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A METHOD TO OBTAIN A WINO MODEL FOR THE BOUNDARY LAYER
IN A REPRESENTATIVE TROPICAL REGION

E.H. ABU BAKR, M. RUTTEN, P.T. SMULDER, G. VOSSEERS, J. WIERINGA

SUMMARY
A discussion is given of the construction of a reference database, which can be used for developing a boundary layer model for tropical regions. The representative region selected for the investigation is an area of 20,000 sq.km around Khartoum (Sudan). The assembled surface wind data are corrected for exposure, and their reliability is checked. It is shown that due to the seasonal influence of the Inter-tropical-Convergence-zone any full-year representation of wind frequency distribution is misleading and that seasonal analysis is required. The average wind profile to 2 km height shows a jet-like appearance, which invalidates the use of simple relations between large-scale free atmospheric wind and surface wind climate. It is shown that for the winter season an Ekman wind profile with thermal wind modification might prove useful.

1. INTRODUCTION
Reliable assessment of wind energy potential in countries without a sufficient number of meteorological stations is an outstanding problem. One solution for this problem is the development of some model to interpolate horizontally between the few available stations with surface wind and/or upper wind data. Such models have been developed in the last decade for temperate-latitude countries, Denmark and the Netherlands in particular. However, these models are based on geostrophic similarity principles, assuming reasonably high Coriolis forces, while in the tropics such forces are much smaller.

Additionally in the tropics the air flow is dominated by other mechanisms, such as the large diurnal course, or monsoons. Consequently, the analysis of the boundary layer in the tropics cannot follow quite the same pattern as temperate-latitude models.

In 1985 Eindhoven University (The Netherlands) started a research programme to develop a methodology for evaluating the wind potential in tropical regions; the Khartoum region in Sudan was taken as a test case [1]. 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.

In this article the climatological and geographical wind characteristics of the Khartoum region will be described and a preliminary analysis of the surface and upper air data is presented.

2. THE CLIMATOLOGICAL AND GEOGRAPHICAL WIND CHARACTERISTICS OF KHARTOUM SURROUNDINGS (CENTRAL SUDAN)
Sudan is a very large country (about 2.5 x 10^6 km^2) with the broad Nile valley across the middle and on this borders some hills and mountains on the east near the Red Sea coast, on the south near the border with Kenya and Uganda and in the west near the border with Chad, see fig.

1. The relief of the Khartoum surroundings is relatively flat (dz/dx = 5 x 10^-3) over 10^6 km^2 around Khartoum.

The climate in this region is semi-desert. Physically, it is strongly dependent on the Inter-Tropical-Convergence-Zone (I.T.C.Z.) the high pressure belts and the low pressure belts [2]. The wind regime in Sudan is controlled by these pressure belts. In Central Sudan there are four seasons:

a. The winter season (Dec.-Feb.) where the I.T.C.Z. is far south (+ 5° N)
b. The advancing monsoon (March-May); at the end of this season the I.T.C.Z. passes over the Khartoum region towards the North.
c. Monsoon (June-Sept.); at the end of this season the I.T.C.Z. passes over the Khartoum region southwards.
d. Retreating monsoon (Oct.-Nov.) where the I.T.C.Z. is south of Khartoum region. Sandstorms "haboobs" are encountered during the whole year. Their occurrence with gusts exceeding 30 m/s [2], should be taken into account for wind turbine risk analysis.

A comparison between the monthly averaged data (1984) from Khartoum airport data and Shambat agrometeorological data (Shambat is about 8 km north of Khartoum) is shown in fig. 2. Objective terrain corrections have been made for the two sets of data. It is clear from the figure that the data are reliable (with correlation coefficient \( r = 0.84 \)), and they are in good agreement on the average. Wind data of this level of accuracy are quite useful material, both for wind energy potential estimates and for model development. Using them is more economical than to put in a new network of measuring equipment to estimate the wind potential.

![Fig. 1 Relief map of the Sudan](image)

**Fig. 1** Relief map of the Sudan (From the Sudan Survey Topography)  
- 2000m,  
- 1500,  
- 1000,  
- 500,  
- 0

**Fig. 2** Comparison of monthly averages of the wind potential data from Khartoum and Shambat (Shambat is about 9 km North of Khartoum)  
- \( U_{\text{Khartoum}} = 0.7 \text{ m/s} = 1.00 \pm 0.17 \text{ U_{Shambat}} \)  
- Correlation coefficient \( r = 0.84 \)

4. DATA ANALYSIS

4.1 Frequency distribution

Frequency distributions for the Khartoum data (1983,84) were plotted on cumulative Weibull paper and the average distribution shape parameter \( K \) was obtained by linear averaging [6]. A \( K \)-value in the range 3-4 is obtained for November, December, January and February which is due to the constant north trade wind. May, June, July and September give a \( K \)-value below 2 which is due to large wind variations. The other months give a \( K \)-value in the range 2-3.

Fig. 3 shows the large variation of the distribution between the seasons. Obviously for wind energy application it is advisable not to restrict analysis to the annual distribution. The application of wind energy will be more efficient in the winter than in other seasons. Fortunately, in the winter the demand for water pumping is very high for winter crop irrigation.

5. DATA REPRESENTATION

To obtain sufficiently detailed information about the wind regime in Khartoum region hourly wind data are needed. Hourly meteorological data from Khartoum airport (381m. a.s.l.) and Wad-Medani station (which is about 180 km south of Khartoum) for two years (1983,84) were compiled in a Burroughs Computer. The data have been corrected for writing and systematic errors by comparison between the two sets of data. Obviously erroneous data were removed and compiled as not-recorded. Also we used data from nearby stations (where few hours of wind observations are recorded) to check the quality of the data (e.g. Wadi Sainde and Shambat).

From the roughness characteristics of the surrounding terrain of each station [4], using the Davenport terrain-classification, the data were further corrected for the roughness. The potential wind speed is calculated for each set of data by the help of the exposure formulas [5]. Also the standard deviation for the wind speed is calculated. The data are represented in monthly matrix tabulations (hours versus wind).

![Data representation](image)
Fig. 3 Percentage frequency distribution of potential wind speed at Khartoum for data of 1983 and 1984 combined.

--- Annual distribution.
   The Weibull distribution shape factor (K) = 1.75
   --- January distribution. K = 3.2
   --- May distribution. K = 1.5

4.2 Diurnal course and stability

The day-to-day variations present in the data are averaged out by taking the average of the hourly data for every month. The hourly average is presented graphically as diurnal plots. Fig. 4 is an example of the diurnal course of the wind speed.

The ratio \( v_0/U \) in which \( U \) is the monthly average for each hour of the day (\( v_0 \) is the wind speed at 10 m) was calculated for (1984,83) Khartoum airport and Mad-Madani data. While fig. 4 shows the steadiness of the winter regime (small wind speed deviation bars), very large \( v_0/U \) ratios were found for the May and September speed data (\( \sim 60\% \)). Moreover the diurnal wind direction course for these months shows large variations. This can be explained by two 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 in September southwards.

We conclude that the data of these two months are difficult material for basic physical modelling because of their large variations. However, it can be used to indicate the passage of the I.T.C.Z.

The diurnal wind course shows a remarkable unstable character during the daytime (see fig. 4) which originates from the high sensible heat flux received. The sensible heat flux \( (H) \) is:

\[
H = Q - S - L
\]

where \( Q \) is the net radiant flux density, \( L \) the latent heat of evaporation and \( S \) represents the soil heat flux. The latent heat of evaporation in Khartoum is so low that it can be neglected. For a land surface \( S \) is small in comparison with \( Q \). A good estimation for \( S \) is \( S = 0.1 Q \) which implies:

\[
H = 0.9 Q
\]

From the hourly values of \( Q \) averaged over 10 years obtained from reference (1), it follows that for example the noontime January values of \( H \) are about 600 W/m².

Fig. 4 shows a large difference between the day and night wind speeds. This results from a 15°C temperature difference between the day and night which is a characteristic of semi-desert regions.

A more complete physical-meteorological analysis of the stability should be based on values of the Monin-Obukhov length \( (L) \) and related parameters, e.g. the frictional velocity \( \left( U^* \right) \) (9). They can be calculated from the available station data of surface wind, roughness length, temperature data and sky cover. These calculations are executed by an iteration process using the energy balance equation, and the Businger-Over equations (7).

4.3 Radiosonde profile behaviour

In our investigation we also analysed the 11.15 G.M.T. upper air data (pressure, temperature, wind and humidity) of 1983 and 1984 from Khartoum airport (surface elevation 381m. a.s.l.). The monthly average data were plotted as vertical profiles see fig. 5. The relative humidity is not plotted; it is very low (less than 50%) and not directly relevant to our argument here.
From the vertical profiles the upper limit of the planetary Boundary Layer (PBL) was determined. It is characterised by increase in potential temperature (the potential temperature is constant in the convective layer i.e. below the upper limit of the PBL) and a clear change in the wind direction. For example, from the 1985 data in the winter and the advancing monsoon season the upper limit of the PBL is observed around 850 mb (see e.g. Fig 5), whereas in the monsoon and retreating monsoon the upper limit seems to be above 800 mb. Throughout the year except in May, June, September and October, these daily wind profiles show a jet-like structure around 900 mb which gives the profile a very special shape, different from the inland wind profiles usually observed elsewhere.

Recently similar profiles have been observed in the Arabian Sea [11] and were explained as an influence of the Somalia-jet. However, this explanation is not valid at the north west side of the Ethiopian highland. We rather suppose that the jet-like structure observed in Khartoum could be the result of thermal convection and thermal wind, resulting from the magnitude of the horizontal temperature gradient, which around Khartoum is about 0.7°C/100 km. Thermal wind variation of the free atmosphere wind profile might account for the strong variation with height of the wind speed in the lower Kilometer. This might partly explain the phenomenon i.e. from the surface to the maximum wind speed level.

The decrease of wind speed above 1 km cannot be explained by one radiosonde and surface wind data. Quantitative comparisons of upper-air flow above 1 km over a large region is required and for the purpose of such analysis more data from Sudanese radiosonde stations are planned to be investigated.

Using the usual free atmospheric wind equation [103] we can write:

\[
\frac{dU_y(z)}{dz} = -g \left( \frac{R T_f - T}{CP \theta} \right)
\]

where \( U_y \) is the horizontal free wind component and \( f \) is the coriolis parameter \((0.3\times 10^{-4} \text{ s}^{-1} \text{ for Khartoum})\). \( R, C_P \) are standard physical constants. Using these temperature and pressure data (from the Khartoum region) corrected to a standard height the \( \frac{dT}{dy} \) and \( \frac{1}{T} \) were calculated for different periods in the day. Substituting the obtained values in equation (3), it was found that the third term is about 15 times the second term. Therefore as a first approximation we neglect the second term. The vector form of equation (3) is:

\[
\frac{dU_y(z)}{dz} = -g \nabla \cdot \mathbf{T}
\]

Integrating (4) we obtain

\[
U_y(z) = U_y(0) + \int_0^z \nabla \cdot \mathbf{T} \text{ d}z
\]

where \( U_y(0) \) is the free atmospheric wind at z=0 and \( U_y(0) \) is the thermal wind. Using the values of \( U_y(z=15) \) (where \( h \) is the height of the PBL) from the measured upper air data and calculating \( U_y(0) \) using the surface isotherm chart (considered to be representative for the entire depth of the PBL), we can then calculate \( U_y(z) \) using equation (5).

A relation between the upper \( U_y(0) \) and the surface measured wind speed \( U_y \) at 15 m is required. Such a relation can be formulated by:

\[
U_y = f(z, \theta, 1) \ U_y(0)
\]

The elaboration of this equation is presently being investigated.

Our purpose is to calculate \( U_y(z) \) for 100 m/s using equation (5). The working assumption is that the layer is well-mixed between the surface and \( h \) (at typically 1 km height). In the Khartoum case this assumption of strong convective mixing is quite acceptable in daytime. The diffusion coefficient in such a very unstable tropical boundary layer should be approximately constant. A reasonable description for such a case could be the classical Ekman boundary layer (BL) solution (which is based on constant diffusion coefficient over the whole boundary layer) corrected for thermal wind effects. This model can be achieved by substituting the values of \( U_y(z) \) for 100 m/s, in the Ekman BL solution:

\[
U(z) = U_y(z) (1 - e^{-\gamma z^2})
\]

\[
V(z) = U_y(z) (e^{-\gamma z^2} \sin \theta z)
\]

where \( \gamma = (f/2 K_h) \frac{1}{z} \)

\( K_h \) is the eddy momentum coefficient.
In case of a profile at the latitude of Khartoum, $U_m = 10\text{m/s}$ is a typical value for tropical convective layers (12). With this value the steep wind profile between the surface and 1 km height in fig. 5 might be reasonably well described. Checking the accuracy of such methodology needs more upper wind speed data than available in the Khartoum profile. Such detailed information is under investigation.

5. CONCLUSION

Too often, the Meteorological data from some country are considered to be unreliable without proper checks. In the case of Sudan the wind data from the Khartoum Meteorological office were investigated, corrected for exposure, and the results were found to be of sufficient quality for wind energy analysis. It is concluded that such an approach may often be more economical than measuring a new set of wind data for estimating the wind potential.

From the frequency distribution plots (fig. 3) one observes, that the monthly distribution are much more important than the annual distribution in considering wind energy application for the Sudan. For a reason the monsoon season is recommended for wind energy application:

a. The high wind speeds and the large K-value (between 3 and 4).

b. The high demand of water pumping for winter crop irrigation in the Sudan.

The surface wind data for Khartoum region shows that the I.T.C.Z. plays a major role in classifying the seasons and consequently the variation in the wind regime.

The diurnal wind course shows a noticeable unstable character (see fig. 4) which is due to the large sensible heat flux received. Also a large difference between the day and night wind speeds results from the temperature difference between the day and night (about $15^\circ\text{C}$).

The upper-air data (at noontime) shows a remarkable jet-like structure in most months. This jet-like structure is assumed to be related to the thermal wind. A description for such profile is found to be a classical Ekman RL solution corrected for thermal wind effects.

The main conclusion is that it is definitely not possible to relate Sudanese surface wind ($U$) data to the free atmosphere wind ($U_m$) data in a simple fashion. Complete modelling of the relation of $U$ and $U_m$ requires additional data and investigation. Further detailed results of this research will be submitted for publication in an appropriate journal.

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