ministerie van verkeer en waterstaat

koninklijk nederlands meteorologisch instituut

Central Sudan surface wind data and climate characteristic

E.H. ABu Bakr

scientific reports WR 88-01

wetenschappelijke rapporten WR 88-01

de bilt 1988

KNMI

CENTRAL SUDAN SURFACE WIND
DATA AND CLIMATE CHARACTERISTIC

E.H. ABu Bakr

Contents

SUMMARY

Since the last decade the modelling of the tropical boundary layer is an outstanding problem, due to the special mechanisms governing the air flow in the tropical regions, (different from the air flow mechanisms in temperate-latitude) such as large temperature variations and the monsoon phenomena. The enormous demand for wind energy in tropical regions is the main reason for this investigation, to estimate the wind speed using the tropical boundary layer physics.

In this article we represent a representative data set from a reference data base which is used for developing a boundary layer model for tropical regions. The representative region selected for this investigation is an area of 56,000 sq. km around Khartoum, Sudan. Some reasons for this choice are:

1. The surroundings of Khartoum are homogeneous and reasonably flat savannah over large distances. In this region there are four meteorological stations with useful wind data, so the station density is acceptable for quality control.
2. Application of wind energy in this area is estimated to be economical, and the region is much in need of water pumping for irrigation and drinking water.

Various procedures applied to obtain a homogeneous wind data base are presented, such as reliability checks, azimuth-dependent exposure correction, and correction for standard height. The characteristics of climate in this region is discussed, especially the passage of the Intertropical Convergence Zone and its influence on the wind regime.

The wind data used in this investigation have been supplied by the Khartoum Meteorological Office. The stations dealt with are: Khartoum airport station, Shambat station, Wad Madani station and Atbara station.

1.1 Physical survey of the Sudan

Sudan is the largest country in Africa; it covers an area of about 2.51×10^6 km^2, which is about 1.7% of the world's land. It shares frontiers with: Egypt, Libya, Chad, Central African Republic, Zaire, Uganda, Kenya, and Ethiopia. The relief of the country is generally flat, except for some hills (in the east and centre of the country) and mountains (in the west and south of Sudan). It is estimated that 25% of the country is lower than 400 m above sea-level, about 20% lies between 400 and 500 m, about 50% lies between 500 and 1200 m and about 5% lies between 1200 and 3500 m. In Fig. 1.1 shows the relief of the country, is roughly indicated.

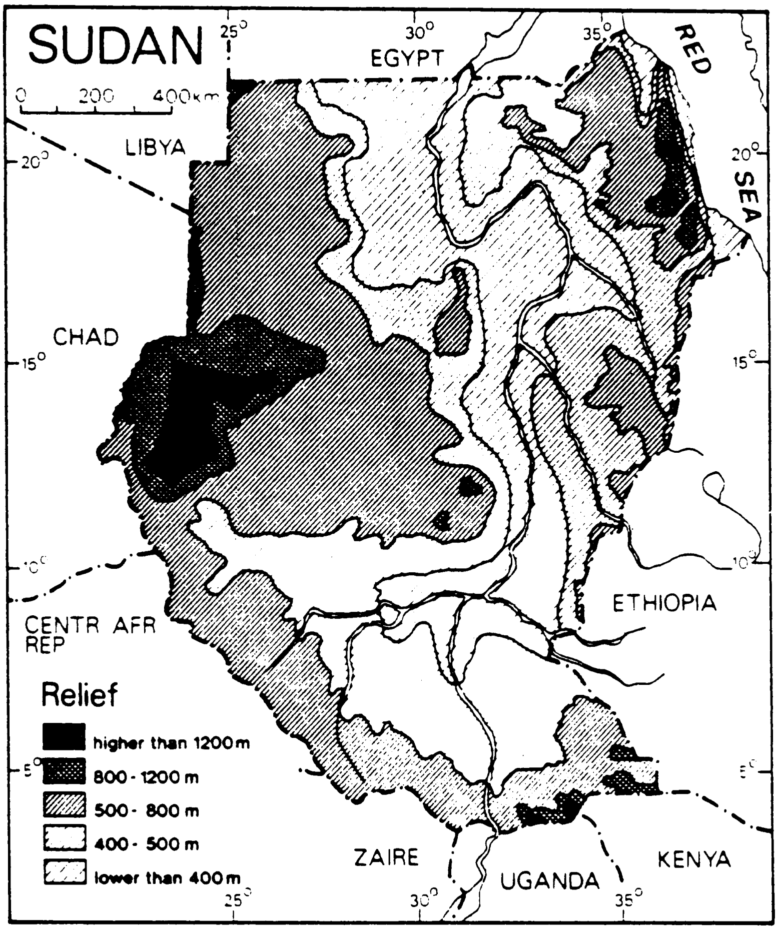


Figure 1.1 Relief map of the Sudan (from the Sudan Survey Topography Department).

The vegetational structure of the land can be divided into six regions: desert, semi-desert, dry savannah, humid savannah, marshy lands and mountain vegetation (see fig. 1.2). This devision according to the vegetation is strongly related to the annual precipitation. The rainfall varies from 2000 mm in the tropical region to practically zero at the northern frontier [2]. The amounts of rainfall correlates with the average temperature in the Sudan, especially in the north of the country. The temperature in the Sudan is strongly dependent on the latitude; the higher the latitude the higher the temperature and the lower the amount of rainfall. In the north the temperature can go up to 45° C in the Sahara while for the south the maximum temperature is about 35° C. In the north the difference between the day temperature and night temperature is about 15° C, whereas in the south this difference is not remarkable.

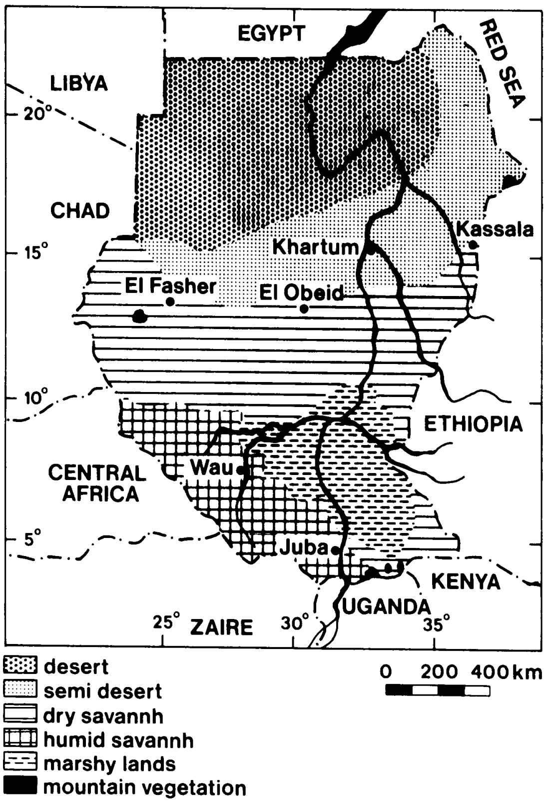


Figure 1.2 Vegetation map (received from the Sudan Survey Topography Department).

1.2 Climate of Central Sudan

Central Sudan has a Sahara-Tropical climate, which means that there is a high diurnal temperature variation and little rainfall. Physically we can explain the climate in Central Sudan by motion of the high and low pressure belts in the north hemisphere at different times in the year. The main pressure belt which plays an important role in the climate of the Sudan is the Inter Tropical Convergence Zone (I.T.C.Z.), which is a low pressure belt around the earth resulting from the intense heating of the earth by the sun in the tropical zone (see fig. 1.3). The time and velocity of the I.T.C.Z. is variable, since the I.T.C.Z. is a large-scale climatological phenomenon [3]. A major determinant in the annual course of the climate in the Sudan is the seasonal position of the Inter Tropical Convergence Zone (I.T.C.Z.) relative to the Sudan, as will be detailed below [3].

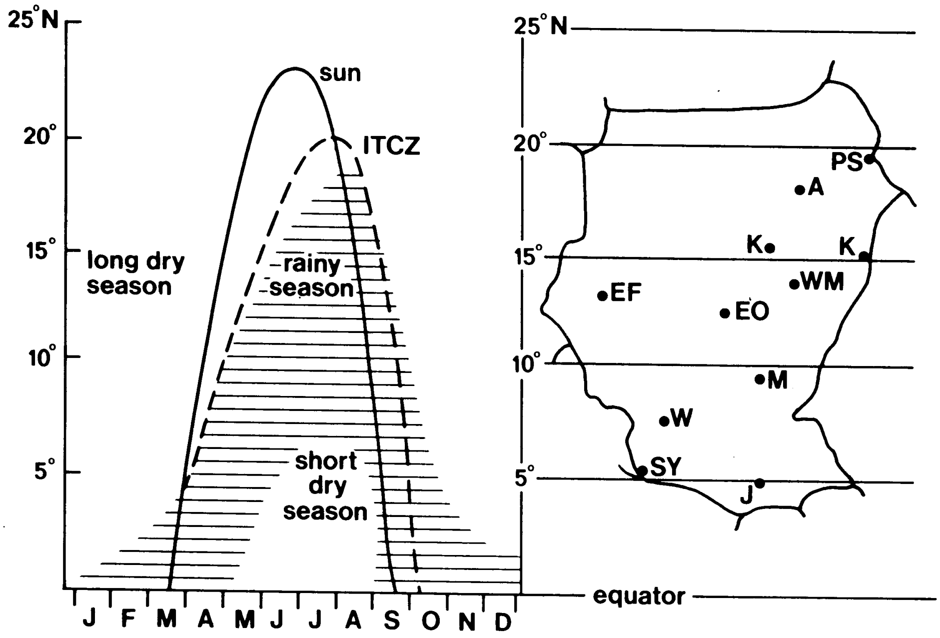


Figure 1.3 The motion of the I.T.G.Z. and the sun motion versus latitude (from Noordwijk 1984 [10]).

In Central and North Sudan there are four seasons:

a. The winter season (December-February).

In this season the pressure is high to the north of Sudan and in the Sahara. As a result a north trade winds blow across Sudan towards the Inter Tropical Convergenze Zone (I.T.C.Z.) which is far south (~ 5° N).

b. The advancing monsoon season (March-May).

In this season the I.T.C.Z. moves towards the north and is associated with a low pressure area, resulting in high temperature gradients.

c. Monsoon season (June-September).

In this season the I.T.C.Z. which gradually moves northwards, is associated with a large pressure depression north-west of Sudan. This results in a south-west humid air stream (from the South Atlantic ocean) towards the north. The prevailing wind is from the south-west. Usually during this season the occurrence of sand storms (Haboobs) is more frequent than during the other seasons (see section 1.3).

d. Retreating monsoon (October-November).

In this season the I.T.C.Z. reaches its maximal latitude northwards and starts to move back south in the end of October. The prevailing wind is from the North.

A more detailed overview of the climate in Sudan is given in table I. This table shows the influence of large scale climatological phenomena such as the Arabic anticyclone and the Red Sea Trough [4].

Winter season or dry season (Dec.-Feb.)	Advancing Monsoon season (March-May)	Rainy season Monsoon (June-Sept.)	Retreating Monsoon season (Oct.-Nov.)
1. The Sahara High (S.H.) controls the air circulation in this season and there is north-north easterly flow over the whole country, except for the southern part of the Red Sea area. The S.H. is dynamic in behaviour and the anticyclonic circulation associated with it extends to great heights. Therefore very dry air prevails over the country and the weather is fine with clear skies. The northerly wind is relatively cooler and becomes warmer as it moves south.	The S.H. in this season moves towards north-west Africa as a ridge of high-pressure.	The Thermal Low in the southern Sahara is replaced by deep Sahara anticyclonic circulation at a height less than 3 km. It results in anticyclonic circulation of winds over the north-west of Sudan.	S.H. is remarkable in this season and an anticyclonic circulation exists in the whole north-west Africa and adjoining parts of north-west Sudan.
2. The Arabic High (A.H.) produces anticyclones which induce north-easterly air stream. Over the Red Sea this air stream appears as a southerly wind. Approaching the coastal hills it gives showers and thuncerstorms. It sometimes causes early morning fog or stratus cloud over the hills.	In this season the A.H. is weakened.	The A.H. gives place to a deep low pressure area over Arabia and Iraq. This low pressure system results in a weak wind flow over the north-east Sudan.	The A.H. starts to develop again forming anticyclonic circulation which affects the north-east Sudan.
3. The S.H. & A.H. converge towards each other to form a stationary front which is known as the Red Sea Trough (R.S.T.). The front normally lies along the Red Sea coast but may be displaced east or west depending on the intensity of the S.H. & A.H. The present of this front contributes in thunderstorms and showers in the Red Sea regions.	The R.S.T. results in occasional thunderstorm and showers in the Red Sea hills.	No effect.	The R.S.T. is very active in this season. Port Sudan area and the neighbouring Red Sea hills get the heaviest rainfalls of the year during this season.

4. During this season the I.T.C.Z. is south of Sudan.	In late April the I.T.C.Z. is usually about 10° N over eastern Sudan. Associated with the I.T.C.Z. there is low pressure area which is known as Sudan Low; it is a part of the thermal equator and oscillates north and south with the declination of the sun. As the season advances the I.T.C.Z. and the Low move northward.	In this season the I.T.C.Z. moves northward. It results in a south-west humid air stream.	In this season the I.T.C.Z. reaches its maximum northward and starts to move back southwards.
5. The low pressure over Central Africa forms part of the equatorial low pressure belt which is shallow and purely thermal in character. This low pressure has not much effect on the climate in this season.	No effect.	The low pressure over Central Africa in the winter is replaced by two ridges of high pressure which extend into central Africa from two large scale subtropical anti-cyclones; one into the south Indian Ocean and the other into the south Atlantic Ocean. This formation of anti-cyclones results in moist air stream which penetrates the Sudan as south westerly streams south of the I.T.C.Z.	No effect.
6. The Mediterranean depressions give rise to a strong cold front which sweeps along north Sudan causing wide spread blowing sand in its rear.	The effect of the low pressure is the same as in the winter season but the sandy winds are more frequent in this season because of the high lapse rate During the last part of the season the cyclonic activity in the Mediterranean decreases.	No effect.	No effect.
7. The intensification of the cold anti-cyclone over Central Asia and its displacement westwards causes a flow of cold air streams which move through south Russia and across the Mediterranean and streams over eastern north Sudan.	No effect.	No effect.	No effect.

Table I The behaviour of various pressure belts during the four seasons.

1.3 Sand storms in Central Sudan

One of the important climate phenomena in Central and North Sudan are three kinds of storms [4];

1. Haboob (squalls) i.e. dust storms associated with Cd clouds (cumulus clouds) which occur in the preiod April-Sept. Fig. 1.4 gives a model for the Haboob.
2. Dust storms caused by steep pressure gradients for south/south westerly winds south of the intertropical front which occur in the period May-Oct.
3. Dust storms caused by the continental polar air reaching Sudan as cold fronts associated with strong eastern depressions. They occur in the period Feb.-April.

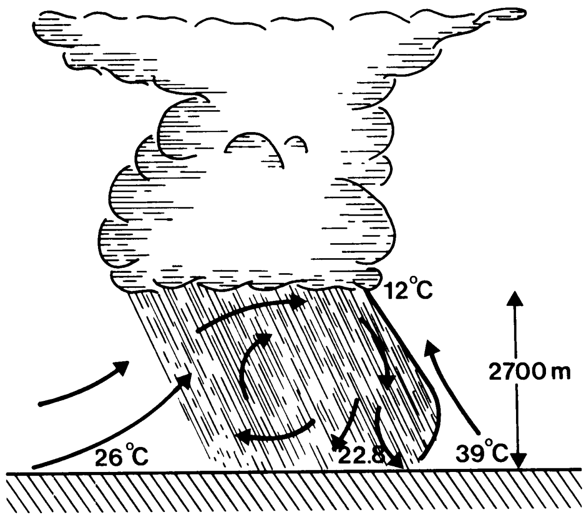


Figure 1.4 A model of the Haboob (obtained from Khartoum Meteorological Office).

More detailed description of the three kinds of storms is given in the following:

1. The start of the Haboob is usually a strong wind, fall in temperature, and rise in pressure and it is associated with dust storm and Cd clouds. The wind speed reaches at least 11 m/s. There are line squalls (also known as Haboob) which are lines of violent Cd cells known as disturbance lines, oriented from N/NE to S/SW and moving W/SW in the general direction of upper winds at 3 km and above. They can travel a distance about 16 km or more. The travelling speed is estimated between 12-14 m/s. these line squalls are associated with heavy showers. the line squalls observed at Khartoum are thought to be formed along the Ethiopian foot hills in the vicinity of Kassala. The conditions that

favour the formation of active squall-type thunderstorm cells or line squalls are:

a. A layer of mist southwesterly stream at the height of 1700-2700 m.
b. A steep inclination of the I.T.C.Z. from the surface upwards.
c. The existence of lower level convergence and upper level divergence.
d. Existence of the state of latent instability.

It was observed in Khartoum region in the period 1953-1957 that the dust storms in July-Sept. occur between (15-23) L.T. Their duration varies between 1 to 4 hr., 80% is less than 2 hr., 40% of the squalls last for half an hour and 60% less than one hour [4].

Comparing the incidence of thunderstorms in Khartoum, El Obeid and Wadi Halfa in the period 1953-1957 one observes that El Obeid has the highest occurrence of thunderstorms with an average of 56 days per year. Apparently the presence of the Nuba mountains in the south of El Obeid helps the development of thunderstorms activity in this area. Khartoum has an average of 27 days a year and Wadi Halfa 1 day a year [4]. The monthly frequency of dust storms and squalls (from Khartoum airport) for four years is given in table II.

Year	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1953	0	0	0	$0,\bar{1}$	$7,\overline{13}$	$3,\bar{8}$	$8,\overline{11}$	$9,\bar{7}$	$9,\overline{20}$	$1,\bar{3}$	1	0
1954	0	0	0	$1,\bar{3}$	$2,\bar{8}$	$1,\bar{2}$	$11,\overline{13}$	$3,\bar{4}$	$3,\overline{11}$	$1,\bar{2}$	0	0
1955	1	0	0	0	$0,\bar{7}$	$3,\overline{14}$	$4,\overline{13}$	$7,\bar{8}$	$4,\bar{7}$	$0,\bar{0}$	0	0
1956	0	0	0	0	$2,\bar{2}$	$10,\bar{8}$	$1,\overline{10}$	$5,\overline{11}$	$3,\overline{12}$	$0,\bar{6}$	0	0
1957	0	0	0	0	$4,\overline{11}$	$1,\bar{5}$	$4,\overline{12}$	$9,\overline{12}$	$7,\overline{14}$	$2,\bar{3}$	0	0

Table II Monthly frequency of dust storms and squalls at Khartoum (airport data) in days a month. The numbers with a dash denote frequency of squalls days.

2. The occurrence of pressure gradient dust storms depend on the following factors:
   a. The speed of motion of the air layers near the sand or dust in the surface. The greater the speed of motion of air the greater the transfer of momentum from the air to the sand or dust particles. This effect will result in dust or sand rising from the ground.
   b. The increase of the degree of turbulence of the air resulting from the temperature difference between the surface and the air layer

above it. If the air layer is relatively cooler than the ground, the difference in temperature results in sandy wind.

c. Extent of the desert surface over which the wind blows.

In the north eastern desert, severe dust storms of this type sometimes cover railway lines under mounds of sand, dislocating communication. The gap between the Red Sea hills and the hills of Eritrea, in the vicinity of Tokar, provides a tunnel effect to the South westerly wind, thus increasing the wind speed. As a result the Tokar area experiences frequent and long periods of blowing sands particularly in the months of July and August.

3. During the winter season in the northern hemisphere depressions are formed on the polar front and move eastwards with prevailing westerlies. With the advance of the season these depressions go more south and pass the Mediterranian.

   The passage of the cold fronts over the desert areas causes wide spread blowing sand (sandy winds) and, locally, sand storms. This type of sand storm is much observed in Wadi Halfa. Sometimes, cold fronts may not reach Sudan but as a result dust (sand) may drift over Egypt and affect Wadi Halfa. In rare cases thunderstorm activity may occur in the lower layer and a steep pressure gradient may build up, causing a short period of sandy winds at Wadi Halfa.

   Some of the cold fronts affecting Wadi Halfa, particularly in May diffuse before reaching Khartoum and El Obeid, owing to the following reasons:

   1. The westerly depressions after March begin to take a more and more northerly course as the season advances into summer, so that the associated cold fronts, when they reach the Sudan during May and later are usually weak.
   2. The slow movement of the fronts cuases them to be diffused.
   3. Sometimes the presence of I.T.C.Z. north of Khartoum and El Obeid may stop further southward movement of the weak fronts.

The maximum gust speed recorded until 1964 selected from 12 stations, (using a Dines pressure tube anemograph) is represented in table III.

Station	Maximum gust speed (m/s)
Wadi Halfa	32.4
Karima	30.2
Atbara	37.8
Khartoum	47.3
Kassala	37.8
Wad Madani	35.6
El Obeid	37.4
El Fasher	39.2
El Geneina	34.7
Kosti	38.7
Malakal	36.5
Port Sudan	35.1

Table III The maximum gust speed recorded until 1964 using Dines pressure tube anemograph [5].

1.3 Meteorological stations

In Sudan there are 53 meteorological stations where wind data are collected. At 22 stations: Wadi Halfa, Station No. 6, Abu Hamed, Port Sudan, Dongola, Karima, Atbara, Khartoum, Kassala, Wad Madani, El Gedaref, El Duim, El Fasher, Sennar, El Geneina, El Obeid, Kosti, El Damazin, Gazala Gawazat, Malakal, Wau and Juba, the wind direction and speeds are measured by vanes and Dines pressure tube anemographs at a height of about 15 meter above ground level [3]. At the others only Beaufort estimates are available. In fig. 1.5 the geographical position of these stations are shown on a map.

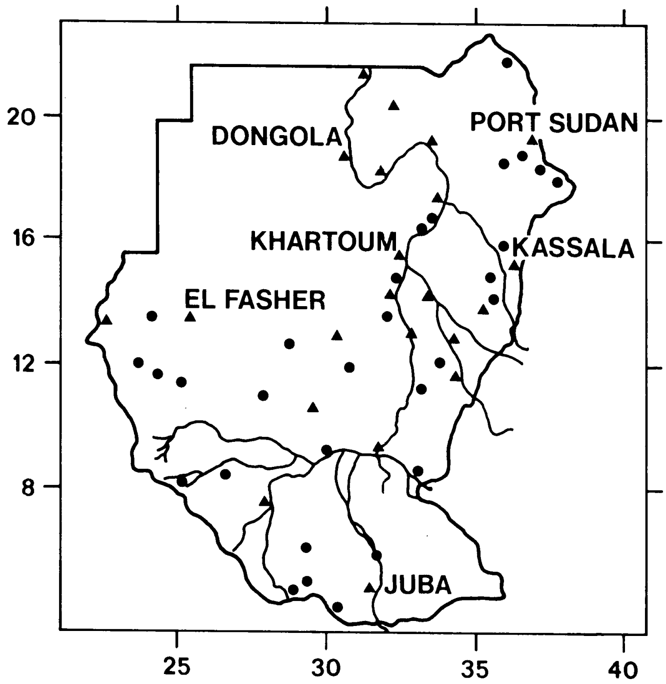


Figure 1.5 The position of meteorological stations in the map.
▲ represent stations where wind speed is recorded by Dines pressure-tube anemograph at heigh of about 15 meters above the ground level.
● represent the stations where the wind force is estimated by the Beaufort scale.

In the Sudan there are three radiosonde stations: Khartoum, El Fasher and Port Sudan. Radiosonde observation is once every 24 hours at 1100 G.M.T. In Wadi Halfa, Abu Hamed, Dongola, Kassala, El Obeid, Juba, Wau, El Damazin and Malakal only Pilot Balloons are sent up twice every 24 hours at 1100 G.M.T. and 2200 G.M.T.

In this report we will consider only surface data which are obtained from the Khartoum meteorology office. Table IV gives a summary of the annual mean wind speed and direction for the period (1970-80) for all stations in Sudan. For review purposes it is assumed that these data are correct, and some summaries and useful conclusions are given. However, some of these data may show some errors, which we will illustrate in a latter part of this section.

Station	lat.(N)	long.(E)	alt.(m) above sea level	Mean wind speed (m/s) and direction Dec.-Feb.	March-May	June-Sept.	Oct.-Nov.
Halayib	22 5'	36 7'	350	3.1 W	3.1 NW	3.1 NW	3.1 NW
Wadi Halfa*	21 49'	31 21'	190	4.2 NNW	4.3 NNW	3.9 NNW	4.4 NNW
Gebeit	21	36	?	2.7 NE	2.7 NE	2.7 NE SW	2.7 NE
Station no. 6	20 45'	32 33'	470	2.7 N	2.8 N	2.7 N	2.7 N
Dongola*	19 10'	30 29'	228	4.7 N	4.9 N	4.5 N	4.7 N
Port Sudan*	19 35'	37 13'	5	4.7 N	3.8 N	3.1 N	3.6 N
Abu Hamid*	19 32'	33 20'	315	5.8 N	4.6 N	3.7 N	4.9 N
Karima*	18 33'	31 51'	250	4.9 N	5.0 N	4.1 $NNW_{6,7}N$	4.7 N
Tokar	18 26'	37 44'	20	2.8 N	2.7 N	2.7 $N_{6}SW$	3.3 NE
Haiya	18 40'	36 40'	?	5.6 NE	4.7 NE	4.7 SW	4.4 NE
Atbara*	17 40'	33 58'	345	2.8 N	2.4 N	2.2 $SW_{6}SSW$	2.0 N
Hudeiba	17 34'	33 56'	350	2.9 N	2.8 N	2.8 NW_{6},SW	2.7 N
Aqeq	18 2'	38	?	2.9 N	2.9 N	3.2 W	3.1 E
Shendi	16 42'	33 26'	360	2.7 NE	2.7 NE	2.7 SW	2.7 NE
Wadi Seidna	15 40'	32 33'	?	4.3 N	4.4 NE	5.4 SW	4.0 $SW_{10}N$
Arona	15 50'	36 9'	430	2.7 NE	2.7 NE	2.9 $SW_{6}S$	2.7 NE
Shambot	15 40'	32 32'	380	3.1 N	2.8 N	2.8 SSW	2.9 NNW,N
Khartoum*	15 36'	32 33'	381	4.3 N	4 $N_{3,4}SSW_{5}$	3.8 SSW	3.3 N
Jebel Awelia	15 40'	32 33'	?	2.7 N	2.7 NE	2.7 SW	2.7 NE,N
Kassala*	15 28'	36 24'	500	1.8 NNE	1.8 $NNE_{3,4}S$	2.4 S	1.3 S,NNE
Halfa El Gadida*	15 40'	35 20'	?	3.0 NNW	2.8 $NNW_{3,4}S$	3.6 S	2 S,NNE
Wad Madani*	14 23'	33 29'	405	2.9 N	3.1 $N_{3,4}SW$	4.2 $SSW_{6}S$	2.3 S,NNW
El Shawak	14 24'	35 51'	510	2.7 N	2.7 $N_{3,4}SW$	2.7 $S_{6,9}SW$	2.7 S,N
Kutum	14 40'	24 50'	?	2.5 SE	2.7 $SE_{3}SW$	2.7 SW	2.7 NE
El Gedaref*	14 02'	35 24'	600	2.7 N	2.4 N	2.8 $SW_{6,7}S$	2.7 NNE
Ed Duim	13 59'	32 20'	380	2.8 N	2.7 N	2.7 S	2.7 N
El Obied*	13 10'	30 14'	570	3.9 N	2.8 N,SSW_{5}	3.1 SW	3.2 NNE,N
El Geneina*	13 29'	22 27'	805	4.0 NNE	3.0 NNE	2.1 W	2.7 NE
El Fasher*	13 38'	25 20'	730	2.2 NE	2.5 NE	2.3 SSE,ENE_{9}	2.2 NE
Sennar	13 33'	30 14'	570	2.7 NE	2.5 NE,SW_{5}	2.6 SW	2.7 SW
Kosti*	13 10'	30 14'	380	2.9 N	2.4 NNW	2.3 S	1.8 S,NNW
Zalingo	12 54'	23 19'	900	1.8 E	1.8 E	1.8 W	1.3 W,E
Abu Na'ama*	12 44'	34 8'	445	3.1NNE	3.1 NNW	3.0 S	2.5 S,NNW
En Nahud*	12 42'	28 26'	565	3.0 NNE	2.0 NNE	2.0 SSW	2.5 NNE
Kas	12 5'	24 20'	?	2.7 E	2.7 E	2.9 $SE_{6}SW_{7}NW$	3.1 E
Nyala	12 04'	24 53'	655	2.9 NE	2.7 NE	2.5 SW	2.9 NE
Rashad	11 52'	31 03'	885	3.0 N	3.0 NE	2.9 $NE_{6,7}SW$	2.7 NE
El Damazin*	11 49'	34 24'	470	2.9 N	2.9 $W_{3,4}S$	2.6 S	2.2 S,N
Babanosa	11 20'	27 40'	543	2.8 NE	2.8 NE,S	2.7 S	2.7 SW,N
Er Renk	11 7'	33 10'	?	2.7 $N_{12,1}NW$	2.7 NW SW_{5}	2.0 S	2.0 S,NWE
Kadugli*	11 0'	29 43'	500	3.4 NNE	2.7 NE,SW	2.7 SW	2.7 NE
Malakal*	9 33'	31 39'	390	4.1 NNE	2.9 NNE	2.1 S	2 SW,NNE
Bentiu	9 14'	31 39'	390	2.7 $N_{12,1}NE$	2.9 $NE_{3}S_{4}SW$	2.7 SW	2.7 S,N
Aweil	8 8'	27 30'	?	2.7 $NW_{12,1}NE$	2.7 $NE_{3}SW$	2.7 SW	2.7 NE,NW
Nasir	8 7'	33 15'	?	4.0 N	3.9 $N_{3}S$	3.1 S	3.4 S,N
Roga	8 5'	25 50'	?	2.7 NE	2.7 $NE_{3}SW$	2.7 SW	2.7 SW,WE
Waw*	7 42'	28 01'	435	1.8 $N_{12}NNE$	1.8 $E_{3}SSW$	1.8 W	1.8 SW,NE
Bor	6 3'	31 45'	?	2.7 NW,SW	2.7 SW	2.7 SE	2.7 SE,NE
Rumbek	6 8'	29 45'	?	2.7 $N_{12}NE$	2.7 $NE_{3}S$	2.7 $S_{6}SW$	2.7 SW,N
Maridi	5 10'	29 30'	?	2.7 N	2.7 $N_{3}SE$	2.7 $SE_{6}SW$	2.7 S,SE
Juba*	4 52'	31 36'	460	1.5 NE	1.8 S	1.3 S	1.3 S
Yambio	4 34'	28 24'	650	2.7 NE	2.7 SW	2.7 SW	2.7 SW,NE
Yei	4 2'	30 50'	?	3.1 NE	2.7 SE	2.7 SE	2.7 SE

Table IV Summary of the annual average wind speed and direction for period 1970-1980. The stations which have asterisk (*) are stations where wind speed is measured by Dines pressure tube anemograph. The index of the direction refers to the month.

The change in wind direction from the north of Sudan to the south in table IV can be illustrated by the motion of the I.T.C.Z. From the table it can be concluded that the I.T.C.Z. is around Khartoum in the period March-May and around Karima in the period Oct.-Nov. This estimation of the I.T.C.Z. motion is in agreement with fig. 1.3.

From the data in table IV one can observe that the wind speed in the Nile valley just along the river is higher than in areas in the same latitude far from the Nile (except for Jebel Marra and the Red Sea regions). Possible explanation should take into account that the elevation of the Nile valley is the lowest compared to the rest of the country.

From the wind direction data for the period 1940-1970 (available in the Meteorology Office in Khartoum) we constructed wind roses for a number of stations, which are plotted in fig. 1.6.

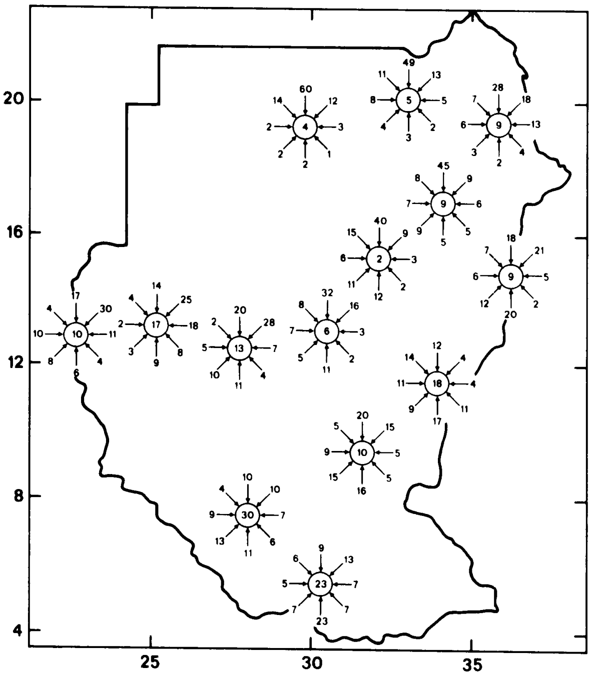


Figure 1.6 Percentage frequency of wind direction (wind roses) for the period 1940-1970. The encircled figure is the percentage of calms which is highly dependent on the up keep of the instrumentation, the reliability of these calms percentages is questionable.

Figure 1.6 shows the percentage of wind occurrence in the eight compass direction and also the calm percentage. From the figure we see that in the north of the country the prevailing wind is from the north and north east direction and the percentage of calms does not exceed 10%. But in the south of the country the effective wind is from the south and south west and the percentage of calms exceeds 20%.

In the analysis of the data sets from some stations there are remarkable discrepancies to be observed in the data sets. This is illustrated in the following:

1. When we compare the wind speed data from Kosti (13° N) with those from Malakal (9° N) (Kosti is at the same height above sea level as Malakal) during the winter when the northeast trade wind is dominant, we observe that the recorded data at Kosti are about 2.9 m/s whereas those at Malakal 4.1 m/s (see table (IV)). Geographically higher wind speeds are expected at Kosti. A possible explanation for this discrepancy could be provided by ref. [10] where it is mentioned that the station in Kosti was affected by growth of some trees in the north east direction.
2. In Kassala independent measurements were done by Y.H. Hamid et al. [10] in a representative area 5 km east of the meteorological station at about 8 m above ground level. The average wind speed was 4.8 m/s which is about 80% more than the data recorded at the same time at the meteorological station of Kassala.

The uncertainty in the data is expected to be due to the following reasons:

a. The growth of trees and new buildings around the stations.
b. The less than perfect maintenance and calibration of the measuring equipment. An example of this is that in most stations the Dines air pressure tube anemographs are based upon an assumed air density of 1.226 kg/m^3. In fact the actual air densities (which is strongly dependent on the seasons) at various stations are about 1.1 kg/m^3 or less [5].
c. Replacement of measuring equipment by another type.

To find a solution for the uncertainty problem of the data, we made a detailed study about some stations. This study is based on visiting the station to investigate the station surroundings and checking the measuring equipment and the obtained hourly data see table V. In the following chapter some important results from the four representative stations will be discussed.

Type of the data	Stations	Years
1. Surface-wind hourly data measured by means of Dines pressure tube anemograph. The measurements are at 15 m above the ground level.	Khartoum	1982, 83, 84
	Atbara	1982, 83, 84
	Wad Madani	1982, 83, 84
	El Obeid	1984
2. Surface wind 3-hourly average data: period of measurements between (0300-0900) G.M.T. Dines pressure-tube anemograph (10 m. above sea level) is used.	Wadi-Seidna	1984
3. Surface-wind 6 hours mean data. Cup anemometer measurements at 13 m.	Shambat	1984
	Wad-Madani	1984
4. Surface temperature, hourly data.	Shambat	1984
	Atbara	1984
	Dongola	1984
	Khartoum	1983, 84
5. Surface pressure 3 hourly data	Khartoum	1983, 84
	Atbara	11984
6. Soil temperature for different depths in the soil (recorded at 06, 12, 18 hours).	Shambat	1984
7. Global radiation recorded hourly.	Dongola	1984
	Shambat	1984
8. Relative humidity recorded hourly.	Shambat	1984
	Dongola	1984
	Khartoum	1984

Table V Tabulation of the surface data obtained from Khartoum Meteorology Office.

2. THE METEOROLOGY STATIONS AT KHARTOUM, SHAMBAT, WAD MADANI AND ATBARA

Our investigation is concentrated on the area around Khartoum. Shambat is about 8 km north of Khartoum, Wad Madani is situated 190 km south of Khartoum, and Atbara 280 km north of Khartoum (see fig. 2.1).

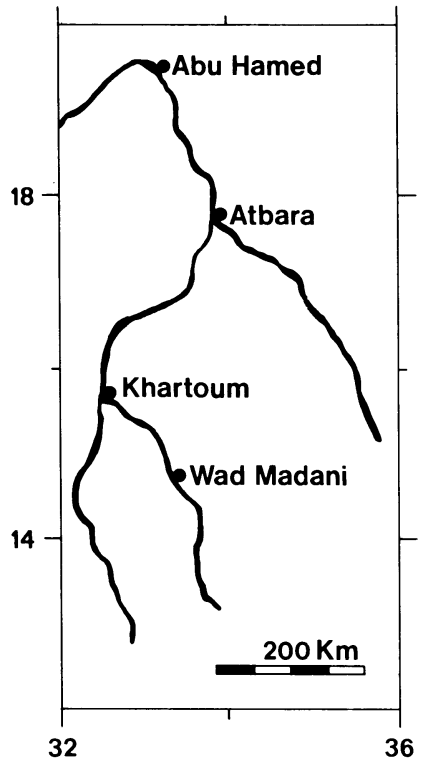


Figure 2.1 An enlarged part of the Sudan map to show the position of the three stations; Atbara, Khartoum and Wad Madani.

The considerations which resulted in the choice of this region are threefold:

a. The surroundings of Khartoum are homogeneous and consist of reasonably flat savannah over large distances ($dz/dx \approx 1 \times 10^{-3}$ over 10^4 km^2).
b. In this region the density of meteorological stations is high compared with the rest of Sudan. There are four meteorological stations, which is an acceptable number of stations to check the quality of the obtained data.
c. Application of wind energy in this area is estimated to be economical, and there is a large demand for water pumping (for irrigation and drinking water).

The WMO code numbers of the three stations are: Atbara (62680), Khartoum (62721) and Wad Madani (62751).

2.1 Khartoum airport station (380 m a.s.l.)

The airport is located about three kilometers east of the Centre of Khartoum. About one kilometer from the airport in the north and north-east directions there are a number of buildings which are 6 to 10 m in height. Fig. 2.2. shows the surroundings of the airport.

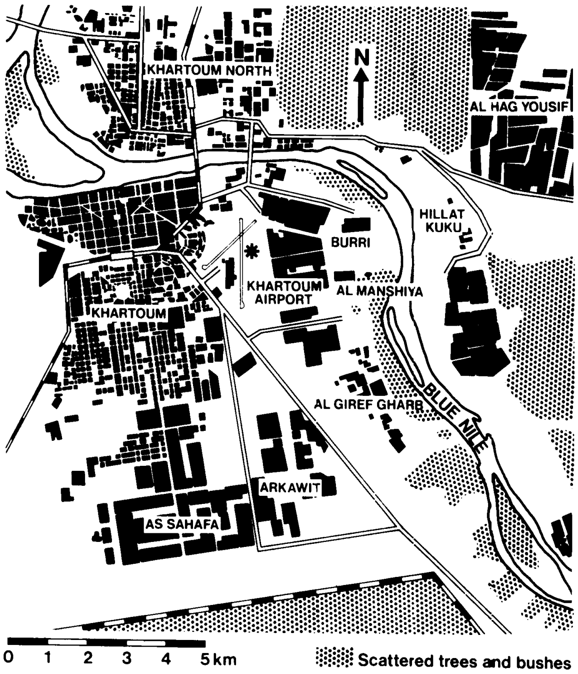
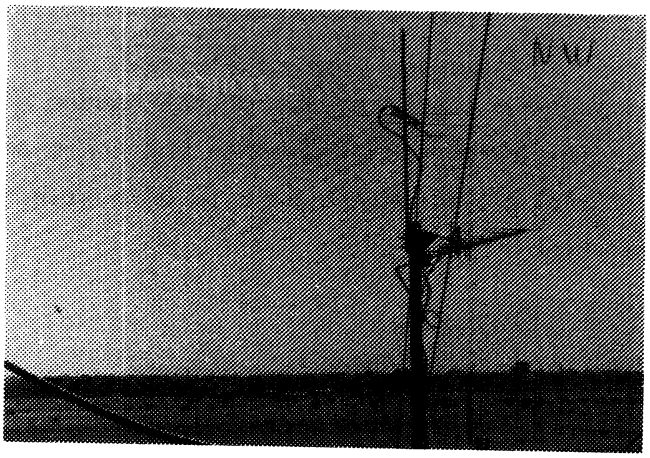
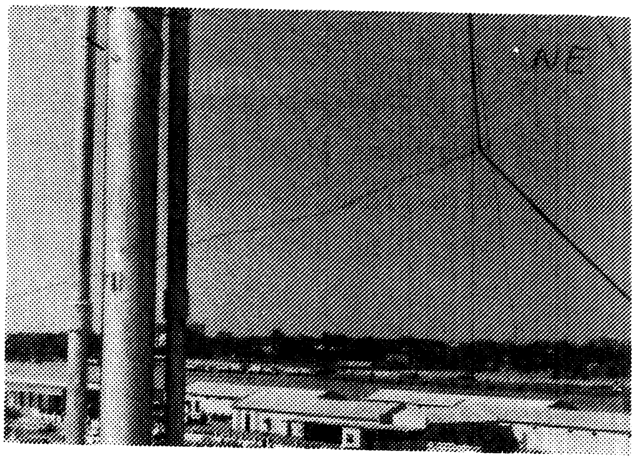


Figure 2.2 A map to show the surroundings of Khartoum airport. The location of the meteorological station is indicated by *.

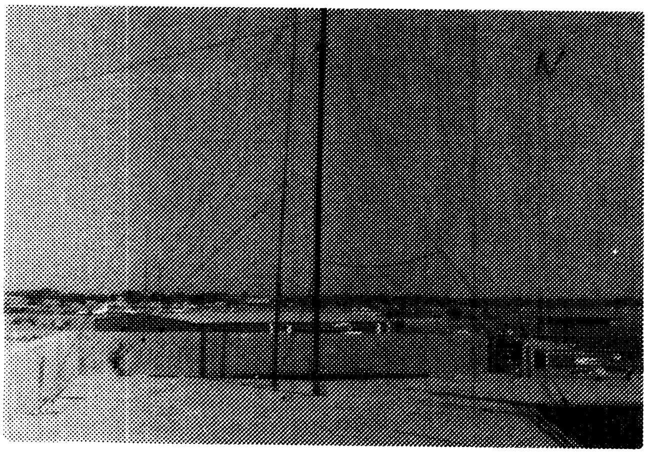
To have a better idea about the close surroundings, photos were taken of the airport surroundings for different azimuths (see fig. 2.3). The wind speed at about 15 m a.s.l. is recoreded hourly, using pressure tube Dines anemograph. In this station the calibration and equipment maintenance is done every six months. The maintenance consists of cleaning the tubes of the anemograph and changing the distilled water. The history of the hourly data collection for Khartoum airport goes back to 1936.



a - north-west azimuth



b - north-east azimuth



c - north azimuth

d - south azimuth

Figure 2.3 Khartoum airport station close surroundings (the prevailing wind directions are north and north east).

2.2 Shambat Agrometeorological Station

Shambat is the main agrometeorological station in Khartoum region. The station is located at about 8 km north of Khartoum-Airport. Fig. 2.4 shows the surroundings of the station.

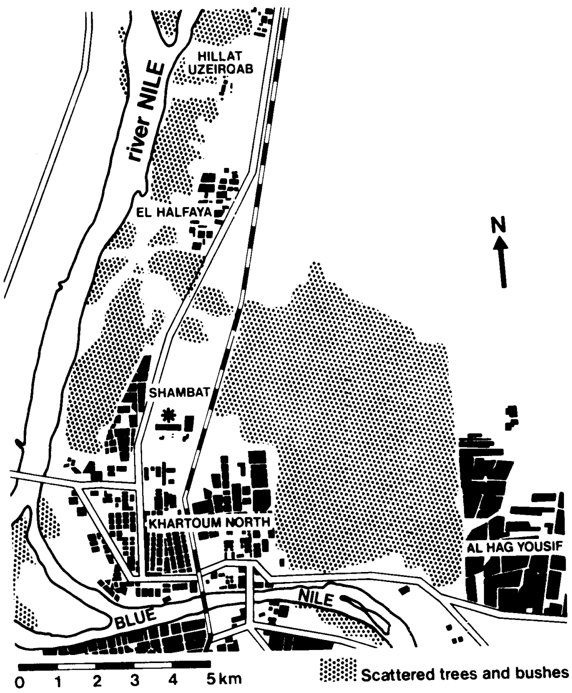
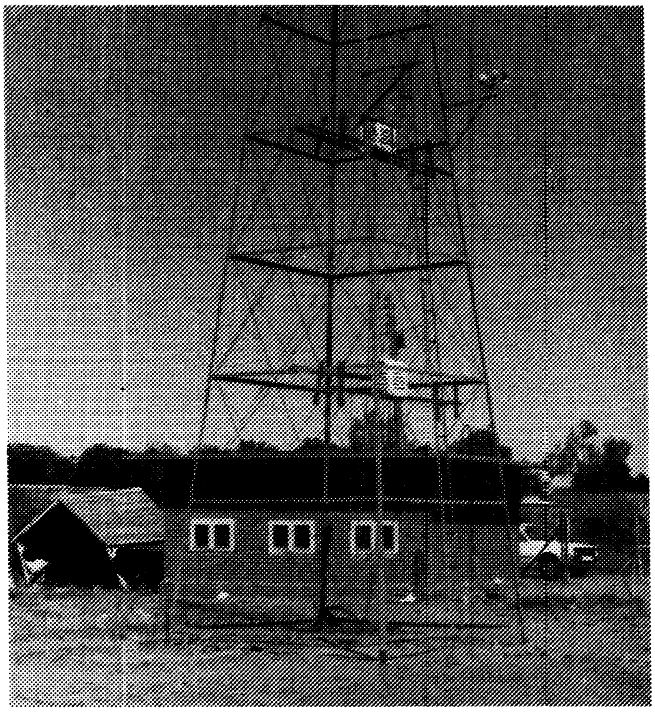


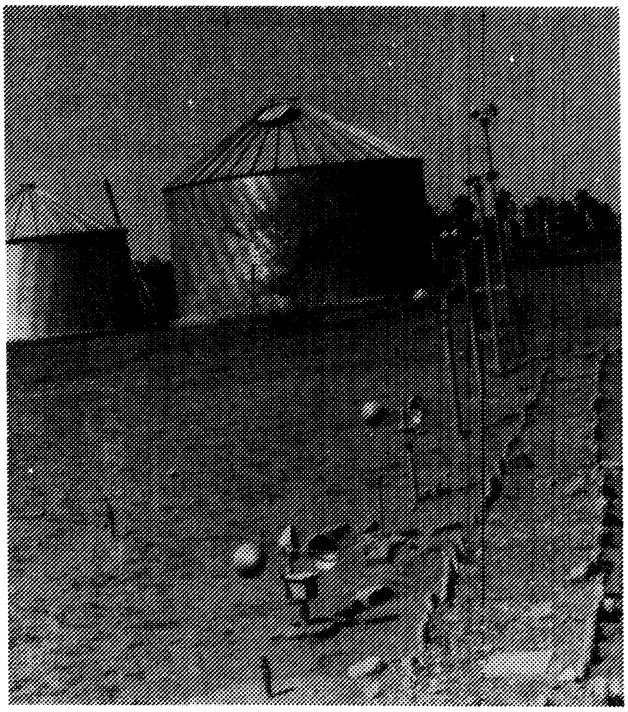
Figure 2.4 A map to show the surroundings of Shambat station which is identified by * in the map.

The station has a mast which holds nine cup-anemometers (Casella-type which has a mechanical counter that indicates the total run of the wind). The anemometers are placed at different heights from 0.5 m. to 13.0 m. Measurements are collected every three hours in the period (6-18) L.T. In this mast there is also an arrangement that the temperature can be measured at the different levels. However this type of temperature measurements are not recorded during the last five years.

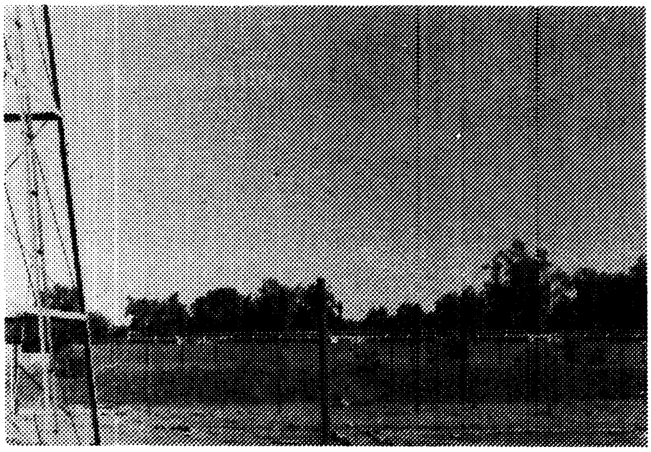
Fig. 2.5 shows photos of the close surroundings of the station. Maintenance is hardly done for these cup-anemometers. Calibration is carried out once every year and since there is no wind tunnel available in Sudan Calibration is performed by comparing the anemometer with a standard one.



a - north-west azimuth



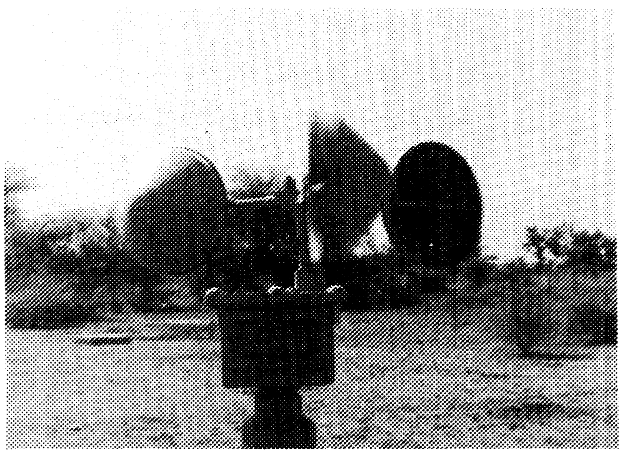
b - south-west azimuth



c - north azimuth

d - west azimuth

e - east azimuth



f - the anemometer used (Cassella type)

Figure 2.5 Shambat station close surroundings (the prevailing wind directions are north and north-east).

For comparison I measured the wind speed using a cup-anemometer (Maximum Anemometer with Aeolian Kinetics Windor Counter WP 4000, calibrated in wind tunnel of the University of Eindhoven) borrowed from the Wind Energy test field, University of Eindhoven. The Max. Anemometer was placed near the station anemometer at 10 m. The two resulting sets of data are represented in table VI and plotted in fig. 2.6. Fig. 2.6 shows that the station anemometer records lower wind speed (about 0.3 m/s) which may be due to insufficient maintenance. In the average the percentage difference between the two sets of data is (13.1±10.5)%.

GMT	Wind speed measured by reference anemometer (U_r)	Wind speed measured by the available station anemometer (U_s)	Percentage difference $\left\|\left(\frac{U_r-U_s}{U_r}\right)x100\right\|$
5.30	3.2	2.5	22
6.30	3.1	2.7	13
7.30	2.8	2.8	0
8.30	3.6	3.9	6
9.30	4.1	3.7	10
10.30	4.4	4.0	9
11.30	3.6	3.3	8
12.30	3.6	2.8	22
13.30	2.3	2.1	9
14.30	2.4	2.5	4
15.30	1.5	1.0	33
16.30	1.4	1.0	29
17.30	2.8	2.5	11
18.30	3.3	3.2	3
19.30	2.9	2.6	10
20.30	1.4	1.0	29

Table VI Wind speed (m/s) measured by reference anemometer (U_r) compared with the wind speed (m/s) measured by the available anemometer (U_s) in Shambat station. The two anemometers are placed at 10 m. above the ground level. The averaging periods are (5-10) min.

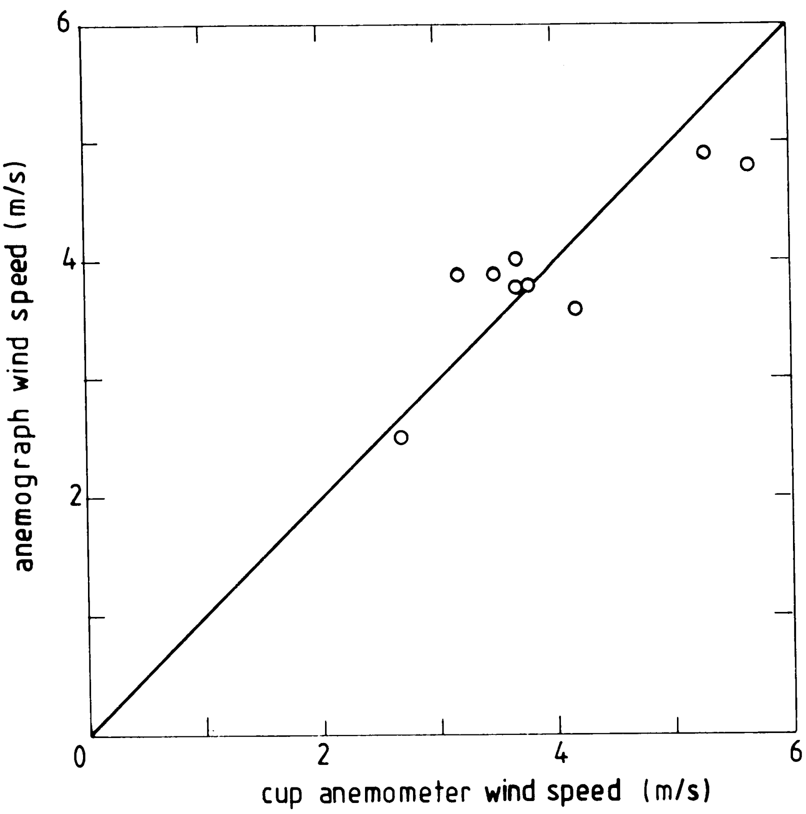
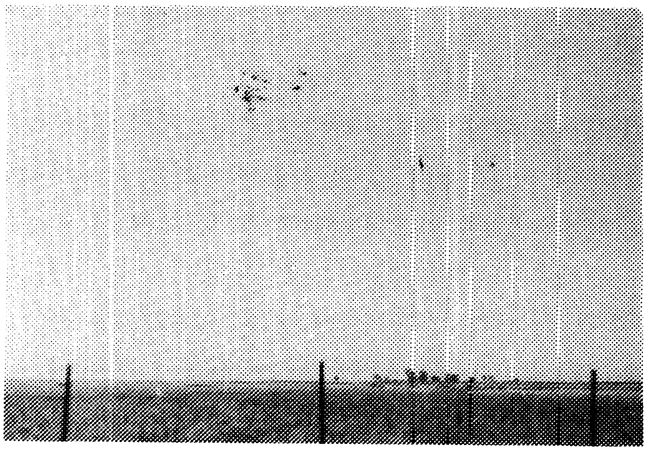


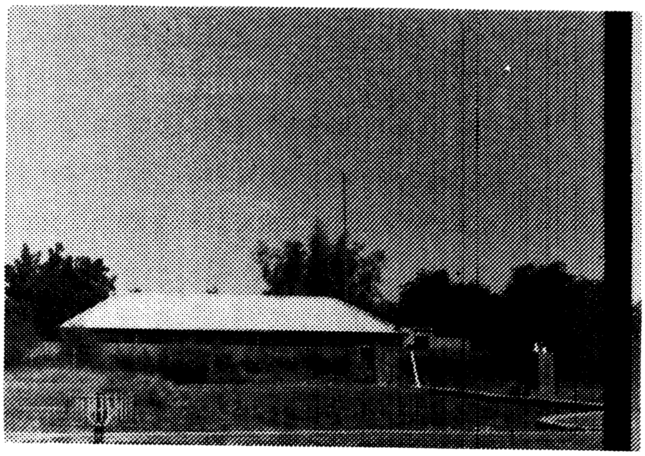
Figure 2.6 The wind speed measured by the anemometer from Shambat station (U_s) versus the wind speed measured by the reference anemometer (U_r).

2.3 Wad Madani station (405 m a.s.l.)

Wad Madani station is about 190 km south of Khartoum airport. It is an agrometeorological station which is equipped with a pressure tube Dines anemograph. There is a mast which holds nine cup-anemometers (Casella type), placed at different levels in the range of 0.5 m to 9.14 m. The measurements at 9.14 m and 6.10 m height are recorded once a day as an average for the 24 hours. The anemograph is at about 15 m above ground level and it records hourly data. The distance between the anemograph and the mast is 30 m. Calibration and maintenance is done once a year. Fig. 2.7 shows some photos for the close surroundings of the station.

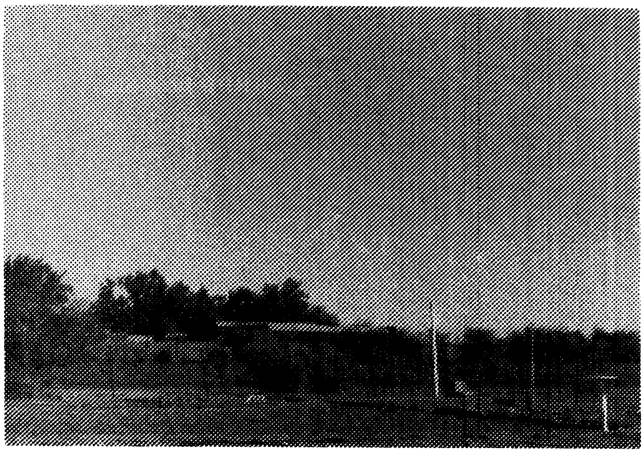


a - north azimuth

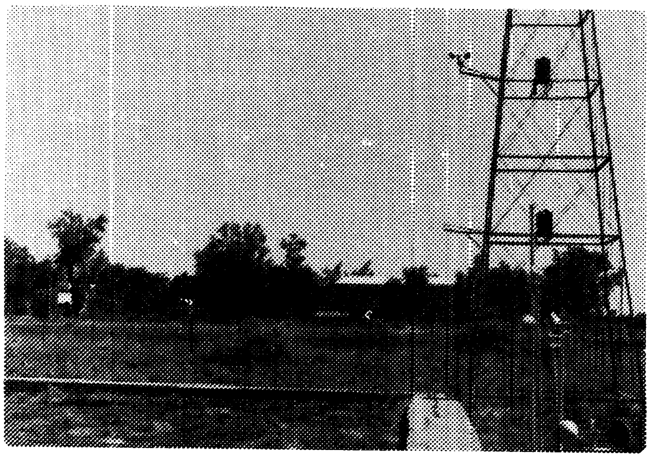


b - south-west azimuth

c - north-east azimuth



d - south azimuth



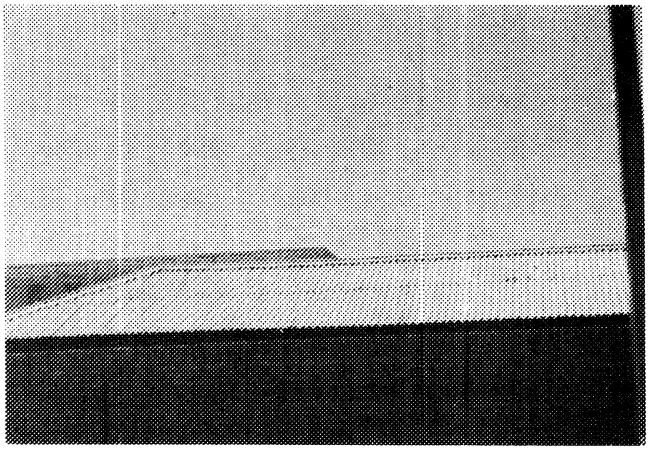
e - east azimuth

f - south-east azimuth

Figure 2.7 Wadi Madani station close surroundings (north and north-east are the prevailing wind directions).

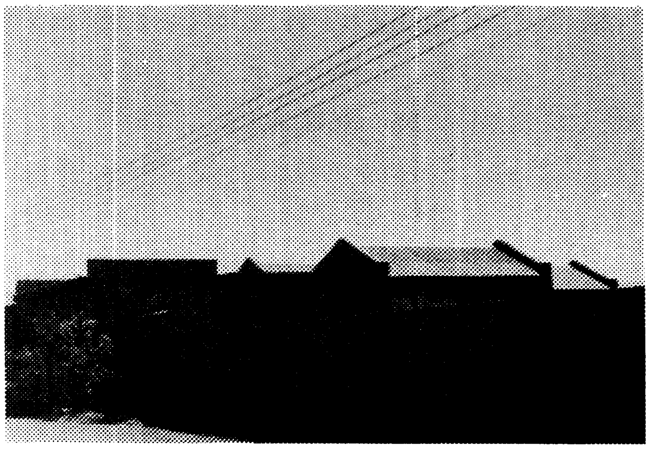
2.4 Atbara station (345 m a.s.l.)

Atbara station is about 280 km north of Khartoum. Fig. 2.8 shows photos of the close surroundings of the station. The wind speed at about 15 m a.s.l. is recorded hourly using pressure tube Dines anemograph. The maintenance is done every six months. The history of hourly wind speed measurement goes back to 1940. At the north azimuth there are houses at about 20 m from the anemograph position. The height of the buildings is about 6 m. At north-east azimuth the distance between the houses and the anemograph is about 30 m. At the east azimuth the houses and trees are at about 40 m from the anemograph. At south-east azimuth the buildings are at about 40 m from the anemograph. At the south-south-east azimuth the buildings are at about 30 m from the anemograph. At the south-west azimuth the buildings are at about 30 m from the anemograph. At the west azimuth trees of 2 m height are at about 15 m from the anemograph. At the north-west azimuth buildings are at about 20 m from the anemograph. In conclusion the surroundings of the station is very rough resulting in a large aerodynamical roughness.

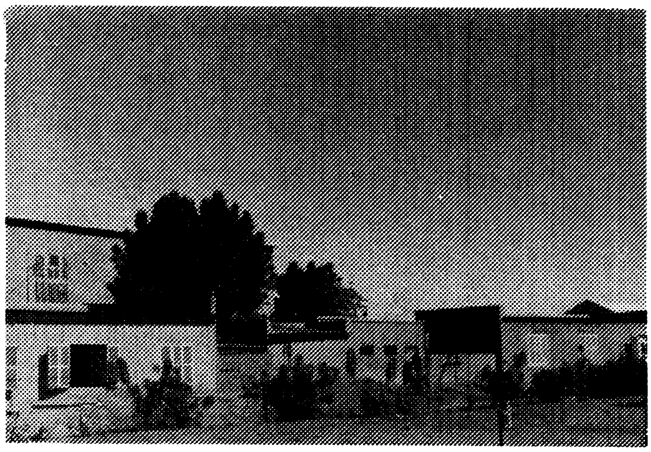


a - north

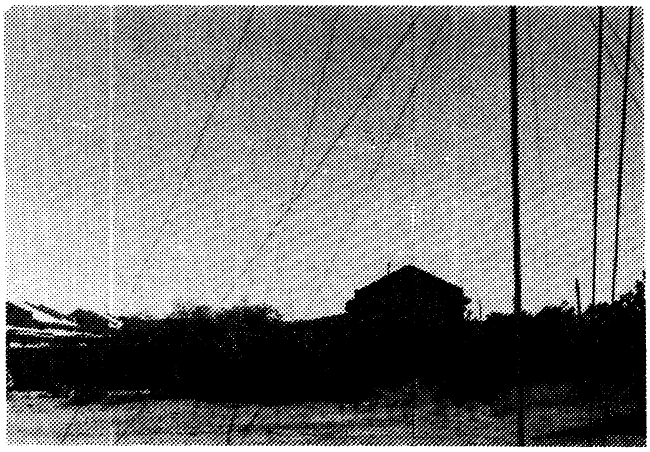
b - south-east



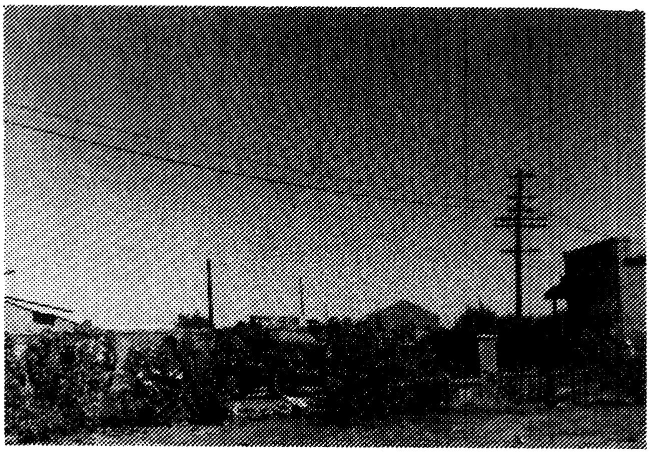
c - north-east



d - south-south-east



e - east



f - south-east

Figure 2.8 Atbara station close surroundings (the prevailing wind directions are north and north-east).

3. DATA ANALYSIS

3.1 Data correction and potential wind calculation

The data are corrected for writing and systematic errors by comparison between two sets of data [8]. The obviously erroneous data were subsequently removed. We also used data from nearby stations (e.g. Shambat station in case of Khartoum to check the quality of the data. From the surrounding characteristics of the stations (see section 2) the roughness length is estimated using the terrain classification of Davenport [6] (see table VII).

Class	Terrain description	z_0(m)
1	Open sea, fetch at least 5 km	0.0002
2	Mud flats, snow; no vegetation, no obstacles	0.005
3	Open flat terrain; grass, few isolated obstacles	0.03
4	Low crops; occasional large obstacles, $x/H>20$	0.10
5	High crops; scattered obstacles, $15<x/H<20$	0.25
6	Parkland, bushes; numerous obstacles, $x/H\sim10$	0.5
7	Regular large obstacle coverage (suburb, forest)	1.0
8	City centre with high- and low-rise buildings	?

Adapted from Davenport(1960) in z_0-form by Wieringa (1980)
Notes: Here x is a typical upwind obstacle distance and H the height of the corresponding major obstacles. For class 7, the applicability of logarithmic exposure corrections modelling is doubtful, and requires at any rate the substitution of (z-d) for z the formulae, where d is the displacement length (d ~ 0.7 x average obstacle height: see Brutsaert (1975)). Class 8 is analytically intractable and can better be modelled in a wind-tunnel.

Table VII Davenport roughness classification (from Wieringa (1986) [6]).

The estimations of the roughness length are taken in azimuth sectors of 45°. The roughness lengths obtained for Khartoum and Wad Madani are tabulated in table VIII.

Azimuth sectors	Khartoum airport	Wad Madani
	roughness length (m)	
0 - 45	0.3	0.2
45 - 90	0.3	0.3
90 - 135	0.4	0.3
135 - 180	0.5	0.3
180 - 225	0.4	0.3
225 - 270	0.3	0.3
270 - 315	0.2	0.2
315 - 360	0.2	0.2

Table VIII The estimated roughness length for Khartoum station and Wad Madani station.

For Atbara the roughness (z_o) is estimated 1.0 m for all directions since from all directions the upwind obstacle distance (x) is less than 6 times the height of the obstacle (H) (i.e. $x/H < 6$). The displacement height (d) is estimated to be 4 m ($d \sim 0.7$ H). As a result of the large aerodynamical roughness to use the logarithmic exposure correction we substituted the mast height (z_s) by (z_s-d).

Using the estimated roughness length in table 3.2 the data are subsequently corrected for exposure. The potential wind speed at a standard height (10 m) is determined using the logarithmic wind profile equation [6]:

$$U_p = 0.76\ U_{15}\ \ln(\frac{60}{z_o})\ /\ \ln(\frac{15}{z_o}) \qquad (1)$$

where U_p is the potential wind speed (at 10 m), U_{15} is the wind speed at 15 m, the height at which the original data are measured.

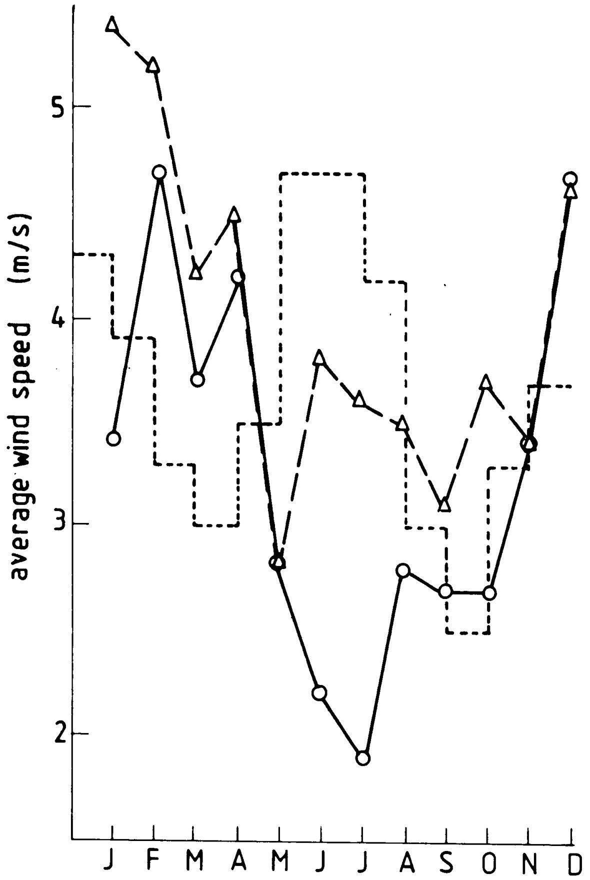


Figure 3.1 Mean potential wind speed of 1983, 1984 versus month.
Δ Khartoum, ... Wad Madani, o Atbara.

Comparison of the monthly mean potential wind speed from the three stations is shown in fig. 3.1. It is seem that the data from Atbara are low compared with the Khartoum data, especially the winter season data. One expects that the Atbara winter wind regime is higher than that in Khartoum since the winter in Sudan is characterised by north trade wind and the more north the region is the higher the winter wind speed, especially in the Nile valley as discussed in section 1.4. For example, the winter wind speed in Abu Hamed (which is about 250 km north of Atbara) is higher than that in Khartoum (see table II), then one expects that the winter wind speed at Atbara is higher than that of Khartoum or at least equal to it, but not less. We therefore think that the actual winter wind speed is higher than what is measured. Unfortunately there are no nearby stations within Atbara surroundings to check the quality of the data and also no independent check by other means from the station.

To check the reliability of the data from Khartoum and Wad Madani we used data from nearby stations or data from the same station measured by means of other equipment. In case of the Khartoum data we used data from

Shambat agrometeorological station, which is 8 km north of Khartoum. The data from Shambat are 6-hourly average data, cup anemometer measurements. Objective terrain corrections have been made for the data.

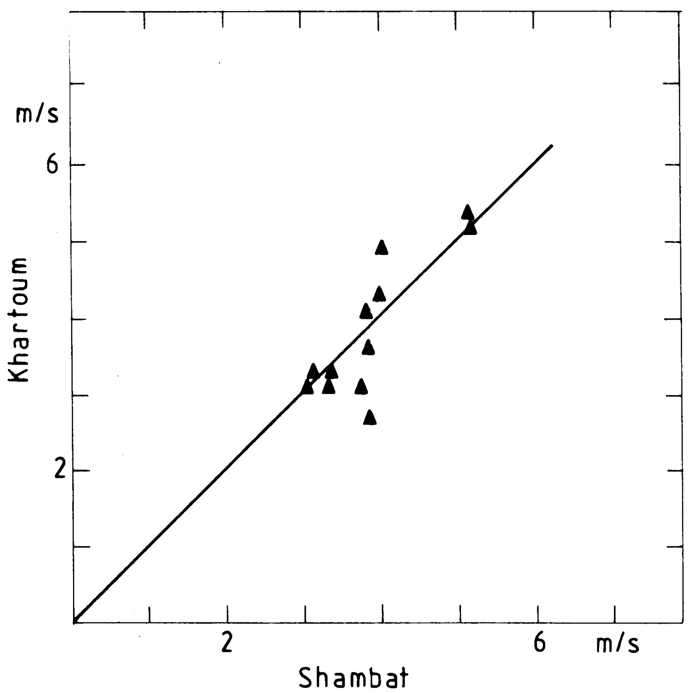


Figure 3.2 Comparison of the monthly averages of the potential wind speed from Khartoum and Shambat. The correlation coefficient (r) = 0.84.

Fig. 3.2 shows the comparison of the monthly averaged of the potential wind for the two sets of data. The data are found to be reliable with correlation coefficient r = 0.84. In case of Wad Madani we used independent data from the same station, 6-hourly mean data measured by cup anemometer.

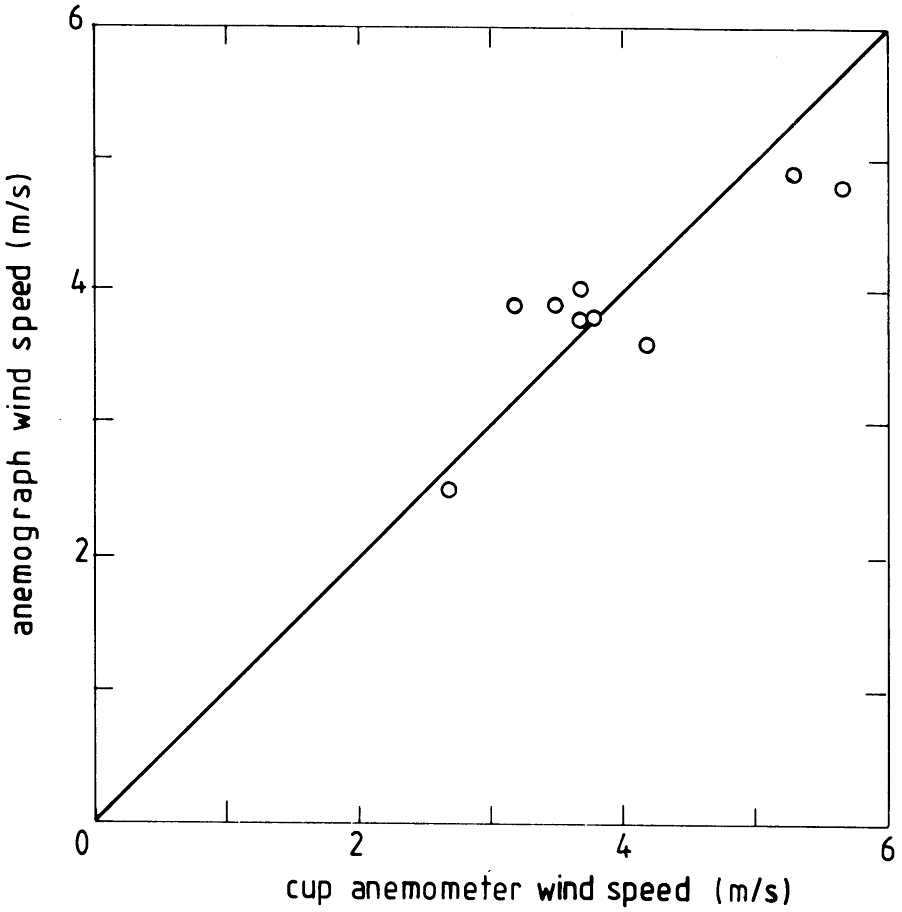


Figure 3.3 Comparison between the cup anemometer data and the anemograph data from Wad Madani for 1984. The correlation coefficient (r) = 0.86.

Fig. 3.3. shows the comparison between the two sets of data. The data are on the average in a good agreement with each other with correlation coefficient of 0.86.

In conclusion we can say that the wind data (from Khartoum and Wad Madani) with this degree of accuracy are useful both for wind energy potential estimates and for model developments.

3.2 The diurnal wind course

To study the behaviour of the wind regime in the 24 hour cycle we calculated the average of the hourly data for every month. The hourly average are presented graphically as diurnal plots. It is observed that the diurnal fluctuation is dependent on the seasons.

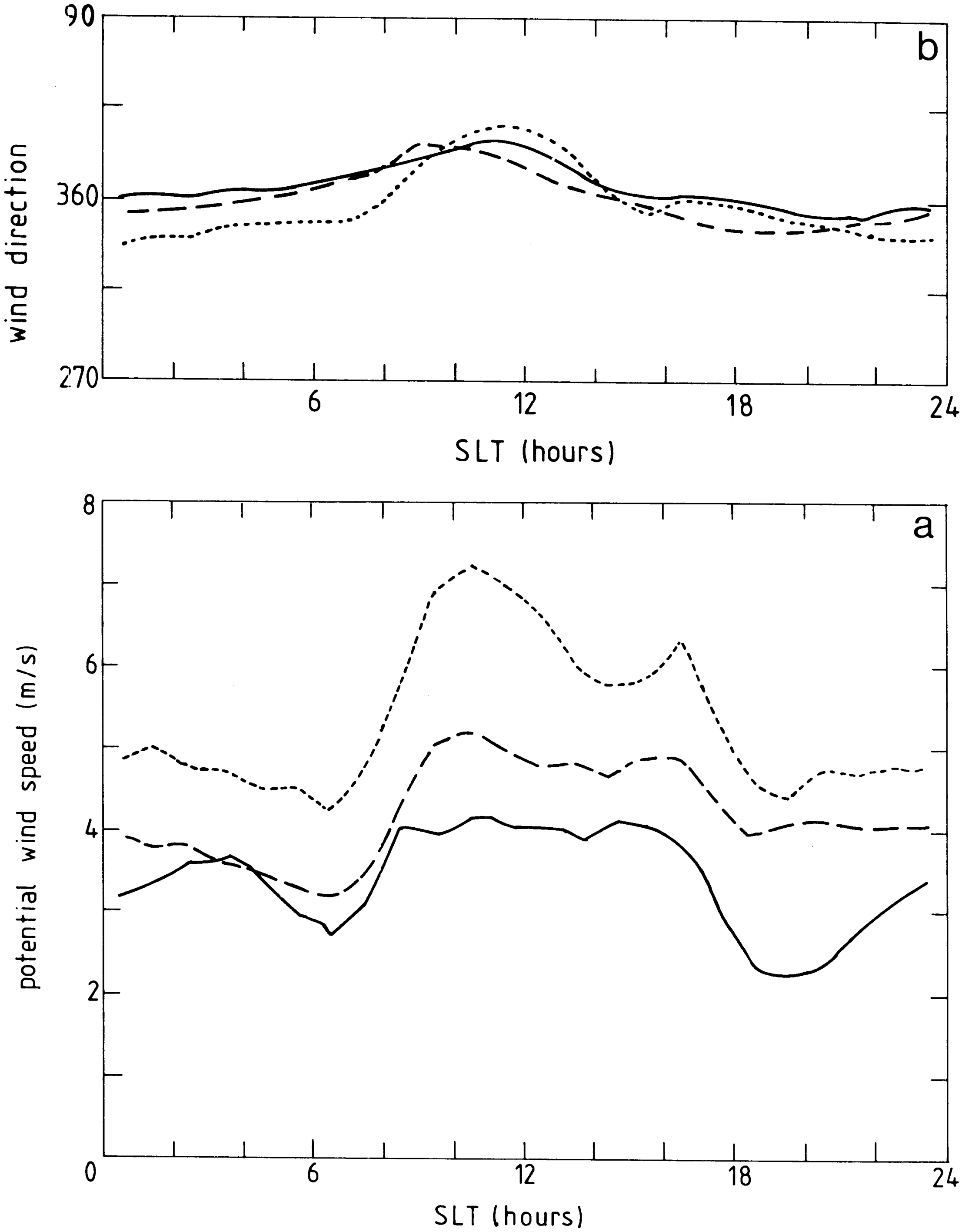


Figure 3.4 a - The potential wind speed diurnal course of January 1984.
b - The wind direction diurnal course of January 1984.
——— Atbara, -----Khartoum,— — —Wad Madani.

Fig. 3.4a shows an example of the seasonal diurnal fluctuation. Atbara shows low wind regime, though the behaviour of the diurnal course is similar to that of Khartoum and Wad Madani. The diurnal wind course shows a remarkable unstable character during the day. Just after sunrise the wind speed increases sharply whereas just before sunset it drops substantially (sunrise is at about 6 hours and sunset at 18 hours local time). This observation coincides in time with the highest temperature gradient during the day. We are therefore convinced that these sharp changes are correlated with the high sensible heat flux received. For example, the average sensible heat flux received in Khartoum region is about 600 W/m^2 [7]. The large difference between the day and night wind speed, especially in the winter and advancing monsoon, must be due to the large difference between the day and night temperature (about 15° C). In the monsoon and retreating monsoon the difference between the night and day wind speed and temperature is smaller due to the cloudy night during these seasons.

The seasonal diurnal wind courses do not change qualitatively from one year to the other. This is checked by comparing data of different years and also data from other stations. The diurnal course of the wind direction in the winter, retreating monsoon and advancing monsoon (except May) is constant in the night and changes during the day from the northwest to northeast in a range of 60°. Fig. 3.4b gives an example of the wind direction diurnal course.

The largest variations in wind direction are observed in May and September (see fig. 3.5) which can be explained by the passage of the I.T.C.Z. The wind direction changes from north to southwest in May and changes from southwest to north in September.

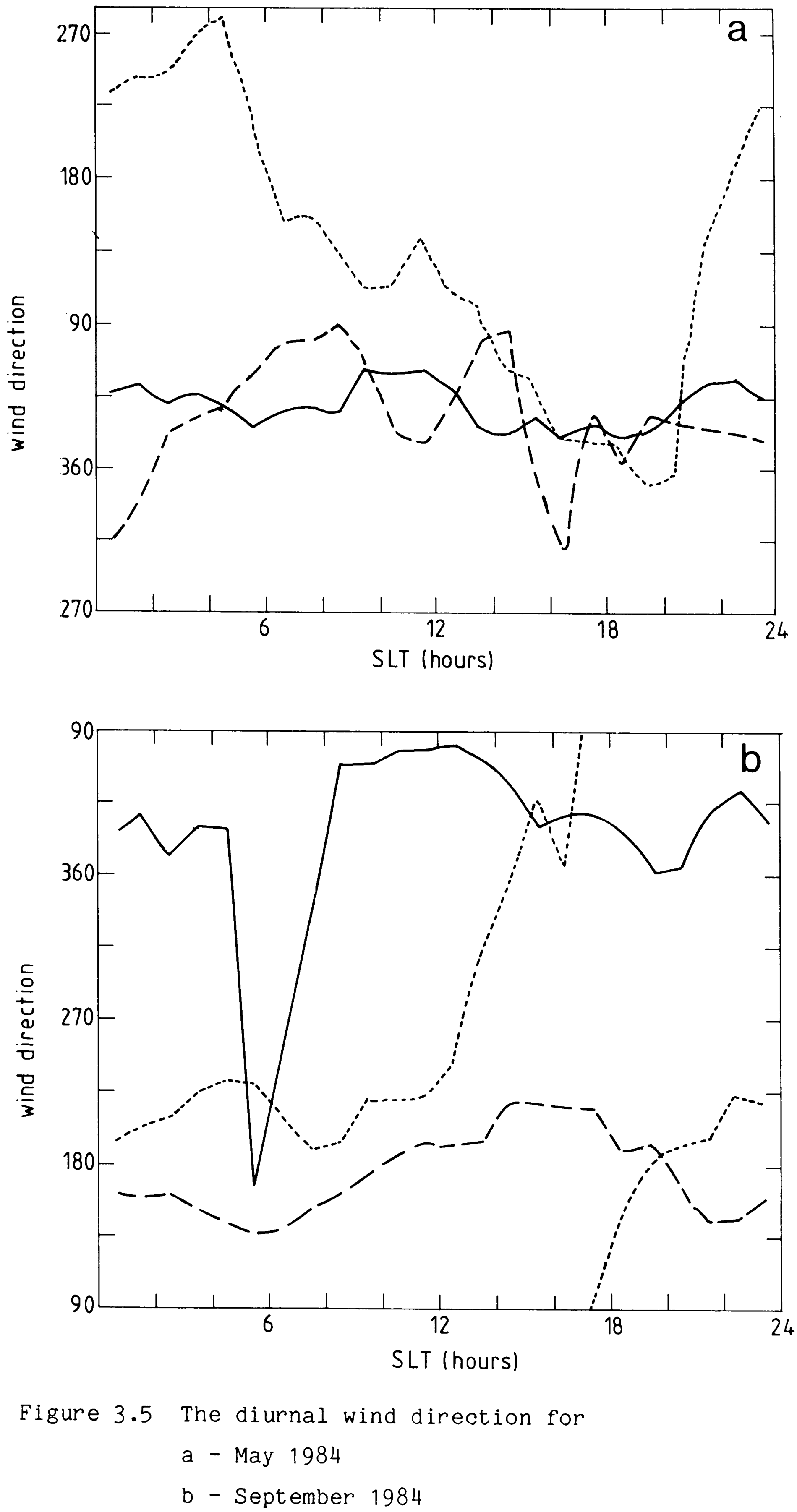


Figure 3.5 The diurnal wind direction for

a - May 1984

b - September 1984

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

In order to find a measure for the wind variation we introduce the ratio σ_u/U [8] (where u is the monthly average for each hour of the day (n=30) and σ_u the standard deviation. The value of σ_u/U is a very good indication for the wind seasonal variation. Table IX shows the values of σ_u/U for 1983 and 1984 for the Khartoum airport and Wad Madani data (see appendix A). Atbara data are not considered because of the high uncertainty in the data.

Month	(σ_u/U)%			
	Khartoum		Wad Madani	
	1983	1984	1983	1984
January	28	28	22	25
February	27	32	24	25
March	41	39	32	33
April	39	37	41	30
May	58	60	59	59
June	55	41	60	52
July	57	53	50	42
August	41	52	40	44
September	58	59	75	60
October	37	47	-	42
November	28	42	30	21
December	28	39	28	23

Table IX The monthly values of (σ_u/U)% for 1983, 1984 for Khartoum and Wad Madani.

It is observed that the winter season has the most steady wind speed, i.e. small σ_u/U ratio. The largest σ_u/U ratio is observed in May and September. The diurnal wind directions in these months show large variations, which are caused by the following reasons:

a. The low wind speed recorded in these months.
b. The influence of the I.T.C.Z. which passes over this region in May northwards and September southwards. We conclude that the data of these two months are difficult material for basic physical modelling because of their large variation. They can be used, however, to indicate the passage of the I.T.C.Z.

The calculated values of σ_u/U for different seasons are in agreement with our expectations for the seasonal variation. In the winter σ_u/U has its lowest value (30±10)% which is due to the north trade wind. In the advancing monsoon the value increases to (40±10)% which is due to the changing of the prevailing wind direction from north trade wind to a southwest humid wind which originates from the south Atlantic ocean. The monsoon shows the highest value (50±10)%, due to the interaction with the dry air stream from the south. In the retreating monsoon the value of σ_u/U decreases to (40±10)%, due to the retreatment of the humid air stream to the south and a prevailing northeast trade wind.

3.3 Frequency distribution of the potential wind

The calculated frequency distributions for Khartoum and Wad Madani are presented in Appendix B, the frequency distribution of Atbara is not considered because of the high uncertainty in the data for example the calm frequency in 1984 from Atbara is 4 times larger than that at Khartoum. Fig. 3.6 shows the frequency distribution behaviour in Khartoum which indicates large variation of the distribution between the seasons [8].

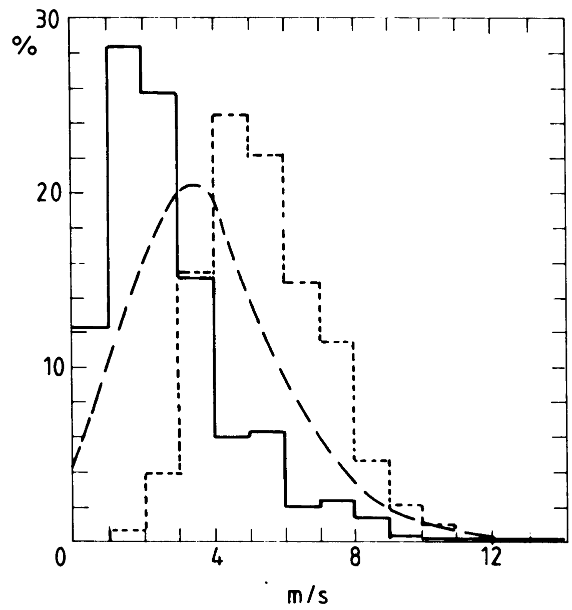


Figure 3.6 Percentage frequency distribution of potential wind speed at Khartoum for data of 1983 and 1984 combined.

---- Annual distribution with a Weibull distribution shape factor (k) of 1.75.

------ January distribution with a shape factor (k) of 3.2.

—— May distribution with a shape factor (k) of 1.5.

We also used the Weibull cumulative distribution paper to represent the frequency distribution and to obtain the shape factor (K). The shape factor (K) is a good indicator of the type of wind regimes [9]. Fig. 3.7 gives an example of the Weibull distribution plots. The K-values versus the months are plotted in fig. 3.8. High K-values ($K \geq 3$) indicate a steady wind regime (i.e. trade wind regime) and low K-values ($K \leq 1.5$) indicate large wind variations. From fig. 3.8 we see that the winter shows a trade wind characteristic and May and September show the largest wind variations. These results are in a good agreement with the analysis of the diurnal course in section 3.2 using σ_u/U ratio method.

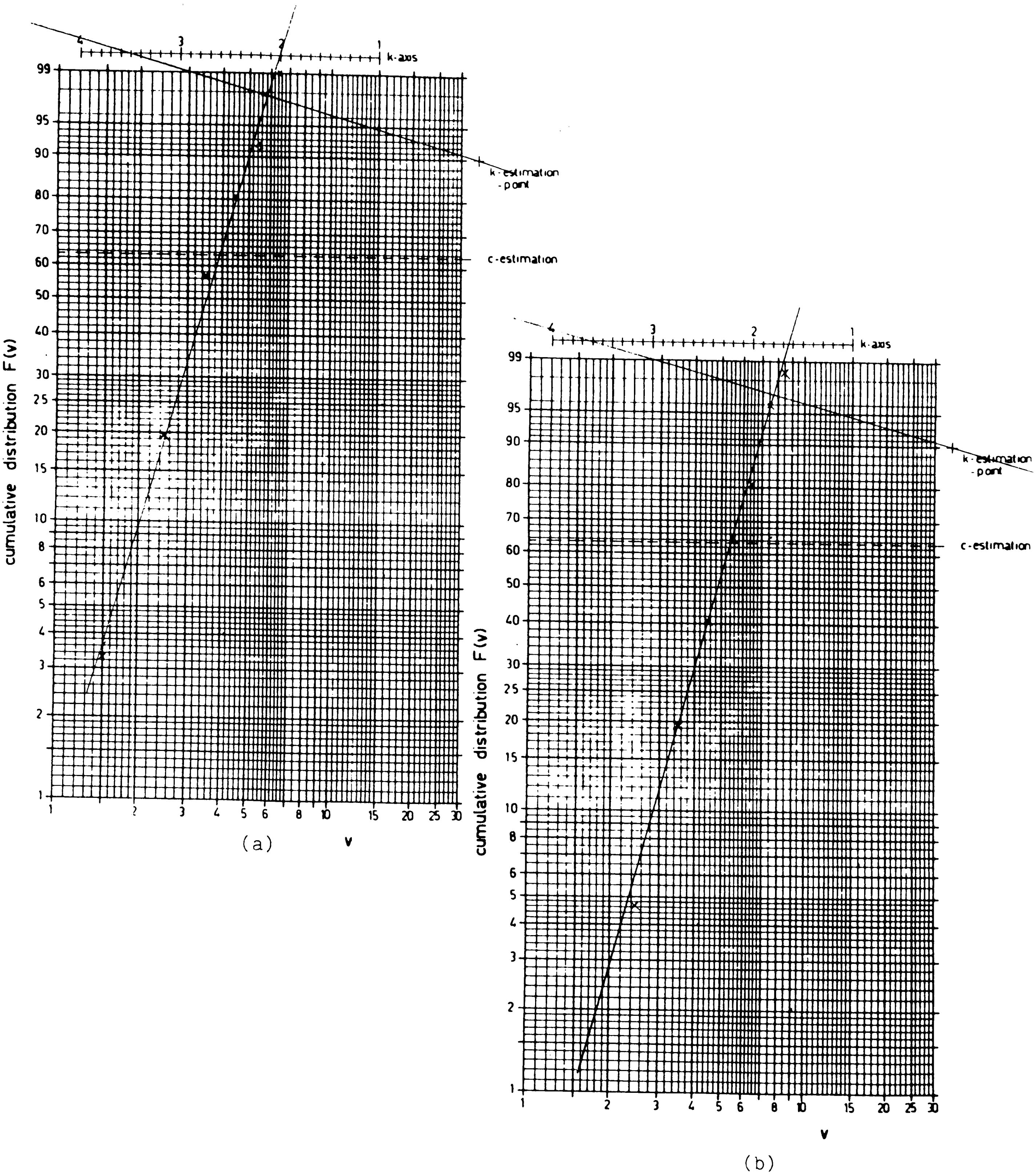


Figure 3.7 Weibull probability paper for wind energy studies.

a - Wad Madani data for February 1984. Shape factor (k) = 3.5.

b - Wad Madani data for January 1983. Shape factor (k) = 3.6.

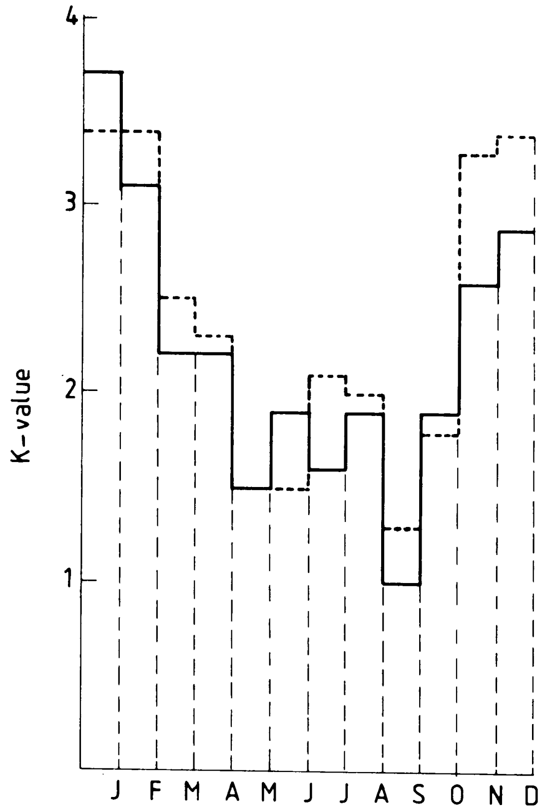


Figure 3.8 The k-value versus month for 1983, 1984.

——— Khartoum

--------- Wad Madani

4. CONCLUSIONS

The position of the I.T.C.Z. in the Sudan is the major determinant in classifying the seasons and consequently the variation of the wind regime.

In most cases the meteorological data from some countries are considered to be unreliable without proper checks. In the case of Sudan the wind data from Khartoum, Atbara and Wad Madani were investigated, corrected for exposure and the results from Khartoum and Wad Madani were found to be of sufficient quality for wind energy analysis. However, Atbara data are found to be unreliable because of the large aerodynamical roughness. Additionally, there is no nearby station in the surroundings of Atbara to check the quality of the data and also no independent check by other means from the station.

The diurnal wind course shows a noticeable unstable character (see fig. 3.4) which is probably due to the large sensible heat flux received. Consequently there is a large difference between the day and night wind speeds since the temperature difference between the day and night amount to about 15° C.

May and September data give a very large (σ_u/U) ratio (about 60%), indicating large variations. This is due to low wind speed recorded in these months and the influence of the I.T.C.Z. which passes over this region in May northwards and in September southwards. These large variations in May and September are also observed in the wind direction diurnal course (see fig. 3.5). The change in frequency distribution is strongly dependent on the seasons (fig. 3.6) which means that the monthly distribution is much more important than the annual distribution in considering wind energy application for the Sudan and Sahelian countries since they have similar climate.

Appendix A

A1 Khartoum Airport potential wind speed (m/s) 1983

L.TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0030	5.2	3.9	3.5	3.6	2.0	3.8	3.7	3.5	2.9	4.9	4.4	4.3
0130	5.5	4.2	3.8	3.9	2.3	4.6	4.6	3.7	3.4	4.9	4.5	4.4
0230	5.4	4.4	3.7	3.6	2.5	4.2	4.3	3.6	3.1	4.9	4.2	4.4
0330	5.4	4.1	3.9	3.6	2.5	4.0	4.2	3.5	3.0	4.5	4.0	4.4
0430	5.2	4.1	3.6	3.4	2.3	4.1	4.4	3.5	3.0	4.3	4.0	4.4
0530	4.8	4.1	3.7	3.3	2.2	3.6	4.4	3.4	2.8	3.9	3.8	4.1
0630	4.8	3.8	3.4	3.4	2.2	3.7	4.2	3.5	3.1	3.8	3.9	4.1
0730	5.0	4.3	4.2	4.2	2.9	4.6	5.0	3.9	3.6	4.2	4.1	4.7
0830	5.9	5.5	5.7	5.6	3.6	5.2	5.3	4.4	3.4	4.5	5.1	6.4
0930	6.7	6.7	6.3	6.1	4.2	5.5	5.3	4.6	3.5	5.1	5.6	6.5
1030	6.6	7.3	6.1	5.9	3.8	5.4	5.2	4.6	3.2	5.2	5.7	6.5
1130	6.2	7.0	5.3	5.1	3.2	5.1	4.8	4.3	3.1	5.0	5.1	6.2
1230	6.0	6.6	4.9	4.7	2.8	4.7	4.2	4.0	2.5	4.7	4.6	6.0
1330	5.8	6.3	4.8	4.2	2.6	4.3	4.0	3.8	2.6	4.4	4.3	5.8
1430	5.8	5.9	4.9	4.3	2.5	4.2	3.7	3.8	2.3	4.2	4.1	5.6
1530	5.7	5.9	4.8	4.3	2.3	3.7	3.5	3.5	2.1	4.0	4.1	5.6
1630	5.6	5.9	4.7	4.2	1.9	3.3	2.8	3.1	1.8	3.6	3.8	5.3
1730	5.1	4.8	4.2	3.5	1.7	2.8	2.8	3.0	1.8	3.1	3.0	4.3
1830	5.0	3.9	3.4	2.8	1.4	2.4	2.5	3.0	1.4	3.0	3.1	3.8
1930	5.0	3.8	3.2	2.8	1.6	2.2	2.5	3.4	2.2	3.7	3.4	3.9
2030	5.1	3.6	3.2	3.1	1.7	2.9	3.1	3.9	2.6	4.0	3.9	3.8
2130	5.3	3.8	3.4	3.4	1.6	3.7	3.8	3.8	3.1	4.1	4.2	4.1
2230	5.3	3.8	3.5	3.5	2.0	3.2	4.7	3.8	3.0	4.4	4.4	4.4
2330	5.2	3.8	3.6	3.6	2.0	3.2	3.6	3.7	3.2	5.0	4.6	4.2

A2 Khartoum Airport potential wind speed (m/s) 1984

L.TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0030	4.8	4.6	3.6	4.0	2.8	3.9	3.1	4.4	3.1	2.9	2.7	3.9
0130	5.2	4.8	3.8	4.3	3.1	4.3	3.2	4.0	3.2	3.0	2.8	4.0
0230	4.7	4.6	3.6	4.7	3.0	4.0	3.5	3.6	3.4	3.1	2.7	4.2
0330	4.7	4.7	3.7	4.7	2.7	3.8	3.4	3.2	3.3	3.3	2.5	4.2
0430	4.5	4.8	3.6	4.6	2.8	4.0	3.2	3.0	3.0	3.1	2.3	4.3
0530	4.5	4.6	3.5	4.4	3.0	3.7	3.2	2.9	3.0	2.7	2.4	4.2
0630	4.2	4.7	3.6	4.0	2.8	3.5	3.2	3.0	3.0	2.5	2.3	4.0
0730	4.8	4.9	4.2	5.1	3.4	3.5	4.0	3.5	3.3	2.8	2.8	4.1
0830	5.8	6.3	5.2	6.0	4.2	4.2	4.6	4.2	4.2	3.6	3.8	4.9
0930	6.9	6.9	6.1	7.0	4.6	4.0	4.3	4.0	4.3	4.3	4.2	5.5
1030	7.3	7.1	6.1	7.4	4.5	3.8	3.8	4.1	4.1	4.5	3.9	5.5
1130	7.0	7.1	5.4	6.8	4.3	3.9	3.5	3.9	3.9	4.5	3.6	5.1
1230	6.6	6.8	4.8	6.4	4.0	3.8	3.3	3.5	3.5	3.9	3.2	4.6
1330	6.0	6.8	4.6	6.0	3.6	3.9	3.0	3.5	3.4	3.5	3.1	4.5
1430	5.8	6.7	4.5	5.8	3.5	3.7	2.9	3.4	3.2	3.1	3.0	4.5
1530	5.8	6.4	4.4	5.6	3.5	3.9	2.7	3.4	2.8	3.0	2.8	4.6
1630	6.3	6.3	4.4	4.9	2.9	3.6	2.3	2.8	3.4	2.8	2.6	4.4
1730	5.4	5.8	3.8	3.9	2.5	3.2	1.8	2.3	3.1	2.5	2.0	3.8
1830	4.6	4.5	3.1	3.1	2.0	2.6	1.7	1.8	2.9	2.6	1.7	3.5
1930	4.4	4.5	3.3	3.2	2.0	2.5	1.9	1.7	3.3	2.5	1.8	3.5
2030	4.7	4.2	3.5	3.6	1.9	2.6	2.8	2.3	3.2	2.4	2.0	3.6
2130	4.7	4.2	3.6	3.9	2.9	3.0	2.8	2.9	3.3	2.5	2.2	3.7
2230	4.8	4.2	3.5	3.9	2.8	3.8	2.9	3.5	3.0	2.6	2.3	3.9
2330	4.8	4.2	3.6	3.9	2.7	4.1	2.9	4.1	2.6	2.7	2.5	4.1

A3 Khartoum wind direction 1983

L.TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0030	333	332	332	326	321	193	212	225	253	332	351	355
0130	332	332	334	329	338	195	199	218	251	224	352	355
0230	333	332	333	326	335	217	204	219	254	332	355	357
0330	337	330	336	329	333	215	201	223	233	336	355	360
0430	338	335	339	334	340	214	203	230	217	335	357	002
0530	337	336	342	338	336	211	204	233	222	339	358	003
0630	339	344	345	341	343	202	207	225	226	335	360	009
0730	340	350	352	353	004	205	214	233	239	336	005	014
0830	354	004	004	006	015	224	218	242	257	358	016	028
0930	004	019	013	011	023	241	238	255	278	025	023	034
1030	004	021	018	009	028	243	238	256	283	033	033	040
1130	002	019	013	360	025	248	243	260	282	032	032	041
1230	355	016	004	347	015	265	246	263	286	030	016	038
1330	351	015	352	337	341	285	244	263	300	022	002	031
1430	349	356	349	329	333	294	252	262	301	357	359	022
1530	347	349	344	327	332	304	253	264	294	349	357	012
1630	347	348	342	329	328	296	242	266	327	349	356	011
1730	341	350	343	332	327	298	245	261	321	352	351	005
1830	335	344	339	329	316	291	217	233	250	347	345	003
1930	334	339	336	324	319	246	211	228	235	338	339	001
2030	333	336	332	322	310	218	195	216	241	333	336	360
2130	334	330	334	322	304	164	188	218	241	330	337	355
2230	333	331	332	326	304	187	203	220	235	331	342	353
2330	333	332	331	324	306	194	220	221	241	332	346	351

A4 Khartoum wind direction 1984

L.TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0030	337	345	354	001	232	276	257	252	197	353	333	335
0130	340	347	355	005	242	274	249	254	207	347	337	336
0230	340	350	356	007	245	275	246	263	231	356	340	340
0330	346	354	360	010	269	272	238	242	228	002	340	338
0430	346	353	001	008	282	265	230	255	236	006	342	342
0530	348	355	005	009	219	257	222	240	232	012	348	342
0630	348	001	008	015	157	254	221	236	210	010	351	345
0730	352	005	017	021	159	256	223	229	192	022	002	352
0830	006	019	027	033	141	268	235	238	197	035	014	006
0930	021	031	033	040	115	277	259	272	223	055	022	015
1030	033	035	038	043	115	288	271	281	222	058	024	021
1130	035	035	033	045	146	289	275	283	224	060	019	022
1230	030	029	028	034	116	288	279	290	244	050	009	014
1330	018	022	017	027	104	293	287	284	310	044	004	007
1430	001	016	009	017	064	299	300	301	353	022	356	001
1530	351	014	360	016	057	296	301	307	051	009	350	356
1630	359	011	356	011	019	297	308	311	006	004	348	347
1730	358	009	358	008	016	295	312	313	101	004	343	346
1830	354	358	356	002	015	298	277	318	154	011	336	342
1930	348	360	355	359	351	299	266	306	184	359	336	338
2030	346	355	355	355	355	295	249	266	193	352	331	338
2130	342	352	356	357	137	300	259	246	197	347	332	332
2230	340	349	356	359	185	304	250	259	224	350	332	335
2430	339	344	354	001	226	266	256	253	219	351	333	333

A5 Wad Madani potential wind speed (m/s) 1983

L.TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0030	4.1	3.2	2.4	2.1	3.3	5.2	4.3	3.8	2.3	/	2.6	3.1
0130	4.0	3.4	2.3	2.1	3.3	5.6	4.7	3.7	2.4	/	2.4	3.2
0230	3.8	3.1	2.4	2.2	3.1	5.2	4.5	3.3	2.3	/	2.4	3.1
0330	3.6	3.0	2.4	1.9	2.7	5.0	4.3	3.4	2.1	/	2.3	3.2
0430	3.5	3.0	2.2	1.8	2.6	4.2	4.0	3.1	2.0	/	2.1	3.4
0530	3.2	3.2	2.1	1.7	2.7	4.0	3.6	2.8	1.6	/	2.1	3.1
0630	3.2	3.0	2.1	1.8	2.9	3.6	3.7	2.9	1.5	/	2.0	3.0
0730	3.6	3.4	2.5	2.4	3.4	4.6	4.5	4.0	2.1	/	2.2	3.3
0830	5.1	4.5	3.6	3.3	4.3	5.4	5.6	5.0	3.4	/	3.2	4.2
0930	5.6	5.0	4.0	3.5	4.5	6.0	6.5	5.6	4.1	/	3.6	4.5
1030	5.4	5.2	3.9	3.3	4.6	5.9	6.6	5.8	3.8	/	3.5	4.6
1130	5.3	4.9	3.7	3.0	3.6	5.4	6.2	5.3	3.5	/	3.3	4.2
1230	4.9	4.5	3.3	3.0	3.3	5.2	5.4	5.1	3.2	/	3.0	3.9
1330	4.8	4.4	3.4	2.9	3.5	4.7	4.7	4.7	2.8	/	2.9	4.0
1430	4.7	4.4	3.4	2.8	3.3	4.2	4.3	4.5	2.3	/	3.1	3.9
1530	4.8	4.4	3.3	3.0	3.4	3.9	4.3	4.2	2.2	/	3.4	4.1
1630	5.0	4.3	3.3	2.9	3.4	3.6	3.7	3.5	1.8	/	3.4	3.9
1730,	4.5	3.9	3.0	2.5	3.3	3.7	3.9	3.4	1.2	/	2.4	3.1
1830	4.0	3.0	2.4	2.0	2.8	3.7	3.4	2.5	0.7	/	2.1	2.8
1930	4.0	3.0	2.2	1.9	3.0	3.9	2.7	2.6	1.1	/	2.2	2.9
2030	4.1	3.2	2.3	2.1	3.3	3.8	3.3	2.6	1.4	/	2.5	3.0
2130	3.9	3.3	2.3	2.1	3.3	3.4	3.3	3.1	1.8	/	2.5	2.9
2230	4.0	3.2	2.4	2.1	3.1	4.0	3.6	3.0	2.3	/	2.7	3.1
2330	4.2	3.3	2.4	2.1	3.2	4.8	3.6	3.6	2.2	/	2.6	3.0

A6 Wad Madani potential wind speed (m/s) 1984

L.TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0030	3.9	3.4	3.4	3.4	3.4	4.9	4.8	5.1	3.8	2.2	3.6	3.5
0130	3.9	3.8	3.4	3.5	3.4	4.8	5.1	4.6	3.5	2.4	3.7	3.6
0230	3.8	3.8	3.5	3.3	3.6	4.4	4.9	4.0	3.6	2.1	3.6	3.7
0330	3.6	3.9	3.3	3.0	3.1	4.3	4.9	3.3	3.5	2.2	3.4	3.6
0430	3.5	3.6	3.3	2.9	2.8	4.2	5.1	3.4	3.2	2.3	3.5	3.5
0530	3.3	3.3	3.2	2.7	2.8	4.3	4.7	3.6	3.6	2.1	3.2	3.3
0630	3.2	3.1	2.9	2.5	3.3	4.3	5.2	3.7	3.6	1.9	3.2	3.1
0730	3.4	3.5	3.5	3.0	4.2	6.3	6.3	4.9	4.7	2.3	3.7	3.6
0830	4.2	4.4	4.4	3.9	4.9	7.0	7.2	6.5	5.8	2.8	4.7	4.4
0930	5.0	4.8	4.9	4.5	5.3	7.1	7.3	6.9	5.8	3.0	4.9	4.9
1030	5.2	5.0	4.7	4.6	5.1	6.4	6.4	6.4	5.3	3.1	4.9	4.7
1130	5.0	5.1	4.4	4.4	4.6	6.0	6.0	5.8	4.7	3.1	4.4	4.5
1230	4.8	4.8	4.3	4.4	3.9	5.7	5.3	5.0	4.3	3.0	4.3	4.3
1330	4.8	4.7	4.4	4.3	3.7	5.6	5.1	4.6	3.9	2.8	4.4	4.4
1430	4.7	4.6	4.4	4.2	3.6	5.1	4.5	4.1	3.7	2.8	4.5	4.5
1530	4.8	4.7	4.8	4.3	3.4	4.9	4.2	3.7	3.2	3.1	4.4	4.4
1630	4.9	4.6	4.6	4.2	3.2	4.1	4.4	3.9	3.2	2.8	4.4	4.3
1730	4.3	4.0	4.2	4.0	3.2	4.1	3.7	3.7	3.1	2.5	3.5	3.6
1830	3.9	3.3	3.3	2.9	3.0	4.0	3.4	3.5	2.8	2.0	3.3	3.5
1930	4.1	3.3	3.4	2.8	3.1	3.0	3.1	3.4	2.9	2.0	3.4	3.6
2030	4.1	3.3	3.3	3.1	3.5	3.4	3.3	3.9	3.2	1.9	3.3	3.6
2130	4.0	3.4	3.3	3.1	3.5	4.2	3.4	3.9	3.0	2.1	3.5	3.5
2230	4.0	3.5	3.3	3.2	3.4	4.4	4.0	4.6	3.4	2.3	3.4	3.5
2330	4.0	3.5	3.5	3.2	3.6	4.8	4.7	5.0	3.6	2.3	3.6	3.7

A7 Wad Madani wind direction 1983

L.TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0030	008	029	038	345	330	195	181	193	199	///	345	008
0130	011	029	039	347	341	191	180	195	198	///	348	008
0230	017	032	041	352	348	200	182	200	204	///	348	012
0330	016	035	041	355	010	208	186	200	192	///	354	019
0430	016	038	043	358	020	206	190	196	179	///	001	018
0530	016	040	046	003	039	204	196	185	169	///	011	019
0630	020	043	051	008	097	203	191	182	183	///	010	019
0730	023	045	058	017	110	212	186	192	191	///	016	026
0830	034	051	060	025	099	231	195	201	203	///	028	035
0930	037	051	060	027	107	220	202	208	210	///	031	040
1030	036	050	060	022	118	221	214	218	229	///	038	035
1130	035	048	056	014	164	230	214	220	232	///	029	026
1230	029	042	045	355	265	233	215	222	238	///	018	009
1330	022	040	033	339	284	232	212	222	242	///	349	002
1430	014	032	032	333	298	234	216	222	246	///	332	353
1530	009	028	028	327	292	238	221	225	254	///	326	352
1630	005	025	028	325	314	238	217	226	253	///	325	348
1730	002	025	024	331	318	247	212	214	235	///	325	344
1830	358	020	023	334	293	221	199	198	215	///	327	341
1930	357	022	027	329	305	204	191	198	184	///	333	348
2030	004	021	031	332	291	222	190	192	170	///	334	350
2130	005	026	031	332	298	216	190	187	187	///	340	354
2230	009	030	033	334	302	195	187	186	190	///	342	358
2330	009	031	037	341	305	215	187	188	194	///	344	004

A8 Wad Madani wind direction 1984

L.TIME	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0030	353	001	003	025	315	287	237	216	163	248	319	340
0130	355	002	005	032	341	272	230	218	161	320	318	341
0230	356	006	010	037	021	293	213	217	162	328	324	347
0330	359	012	013	038	032	308	208	216	152	333	324	348
0430	360	016	016	041	039	288	209	208	143	334	327	347
0530	002	020	021	045	058	286	216	193	137	354	332	351
0630	007	023	023	046	077	295	218	200	140	346	333	355
0730	011	026	032	053	080	304	216	207	154	018	336	354
0830	023	035	039	061	090	318	227	221	162	033	345	011
0930	028	034	041	063	061	325	241	228	175	046	356	018
1030	025	035	038	053	023	318	254	239	186	018	352	023
1130	022	033	033	064	026	323	259	244	194	030	345	013
1230	022	027	012	022	042	306	262	248	193	349	333	355
1330	005	019	360	021	079	329	276	250	195	322	320	346
1430	001	010	353	014	085	349	275	249	218	307	320	338
1530	357	003	347	011	357	319	278	250	217	292	320	336
1630	351	359	347	017	308	323	279	248	215	293	313	334
1730	347	359	342	017	034	320	275	245	214	278	309	333
1830	345	353	344	020	003	284	239	239	187	278	308	332
1930	345	352	347	019	033	323	235	234	193	294	308	334
2030	348	356	347	018	029	304	232	228	164	306	310	337
2130	351	356	355	020	026	257	231	214	143	309	316	337
2230	352	357	358	021	022	271	234	211	146	315	316	336
2330	355	350	002	023	010	267	240	208	159	324	318	338

A9 Potential wind standard deviation for Khartoum and Wad Madani

Station	Standard deviation of the potential wind							
	Winter		Advancing Monsoon		Monsoon		Retreating Monsoon	
	day	night	day	night	day	night	day	night
Khartoum	1.8	1.3	1.8	2.0	1.9	2.2	1.1	1.7
Wad Madani	1.0	0.9	1.8	2.0	2.0	2.3	1.0	0.9

Appendix B

B1 Khartoum potential wind frequency distribution 1984

RANGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	000	000	013	020	077	017	061	074	067	057	049	007
1-2	002	006	063	041	155	065	163	122	122	119	192	098
2-3	028	051	151	082	186	167	206	169	101	277	228	149
3-4	123	111	137	125	111	191	121	166	216	131	141	110
4-5	206	164	153	127	057	094	068	077	069	065	060	085
5-6	168	107	107	094	128	065	107	056	066	064	046	027
6-7	084	092	094	065	022	020	014	028	025	024	012	110
7-8	055	084	024	077	024	018	022	018	024	021	006	055
8-9	050	042	011	024	017	009	014	019	014	003	003	019
9-10	022	027	003	009	002	002	001	003	004	000	000	001
10-11	005	012	001	014	001	001	003	000	004	000	000	003
11-12	000	000	000	004	000	000	002	000	002	000	000	000
12-13	000	000	000	000	000	000	000	000	002	000	000	000
13-14	000	000	000	004	001	000	000	000	000	000	000	000
14-15	000	000	000	000	000	000	000	000	000	000	000	000
15-16	000	000	000	000	000	000	000	000	000	000	000	000
16-17	000	000	000	000	001	000	000	000	000	000	000	000

B2 Khartoum potential wind frequency distribution 1983

RANGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	000	004	004	019	099	031	073	029	071	021	000	000
1-2	005	012	058	087	254	139	094	078	189	045	020	003
2-3	030	092	159	131	185	125	121	151	191	090	100	087
3-4	108	135	186	137	107	133	158	171	120	177	246	174
4-5	158	119	093	133	030	098	059	103	047	186	124	147
5-6	164	120	072	115	025	078	088	137	035	094	150	136
6-7	137	090	086	056	006	039	032	036	012	064	051	095
7-8	114	078	060	027	009	038	037	015	012	045	018	072
8-9	017	016	019	007	001	011	056	003	009	017	004	019
9-10	006	005	004	008	001	007	012	002	003	001	000	008
10-11	005	001	000	000	001	009	006	001	006	001	000	003
11-12	000	000	002	000	000	005	003	000	000	000	000	000
12-13	000	000	000	000	000	001	001	000	001	000	000	000
13-14	000	000	000	000	000	003	003	000	000	000	000	000
14-15	000	000	000	000	000	000	000	000	000	000	000	000
15-16	000	000	000	000	000	001	000	000	000	000	000	000
16-17	000	000	000	000	000	001	000	000	000	000	000	000
17-18	000	000	000	000	000	000	001	000	000	000	000	000
18-19	000	000	000	000	000	000	000	000	000	000	000	000
19-20	000	000	000	000	000	001	000	000	000	000	000	000

B3 Wad Madani potential wind frequency distribution 1983

RANGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	000	001	016	072	064	043	050	036	219	///	026	007
1-2	002	037	155	204	118	088	091	067	174	///	146	066
2-3	077	133	296	233	209	130	106	168	071	///	203	179
3-4	259	261	178	149	145	119	130	164	064	///	054	276
4-5	202	146	070	050	082	076	095	116	041	///	005	140
5-6	130	064	018	011	027	065	076	098	015	///	000	056
6-7	066	026	011	001	032	062	078	048	010	///	000	016
7-8	005	002	000	000	032	052	055	026	060	///	000	004
8-9	000	000	000	000	013	028	036	013	000	///	000	000
9-10	000	001	000	000	009	015	014	001	001	///	000	000
10-11	000	000	000	000	005	009	008	002	000	///	000	000
11-12	000	000	000	000	000	009	001	000	000	///	000	000
12-13	000	000	000	000	000	007	002	000	000	///	000	000
13-14	000	000	000	000	000	004	001	000	000	///	000	000
14-15	000	000	000	000	000	005	000	000	000	///	000	000
15-16	000	000	000	000	000	002	000	000	000	///	000	000
16-17	000	000	000	000	000	000	000	000	000	///	000	000
17-18	000	000	000	000	000	001	000	000	000	///	000	000
18-19	000	000	000	000	000	000	000	000	000	///	000	000
NR	003	001	000	000	008	005	001	005	001	///	000	000

B4 Wad Madani potential wind frequancy distribution 1984

RANGE	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
0-1	000	001	007	003	070	049	017	013	070	072	000	000
1-2	011	022	032	053	104	081	077	074	077	163	016	014
2-3	104	111	179	211	183	102	102	140	184	310	151	134
3-4	257	265	265	231	144	087	115	144	121	153	255	243
4-5	201	084	120	125	071	087	109	106	064	028	169	249
5-6	047	045	064	051	062	060	066	071	073	016	114	094
6-7	016	006	059	042	032	063	111	074	046	020	012	006
7-8	001	000	015	003	027	080	068	062	038	000	003	003
8-9	000	000	002	001	030	044	048	040	016	000	000	001
9-10	000	000	000	000	011	034	013	012	008	000	000	000
10-11	000	000	000	000	004	020	006	003	007	000	000	000
11-12	000	000	000	000	001	040	001	003	005	000	000	000
12-13	000	000	000	000	001	080	000	001	004	000	000	000
13-14	000	000	000	000	002	000	000	000	001	000	000	000
14-15	000	000	000	000	001	001	000	000	000	000	000	000
15-16	000	000	000	000	000	000	000	000	000	000	000	000
NR	001	000	000	000	001	000	000	001	006	000	000	000

ACKNOWLEDGEMENT

The author is profoundly indebted to the staff members of the meteorological office in Khartoum and the meteorological staff of Shambat, Atbara, Wad Madani stations for their assistance in the data collection and further necessary information. I also thank Prof. Dr. J. Wieringa for revising the text. I wish to express my gratitude to the WMO and Khartoum Meteorological Department for giving permission to use all needed data and information. The research program is supported by the Netherlands Foundation for the Advancement of Tropical Research (WOTRO) with financial aid from the Netherlands Organization for the Advancement of Pure Research (ZWO).

REFERENCES

[1] G. Vossers, P.T. Smulders (1985): "Proposal to develop a methodology to evaluate the wind potential in tropical regions", Report R 772 D, Wind Energy Group, Laboratory of Fluid Dynamics and Heat Transfer, Physics Department, University of Eindhoven, Netherlands.

[2] K.M. Barbour (1961): "The Republic of the Sudan Regional Geography", University of London Press.

[3] E.H. ABu Bakr (1986): "Preliminary survey of the Sudan wind regime", Report R 778 D, Wind Energy Group Laboratory of Fluid Dynamics and Heat Transfer, Physics Department, University of Eindhoven, Netherlands.

[4] Y.P.R. Bhalotra (1963): "Meteorology of Sudan", Memoir no 6, Sudan Meteorological Service.

[5] Y.P.R. Bhalotra (1964): "Wind energy for windmills in Sudan", Momoir no 7, Sudan Meteorological Service.

[6] J. Wieringa (1986): "Roughness dependent geographical interpolation of surface wind speed averages", Quart. J. Roy. Meteor. Soc., 112, 867-889.

[7] E.H. ABu Bakr (1982): "Study of cylindrical parabolic concentrator", B.Sc. Thesis, University of Khartoum, Sudan.

[8] E.H. ABu Bakr, M. Rutten, P.T. Smulders, G. Vossers, J. Wieringa (1986): "A method to obtain a model for the boundary layer in a representative tropical region". Proc. European Wind Energy Conf. (Rome 1986) Vol. 1, 213-218.

[9] M.J.M. Stevens, P.T. Smulders (1979): "The estimation of the parameters of the Weibull wind speed distribution for wind energy utilization purposes", Wind Engineering, 3, 132-145.

[10] Yahia H. Hamid, W.A.M. Jansen (1980): "Wind energy in Sudan", CWD Report, Amersfoort, the Netherlands.

[11] M. van Noordwijk (1984): "Ecology textbook for Sudan", Khartoum University Press.