear to be two important overall studies about the wind regime in the Sahel:

- the wind map by Le Gouri r s and Guetti [12], 1986;
- the wind map by the French Meteorological Service [10], 1957.

The latter map was used by Poulissen/Van Doorn [11] to conclude the wind potential to be insufficient for water pumping in large parts of the region, especially in South Mali and Burkina Faso.

In the last years it has been shown [13,14,15] that there are some problems connected with the wind studies mentioned:

- Both wind maps only give annual averages of wind speed. However, it will be shown in this study that diurnal and seasonal variations of wind speed and direction are too important to be disregarded when estimating the wind potential for water pumping.
- Both studies use uncorrected wind speed measurements. It appears from later studies as those by ABu Bakr [13,14] that wind data should be corrected for the surroundings of the anemometer to obtain the so-called potential wind speed for the region concerned. Neither of the above studies, however, gives ample information about the anemometer surroundings, height, calibration, etc.

The purpose of this study is twofold:

1) Investigate the climate of the region, in particular the wind regime, to obtain a general impression of the climatological factors and their effect on the wind regime.

2) A literature study on the available wind data for the region; a preliminary study on the seasonal and diurnal wind variations.

1. The Sahelian Region

1.1 General description of the Sahelian Region

The name "Sahel" originates from the Arabic word "sahil", which means "shore" or "border". The Arabs use this term to indicate the intermediate area between the desert and the regions with ample precipitation. So in fact the whole Sahara ("desert") is surrounded by a sahelian zone. The name Sahel, however, is mainly used to indicate the transitional area south of the Sahara. This Sahelian zone extends from the Atlantic Ocean inland up to Sudan.

Delimitation of the Sahelian Region is usually based upon mean annual precipitation levels. The northern border is usually taken along the 200 mm precipitation-isoline. The southern border, between the Sahelian zone and the Sudan-region, is then chosen at the 600 mm isoline. Thus defined, the Sahelian region has a length of approximately 4000 km and a maximum width of appr. 400 km (fig. 1.1). In other publications, the Sahelian region may be defined as the region on the African continent between 14 and 24 °N.

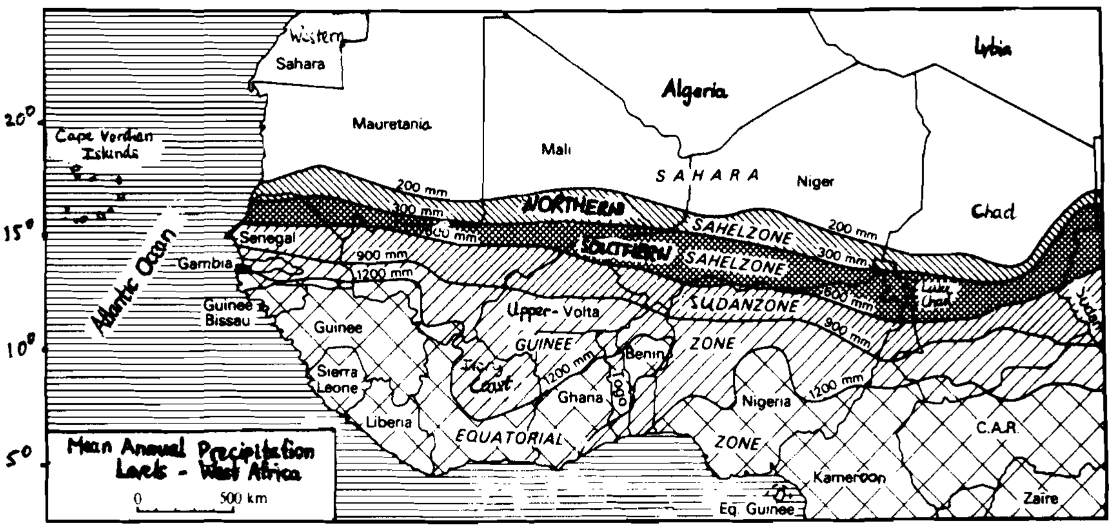


Figure 1.1. The northern and southern Sahelian regions [1].

Figure 1.1 shows that there are basically seven Sahelian countries: Senegal, Mauretania, Mali, Burkina Faso (Upper Volta), Niger, Chad and the Cape Verde Islands.

The relief is generally flat, between 200 and 500 m above sea level. Exceptions are the areas near the coast (0-200 m), and some low mountains, for example the Hombori-mountains in Mali, reaching to about 950 m. Most important rivers are the Senegal and the Niger rivers. Vegetation mainly consists of grass and low bush (steppe). In the northern zone, larger and larger areas without vegetation start to appear. Trees generally cover less than 5% of the total area.

A more detailed map of this region can be found in appendix 1.

1.2 The Population

Figure 1.2 gives an impression of the density of population in the Sahelian countries. Table 1.1 gives some extra information about the total population and the annual growth.

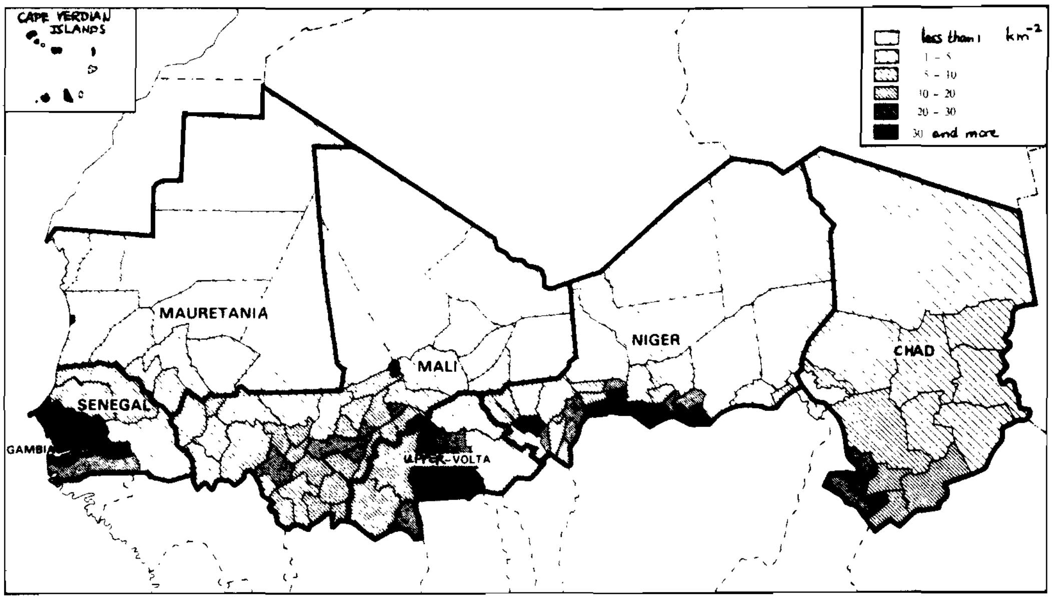


Figure 1.2. Density of population in Sahelian countries [1] (1976).

Table 1.1: population and growth rate ([1], [2])

Country	1979 population (x 1000)	area (x1000 km^2)	1970-1979 mean annual growth rate (%)
Cape Verde Islands	319	4.0	1.8
Senegal	5 518	201.4	2.6
Mauretania	1 588	1030.7	2.7
Mali	6 465	1240.7	2.6
Burkina Faso (Upper Volta)	6 728	274.2	1.6
Niger	5 150	1267.0	2.8
Chad	4 417	1284.0	2.0
(The Netherlands	14 091	36.6	1-1.5)

The population in the Sahelian Countries is generally divided into three groups:

- The cattle-breeding nomads, representing 32 % of the total population in Mauretania, 13% of the population in Niger, Chad and Mali (on the average), and less than 3% in the remaining countries.
- The rural population, the largest group, represents 70-80% of the population in all countries except for Mauretania.
- The urban population, the third group, is small in Sahelian countries: less than 21% of the total population lives in cities, save in Senegal, the Cape Verde Islands and (recently) Mauretania.

In all countries mentioned, the capital can be considered as the
primate city.

The population is never an ethnic unity in Sahelian countries; this diversity originates from the colonial period.

In the nineteenth century, the colonial powers (especially France and England), in great political tension and competition, divided their possessions in West Africa into territories whose frontiers respected neither ethnic nor cultural affinities. Where no natural borders (e.g. a river) were present, frontiers were drawn straight.

The colonial empires in West Africa were kept together mainly by authoritarian rule and imposition of the language and culture of the administering power.

Within a period of a few months in 1960 all the countries mentioned, except for the Cape Verde Islands, gained independence. The rather arbitrarily drawn borders, however, still cause a lot of problems between the different tribes and ethnic groups in each coutry [2].

Languages spoken are Arabian, Sudan and Touareg-languages, such as Berber, Chadian, Mande, Western Atlantic, Voltaic, Afro-Asian. French, however, remained an important language after the colonial period. Official documents are usually written in French.

2. The climates in the Sahel

2.1 General

The climate and the life surroundings in the Sahel are mainly characterized by a wet and a dry period, during the northern summer and winter respectively. Just before the beginning of the wet season the Sahel is a semi-arid to arid region with very low humidity and virtually no rainfall. Winds are the hot and dry E-NE Harmattan winds. At the end of the wet season, however, one sees a variety of vegetation, humidity is high and winds are generally southwesterlies.

This, of course, is a very general picture: in the coastal regions of Mauretania and Senegal, for example, the Atlantic Ocean has a major influence on the climate and weather extending for about 20-40 km inland (this is the average influence of sea-breezes inland).

Many climatological aspects of the Sahelian region can be explained from the movement of an important tropical phenomenon, the Inter Tropical Convergence Zone, over the African continent. This phenomenon will be examined in the next section. Furthermore, some aspects of the climate, in particular of the wind regime, in West Africa (rather than just the Sahelian region) will be examined.

2.2 The Inter Tropical Convergence Zone

The climate of West Africa in influenced by two air masses: dry, tropical continental (cT) air, originating from the Sahara and humid, tropical maritime (mT) air, from the Atlantic ocean. The interaction of these air masses results in the so-called Inter Tropical Convergence Zone (ITCZ). In other publications, this phenomenon may also be referred to as Inter Tropical Front (ITF, FIT), Inter Tropical Dicontinuity (ITD) or Equatorial Trough. This is a low pressure zone in the tropics, oscillating between about 20^{o}N and 20^{o}S. The ITCZ is related to maximum solar heating at tropical latitudes, causing the air to rise and thus forming a low pressure belt: the ITCZ moves seasonally with the sun, as shown in figure 2.1.

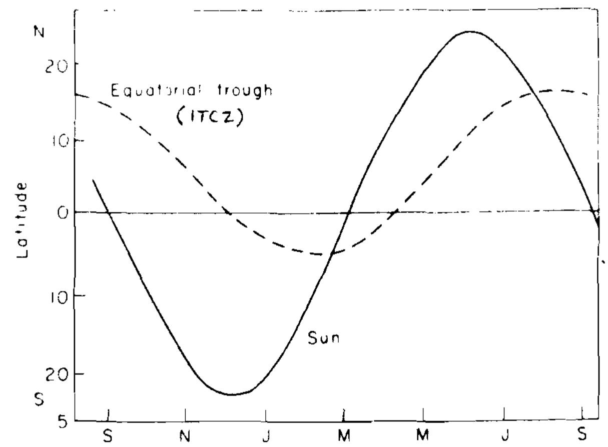


Figure 2.1. Annual movement of the sun's zenith (solstice) and of the ITCZ [4].

The movement of the ITCZ lags behind that of the sun by two months, and its latitudinal excursion is only half that of the sun. This is explained by the fact that the heating of the atmosphere does not stop at the solstice: highest temperatures are reached a month later over large land areas and two months later over the oceans.

Furthermore, the annual average position of the ITCZ is about 5°N. This latitude is called the meteorological equator: the northern meteorological hemisphere is smaller than the southern meteorological hemisphere. This may be caused by the larger ocean covered area below the geographical equator, oceans taking a longer time to heat up compared to land masses.

In West Afrika, the ITCZ is generally situated as shown in figure 2.2, for January and July. Note the curvature along the coast line in January, caused by the greater heat capacity of water compared to land. The ITCZ moves faster over the continent than it does over oceans, resulting in a larger latitudinal excursion over continents. This shown on a world-wide scale in figure 2.3. Both figures are very general, giving the average position over a number of years.

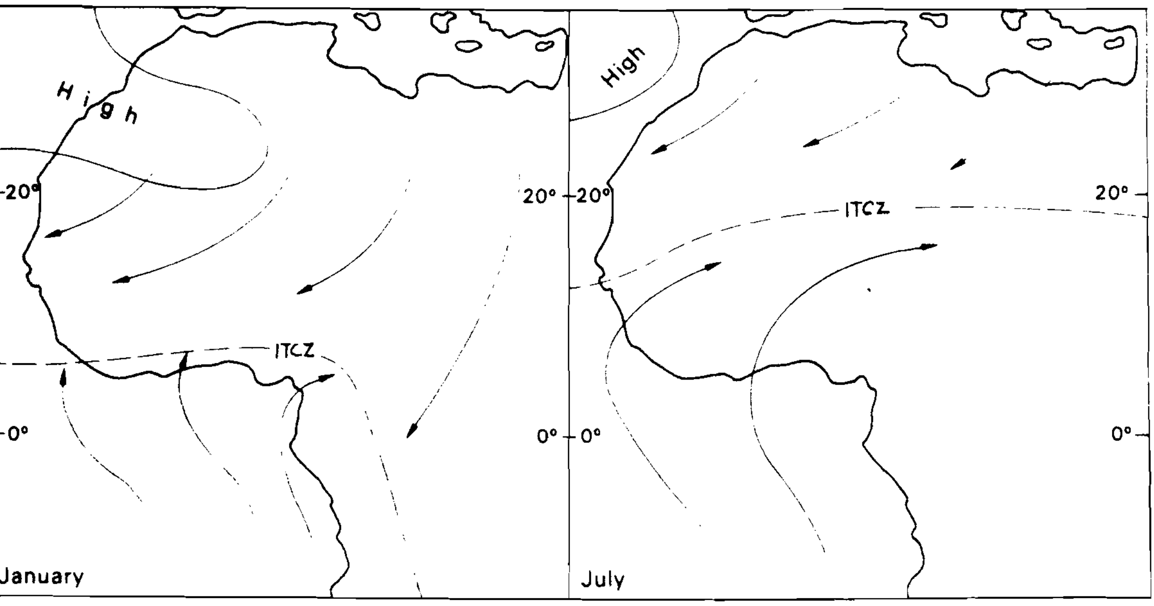


Figure 2.2. The ITCZ over West Africa in January and July [3].

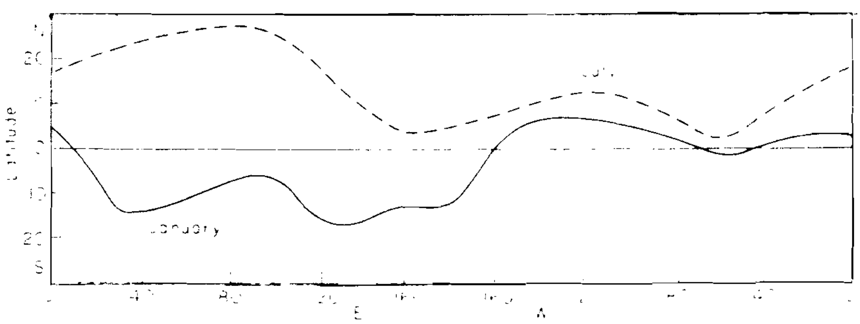


Figure 2.3. Mean positions of the ITCZ in January and July [4].

The ITCZ does not move uniformly with time, if relatively short time spans are considered. This is shown in figure 2.4, where daily variations of the ITCZ over West Africa in December/January and in July are shown. The northern movement of the ITCZ is rated at 160 km/month, whereas its southern movement is about twice as fast.

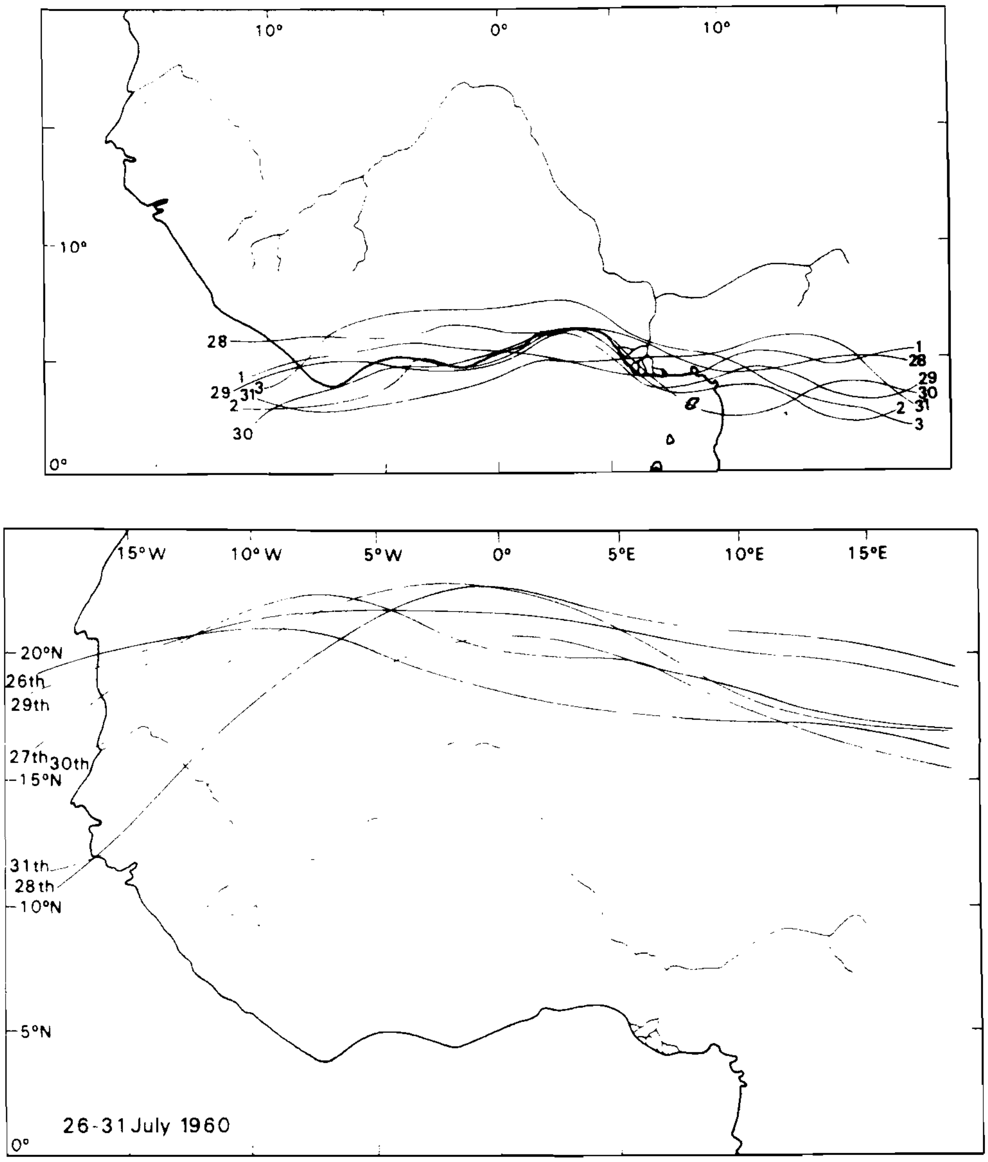


Figure 2.4. Diurnal variations of the ITCZ's position over West Africa; Dec 28, 1955 to Jan 3, 1956 (above) and July 26-31, 1960 (below) [3].

Figure 2.5 relates pressure and wind constancy to the position of the ITCZ (wind constancy is the fraction of time the wind blows from a certain definite direction). These are simple distributions, more or less symmetrical on both sides of the ITCZ.

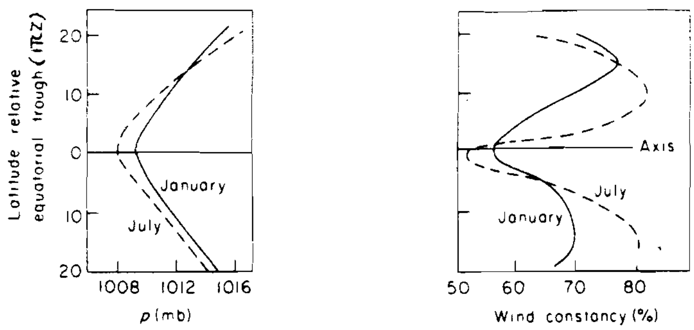


Figure 2.5. Pressure and wind constancy relative to the latitudinal position of the ITCZ [4].

In fig. 2.5 seasonal variations disappear, indicating that functions of the ITCZ's position are constant throughout the year. Pressure, by definition, has its minimum at the ITCZ, while winds are most constant in the subtropical regions where trade winds prevail.

Situated at subtropical latitudes are three important high pressure belts: the anticyclone of the Azores to the North-West of Africa, the anticyclone of North Africa situated in the Sahara, and the St. Helena anticyclone to the South-West of Africa. These anticyclones move seasonally with the ITCZ. The succession of the seasons in West Africa is related to the annual movement of the ITCZ, as will be shown in the following section.

Having examined the movement of the ITCZ over West Africa, fig. 2.6 gives an impression of the general structure of the ITCZ.

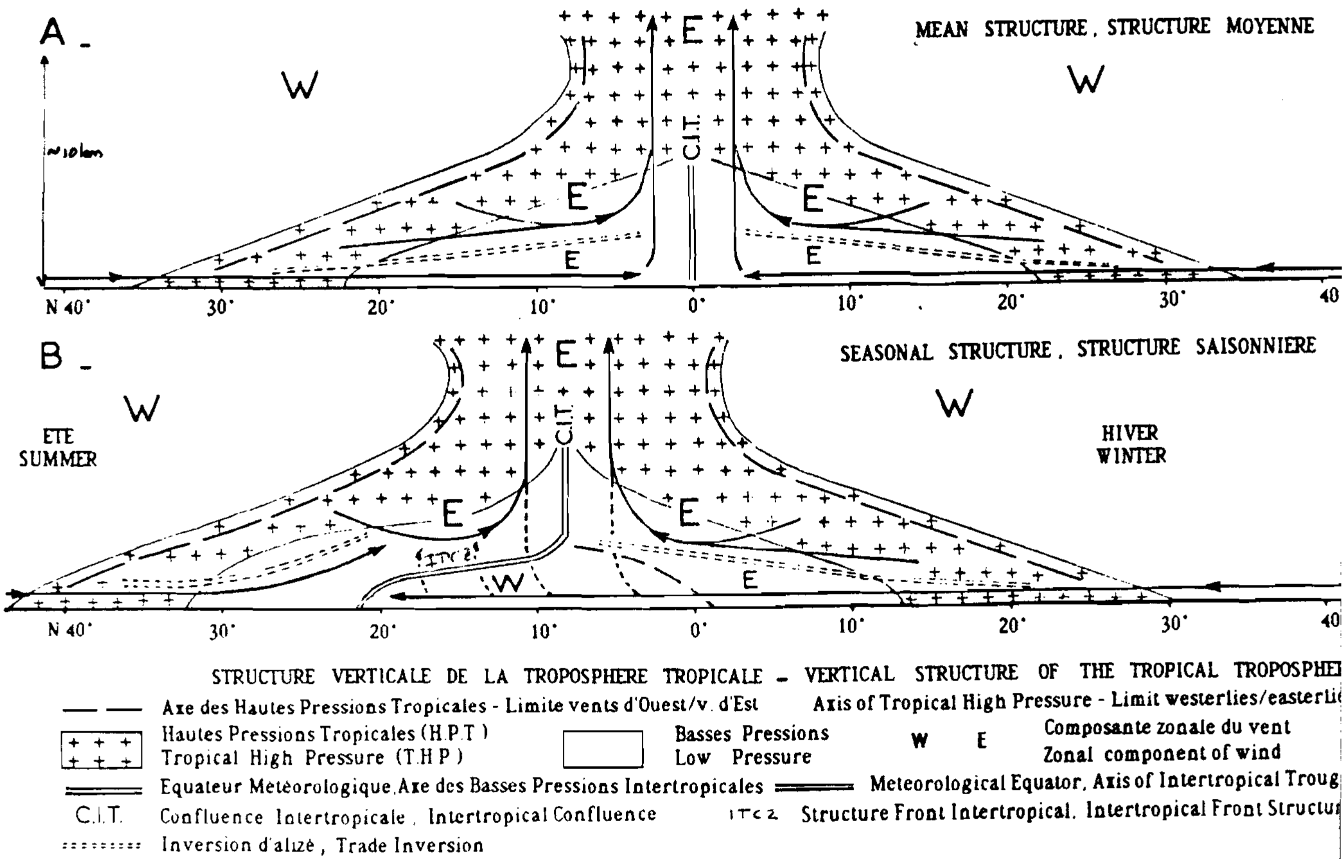


Figure 2.6 A&B: The structure of the ITCZ [7].

Looking at fig. 2.6 A, the low and high pressure belts can clearly be seen: low pressure at tropical latitudes and high pressure at subtropical latitudes (at ground level). The border between the westerlies and easterlies represents the limit of the tropical region at different heights: the deepest penetration of the polar air masses. This border is sometimes called "axis of tropical high pressure" [7]. The trade inversion is the upper border of rising tropical air (caused by solar heating). Above it are sinking air layers (cooler air). Reference [7] provides additional information about the trade inversion.

Figure 2.6 B gives the seasonal picture, during the northern summer: the ITCZ is situated at about 20°N. The general structure of 2.6 A remains clearly visible, but the ITCZ is curved at increasing heights. Figure 2.6 A gives the average situation over the year in tropical regions.

2.3. The weather zones and the succession of the seasons

Five weather zones may be recognised as being associated with the ITCZ. These zones fluctuate with the annual fluctuation of the ITCZ. The weather at a certain site depends on the characteristics of the prevailing weather zone. Figure 2.7 gives a simplified picture of the atmospheric cross-section in the tropics.

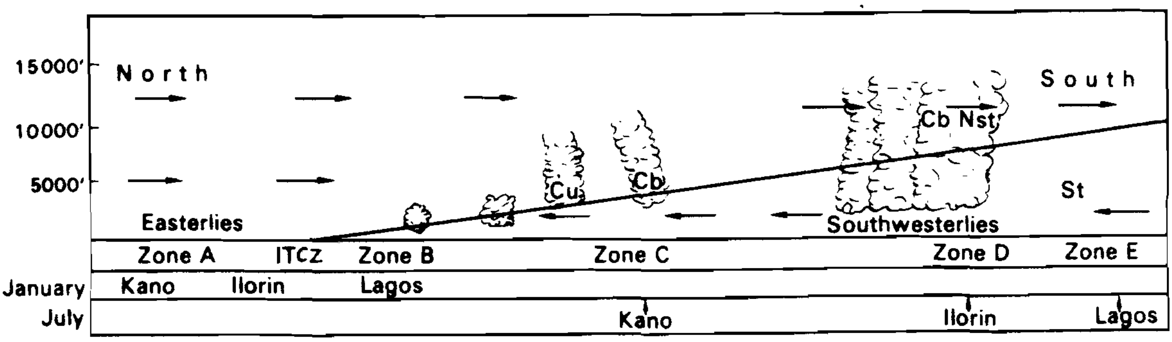


Figure 2.7. The ITCZ and the weather zones [3].

The weather zones (A-E) are indicated with their approximate position in January and July, as related to some of the larger towns in Nigeria. Each zone has its specific weather characteristics, which are the following:

Zone A. The southern boundary of this zone is indicated by the maximum penetration towards the South of the dry desert winds: the surface ITCZ. It is a rainless zone with hot days (35-40 ^{o}C) and relatively cool nights (18-21 ^{o}C); winds are generally easterlies: dry desert winds. There also is very little cloud, just cirrus (Ci clouds) at great hights.

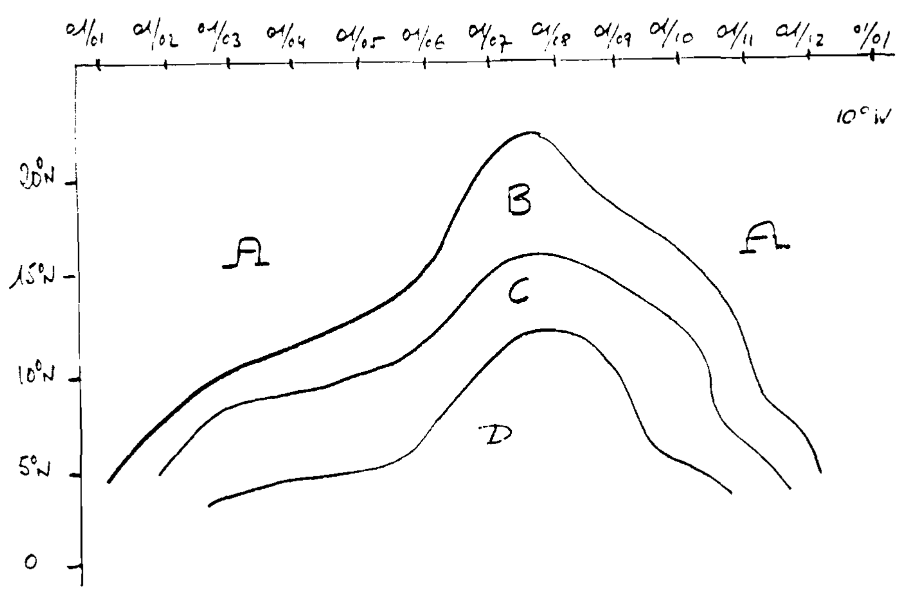
Zone B. This zone extends southwards for appr. 300 km. It has little rain (76 mm/month) and warmer nights (21-24 ^{o}C) and days (35-43 ^{o}C, inland). Winds are generally southwesterlies. These winds originate from SE winds on the southern hemisphere, but deviate to the right due to the coriolis force after passing the equator (see section 2.6.2). On 1-5 days a month, isolated thunderstorms may break out. Fog may appear at night.

Zone C extends for about 600-800 km southwards. The boundary between zones B and C is not at all well-defined. Zone C experiences a monthly rainfall of about 127 mm, mainly caused by "disturbance lines": either well-defined squall lines or a broken area of more or less isolated thunderstorms. Mean night and daytime temperatures are generally the same as in zone B. However, daytime temperatures vary much more than in zone B, so that very high temperatures may be recorded (50 ^{o}C). Winds are generally southwesterlies.

Zone D. The northern border of zone D is very hard to define: in some textbooks zones C and D are not distinguished at all. Zone D extends for about 300 km and is characterised by heavy rainfall, referred to as "monsoon rains" on the coast. Winds are somewhat stronger than in zone C, but SW remains the prevailing wind direction. Skies are clouded most of the time (cumulus (Cu) and cumulonimbus (Cb) clouds), night temperatures are generally the same as in zones C and B, days are somewhat cooler (27-29 ^{o}C).

Zone E only penetrates a relatively short distance inland in July and August (along the southern coastline) and is hardly of any importance for the Sahelian region. The weather is relatively cool and dry: night temperatures of about 21 ^{o}C and daytime temperatures of 26-30 ^{o}C. The southwesterly winds are at their strongest in zone E. Skies are generally clouded, there appears much stratus cloud with a base of only 200-300 m.

The only zones of importance for the Sahelian region are the A, B and C weather zones. In exceptionally wet years, zone D weather may occur. To illustrate the influence of the weather zones, fig 2.8 shows the penetration of the weather zones into the African continent at three different longitudes, averaged over a number of years. The penetration of the weather zones is shown on an annual basis: along the horizontal axis are the months of the year.



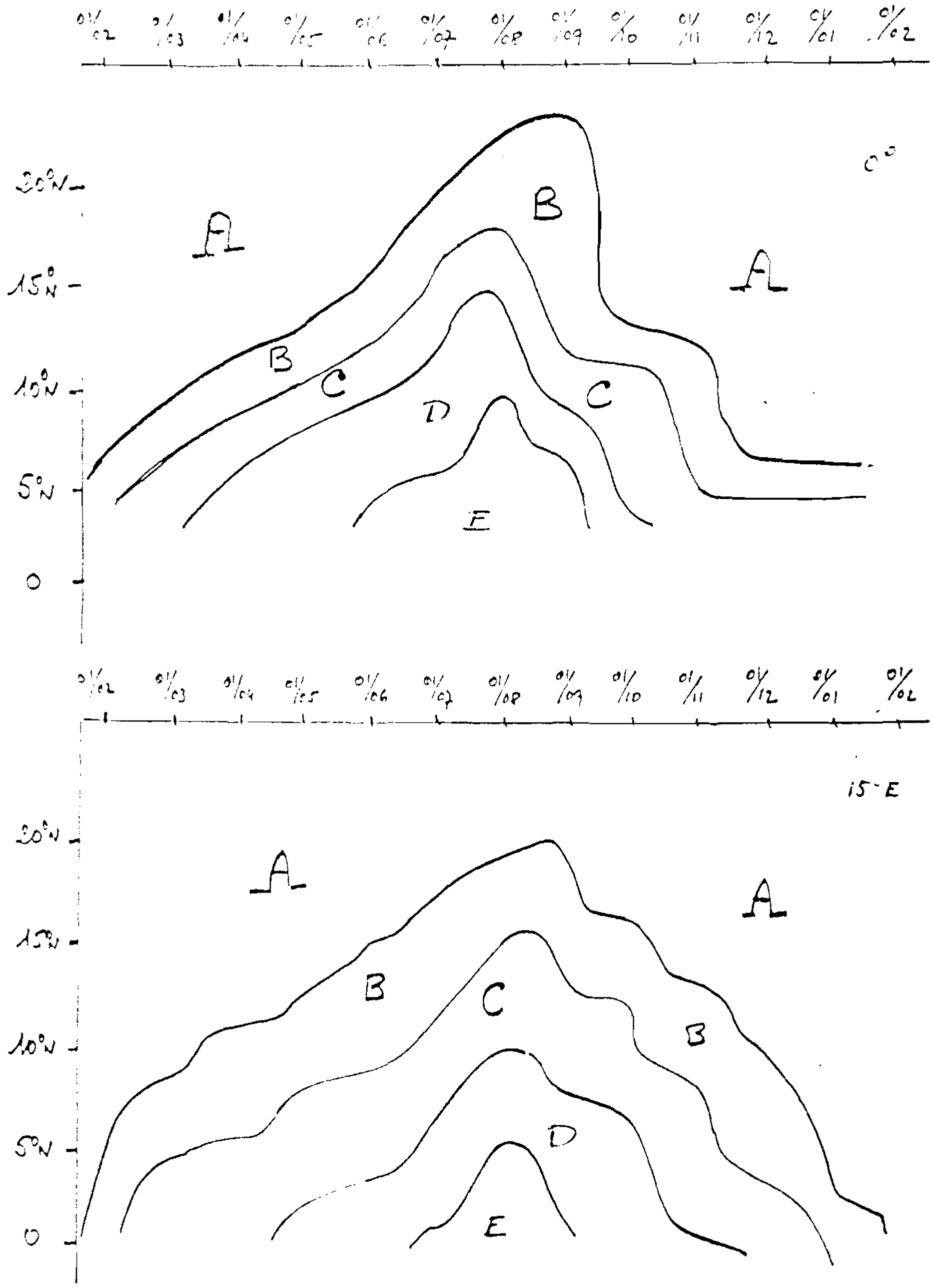


Figure 2.8. The penetration of the five weather zones over the African continent at longitudes 10°W, 0° and 15°E [8].

The movement of the ITCZ over West Africa gives rise to two clearly distinguished seasons, the dry and the wet season, and two intermediate seasons.

The dry season: the ITCZ situated near the southern coastline: November-March. In the Sahelian region zone A weather prevails.

The wet season: the ITCZ is situated at about 20°N: June-August. Zone B and C weather in the Sahelian region.

Intermediate season: April/May. Zone B weather, with many disturbances, exept to the north of the ITCZ, where zone A weather is experienced.

Intermediate season: September/October. High humidity (100% relative), clouded skies, little sunshine, still many disturbances due to zone C weather, especially in the South.

The wet season is sometimes referred to as monsoon season. The first intermediate season (April/May) is then called "advancing monsoon" and the second intermediate season (September/October) the "retreating monsoon" [6].

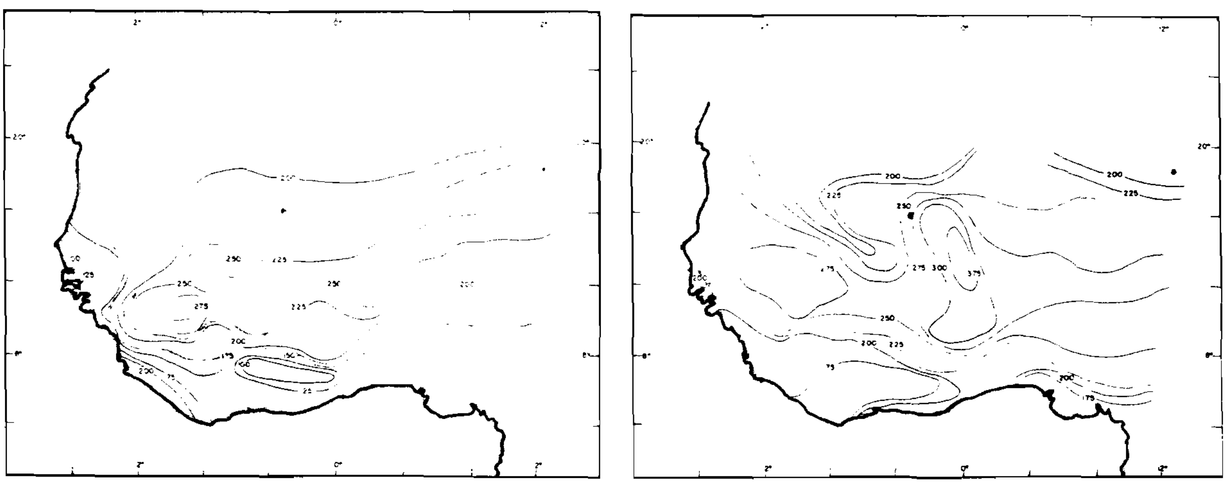
Before turning to the wind systems in the Sahel, we will examine some other aspects of the climate in the region, because many of these factors either influence, or are themselves influenced by the wind regime.

2.4. Radiation and temperature

Being the major energy source, the radiation of the sun is the most important factor determining the climate and weather on earth. As we have seen, maximum solar heating at tropical latitudes results in the ITCZ, probably the most important climatological phenomenon in the tropics.

Fig. 2.9 shows values for the received net radiation over West Africa, i.e. the observed solar radiation minus the effective outgoing radiation (mainly infrared radiation). Units in fig. 2.9 are Langleys/day;

$$1 \text{ Langley} = 41,84 \text{ kJ/m}^2$$



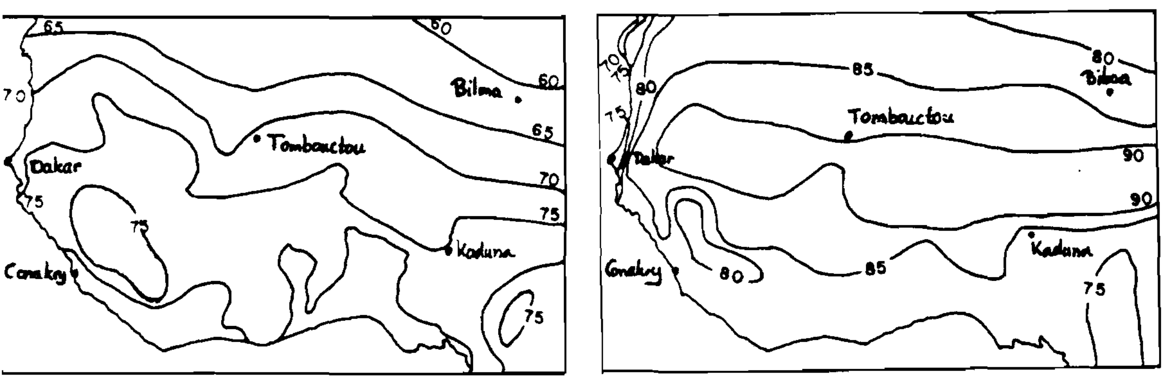
January July

Figure 2.9. Net solar radiation over West Africa (Langleys/day) [3].

In January high net radiation values are found in the Sahelian region due to a large dust content in the air, caused by the very constant Harmattan winds. Lower values in the Sahara are caused by a large amount of outgoing radiation due to no cloud cover. The low values near the southern coast are caused by a heavy cloud cover.
July values are generally higher, because the sun's zenithal position has moved northwards.

The net radiation has, of course, its influence on the temperature distribution. Fig. 2.10 shows the distribution of mean daily temperatures over West Africa for January and July. Units in fig. 2.10 are degrees Fahrenheit.

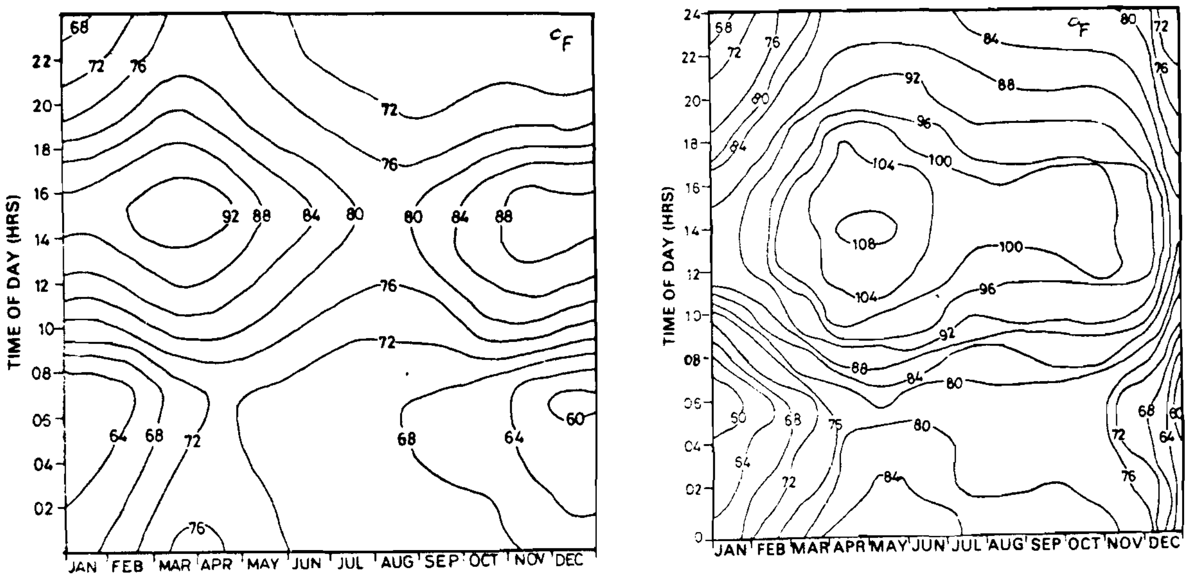
$60^{o}F = 15.6^{o}C$ $80^{o}F = 26.7^{o}C$
$70^{o}F = 21.1^{o}C$ $90^{o}F = 32.3^{o}C$



January July

Figure 2.10. Distributions of mean daily temperature over West Africa (degrees Fahrenheit) [3].

The relatively low values in the Sahara in January are caused by low night temperatures due to strong cooling at night in a region with virtually no cloud cover.
In July, highest values appear around the position of the ITCZ, since it is related to maximum solar heating. The influence of the cooler sea-breezes can be seen from the July picture.
Fig. 2.11 shows the diurnal seasonal patterns for two places in the region: Kaduna in Nigeria and Tombouctou (Timbuktu) in Mali.



Kaduna   Tombouctou

Fig. 2.11. The diurnal seasonal temperature patterns in two locations in West Africa (degrees Fahrenheit) [3].

Highest diurnal variations are measured at the end of the dry season, when there is little cloud cover: March/May in Kaduna and April/June in Tombouctou. When there is more cloud cover, during the wet season, diurnal temperature variations appear to be much less.

Temperature influences the wind regime, especially the diurnal patterns: large diurnal temperature variations result in a strongly variable diurnal wind pattern. This will be examined later.

2.5. Precipitation, atmospheric moisture and the water balance

The annual precipitation pattern in the Sahelian region is largely determined by the passage of the ITCZ. This can be seen from figure 2.12, showing the mean monthly precipitation levels in several Sahel stations. In the Sahelian region, significant values are only found in the wet season - during the months May-September - when the Sahel experiences zone B and C weather.

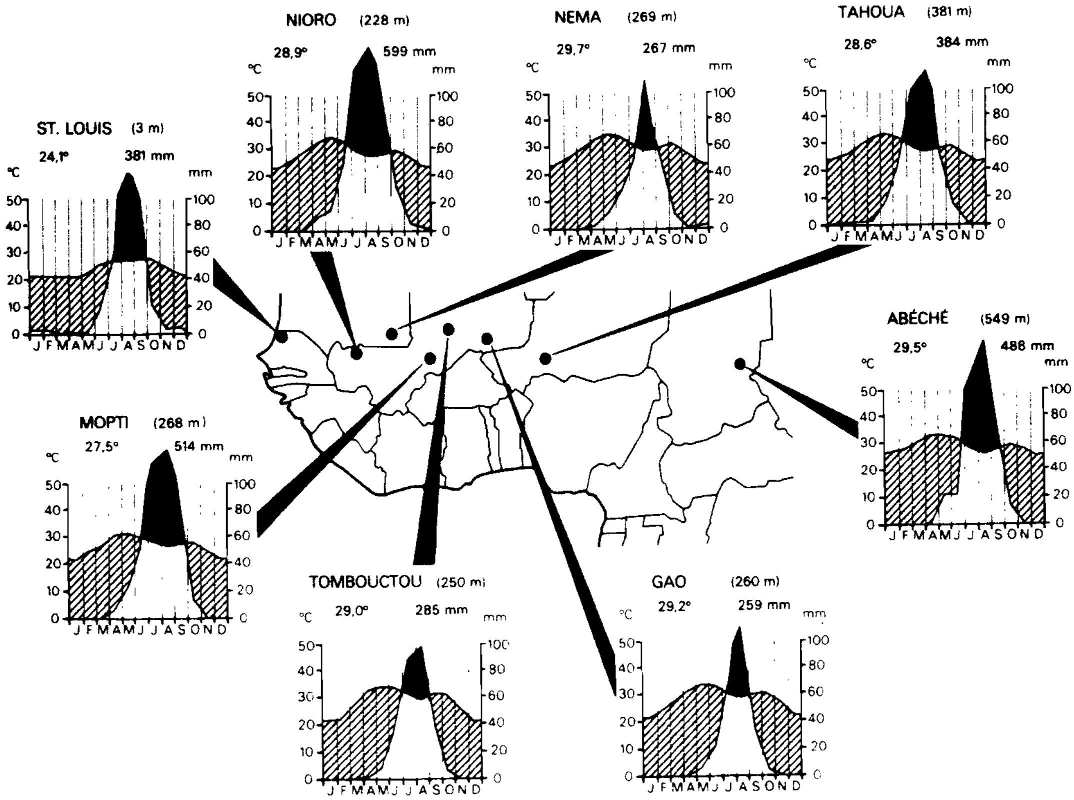


Figure 2.12. Mean monthly temperatures and mean monthly precipitation levels for eight Sahel locations.
Each graph includes a header, giving the name of the station, its altitude, mean annual temperature (°C) and mean annual precipitation level (mm). The upper limit of the shaded area gives the mean monthly temperatures, the other line gives the mean monthly precipitation levels [1].

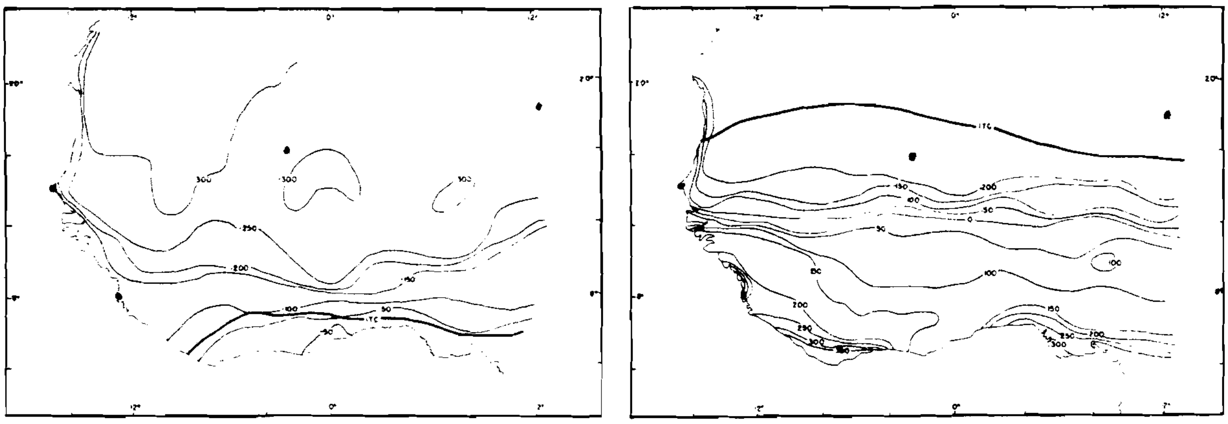
Usually rain does not fall steadily in this region, but in large amounts during heavy and relatively short thunderstorms. These disturbances, sometimes called "squall lines", usually start about 3-5° south of the ITCZ and to the east of Nigeria. They have a speed of about 30-50 km/h and a length up to 300 km. The characteristics of such disturbances are [9]:

- Calm period before the storm.
- Cumulonimbus cloud forming.
- Heavy rainfall (100 mm/h) and high wind speeds (up to 50-60 m/s).
- Light rainfall and high cloud cover after the storm.

Water can disappear from the earth's surface by means of:
- evaporation (caused by solar radiation)
- transpiration (by vegetation)

Evapotranspiration is the name used for these two combined factors. The water balance can be defined as the effects of precipitation and dew minus the effects of evapotranspiration and run-off of water, all quantities measured in mm.

Figure 2.13 shows the water balance for West Africa.



January July

Figure 2.13. The distribution of the water balance (mm) over West Africa in January and July.

In January, a water deficit is found throughout the Sahel, up to 300 mm/month. This water deficit is still found in July but not in such large amounts. The wet season has just started and the amount of rainfall is not sufficient to make the water balance positive in July. The steep gradient around 12-14 ^{o}N is caused by increasing cloud cover and rainfall (zone B and C weather).

Finally, the relative humidity, a measure for the atmospheric moisture, is shown for several Sahel stations in fig. 2.14, at 0800, 1300 and 1800 h. For the Sahel stations (marked *), values are generally highest at 0800 h during the wet season: relative humidities up to 90% are measured then. During the dry season values as low as 15% are found around 1200 h (Bamako).

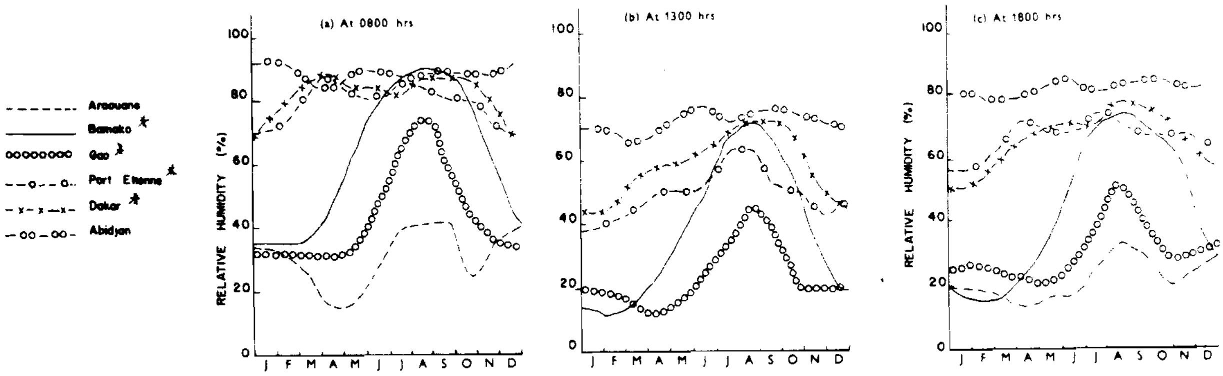


Figure 2.14. Mean relative humidities (%) over the year for six stations in West Africa. Sahel stations are marked with an asterisk.

2.6. <u>Wind systems over West Africa</u> (concentrating on the Sahelian region)

2.6.1. The Hadley circulation

At the location of the ITCZ, air rises due to the intense solar heating; there is a net gain of heat between 38^{o}N and 38^{o}S, while in other areas of the globe there is a net loss of radiation. The deficit is largest at the poles and the surplus is greatest at the equator [5].

Air at higher latitudes sinks and flows towards the ITCZ to replace the rising air. In this closed circulation, warm and humid air is transported from the ITCZ north- and southwards in the upper atmosphere, with a coriolis deviation to the left over the southern hemisphere and to the right over the northern hemisphere. The build-up of a force balance between the coriolis force and the pressure force is sketched in figure 2.15 for the so-called geostrophic approximation, in which the wind is thought to be a frictionless, straight, steady and parallel air flow: a very bad approximation indeed in the lower, turbulent layers of the atmosphere [4,5].

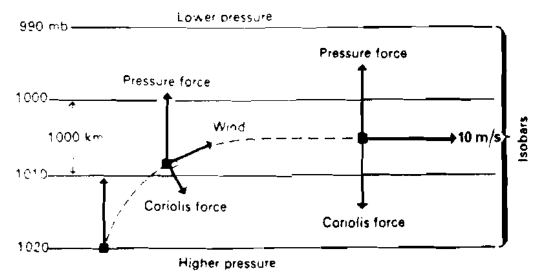


Figure 2.15. The build-up of a force balance between coriolis and pressure forces in a geostrophic approximation [5].

In the lower troposhere, the cooler and dry air from the subtropics is transported to the ITCZ. This general tropical circulation is called the Hadley circulation, as it was first suggested by the British scientist George Hadley in 1735.

The northern and southern movement of the warm and humid air from the ITCZ ceases at about 30^{o}N and 30^{o}S where the air begins to sink: the Hadley circulation has a limited extent. North of 30^{o}N and south of 30^{o}S, the atmospheric motion is characterised by predominantly westerly winds: the so-called Rossby circulation.

A simplified overview of the atmospheric circulation is given in figure 2.16.

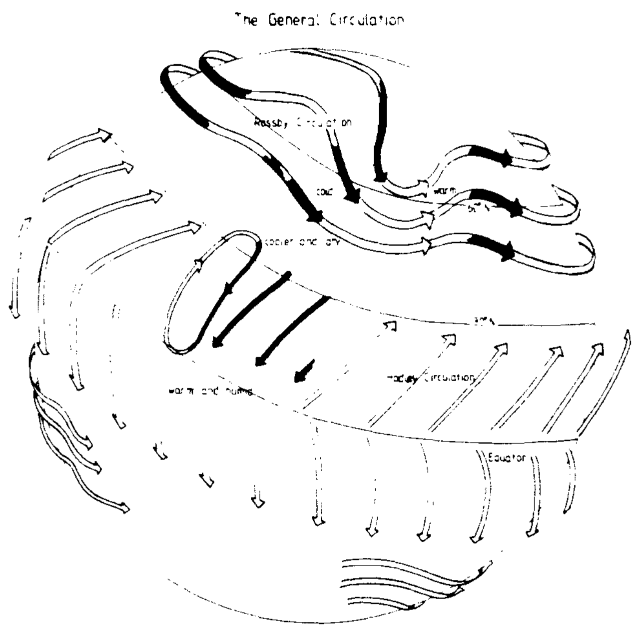


Figure 2.16. A general overview of the atmospheric circulation, showing the Rossby and Hadley circulations [5].

2.6.2. Important winds in the Sahelian Region

Turning from the general circulation to the more local wind systems in the region, there are three important winds to be distinguished:

- trade winds originating from the Azores high;
- Harmattan winds (trade winds) originating from the Sahara high;
- Southwesterlies or monsoon circulation during the wet season.

In figures 2.17 a&b, these surface level air flows over Africa are sketched for the wet and the dry season, respectively.

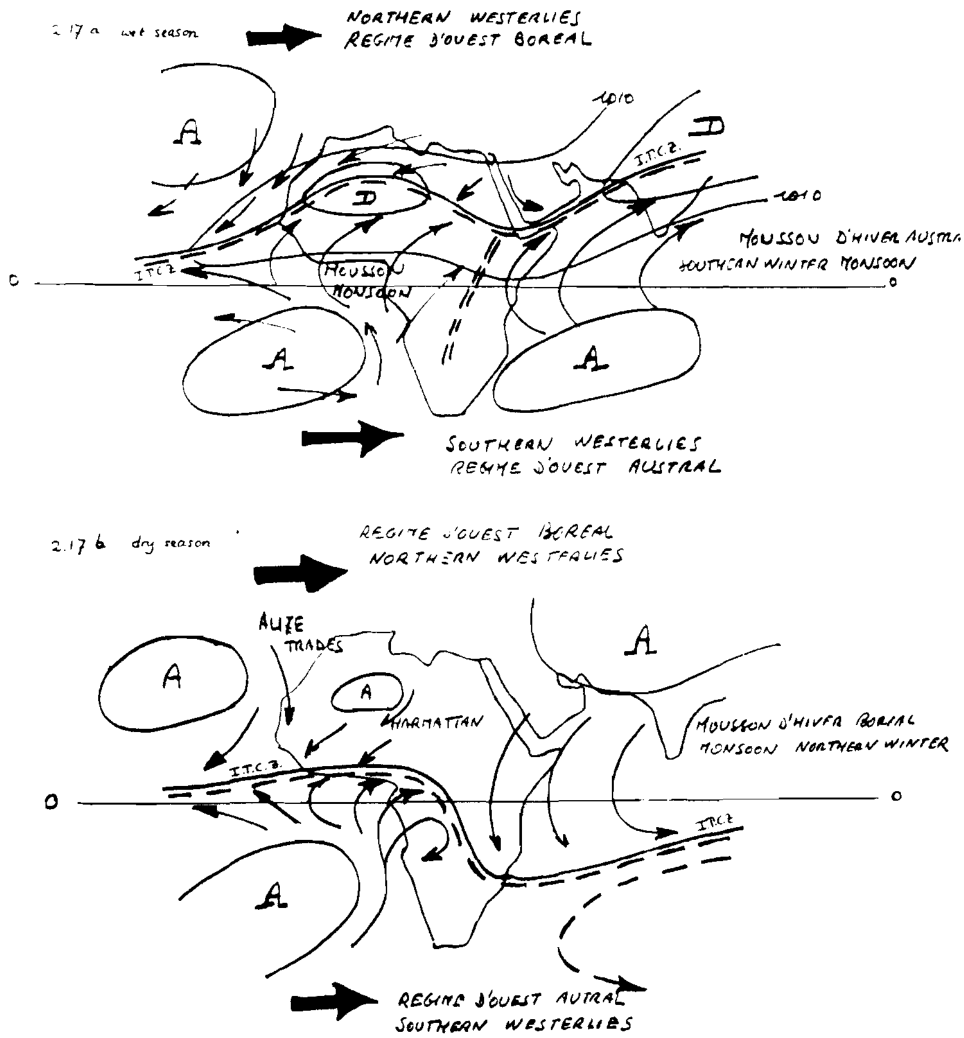


Figure 2.17 a/b. The three important winds over West Africa during the dry and the wet season [8].

The trades from the Azores high are important only for the coastal regions of Senegal and Mauretania: These wind are relatively cool and humid, due to the influence of the Atlantic Ocean.

The Harmattan is a very dry and hot wind, a cT-air flow from the Sahara to the ITCZ, characteristic to zone A weather. As can be seen from figure 2.4, the Harmattan winds are very constant in both speed and direction; Harmattan wind are present 80-90% of the time during the dry season.

South of the ITCZ, the humid westerlies and southwesterlies, mT-air flows, prevail. These westerlies are less constant than the Harmattan winds and are characteristic to zone B, C and D weather.

2.6.3. Local wind systems

As examples of local wind systems, sea-breezes and mountain circulations are described.

The sea-breeze circulation is shown in figure 2.18.

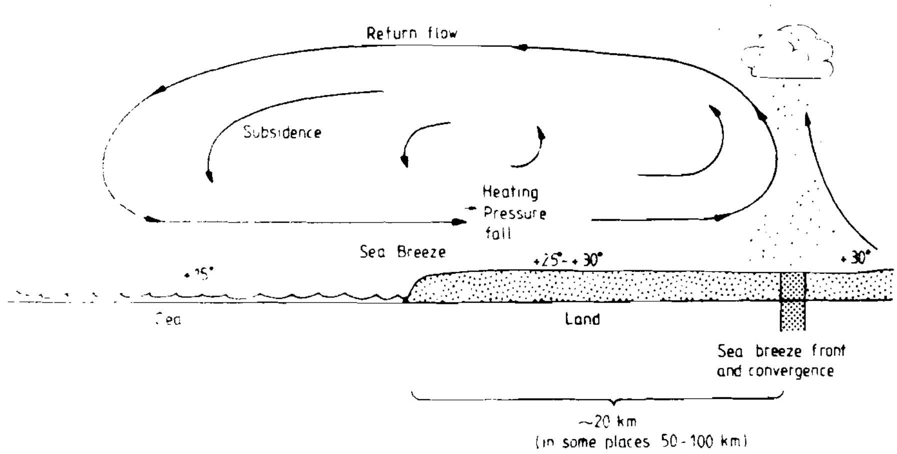


Figure 2.18. A scetch of the sea-breeze circulation [5].

This is a closed circulation caused by the temperature contrast between sea and land and their adjacent air layers. This temperature difference originates from the different heat capacities of land and water, land and the air above it heating up faster during daytime. This causes a rising air flow; the air at the land surface is replaced by the cool maritime air. The air sinks above the cool sea surface, thus completing the closed circulation of fig. 2.18. At night , the process is often reversed ("land breeze") because land cools down faster.

Sea breezes show a maximum daytime wind speed of about 5-8 m/s. Wind directions start perpendicular to the coast line, changing due to the gradual build-up of a coriolis force. Sea breezes penetrate inland about 20-40 km (but sometimes up to

100 km), and are usually accompanied by a sea breeze front between cool maritime air and hot inland air. Thunderstorms are to be expected here.

The principles of mountain and valley winds are sketched in fig. 2.19.

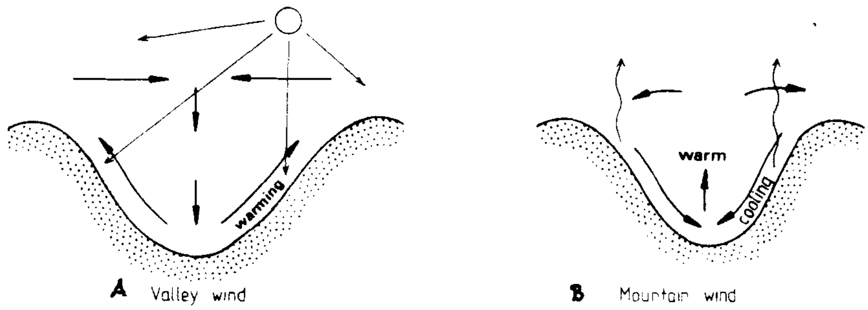


Figure 2.19. Valley and mountain wind circulations [5].

Apart from the effect of the mountains upon the general circulation (mountains causing air to rise), mountains can also cause thermally driven local wind speed variations. During the day (fig. 2.19 a), the mountain slopes are heated by solar radiation, causing the adjacent air to become hotter than the air in the centre of the valley: this results in a valley wind.

During the night, the reverse circulation may develop, the mountain slopes cooling down relatively fast when compared to the air in the centre of the valley; this results in a mountain wind (fig. 2.19 b).

2.6.4. Average annual wind speeds in the Sahel

To obtain an impression of the general distribution of the wind potential over the Sahel, some older Sahel wind maps will be examined. These are presented in figure 2.20.

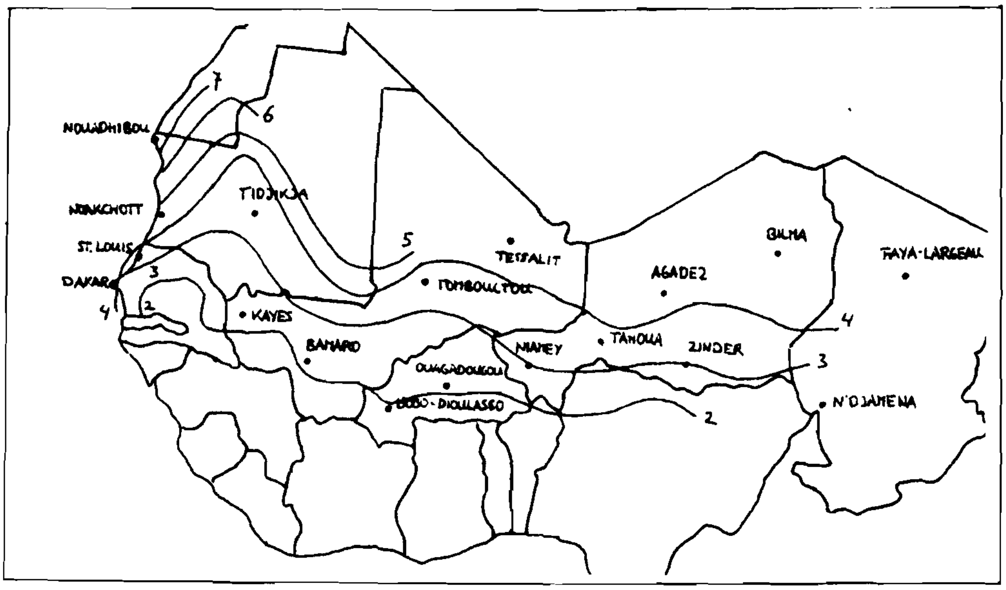


Figure 2.20 a. Mean annual wind speeds over the Sahel (m/s) [10].

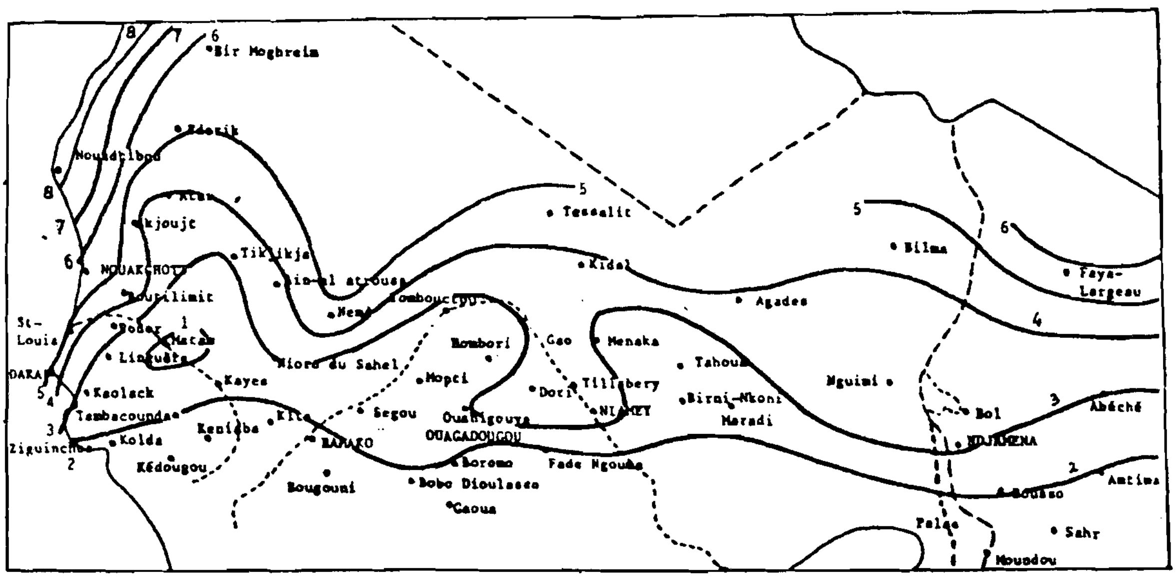


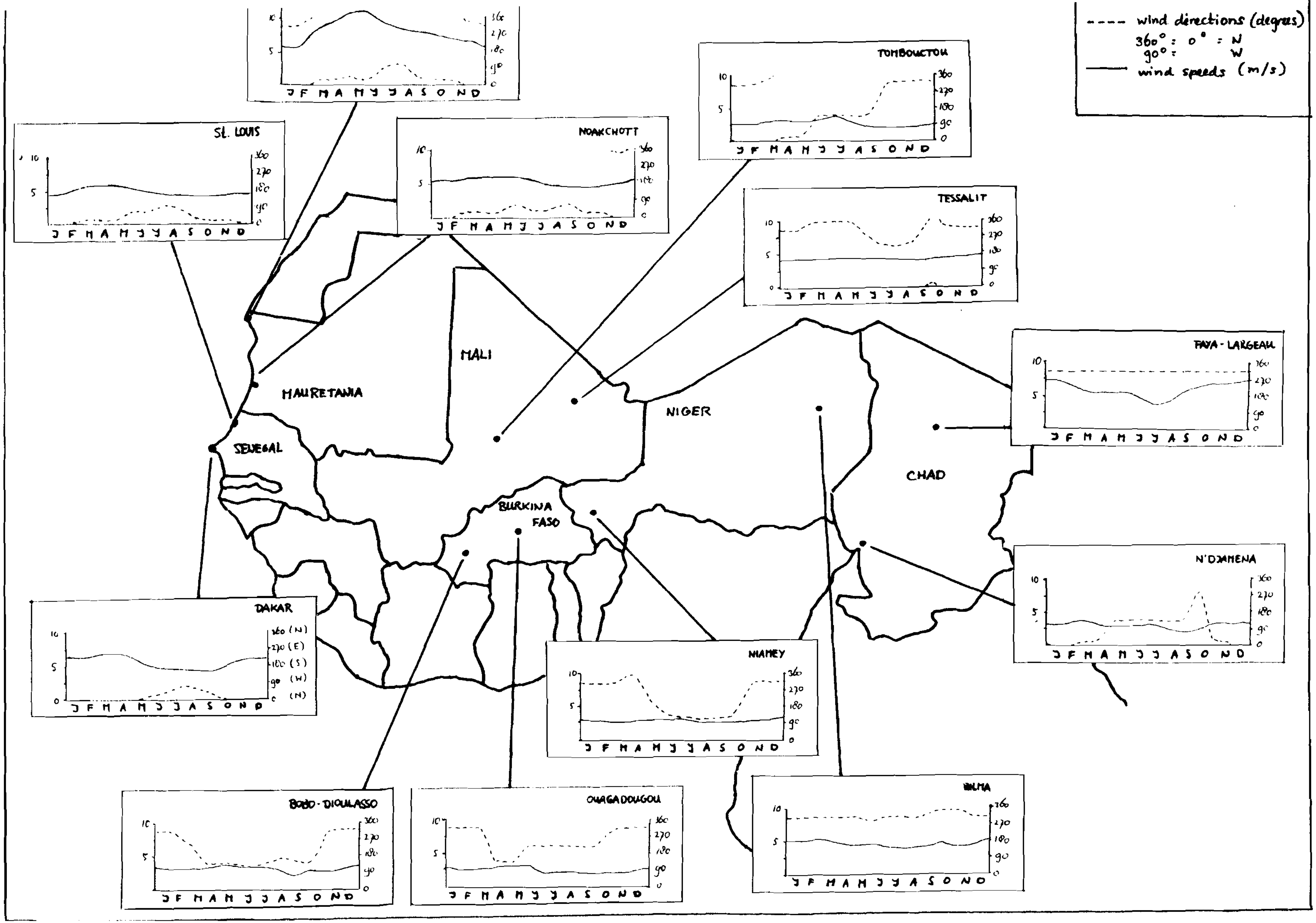
Figure 2.20 b. Mean annual wind speeds over the Sahel (m/s) [12].

Fig. 2.20 a presents a wind map dating from 1957, based on data from the years 1950-1955; fig. 2.20 b dates from 1986 and is based on data the years 1970-1976.

Both maps show a roughly similar distribution of the wind potential; highest wind speeds are found along the coast line of Senegal and Mauretania (Nouadhibou shows a mean annual wind speed of 9.25 m/s in fig. 2.20 b) and in the northern part of the Sahelian region. Mean wind speeds generally decrease at lower latitudes. The distribution patterns are similar, but the 1986 values are generally higher than the 1957 values, and show a sharper decrease towards the south.

It should be pointed out that none of these data have been corrected for the surroundings of the measuring anemometer, as, for example, E.H. Abu Bakr [6, 13, 14] and J. De Jongh [15] have done for Sudan and Senegal, respectively. Thus, these maps should only be considered as giving a general view of the distribution of the wind potential over the Sahelian Region.

Next page: Figure 2.21. (belonging to paragraph 2.6.5.) The seasonal variation of wind speed and direction for 12 Sahel stations. Continuous lines denote wind speed (m/s); dotted lines denote wind direction (degrees). Based on data from [12].



wind directions (degrees)
360° : 0° = N
90° : W
wind speeds (m/s)
ST. LOUIS
NOAKCHOTT
TOMBOUCTOU
TESSALIT
FAYA - LARGEAU
N'DJAMENA
DAKAR
NIAMEY
BOBO - DIOULASSO
OUAGADOUGOU
BILMA
MAURETANIA
MALI
NIGER
CHAD
SENEGAL
BURKINA FASO
J F M A M J J A S O N D
360 (N)
270 (E)
180 (S)
90 (W)
0 (N)

2.6.5. Seasonal wind variations

One of the most important factors when estimating the wind potential in a tropical area is the variability of the wind with the seasons. This is often disregarded in other reports ([10, 11]).

During the dry period, for example, Harmattan winds prevail in the larger part of the Sahel. These trade winds are very constant in speed and direction and relatively strong (up to 5-7 m/s). During the wet season, the winds are generally weaker and more variable. Wind energy for water pumping is more necessary during the dry season, so an annual distribution pattern, disregarding the seasonal variations, does not supply sufficient information about the wind potential for water pumping.

Figure 2.21 (previous page) shows the monthly variation of wind speed and direction for twelve Sahel stations. It is useful to examine these drafts more closely.

The inland stations (except for Faya-Largeau and Bilma) show a similar pattern: the wind direction shows a rapid change from N/NE to S/SW at the beginning of the wet season. Thus, the passage of the ITCZ can clearly be seen from this figure. Furthermore, wind speeds are generally lower during the wet season.

The influence of the ITCZ is not very clear in the coastal stations of Senegal and Mauretania because of the importance of the trade wind from the Azores high and the local sea breezes (2.6.3.). However, a slight change of direction (N to E) can be distinguished.

The stations Faya-Largeau and Bilma show a remarkable constant wind direction. The wind at this stations does not seem to be influenced by the ITCZ. This may be partly explained by the fact that these stations have a high latitudinal position. Furthermore, it should be noted that there is no information about the reliability of any of the data in the reports mentioned ([10,12],chapter 3).

The important conclusion drawn from figure 2.21 is, that seasonal variations in wind speed and direction are too important to be disregarded when estimating the wind potential in the region.

2.6.6. Diurnal wind speed variations and maximum windspeeds

The diurnal wind variations in tropical regions differ significantly from those in moderate regions; the diurnal variations are also different in each season.

Generally the wind speed in a tropical region shows a sharp rise in the early morning (at sunrise), reaches its maximum at about 9.00 am local time, shows a slow fall in the afternoon and a sharp one just before sunset. This peculiar pattern, with its seasonal variations, is shown for Kano (North-Nigeria) in fig. 2.22. The wind speed is indicated in knots (1 knot = 0.514 m/s).

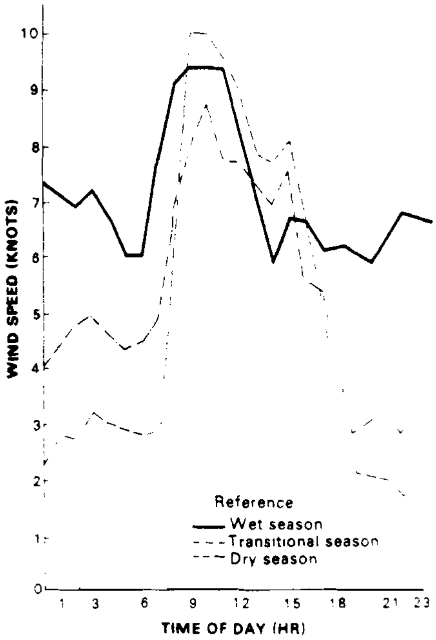


Figure 2.22. Diurnal wind speed variations in Kano, Nigeria for the dry, wet and intermediate season [3].

Dry season: Low values at night caused by surface cooling when there is little or no cloud cover. This results in a temperature inversion a few hundred metres above the ground; thus there is usually little mixing of the lower with the higher air layers, the frictional effect keeping the surface wind speed very low. When the sun rises, the temperature inversion rapidly disappears, the air layers mix and wind speeds become closer to the high values in the higher air layers.

Wet season: The effects mentioned are flattened by the greater cloud cover during the wet season, resulting in smaller diurnal variations.

The maximum wind speeds recorded in seventeen stations in the Sahel are listed in the table below. The period considered is 1968-1977 for all the stations except for Dakar and St. Louis, where the values concern the years 1960-1976.

Table 2.1. Maximum wind speeds over a period of ten years or more for 17 Sahelian stations [12]. Usually maximum gust speed is defined as the maximum speed measured lasting five seconds or more, but this was not mentioned in [12].

Station	Max. speed(m/s)	Year	Station	Max. speed	Year
Dakar	40	1962	Niamey	38	1972
St.Louis	51	1962	Manadi	45	1974
Tambacounda	41	1976	Agadez	30	1972
Ziguinchor	32	1968	Tombouctou	46	1977
Nouakchott	48	1975	Tessalit	35	1970
Nouadhibou	45	1977	Gao	50	1977
Tidjikja	46	1977	Mopti	51	1968
Ouagadougou	30	1968	N'Djamena	60	1975
Bobo-Dioulasso	25	1968			

These maximum gust speeds occuring during the "squalls" mentioned in 2.5 are only of importance when the mechanical sturdiness of a windmill is considered, and need not be considered when a general estimation of the wind potential is made.

2.7. Variability of the climate

In this chapter, the general aspects of the climate in West Africa have been examined, with special reference to the wind regime and the Sahelian Region. In almost all cases the data that have been presented are averages over a number of years.

It is, however, well known that, for example, "wet" and "dry" years occur in the region: presenting the averages over a number of years does not tell the whole story. To illustrate this variability of the climate, fig. 2.23 shows the variations in mean annual precipitation in Zinder, Niger, during the larger part of this century.

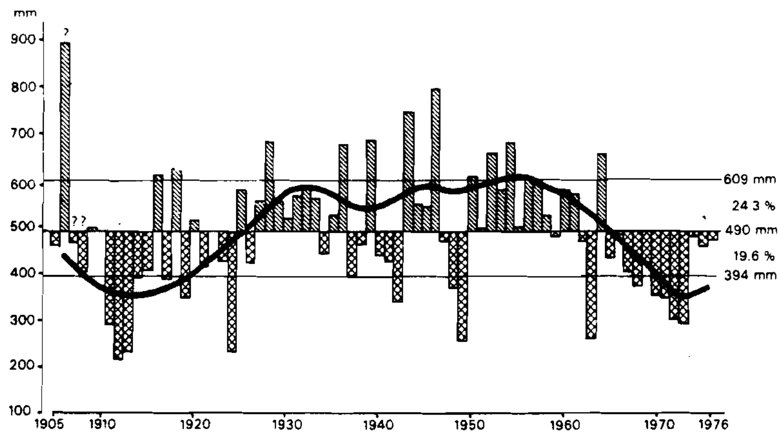


Figure 2.23. Variability of precipitation in Zinder [1]. The precipitation levels are drawn relative to the mean annual precipitation over a number of years: 490 mm. The mean negative deviation to this average is 19.6%, the mean positive deviation is 24.3%.

The dry period since 1965, and especially the years 1971 and 1972, can clearly be seen. It is also obvious, that this was not the first dry period this century: another severe drought can be seen around 1913. It was, however, the dry period of 1971/72 that put the Sahel in the centre of the world's attention.

3. Collecting and processing wind data

3.1 Collecting wind data in the Netherlands

This study started with collecting, investigating and categorising the wind data available at the Technical University Eindhoven (TUE). The data have been supplied with a cover, giving information about the anemometer, surroundings, measurement periods etc. An example is given in figure 3.1.

After this preliminary study, several institutions in the Netherlands were visited in order to find additional data. The institutions visited were:

KNMI (Royal Dutch Meteorological Institute)
Hans Rijf
Kees Lemke

ILRI (Institute for Land Reclamation and Improvement)
Jan Hoevenaars

TUT (Technical University Twente)
Frank Goezinne

CWD (Consultancy services Wind energy Developing countries)
Dick Both

Addresses can be found in appendix 2.

Furthermore, letters requesting information were sent to the French meteorological service and the World Meteorological Organisation secretariats.

The supplementary data obtained in this manner were copied, so that all the presently available information is present at the TUE: a list of these data, including additional information, can be found in appendix 3.

Figure 3.1 on the following pages gives a typical example of a page in a climatological report, concerning the wind speed and direction, and its cover giving the available information.

Figure 3.1. Example of a cover and a data page

SOURCE Asecna, Dakar
SITE AND COUNTRY Saint-Louis, Senegal
STATION Airport
COORDINATES Latitude 16°03 W
Longitude 16°27 N
ALTITUDE 2.16 m

SITUATION

ANEMOMETER: HEIGHT 10 m
TYPE Papillon

SURROUNDINGS Airport, flat terrain

MEASURING PERIOD October 1974

DATA KIND

	Wind Speed (m/s)	Wind Direction degrees	wind rose
Annual Averages			
Monthly Averages	x	x	
Daily Averages	x	x	
Measurements ... x a day			
3 hourly intervals			
per month	x	x	
per day	x	x	
Hourly intervals			
per month			
per day			
Maximum wind speeds			
Lull periods			

REMARKS --

Saint-Louis aéro — Octobre 1974

directions des vents (x 10°)
vitesses des vents (m/s)

dates	00		03		06		09		12		15		18		21		moyennes				
1	30	3	30	3	calme	0	36	3	36	3	32	8	34	7	36	5	32	4.0	34	9	1652
2	36	3	36	2	36	4	02	8	02	5	32	7	34	8	34	4	41	5.1	34	9	1550
3	34	7	calme	0	calme	0	calme	0	28	3	30	4	18	4	20	3	21	2.6	10	11	1650
4	calme	0	calme	0	calme	0	12	3	10	3	16	4	30	2	calme	0	12	1.5	16	7	1415
5	calme	0	calme	0	calme	0	calme	0	calme	0	28	4	34	4	34	3	11	1.4	32	5	1640
6	34	2	34	3	36	4	36	5	34	4	30	5	30	5	32	3	31	4.0	34	6	1115
7	34	3	32	2	32	2	32	3	32	5	30	5	26	5	24	3	28	3.5	29	7	1530
8	28	3	25	3	24	3	24	5	[illegible]	5	26	4	36	6	26	6	35	4.4	24	7	1624
9	26	4	26	5	26	5	25	3	26	5	[illegible]	[illegible]	[illegible]	6	26	5	37	4.8	25	7	2430
10	28	3	24	3	32	2	36	4	16	2	08	1	30	3	calme	0	18	2.1	12	15	[illegible]
11	calme	0	34	2	30	4	34	4	30	3	30	5	28	5	28	5	28	3.5	32	7	1610
12	30	3	calme	0	08	3	16	7	12	5	28	5	30	3	02	2	28	3.5	16	9	0800
13	02	3	calme	0	calme	0	06	2	05	5	30	3	34	5	calme	0	18	2.1	12	11	1904
14	36	2	02	3	04	[illegible]	04	3	04	5	06	5	36	6	36	6	32	4.0	06	8	1205
15	02	6	02	6	02	4	04	4	06	5	02	3	35	5	02	2	35	4.4	06	8	1000
16	02	5	04	5	02	4	[illegible]	5	[illegible]	6	34	5	35	5	36	5	41	5.1	34	7	1400
17	36	3	02	3	02	3	04	4	02	5	34	7	34	5	36	4	34	4.3	34	8	1435
18	02	5	02	5	02	5	02	4	[illegible]	[illegible]	32	5	34	6	36	5	40	5.0	04	8	0818
19	36	5	[illegible]	4	02	4	04	5	[illegible]	4	34	[illegible]	34	4	36	3	33	[illegible]	04	7	1002
20	36	3	02	3	04	2	08	3	10	5	10	4	06	4	02	3	27	3.4	12	7	1040
21	02	2	04	4	08	4	0[illegible]	[illegible]	10	5	02	4	36	4	36	3	31	3.9	08	7	105
22	04	4	04	3	04	3	02	5	36	5	34	[illegible]	36	3	36	4	34	4.3	34	8	1505
23	02	6	36	6	02	6	36	3	02	4	32	7	34	5	36	4	41	5.1	34	8	1515
24	02	6	36	6	36	4	02	3	04	3	32	5	34	6	36	6	40	5.0	36	8	1415
25	36	6	02	5	36	5	02	6	36	5	34	6	36	4	36	5	41	5.1	36	8	0-55
26	36	6	02	4	02	4	02	3	08	5	30	4	36	5	36	5	34	4.3	06	6	1215
27	calme	0	04	3	10	2	12	3	10	6	28	6	32	3	30	[illegible]	25	3.1	28	7	1435
28	24	4	calme	0	calme	0	08	3	08	7	10	6	06	4	08	3	27	3.4	10	10	1125
29	calme	0	calme	0	calme	0	calme	0	14	4	30	4	32	4	36	5	17	2.1	02	6	2100
30	calme	0	calme	0	calme	0	06	2	08	4	34	5	34	2	36	4	17	2.1	34	7	1637
31	36	5	02	2	calme	0	36	1	36	3	32	5	36	6	36	5	25	3.1	3[illegible]	6	1505
moyennes	102		85		7.		109		133		154		143		114		914	1143			
	3.3		2.7		2.5		3.5		4.3		5.0		4.6		3.6		3.7	3.69			

3.2 Processing wind data

In his "Introduction to Wind Energy" [16], Lysen gives a method for processing wind data, starting from hourly measurements at known height, to compute:

- monthly averages, variations over the year;
- diurnal patterns;
- cumulative and frequency distributions of wind speed;
- Weibull shape factors (Weibull presents a mathematical representation of wind speed distributions).

We shall not discuss these matters in detail.

Several literature sources [13,14,16] deal with the wind profile; wind speed increases with increasing height because of the frictional effect of vegetation, buildings etc. The rate of increase with height depends on the roughness of the terrain, represented by the so-called roughness height z_o. This roughness height is listed in table 3.1 for different types of terrain.

Table 3.1. Roughness heights

Terrain description	z_o (m)
flat: beach, ice, snow landscape, ocean	0.005
open: low grass, airports, empty crop land	0.03
high grass, low crops	0.10
rough: tall row crops, low woods	0.25
very rough: forests, orchards	0.50
closed: villages, suburbs	1.0
towns: town centres, open spaces in forests	> 2.0

These values can be used in the standard formula for the logarithmic profile of windshear:

$$\frac{v(z)}{v(z_r)} = \frac{\ln(z/z_o)}{\ln(z_r/z_o)} \qquad (3.1)$$

v(z): wind speed at height z;
z_r: reference height.

For a reference height of 10 m, the above formula is shown in fig. 3.2 for different values of the roughness height z_o.

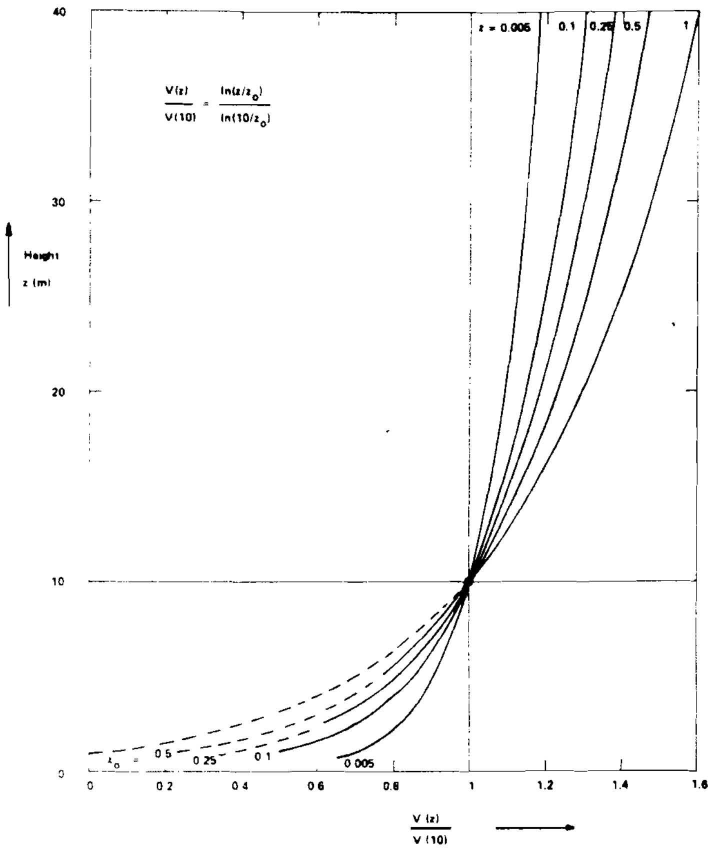


Figure 3.2. The windshear related to a reference height of 10 m, for various roughness heights z_o [16].

Formula (3.1) gives the windshear in one location. To compare two different locations, a more complex formula is needed, based on the assuption [16] that the wind speed at 60 m height is unaffected by the roughness:

$$\frac{v(z)}{v(z_r)} = \frac{\ln(60/z_{or})*\ln(z/z_o)}{\ln(60/z_o)*\ln(z_r/z_{or})} \qquad (3.2)$$

z_{or} = The roughness height at the reference station, where the wind speed is measured at a reference height z_r.

This formula is also appropriate to correct for the surroundings of the anemometer. Suppose the anemometer is placed in a terrain with z_o = 0.10 m, at a height of 8 m. We want to know the potential wind speed: the wind speed measured at 10 m height over an open terrain with z_o = 0.03. This means we have to use the following values:

z_o = 0.03 m;
z = 10 m;
z_{or} = 0.10 m;
z_r = 8 m.

Substitution of these values in (3.2) gives:

$v(z)/v(z_r) = 1.11$,
so that the potential wind speed is about 10% higher than the measured wind speed.

Formula (3.2) was used by De Jongh to correct the mean monthly average wind speeds in St. Louis (Senegal) and Rosso (Mauretania) for the surroundings of the anemometer (for the main wind directions) [15].

ABu Bakr has done this for all wind directions for meteorological stations in Central Sudan [13, 14].

3.3 Results

3.3.1 The data base

The list in appendix 3 represents the data base at the beginning of 1989 at the TUE, concerning the wind energy potential in the Sahelian countries mentioned.

There are, however, many problems connected with these data, the most important of which are:

1. The amount of data.

There are about sixty-five meteorological stations in the region measuring wind speed and direction. This is a very low station density for such an enormous area, especially when compared to a number of about fifty stations for the Netherlands alone.

Most stations do not measure wind speed and direction on an hourly, but on a three-hourly basis, or just 2-4 times a day, thus giving little information about diurnal patterns.

Furthermore, the unprocessed data are hard to obtain; even the World Meteorological Organisation could not present a list of available wind data about the region concerned. Most stations present their results in monthly climatological tables, only giving the average wind speed and prevailing wind direction for each month.

As can be seen from appendix 3, very little specific information is available about Mali, Chad and Burkina Faso.

2. Information about the station and its surroundings.

Most of the stations, even those which publish their three-hourly or even hourly wind measurements, give little or no information about:

- the type of anemometer used;
- the height of the anemometer;
- the surroundings of the anemometer;
- the calibration and maintainance of the equipment.

To give an indication, only the stations marked * in appendix 3 give the anemometer height, and only the stations marked ** give a brief description of the surroundings of the anemometer.

As indicated in section 3.2, the anemometer surroundings are very important to estimate the potential wind speed, i.e. the wind speed over an open area, in a region. Information about the surroundings of a station, preferably photographs or drawings, are essential to estimate the roughness height of the site.

The anemometer height is even more essential: because of the logarithmic wind profile, described in section 3.2, wind data are essentially useless without the measuring height.

3. The reliability of the data.

Hoevenaars and De Jongh visited three stations in the Senegal Fleuve region: St. Louis, Rosso and Podor [15], and found that the potential wind speed may be up to 30% higher than the measured values. Station Podor measurements proved to be totally useless because of heavy screening by trees and other obstacles around the anemometer! This may indicate the unreliability of at least some of the data listed in appendix 3. Without sufficient information about the surroundings of the station, however, it is hardly possible to tell which data are reliable and which are not.

Another example of unreliable data are the Richard-Toll data (app. 3, section 1). These data are probably 2 m - measurements, Richard-Toll being an agroclimatological station, but this is not indicated on the data sheets; one might take them as synoptical (10 m) values and conclude a very low wind potential in the region.

There is another problem about the monthly averages of wind speed and direction as presented in synoptical handbooks such as the "World Survey of Climatology" [9], and the "Handbuch ausgewählter Klimastationen der Erde" [19]:

As can be seen from appendix 4 these data, presented as synoptical measurements, i.e. measurements at 10 m height, are lower than or equal to the 2 m agroclimatological data [18] for over 70% of the stations. This may indicate the unreliability of the data listed in these handbooks.

3.3.2 More information

A letter and several phone calls to the "Service Météorologique Nationale" in Paris, France, have resulted in the adress of a possible data bank in Brussels, Belgium, in charge of which is Mr. Dreze; the address can be found in appendix 2.

The French meteorological service has sent a list of available wind data (both in Paris and in Brussels) concerning the six Sahelian countries this study is primarily dealing with. It is a list of sixty-five meteorological stations in the region and the available data collected by these stations, either in synoptical reports or on magnetic tape. The data concerned are three-hourly measurements, probably both wind speed and direction.

The data bank in Belgium seems to be a promising source of information and should most certainly be considered in future investigations. The list of the stations and the data can be found in appendix 5.

3.3.3 The Chikal data

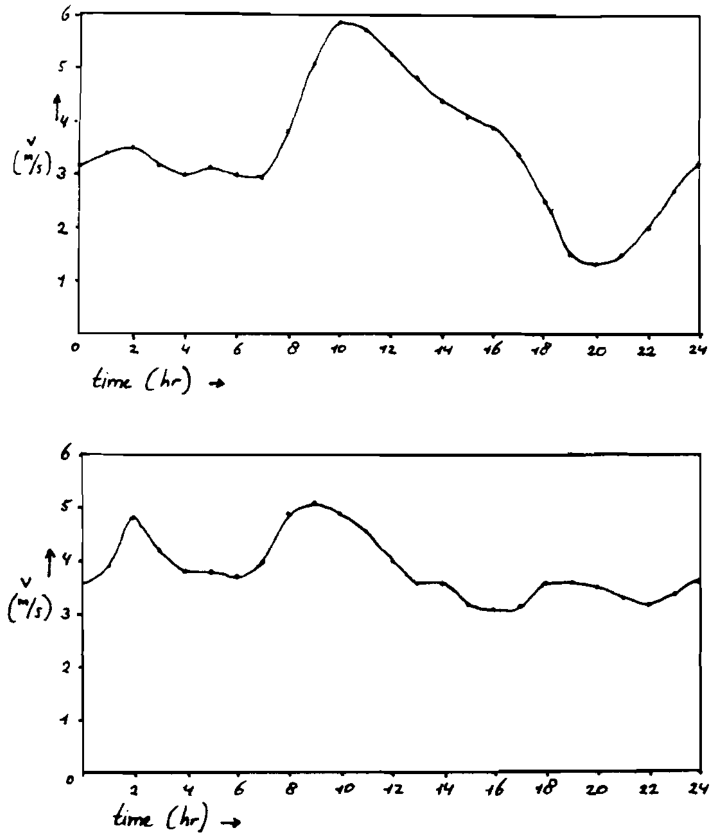
There is one set of hourly data available: the recent measurements for station Chikal, Niger (in the Niamey-Tahoua region, about 50 km to the SE of Abala) at the standard height of 10 m. Chikal was mentioned in the papers of the Niamey wind energy conference in May 1988 [21]. The data consist of:

- hourly wind speed measurements;
- frequency distributions of wind speed and direction;
- hourly, daily, monthly wind speed averages;
- maximum wind speeds per month;
- longest lull period per month;

for the period July 1987 to March 1988.

These data were processed into diurnal patterns for each month and an annual pattern, which was compared to that of Niamey from reference [12].

Figure 3.3 shows two diurnal patterns: that for January 1988 and that for July 1987. The diurnal patterns for the other months are to be found in appendix 6 (also containing an example of an unprocessed data sheet).



January 1988

July 1987

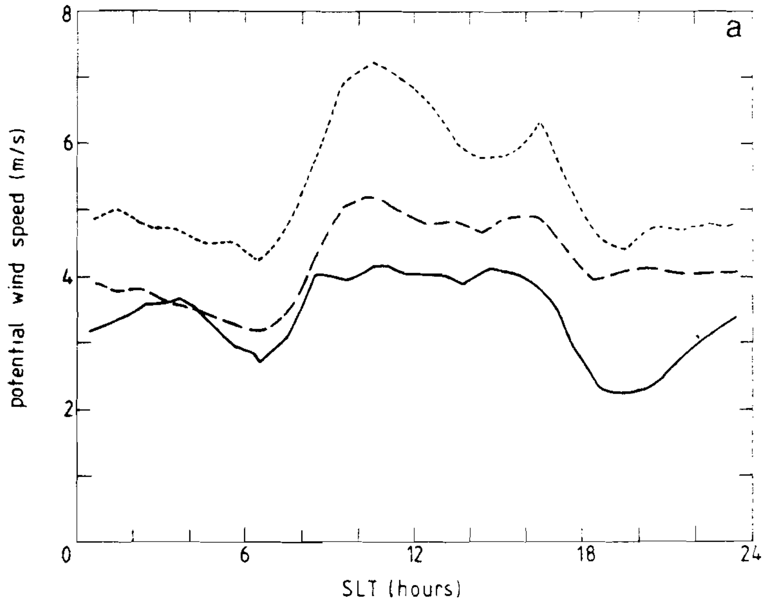
Figure 3.3. Diurnal patterns for Chikal, Niger.

The seasonal variations of these pattens were already described in section 2.6.6:

January: A sharp increase of wind speed around sunrise, a peak around 10 a.m. local time followed by a decrease during the afternoon and a sharp fall after sunrise.

July: Basically the same picture, but more flattened, the rises and falls in the picture being less abrupt. The midnight peak, however, is somewhat stronger than in January.

These diurnal patterns are quite similar to those measured in Sudan and analysed by ABu Bakr in her report [13] and thesis [14], and to those in section 2.6.6; these diurnal patterns are characteristic to semi-arid zones. For comparison, one of the results by ABu Bakr is shown in figure 3.4: diurnal patterns in three central Sudan stations in January 1984.



The potential wind speed diurnal course of January 1984.

—— Atbara, ----- Khartoum, — — — Wad Madani.

Figure 3.4. Diurnal patterns for three central Sudan stations.

Figure 3.5 gives the annual course of wind speed for Chikal and Niamey [12]. The average wind speeds for both stations for the same period are about equal, but the variations over the year are stronger in Chikal. Any thorough comparison, however, is impossible without a complete set of data for Chikal over a number of years.

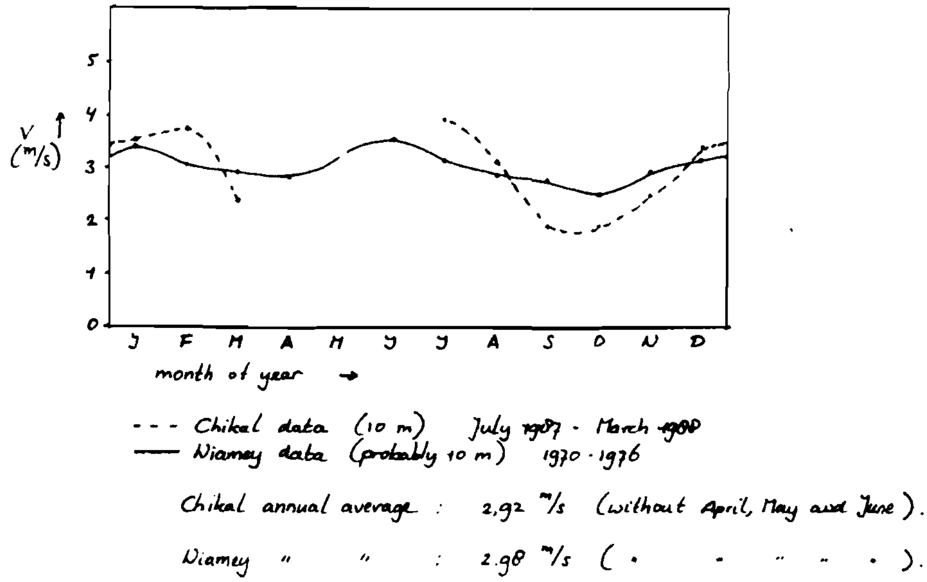


Figure 3.5. Annual wind speed pattern in Chikal and in a station in the same region: Niamey [12].

It seems that the Chikal data are not essentially different from the data in ref. [12]; the mean wind speed over the period July-March, for example, is almost identical to the mean windspeed in a "nearby" station, Niamey, according to [12].

The Chikal data are not likely to be unique as recently a wind measuring programme has been started in Niger, by R. Carothers, Dept. of Mechanical engeneering, University of Waterloo, Ontario, Canada. This appears from the existence of similar data concerning Agadez, Niger. A recent visit to Niger by Frank Goezinne (T.U.T.), however, has not resulted in further unprocessed data or information about the measurement conditions.

4. Conclusions and recommendations

4.1 Conclusions

The Inter Tropical Convergence Zone is the major meteorological phenomenon determining the climate in the Sahelian region. Its annual passage over the region results in strong seasonal patterns in temperature, precipitation, air moisture and the wind regime.

The presently available wind potential estimates about the Sahelian region [10,11,12] are mainly based on mean annual wind speeds and neglect or underestimate the diurnal and seasonal variations, which both are quite important, as shown in sections 2.6.5, 2.6.6 and 3.3.3.

The data base, as given in appendix 3, gives too little information about the anemometer and its surroundings. There are few hourly or at least three-hourly measurements; diurnal patterns can only be determined in considerable detail from hourly measurements. Furthermore, handbook values of mean wind speeds have proved to be highly unreliable.

A study for Senegal [15] has shown that the potential wind speed, corrected for the surroundings of the anemometer, may be up to 30% higher than the uncorrected values used in presently available wind maps of the region. For one station, the measurements proved to be useless because of high screening around the anemometer. ABu Bakr had similar findings in Sudan [13,14].

A source of new information may be the information bank governed by Mr. Dreze in Belgium (app. 2). Without further information, the most reliable wind map for the region (however probably with uncorrected data) is the one presented by D. Le Gouriérès and M. Guetti [12], fig. 2.20 b. This map, however, still disregards diurnal and seasonal patterns and probably underestimates the wind potential in the region.

4.2 Suggestions for further research

The data bank in Belgium (app. 2) merits a visit to investigate and collect the information available: it is also very important to look for information about the station (if present). This might be very fruitful, as can be seen from appendix 5.

To estimate the wind potential in the Sahelian region, it is absolutely necessary to correct the available data for the surroundings of the anemometer. Thus it is necessary to obtain information about the stations in the region, especially:

- photographs or drawings of the surroundings;
- information about the type, height, maintenance and calibration of the anemometer.

This may be done by either visiting these stations (Hoevenaars/De Jongh [15], ABu Bakr [13]) or by writing to agrocultural, or wind/solar energy projects in the region to ask for information about nearby stations.

When specific information about certain stations is available, the necessary corrections can be made and a thorough comparison with accepted wind maps becomes possible.

Literature

Numbers between [ ] refer to the text.
Papers not directly available may be obtained from the Wind Energy Group, TUE (address see app. 2).

[1] "De Sahel, na de grote droogte", several authors, Koninklijk Instituut voor de Tropen (KIT).

[2] Atlas "Jeune Afrique", edited by Regine van Chi-Bonnardel, Éditions Jeune Afrique 1972.

[3] "The Climates of West Africa", by Oyediran Ojo, Heinemann Publishers Nairobi-London, 1977.

[4] "Climate and weather in the Tropics" by H. Riehl, Academic Press, London 1979.

[5] "Meteorological aspects of the utilisation of wind as an energy source", WMO technical note 175, WMO no. 575, Geneva.

[6] "Development of a methodology to evaluate the wind potential in Tropical Regions, Phase 1: Preliminary study of the Sudan wind regime", by E.H. ABu Bakr, March 1986, report R 778 D, Wind Energy Group, Laboratory of Fluid Dynamics and Heat Transfer, Dept. of Physics, TUE.

[6] Was also presented as a conference paper for the European Wind Energy Association Conference, Rome, oct 7-9 1986, entitled: "A method to obtain a wind model for the boundary layer in a representative tropical region".

[7] "L'importance de la stratification aérologique de la troposphere tropicale", by Marcel Leroux.

[8] "La structure de l'équateur météorologique (ZCIT) sur les regions Sahéliènnes", by George Dhonneur, Service météorologique Française.

[7],[8]: Papers of the 11th Course on Tropical Meteorology, Erice, Italy, sept 26th-oct 4th 1986.

[9] "World Survey of Climatology", volume 10: "Africa", chapters 3&6.
Elsevier Publishers, 1972.

[10] "Énergie Éoliènne ,étude appliquée a l'Afrique Occidentale Française", Service Météorologique de l'Afrique Occidentale Française, Paris nov 1957.

[11] "l'Énegie Éoliènne dans le Sahel, étude préliminaire sur les possibilités d'utiliser l'énergie éoliènne dans le Sahel", L.M. Poulissen, J.C. Van Doorn, CWD Amersfoort 1977.

[12] "Wind Energy in the Sahel", D. Le Gouriérès, M. Guetti, EWEA (European Wind Energy Association) conference paper, Rome 1986.

[13] "Central Sudan wind data and climate characteristic", by E.H. ABu Bakr, KNMI report WR 88-01, De Bilt 1988.

[14] "The boundary layer wind regime of a representative tropical region, central Sudan", Ph.D. thesis by E.H. ABu Bakr, TUE 1988.

[15] "The wind potential in the Senegal Fleuve region near Rosso/Podor and St. Louis", by J.A. de Jongh, January 1989, report no. R 945 D, Wind Energy Group, Laboratory of Fluid Dynamics and Heat Transfer, Dept. of Physics, TUE.

[16] "Introduction to Wind Energy", by E.H. Lysen, CWD 82-1, Amersfoort, May 1982.

[17] "The potential of Wind Energy in the Arab World", EWEA 1986 conference paper by A.A.M. Sayigh, Rome 1986.

[18] "Agroclimatological data for Africa", part 1, Food and Agricultural Organisation (FAO), plant production and protection series no.22, vol. 1, Rome 1984.

[19] "Handbuch ausgewählter Klimastationen der Erde", Gerold Richter Verlag, Trier 1983.

[20] "Étude du régime des vents en Afrique Occidentale, possibilités d'utilisation des éoliènnes pour l'exaure d'eau", by I. Cheret, Service de l'Hydraulique de l'Afrique Occidentale Française, 1962.

[21] Papers of the conference:
"Colloque régional sur l'utilisation de l'énergie éoliènne pour le pompage d'eau au Sahel"; Niamey, Niger, May 23-26, 1988:

"l'Énergie Éoliènne en République Islamique de Mauretanie", Ministère de hydraulique et de l'énergie.

"l'Utilisation de l'énergie éoliènne pour le pompage de l'eau au Sahel - Senegal", Ministère de Hydraulique.

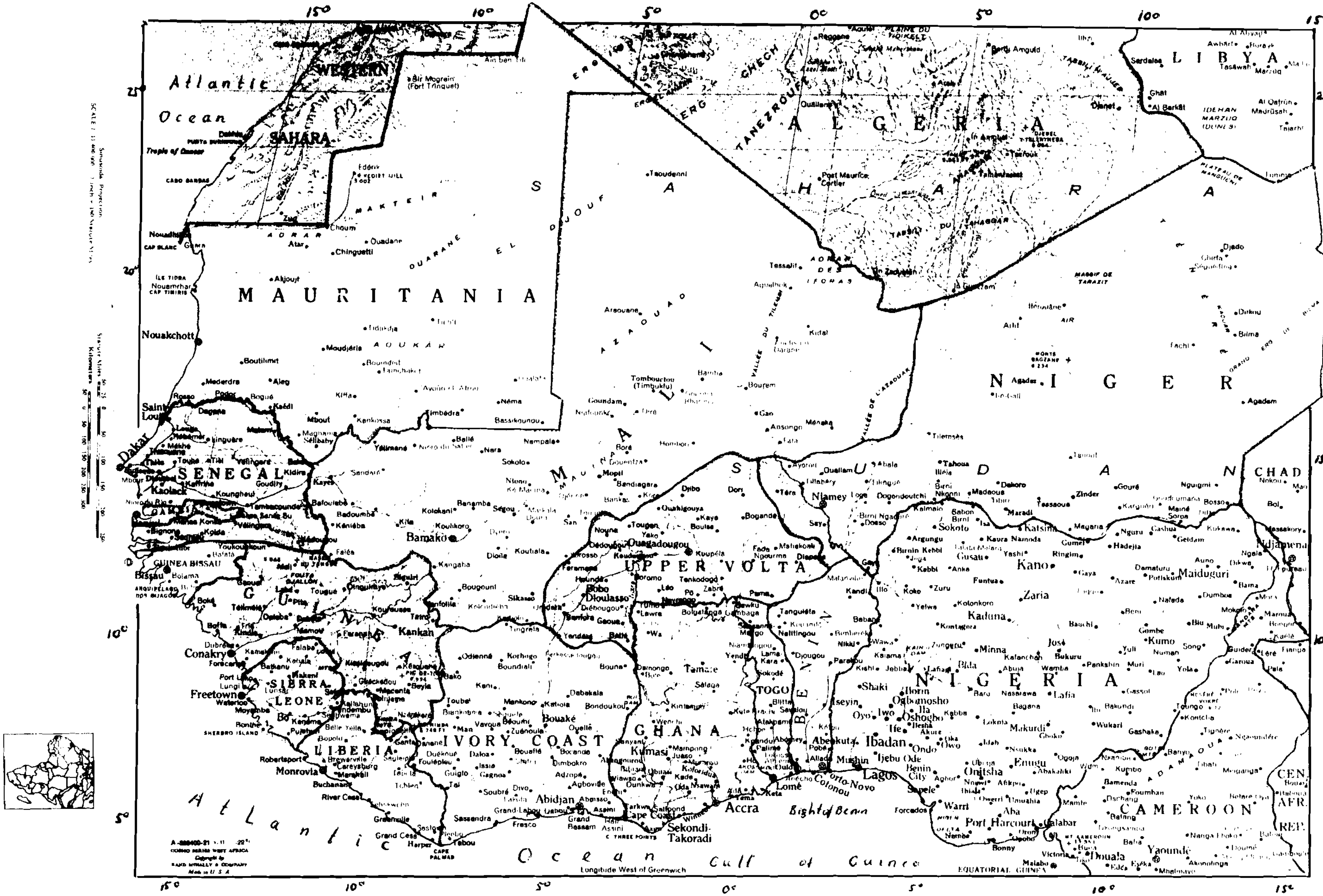
"Aspect météorologique du gisement éolien", by D. Bedard, R. Carothers, A. Maidoukia.

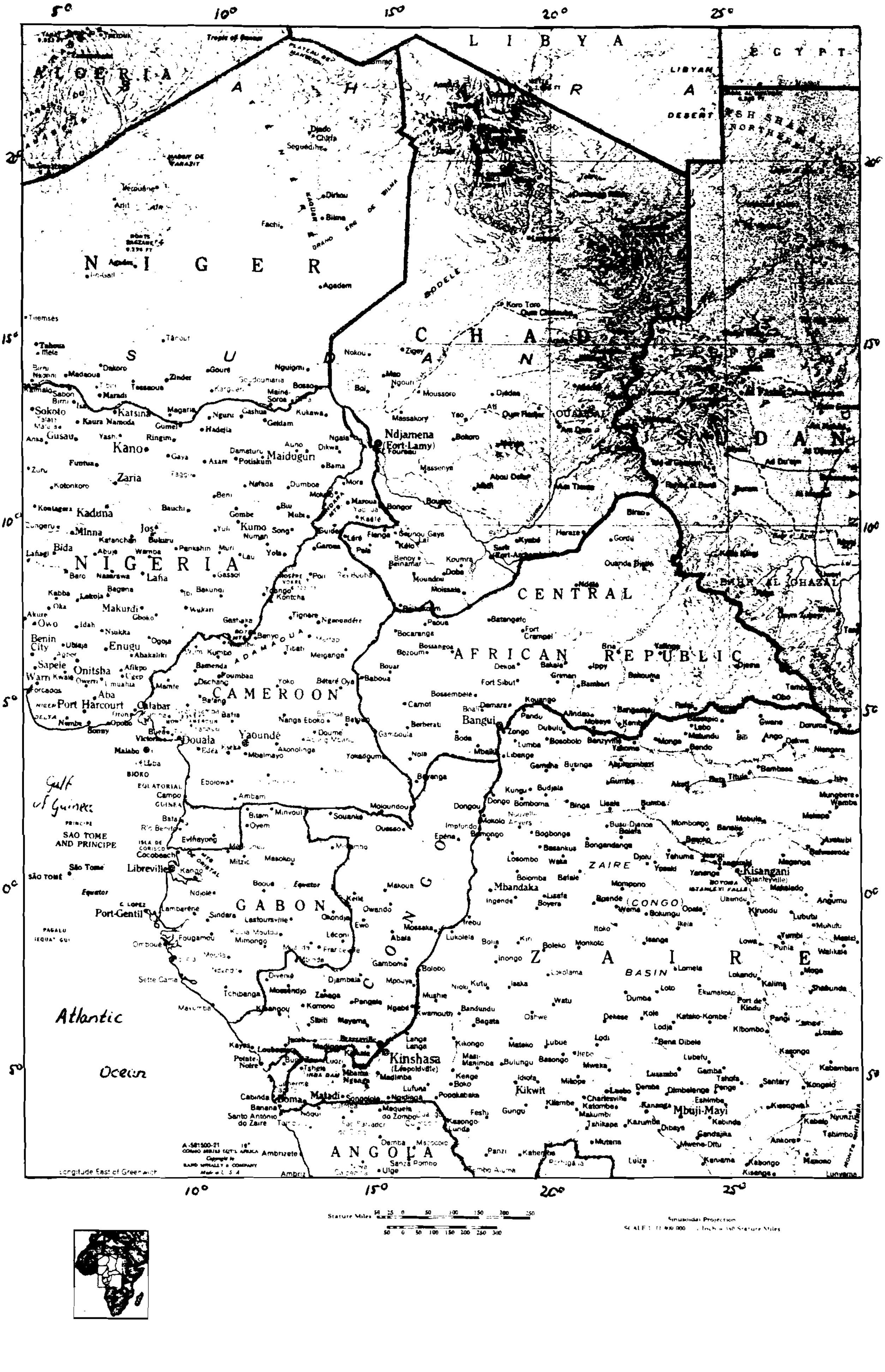
"Utilisation de l'énergie éoliènne pour le pompage d'eau au Niger".

[22] "La détermination de l'évaporation dans un territoire semi-aride pendant la phase de desèchement", prof. G. Tetzlaff, University of Hannover, Germany 1987.

[23] "Wind Energy in the Sahel, geographical repartition", by D. Le Gouriérès, Universtiy of Dakar, Senegal, paper for the Third International Symposium on Wind Energy Systems, Lyngby, Denmark August 26-29 1980.

Appendix 1. Maps of West-Africa




5°
10°
15°
20°
25°
L I B Y A
E G Y P T
ALGERIA
LIBYAN DESERT
N I G E R
C H A D
S U D A N
N I G E R I A
CENTRAL
A F R I C A N   R E P U B L I C
C A M E R O O N
G A B O N
C O N G O
Z A I R E
A N G O L A
Gulf of Guinea
Atlantic
Ocean
Ndjamena
(Fort-Lamy)
Maiduguri
Kano
Zaria
Kaduna
Jos
Minna
Bida
Lafia
Makurdi
Sokoto
Katsina
Gusau
Enugu
Onitsha
Benin City
Port Harcourt
Calabar
Douala
Yaoundé
Bangui
Libreville
Port-Gentil
Kinshasa
(Léopoldville)
Matadi
Boma
Mbandaka
Kisangani
Kikwit
Mbuji-Mayi
SAO TOME AND PRINCIPE
Sinusoidal Projection

Appendix 2
Addresses of institutions mentioned in the text

Stichting Consultancy services Wind energy Developing countries CWD
P.O.Box 85
3800 AB AMERSFOORT
Ir. D. Both tel. 033-682317

ILRI Institute of Land Reclamation and Improvement
P.O.Box 45
6700 AA WAGENINGEN
Ir. J. Hoevenaars tel. 08370-19100 no. 248

Technical University Twente (TUT)
Department of Mechanical Engeneering
Wind Mill Group
P.O.Box 217
7500 AE ENSCHEDE
Ir. F. Goezinne tel. 053-892498

KNMI Royal Dutch Meteorological Institute
P.O.Box 201
3730 AE DE BILT
030-766911

Technical University Eindhoven
Laboratory of Fluid Dynamics and Heat Transfer
Wind Energy Group
Room 01.49
P.O.Box 513
5600 MB EINDHOVEN
Ir. P. Smulders tel. 040-472680
Ir. J.A. De Jongh tel. 040-473191

Direction de la Météorologique Nationale
2 Avenue Rapp
75340 PARIS cedex 07
FRANCE
Mme. Grosse, Chantale tel. 45.56.73.73 (climatologie)

Programme Belgique OMM
Banque de données
Institute Royal Météorologique Belgique
Avenue Circulaire 3
1180 Bruxelles
Mr. Dreze tel. 37.44.43.00

WMO World Meteorological Organisation
    Organisation Météorologique Mondial
Secretariat
41, Giuseppe-Motta
Case Postale No. 5
CH - 1211 Geneva 20
Mr. Lars E. Olsson tel. 34.64.00

Appendix 3

List of collected wind data.

Wind data, concerning the Sahelian region, available at the Technical University Eindhoven, november 1988 (collected at the Dutch institutions).

Stations marked * are stations giving information about the anemometer height; stations marked ** are stations also giving information about the surroundings of the anemometer.

Summary of wind data, available at the Wind Energy Group, Technical University Eindhoven (nov. 1988), concerning the Sahelian countries Senegal, Mauretania, Burkina Faso, Mali, Niger and Chad.

1. Senegal

1.1 Stations: Dakar, Diourbel, Kaolack, Kolda, Linguère, Matam, Podor, St. Louis, Tambacounda, Ziguinchor, Rosso.
- Monthly and annual averages of the years 1961-1976 (wind speed and direction).
- Frequency distributions of wind speed.
Source: report "Wind energy in Senegal, Geographical Repartition", by D. Le Gouriérès, University of Dakar, Senegal [23].

1.2 Station Podor:
** - Three-Hourly data about wind speed (m/s) and wind direction (0-36), period 1973-1982, 6 m altitude. (see [15])

1.3 Station Podor:
** - Monthly and annual wind speed frequency distributions over the years 1970-1975, 6 m altitude.
- Lull periods.

1.4 Station Podor:
** - Monthly wind speed and -direction averages 1951-1981 at 0600, 1200 and 1800 TU, 6 m altitude.
Source: Asecna, Dakar.

1.5 Station Richard-Toll:
* - Monthly wind speed and -direction averages 1962-1974 at 0800, 1200 and 1800 TU, probably measured at 2 m.
Source: Asecna, Dakar.

1.6 Station Saint Louis (airport): 10 m altitude.
** - Three-hourly wind data on speed and direction.
- Daily and monthly averages.
- Frequency distribution. October 1974, source: Asecna, Dakar, (** because of the information in ref. [15]).

1.7 Station St. Louis (airport): 10 m altitude.
** - Monthly averages wind speed 1959-1986.
- Three-hourly wind speed averages 1976-1986.
- Lull periods (v<3 m/s) 1976-1986. Source: Asecna, Dakar.

1.8 Station St. Louis (airport): 10 m altitude.
** - Three-hourly wind data (speed) 1985-1986.
- Monthly, daily and three-hourly averages 1985-1986.
- Maximum windspeeds and lull periods 1985-1986. Source: Asecna, Dakar.

1.9 Stations St.Louis, Dakar-Yoff (Rosso):
* - Wind maps of Senegal: april, october and annual averages over the years 1970-1976, 10 m height.
- Weibull functions, diurnal patterns.
Source: paper: "l'utilisation de l'énergie éoliènne pour le pompage d'eau au Sahel, Senegal" [21].

2. <u>Mauretania</u>

2.1 Station N'Gawley:
- Wind speed and -direction measured once or twice a day, period feb-apr 1984.

2.2 Stations Ajoun-el-Atrous, Nouadhibou, Nouakchott, Néma:
- Monthly averages.
Source: report "The potential of wind energy in the Arab world", by AAM Sayigh [17].

2.3 Station Rosso:
** - Monthly and annual wind speed frequency distributions, period 1970-1975, at 6 m, source: Asecna, Dakar. (** because of the information in ref. [15]).

2.4 Stations Nouakchott, Aioun-el-Atrous, Bir Moghrein, Akjoujt, Atar, Boutilimit, F'Derik, Kaedi, Kiffa, Néma, Nouadhibou, Rosso, Tidjika:
- Monthly wind speed averages, 3 to 4 times a day.
- Maximum wind speeds and lull periods.
- Wind directions (monthly averages, 3 to 4 times a day).
Period: 1966-1980, source: Asecna, Dakar.

2.5 Stations Nouakchott, Nouadhibou:
* - Monthly and annual averages 1960-1984/86, probably measured at 10 m.
- Monthly wind direction averages.
- Wind map of Mauretania.
Source: paper "l"Énergie éoliènne en republique islamique de Mauretanie" [21].

2.6 Stations: Rosso, Tidjikja.

** - Monthly and annual averages 1968-1982.
- Rosso: 3-hourly averages (monthly, annual), frequency distributions, 1982, at 6 m (see [15]).

3. Burkina Faso

3.1 Stations Ouagadougou, Ouahigouya, Dori, Bobo-Dioulasso:
* - Monthly wind speed frequency distributions 1970-1979, source: CCMR (Cellule de Consruction en Millieu Rural), anemometer heights: 11.5, 7.5, 8.2 and 11.4 m respectively.

3.2 Station Bobo-Dioulasso:
- Three-Hourly wind speed and -direction data.
- Frequency distribution 1976 (monthly).
- Lull periods (v<1 m/s or v<2 m/s) over 1969-1976.

3.3 Stations: Bobo-Dioulasso, Ouagadougou, Boromo, Dori, Gaoua, Fada N'Gourna.
- Frequency distributions at 0600, 1200, 1800 TU, wind speed and directions.
- Wind roses and lull periods.

4. Niger

4.1 Station: Niamey.
* - Monthly frequency distributions, wind speed and -direction, period 1951-1955, anemometer height: 13.0 m, 8.11 m after June 1954.

4.2 Station: mobile station situated at Tahoua.
** - Diurnal pattern at 2.4, 5.1 and 9.3 m altitudes, november 2nd and 3rd, 1985.
Source: report "La détermination de l'évaporation dans un territoire semi-aride pendant la phase de desèchement", G. Tetzlaff c.s. [22].

4.3 Station Agadez:
* - Hourly measurements and averages, daily averages (wind speed): july 1987, januari 1988, 10 m height.
- Frequency distributions, wind roses.
- Daily averages & histogram: december 1987.
Source: paper "l'Énergie éolienne pour pomper l'eau dans le Sahel" and "Aspect météorologique du gisement éolienne" [21].

4.4 Stations: Agadez, Niamey, Zinder, Bilma, Gaya, Tahoua,
* N'Konni, Mahadi, Goure, N'Guigna, Giffa, Magaria, Maine-Soroa:

- Monthly frequency distributions of wind speed and - direction at 10 m, plotted on maps of Niger; 1987. Source: "l'Utilisation de l'énergie éoliènne pour le pompage d'eau au Niger", Niamey conference paper, 1988 [21].

4.5 Station: Chikal.
* - Hourly measurements of wind speed (July 1987-March 1988), at 10 m.
- Frequency distributions of wind speed an direction for each month.

4.6 Station: Agadez.
* - Frequency distributions of wind speed and direction. (probably 10 m values, period July 1987 to August 1988)
- Diurnal patterns, monthly averages.
- Maximum wind speeds, longest lull periods per month.

5. <u>Sahelian Countries General</u>

5.1 Stations:
**

Ivory Coast	-	Abidjan
Guinee	-	Kankan, Conacry
Burkina Faso	-	Ouagadougou, Bobo-Dioulasso
Senegal	-	Atar, Dakar-Yoff, Thiès, St.Louis, Tambacounda, Ziguinchor
Mauretania	-	Port Etienne
Niger	-	Niamey, Zinder, Birni N'Konni
Mali	-	Bamako, Gao, Kayès
Togo	-	Lomé

- Monthly wind speed frequency distributions. A very general description of the station, sometimes as short as "airport" or "open terrain", and the anemometer height are included for each station.
- Lull period distributions.
- Wind speed map (based on annual averages). Source: report "Énergie Éolienne, étude appliquée à l'Afrique Occidentale Française, nov 1957", service météorologique Afrique Occidentale Française [10].

Remark: data from this report are also found in the following reports:
"l'Énergie Éolienne dans le Sahel, étude préliminaire sur les possibilités d'utiliser l'énergie éolienne pour le pompage d'eau dans le Sahel", L.M. Poulissen, J.C. Van Doorn [11].
"Étude du régime des vents en Afrique Occidentale, possibilités d'utilisation des

éoliennes pour l'exhaure d'eau", I. Cheret [20].

5.2 Stations: Senegal - Dakar, Ziguinchor
Chad - N'Djamena, Faya-Largeau, Moundou, Abéché
Mauretania - Nouadhibou, Nouakchott, Atar, Nema
Niger - Bilma, Niamey, Zinder
Burkina Faso - Bobo-Dioulasso, Ouagadougou
Mali - Tessalit, Gao, Kayès, Bougouni, Mopti

- Synoptical climatological data, containing monthly average wind speed and -direction. Source: "Handbuch ausgewählter Klimastationen der Erde" Trier 1983, Gerold Richter Verlag [19].

5.3 Stations: Senegal - St.Louis, Dakar, Kaolack, Tambacounda, Ziguinchor
Chad - Abéché, Moundou, Faya-Largeau
Burkina Faso - Bobo-Dioulasso, Ouagadougou
Niger - Bilma, Zinder, Niamey
Mali - Bougouni, Gao, Kayès, Tessalit, Mopti
Mauretania - Nouakchott, Nouadhibou (Pt Etienne), Atar, Nema

- Monthly average wind speed, annual average wind speed.
- Monthly prevailing winddirections.
- Lull periods (%, monthly). (Among a set of synoptical climatological data) Source: "World Survey of Climatology, vol. 10: Africa" (chapters 3&6), Elsevier publishers 1972 [9].

5.4 * Stations: Mali - Tessalit, Kidal, Tombouctou, Gao, Nioro du Sahel, Hombori, Menaka, Same, Kayès, Mopti, Kita, Segou, San, Kenieba, Bamako, Koutiala, Bougouni, Sikasso
Mauretania - Bir-Moghrein, F'Derik, Atar, Nouadhibou, Akjoujt, Nouakchott, Tidjikja, Boutilimit, Rosso, Kaedi, Nema, Kiffa, Ajoun-el-Atrous
Niger - Bilma, Agadez, Tillabery, Tahoua, N'Guigmi, Niamey, Birni N'Konni, Maradi, Zinder, Maine Soroa, Gaya

	Senegal	- St.Louis, Guede, Podor, Linguère, Matam, Dakar-Yoff, Thiès, C.R.A. Bambey, Kaolack, Diourbel, Tamba-counda, Ziguinchor, Kolda, Kedougou
	Chad	- N'Djamena, Bol, Bousso, Moundou, Bokoro, Pala, Sarh, Ati, Faya-Largeau, Am Timan, Abéché, Mongo
	Burkina Faso	- Dori, Ouahigouya, Ouaga-dougou, Fada N'Gourma, Bobo-Dioulasso, Boromo, Gaoua

- Complete set of agroclimatological data on each station, including monthly wind speed averages, measured at, or extrapolated to, 2m altitude.
  Source: "Agroclimatological data for Africa", F.A.O. Plant Production and Protection Series, no. 22, vol 1, Rome 1984 [18].

5.5 Stations:

Stations:	Senegal	- Dakar-Yoff, St.Louis
	Mauretania	- Nouakchott, Nouadhibou
	Mali	- Tessalit, Tombouctou
	Burkina Faso	- Ouagadougou, Bobo-Dioulasso
	Niger	- Niamey, Bilma
	Chad	- N'Djamena, Faya-Largeau

- Monthly and annual wind speed averages, monthly prevailing wind directions, 1970-1976.
- Sahel wind map, Sahel lull period map.
  Source: paper 1986 EWEA wind energy conferention, Rome: "Wind Energy in the Sahel", D. Le Gourières and M. Guetti [12].

Appendix 4
Comparison of synoptical values to 2 m values

In the table below, the synoptical annual average wind speeds (the word "synoptical" implying 10 m - values) from two climatological handbooks are compared to the 2 m values of a third handbook. In 70% of the cases,the synoptical values appear to be lower than, or equal to, the 2 m values.

Handbook 1: World Survey of Climatology [9];
" 2: Handbuch ausgewählter Klimastationen der Erde [19];
" 3: Agroclimatological data for Africa (2 m) [18].

Table A-1. Mean annual wind speeds (m/s) compared.

Station/country	Handbook 1	Handbook 2	Handbook 3
Mauretania			
Nema	2.2	2.2	2.2
Nouakchott	3.5	3.5	3.0
Atar	3.5	3.5	2.0
Nouadhibou	2.2	2.2	5.2
Senegal			
St. Louis	4.4	-	3.4
Dakar	3.9	3.9	4.5
Kaolack	1.7	-	1.3
Tambacounda	1.7	-	2.2
Ziguinchor	2.2	2.2	2.6
Niger			
Bilma	1.3	1.3	2.8
Zinder	1.7	1.7	2.8
Niamey	1.4	1.4	3.1
Burkina Faso			
Ouagadougou	1.7	1.7	2.3
Bobo-Dioulasso	1.7	1.7	2.1
Mali			
Gao	1.9	1.9	3.1
Tessalit	3.0	3.0	3.2
Kayes	1.9	1.9	2.7
Bougouni	0.8	0.8	2.9
Mopti	2.2	2.2	2.3
Chad			
Faya-Largeau	1.8	1.8	2.8
Moundou	1.7	1.7	0.8
Abecher	2.8	2.8	2.3

Note that the values in handbooks 1 and 2 correspond; the values in handbook 1 are stated in km/h, those in handbook 2 in m/s.

Appendix 5
List of available data in Paris and/or Brussels

Paris: Service Météorologique Nationale
Brussels: Programme Belgique OMM Banque de donées
(Addresses in appendix 2)

On the following pages is a copy of the list sent to us by the French meteorological service of their available wind data concerning the Sahelian Region. These data were obtained by them from the institute in Belgium.

Abbreviations used are:

T.C.M. Tableau Climatologique Mensuel
Monthly Climatological Reports
B.M. Bande Magnetique
Magnetic Tape

SENEGAL

- Saint-Louis	1939-1945	**BM**
	1949-1965	**TCM**
	1967-1980	**BM**
- PODOR	1949-1965	**TCM**
	1969-1975,1980	**BM**
- LINGUERE	1949-1965	**TCM**
	1969-1975,1980	**BM**
- MATAM	1949-1965	**TCM**
	1969-1975,1980	**BM**
- DAKAR-YOFF	1946-1965	**TCM**
	1967-1980	**BM**
- DIOURBEL	1949-1965	**TCM**
	1969-1975,1980	**BM**
- KAOLACK	1949-1965	**TCM**
	1969-1975,1980	**BM**
- TAMBACOUNDA	1949-1965	**TCM**
	1967-1980	**BM**
- ZIGUINCHOR	1949-1965	**TCM**
	1967-1980	**BM**
- KOLDA	1949-1965	**TCM**
	1969-1975,1980	**BM**

MAURITANIE

- FORT GOURAUD	1949-1965	**TCM**
	1969-1975,1980	**BM**
- NOUADHIBOU	1947-1965	**TCM**
	1967-1980	**BM**
- ATAR	1947-1965	**TCM**
	1969-1975,1980	**BM**
- AKJOUJT	1947-1965	**TCM**
	1969-1975,1980	**BM**
- NOUAKCHOTT	1949-1965	**TCM**
	1967-1980	**BM**
- TIDJIKA	1949-1965	**TCM**
	1969-1975,1980	**BM**
- BOUTILIMIT	1949-1965	**TCM**
	1969-1975,1980	**BM**
- ROSSO	1949-1965	**TCM**
	1970-1975,1980	**BM**
- NEMA	1949-1965	**TCM**
	1969-1975,1980	**BM**
- KIFFA	1953-1965	**TCM**
	1969-1975,1980	**BM**
- AIOUN-EL-ATROUSS	1952-1965	**TCM**
	1969-1975,1980	**BM**

BURKINA-FASO

- DORI	1949-1965 TCM 1969-1975,1980 **BM**
- OUAHIGOUYA	1969-1975,1980 **BM**
- OUAGADOUGOU	1949-1965 **TCM** + 1967-80 BM
- FADA N'GOURMA	1949-1965 **TCM** + 1969-75,80 BM
- BOBO-DIOULASSO	1949-1965 **TCM** + 1967-80 BM
- BOROMO	1949-1965 **TCM** } + 1969-75,80 BM
- GAOUA	1949-1965 **TCM** }

NIGER

- BILMA	1949-1964 **TCM** 1969-1975,1980 **BM**
- AGADEZ	1949-1964 **TCM** 1969-1975,1980 **BM**
- TILLABERY	1949-1964 **TCM** 1969-1975,1980 **BM**
- TAHOUA	1949-1964 **TCM** 1969-1975,1980 **BM**
- NIAMEY	1949-1964 **TCM** 1967-1980 **BM**
- N'GUIGMI	1949-1964 **TCM** 1969-1975,1980 **BM**
- BIRNI N'KONNI	1949-1964 **TCM** + 1969-75,80 BM
- ZINDER	1949-1964 **TCM** + 1967-80 BM
- MAINE-SOROA	1949-1964 **TCM** + 1967-75,80 BM

TCHAD

- N'DJAMENA	1950-1965 **TCM** 1967-1978 **BM**
- MAO	1950-1965 **TCM**
- BOUSSO	1952-1965 **TCM** 1969-1975 **BM**
- MOUNDOU	1950-1965 **TCM** 1969-1975 **BM**
- PALA	1952-1965 **TCM** 1969-1975 **BM**
- SARH	1950-1965 **TCM** 1969-1978 **BM**
- ATI	1950-1965 **TCM** 1969-1975 **BM**
- FAYA	1950-1965 **TCM** 1969-1975 **BM**
- AM TIMAN	1950-1965 **TCM** 1969-1975 **BM**
- ABECHE	1950-1965 **TCM** 1969-1975 **BM**
- MONGO	1950-1965 **TCM** 1969-1975 **BM**

MALI

- TESSALIT	1948-1965 **TCM**
	1969-1975,1980 **BM**
- KIDAL	1949-1965 **TCM**
	1969-1975,1980 **BM**
- TOMBOUCTOU	1949-1965 **TCM**
	1969-1975,1980 **BM**
- GAO	1949-1965 **TCM**
	1967-1980 **BM**
- NIORO DU SAHEL	1949-1965 **TCM**
	1969-1975,1980 **BM**
- MENAKA	1949-1965 **TCM**
	1969-1975,1980 **BM**
- KAYES	1949-1965 **TCM**
	1967-1980 **BM**
- MOPTI	1949-1965 **TCM**
	1969-1975,1980 **BM**
- KITA	1955-1965 **TCM**
	1969-1975,1980 **BM**
- SEGOU	1949-1965 **TCM**
	1969-1975,1980 **BM**
- SAN	1949-1965 **TCM**
	1969-1975,1980 **BM**
- KENIEBA	1949-1965 **TCM**
	1969-1975,1980 **BM**
- BAMAKO-VILLE	1967-1975,1980 **BM**
- BAMAKO-AERO	1949-1965 **TCM**
	1975-1980 **BM**
- KOUTIALA	1949-1965 **TCM**
	1969-1975,1980 **BM**
- BOUGOUNI	1949-1965 **TCM**
	1969-1975,1980 **BM**
- SIKASSO	1949-1965 **TCM**
	1969-1975,1980 **BM**

Appendix 6
The Chikal wind data

On the following pages:

- An example of the unprocessed data for August 1987, including hourly wind speed measurements, averages, frequency distributions of wind speed and direction.

- Diurnal patterns for Chikal, uncorrected, at 10 m for the period July 1987 - March 1988.

Dossier: (CH8708A) (Range AB1:BC76)
Site. Chikal - A (10m)
Dates: 87/08/01 - 87/08/04 14:55 Mois: Aout 87

Vitesse max (m/s) 27.0 (11eme jour a 13:39 heures)

Duree du calme max (heures) 18 (fin: 21eme jour a 11:39 heures)

Distribution des vitesses (heures)

de (m/s)	0	2.7	3.6	4.5	5.4	6.3	7.2	8	8.9	9.8	10.7	11.6	12.5	13.4	14.3	15.2	16.1	>>17
a (m/s)	2.7	3.6	4.5	5.4	6.3	7.2	8	8.9	9.8	10.7	11.6	12.5	13.4	14.3	15.2	16.1	17	
	280	133	116	80	47	25	14	7	4	3	1	1	1	1	0	0	0	0

Rose du vent (heures)

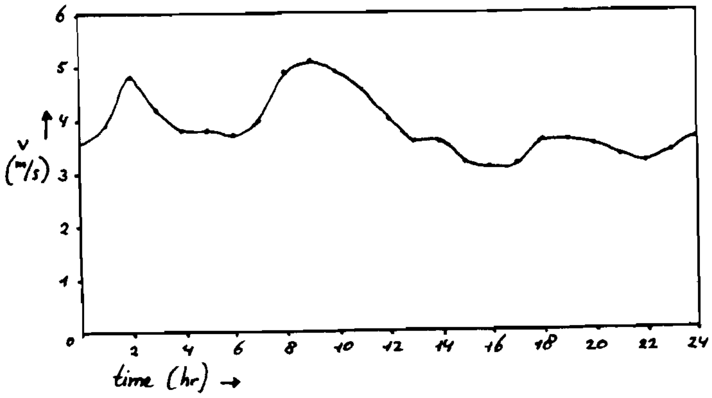
de (m/s)	2.7	5.4	8	>>10.7
a (m/s)	5.4	8	10.7	
N	7	1	0	0
NE	2	0	0	1
E	1	1	1	1
SE	5	4	3	4
S	39	13	4	1
SO	125	33	3	0
O	131	31	2	0
NO	21	3	0	0

Vitesse horaire (m/s)

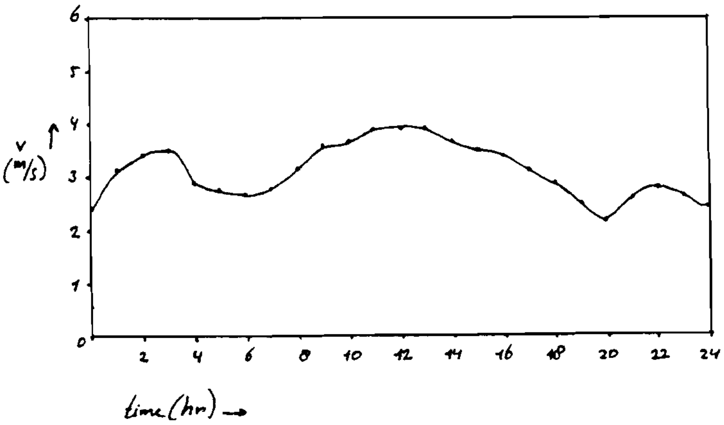
Heure: / Jour	00	01	02	03	04	05	06	07	08	09	10	11	12
1	2.7	3.1	4.1	4.4	4.6	4.2	2.8	3.4	4.8	5.1	4.8	3.5	3.1
2	4.2	4.5	3.7	4.1	3.0	3.1	3.0	2.8	3.9	5.1	5.7	5.0	5.0
3	8.0	7.2	4.0	1.6	0.3	1.2	1.7	0.4	2.7	3.5	4.6	3.7	3.2
4	0.7	0.6	1.6	1.2	0.4	1.6	1.2	1.3	3.8	4.9	4.7	4.8	4.2
5	1.5	1.6	1.5	1.0	1.9	1.6	0.8	1.0	2.6	4.6	4.4	3.6	3.7
6	2.9	3.4	4.2	3.4	3.2	2.3	2.7	2.8	3.6	4.1	4.6	3.9	3.1
7	6.1	7.7	9.1	6.8	4.7	5.7	4.8	3.9	3.4	3.5	2.1	2.6	2.9
8	3.7	3.9	3.7	3.4	2.8	1.9	1.2	1.3	3.8	4.4	4.6	4.6	4.2
9	5.9	6.1	5.8	5.7	5.6	5.4	5.1	5.1	4.7	4.5	4.2	3.4	3.2
10	2.2	2.9	3.1	2.0	2.0	2.9	3.7	5.7	5.3	5.9	6.1	7.2	7.9
11	4.2	10.4	10.1	10.4	4.9	2.9	3.7	6.1	5.4	2.6	1.1	2.8	3.4
12	0.3	1.6	2.9	3.1	3.1	2.1	2.7	2.1	3.7	4.1	4.4	3.8	3.7
13	0.9	1.1	1.3	1.2	0.7	0.0	0.6	1.2	3.8	5.0	5.9	5.0	4.6
14	2.3	2.9	3.5	4.7	4.5	4.7	4.0	4.5	6.1	7.0	6.9	6.5	5.0
15	5.1	3.5	3.2	4.6	3.1	2.5	1.7	2.1	2.5	3.5	4.0	4.9	5.7
16	0.0	0.9	1.1	1.3	1.6	1.3	0.2	1.6	2.9	2.3	2.0	1.3	1.0
17	1.3	2.5	2.6	2.8	2.0	2.6	0.3	0.4	1.9	4.0	3.4	3.2	3.2
18	4.6	5.0	5.8	4.7	4.1	3.5	1.9	3.0	3.0	1.8	1.1	3.0	5.1
19	3.2	3.6	3.5	3.0	2.6	3.8	3.8	4.1	4.5	4.9	5.1	4.9	4.2
20	3.2	3.9	3.6	10.2	11.5	10.6	6.8	4.4	3.9	1.5	3.1	4.9	4.6
21	1.8	1.1	0.9	0.1	0.3	0.3	0.4	1.6	0.7	1.6	2.1	3.0	3.4
22	2.5	0.6	1.2	2.3	2.9	2.6	2.9	1.9	3.9	4.2	4.8	5.5	5.4
23	0.9	0.7	0.3	2.0	1.3	1.3	0.3	0.4	0.2	2.2	4.4	4.8	4.2
24	1.6	1.3	1.8	3.6	3.1	2.8	2.0	2.3	2.6	2.9	2.7	2.1	2.1
25	3.9	4.8	5.5	4.2	4.2	6.4	9.2	7.5	4.2	3.2	1.8	2.2	3.9
26	0.0	0.0	0.0	1.1	0.2	0.3	0.3	0.9	0.7	2.1	3.7	4.2	4.9
27	0.3	9.2	9.1	4.4	0.3	1.5	4.1	1.2	1.0	3.6	4.2	4.8	4.1
28	1.7	0.9	1.7	1.3	1.9	2.2	2.0	3.9	3.9	3.7	3.1	3.0	2.9
29	1.3	1.2	1.1	1.8	1.3	1.6	1.0	1.5	3.0	3.9	3.4	3.6	3.4
30	1.9	3.1	3.0	2.9	3.0	3.4	4.1	3.7	4.7	3.8	4.5	4.2	2.6
31	1.6	1.5	1.9	1.6	0.6	0.7	1.8	1.5	1.7	2.7	3.0	2.7	2.7
moy	2.4	3.2	3.4	3.5	2.9	2.8	2.7	2.8	3.2	3.6	3.7	3.9	3.9
sigma	1.7	2.6	2.6	2.5	2.2	2.2	2.1	1.8	1.5	1.3	1.4	1.3	1.3

Heure: / Jour	13	14	15	16	17	18	19	20	21	22	23	moy	sigma
1	2.3	2.1	1.8	1.6	3.4	3.8	3.0	3.1	2.8	2.7	3.4	3.4	0.9
2	4.8	4.8	3.8	4.5	4.8	3.8	5.7	5.8	14.6	9.9	8.9	5.2	2.6
3	4.0	4.0	4.7	7.8	7.4	4.9	3.7	2.1	1.5	1.1	0.8	3.5	2.3
4	3.4	3.4	3.5	2.8	3.2	3.4	3.1	3.1	2.6	1.5	1.0	2.5	1.7
5	2.8	2.8	2.3	2.8	1.7	0.2	0.2	0.7	3.5	3.4	3.5	2.2	1.3
6	2.6	2.2	2.5	3.0	3.5	5.1	5.1	5.5	6.3	6.4	6.1	3.9	1.3
7	3.0	3.5	3.7	3.8	4.2	4.7	5.4	5.7	5.6	4.9	4.2	4.7	1.6
8	3.7	3.1	2.9	1.8	2.0	3.7	4.2	3.6	4.2	4.4	5.7	3.5	1.1
9	1.8	2.8	4.0	3.7	3.7	3.6	3.2	2.5	2.3	1.5	1.2	4.0	1.4
10	7.5	6.9	6.8	6.6	6.7	5.8	4.9	4.9	4.2	4.2	5.5	5.0	1.8
11	3.9	4.1	5.0	5.8	5.1	3.8	1.9	0.0	0.0	0.0	0.3	4.1	3.0
12	3.5	4.1	4.0	3.8	3.9	3.7	2.8	1.5	0.8	1.3	1.5	2.9	1.2
13	3.8	2.7	1.7	1.6	2.9	2.5	3.2	2.8	3.2	2.9	2.1	2.5	1.6
14	6.3	7.2	8.5	8.3	6.9	6.3	4.8	2.9	4.1	5.7	6.6	5.4	1.6
15	5.3	4.7	4.1	4.1	3.8	4.1	3.2	2.1	1.7	0.6	0.1	3.3	1.4
16	0.9	1.2	2.0	2.0	1.2	2.2	0.6	0.8	1.8	3.0	3.7	1.5	0.9
17	3.8	3.9	2.9	3.0	3.5	3.4	4.0	2.3	5.9	7.9	4.1	3.1	1.6
18	5.9	6.6	6.4	6.1	6.4	5.4	4.5	4.1	3.5	2.8	3.2	4.2	1.5
19	4.6	3.5	3.7	4.2	3.8	3.8	3.0	3.1	2.8	3.4	3.4	3.8	0.7
20	3.2	3.6	3.2	2.9	2.1	0.9	0.6	1.0	1.7	2.5	2.2	4.0	2.9
21	3.9	3.9	3.6	3.0	2.6	2.3	2.3	2.5	4.1	4.0	4.1	2.2	1.3
22	5.7	6.4	5.3	4.2	2.8	2.5	2.6	2.5	1.3	1.3	0.3	3.1	1.7
23	3.0	1.7	1.7	1.7	1.8	1.6	0.8	1.3	1.7	2.8	2.7	1.8	1.3
24	1.2	1.8	1.5	1.3	1.0	1.5	2.2	3.7	3.6	4.0	3.5	2.3	0.9
25	4.0	4.2	2.2	2.6	3.4	2.1	1.2	0.7	1.5	1.2	0.6	3.5	2.1
26	4.8	4.2	3.8	3.4	3.2	2.9	2.3	1.1	0.2	1.3	1.0	2.0	1.7
27	3.7	2.8	1.9	1.2	0.3	1.5	0.1	0.0	0.6	0.2	1.0	2.6	2.5
28	2.5	2.8	2.6	2.7	2.0	1.1	0.9	1.5	2.1	1.7	1.2	2.2	0.9
29	2.3	2.8	1.8	1.6	1.3	0.2	1.6	1.5	2.9	2.8	2.0	2.0	0.9
30	8.0	4.8	4.0	4.5	2.6	1.1	0.2	0.3	0.4	1.3	2.2	3.1	1.7
31	2.5	1.9	1.1	1.6	1.9	1.3	0.4	0.0	0.0	0.6	0.3	1.5	0.9
moy	3.9	3.7	3.5	3.4	3.1	2.9	2.5	2.2	2.6	2.8	2.6	3.1	0.0
sigma	1.7	1.6	1.7	1.7	1.6	1.6	1.6	1.6	1.7	1.9	1.9	1.8	0.0

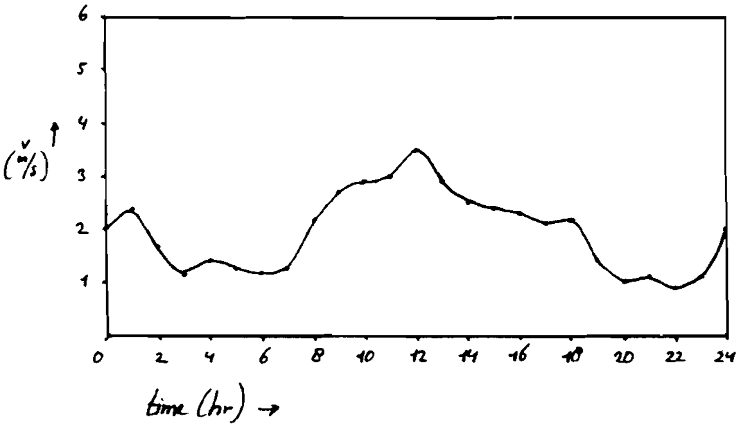
Diurnal patterns:



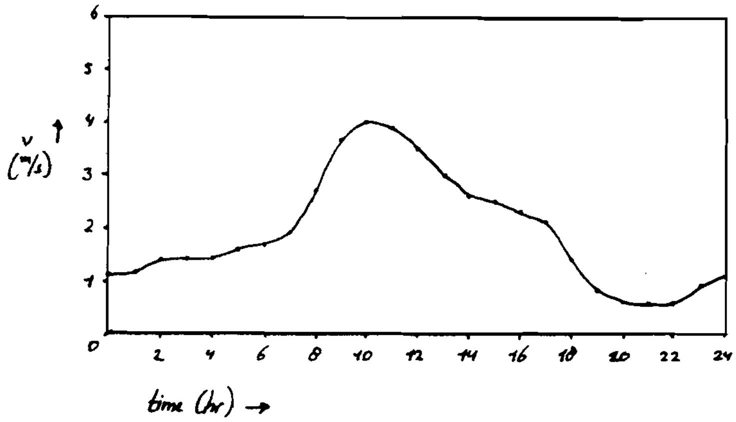
July 1987, Chikal, 10 m.



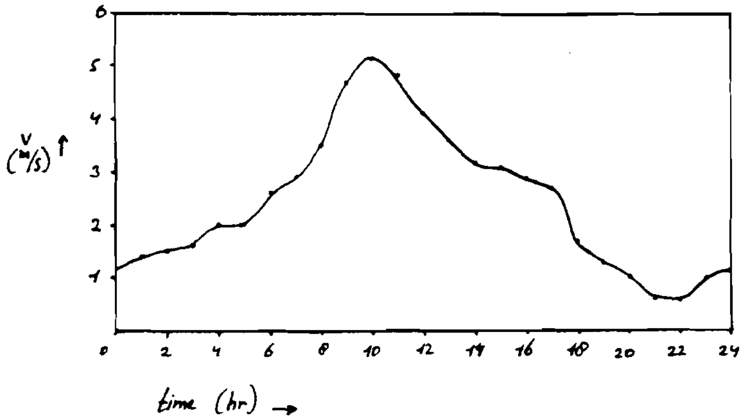
August 1987, Chikal, 10 m.



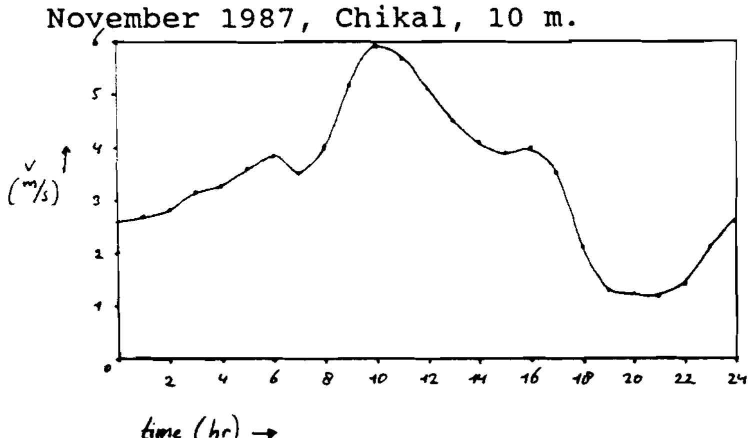
September 1987, Chikal, 10 m.



October 1987, Chikal, 10 m.



November 1987, Chikal, 10 m.



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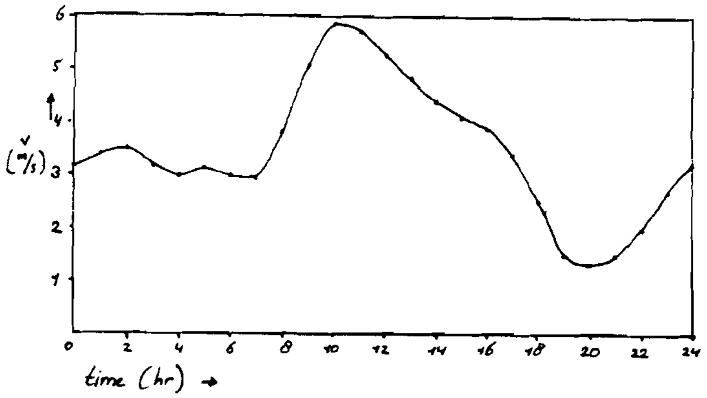
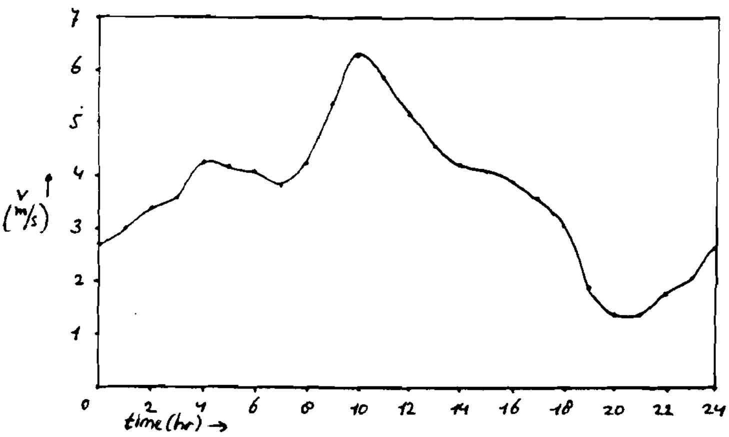
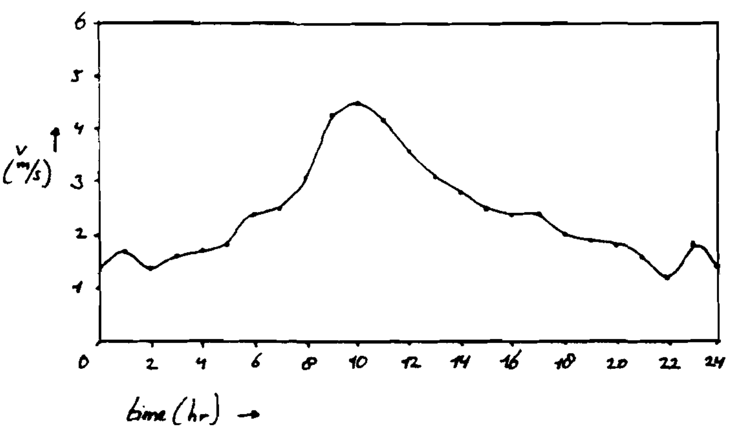


January 1988, Chikal, 10 m .



February 1988, Chikal, 10 m.



March 1988, Chikal, 10 m.