International Journal of Engineering Sciences & Research Technology

(A Peer Reviewed Online Journal)
Impact Factor: 5.164

IJESRT

IJESRT
INTERNATIONAL JOURNAL OF ENGINEERING SCIENCES & RESEARCH TECHNOLOGY

DETERMINING VERTICAL WIND SPEED PROFILE IN THE ATMOSPHERIC LIMIT LAYER ON THE OUAHIGOUYA SITE IN BURKINA FASO

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DOI: https://doi.org/10.29121/ijesrt.v10.i1.2021.9

ABSTRACT

The properties of the vertical profile of the wind speed on a monthly and annual scale at the Ouahigouya site belonging to the Sahelian climatic zone in Burkina Faso were explored in this study. To do this, wind speed and temperature data at 10 m above ground and NASA satellite data at an altitude of 50 m in the atmospheric boundary layer were used over a period of ten years. From the theory of Monin-Obukhov, the logarithmic law and the power law made it possible to develop the variation of wind speed with altitude taking into account the conditions of atmospheric stability. According to statistical performance indicators, it has been observed that the vertical profile of the wind speed adjusted according to the power law and the log-linear law corresponds to the measurements. Regarding the state of stability of the atmosphere, we note that it is generally unstable from 10:00 a.m. to 6:00 p.m. and stable during other times of the day. The annual average wind shear coefficients during the convective and night time diurnal cycle are evaluated at 0.67 and 0.7, respectively. From the power law, the values of the shear coefficients, the average vertical profile on a monthly and annual scale of the wind was obtained by extrapolation of the wind data measured at 10 m from the ground. This study is the first of its kind in this area. To assess the wind resource available on the Ouahigouya site, investors can directly use the vertical wind profile based on the power law for an altitude between 10 and 50 m.

KEYWORDS: wind potential, vertical profile, Monin-Obukhov, shear coefficient.

1. INTRODUCTION

Energy is core important for the development of all human activity today. With galloping population growth, massive industrialization, access to energy has become a major challenge. Added to this is the progressive depletion of the deposit of traditional energy resources and their impact on the environment. In the major concern to reconcile development strategies of the energy sector and environmental protection for sustainable development, the share of renewable energies in the global energy mix has steadily increased [1]. Among the renewable energy sources, wind power has positioned itself as being the most visible in recent years because of its safety with regard to the environment as well as its inexhaustible nature [2]. Meanwhile, work carried out by the African Development Bank clearly indicates that in sub-Saharan African countries and particularly in Burkina Faso, many significant barriers prevent the integration and development of this energy source [3]. One of the brakes is the lack of wind data at altitudes that would be of energy interest. Indeed, the wind potential available at the hub of a turbine (over 10 m) is most often known through the erection of huge towers or even through the use of more expensive systems to perform the measurements. These potential assessment instruments therefore increase the cost of wind projects, often making them economically unsustainable [4].

ISSN: 2277-9655
Impact Factor: 5.164
CODEN: IJESS7

To remove these obstacles, the researchers turned to the extrapolation of the wind speed measured on sites already available, from a standard measurement height (10 m altitude) to another height of energy interest. (Turbine hub level) based on empirical models valid only in the surface layer [5], [6]. The empirical formulas of the power law and the logarithmic law developed by many authors such as [7], [8], [9], [10], [11], [12], [13] are cases specific for a given site. However, the reliability tests of these models on other sites carried out by the authors of [4], [14] have revealed mixed results. The authors therefore suggest the development of a specific model for each site. At our study site, wind data at the height of the hub of a wind turbine is unavailable, except for NASA satellite data [15] averaged over a day at 50 m altitude. In addition, previous work on the estimation of the wind resource at the study site by the authors of [16], has been limited to the altitude of 10 m where data is measured every three hours. To cope with the wind data deficit concerning the site of Ouahigouya at a height above 10 m, satellite data from NASA at 50 m and data from the Burkina National Meteorological Agency (ANAM) at 10 m of altitude were used to develop on this site the best equations for adjusting the wind speed at altitude starting from the power law and the logarithmic law. The vertical wind speed profile adjustment settings contained in these models were determined. The model best suited to the site was used to generate by extrapolation the vertical profile of the wind speed from the data measured at 10 m above the ground.

2. PRESENTATION OF THE STUDY SITE AND THE DATA USED.

With an area of 274,200 km2, Burkina Faso is a state located in West Africa between the parallels 9 ° 20 'and 15 ° 05' north latitude and the meridians 2 ° 20 'east longitude and 5 ° 30 'West longitude at an average altitude of 300 m above sea level. With no access to the sea, it is limited by six (06) other countries: Mali to the west and to the north, Niger to the east, and to the south by Benin, Togo, Ghana and the Ivory Coast. We distinguish three climatic zones based on rainfall and temperature. This is the Sahelian climatic zone located north of the 14th parallel with an annual rainfall of less than 650mm. The Sudano-Sahelian climatic zone located between the parallels 11 ° 30 and 14 ° North latitude with annual rainfalls of between 650 and 1000 mm. The Sudanese climatic zone south of 11 ° 30 'North latitude characterized by annual rainfalls greater than 1000 mm [17]. Our work was carried out on the Ouahigouya site (Sahelian climatic zone). The data used are provided by the meteorological station of the National Meteorological Agency of Burkina Faso (ANAM) for the period from January 2006 to December 2016. The data series used consist of wind speeds and temperature. Daily wind speed data recorded at 50 m from the ground and provided by the NASA Prediction of Worldwide Energy Resource [15] during the same measurement period were used. Figure 1 shows the geographic location of the study site.

Figure 1: Geographic location of the study site

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3. METHOD

3.1. Vertical wind speed extrapolation method

Two methods of extrapolating the wind speed are commonly adopted and take into account the roughness of the terrain and conditions of atmospheric stability [18], [19]. This is the log-linear law based on the similarity model and the power law [10], [11], [13] that were evaluated on our study site.

3.1.1-Log-linear Law

This law takes into account the friction speed, the roughness length and Monin-obukhov length. It is defined by the following expression [19]:

$$v(z)=\left(\frac{u_*}{\kappa}\right)\left[\ln\left(\frac{z}{z_0}\right)-\psi\left(\frac{z}{L}\right)\right] \quad \textbf{(1)}$$

Where L is the Monin-Obukhov length, z_0 the roughness length, u_* the friction speed in m/s, $\psi(z/L)$ is the stability correction function, and κ the Von Karman constant assumed to be 0.4 and z the height of the anemometer against the ground level. The expression of the stability correction function is given by Paulson **[20]**. Under unstable atmospheric conditions, $(z/L<0)$ the expression of $\psi(z/L)$ is given by the equation (2).

$$\psi_m(Z/L)=2\ln\left(\frac{1+x}{2}\right)+\ln\left(\frac{1+x^2}{2}\right)-2\,Arc\tan(x)+\frac{\pi}{2} \quad \textbf{(2)}$$

With:

$$x=\left[1-\left(\frac{\gamma z}{L}\right)\right]^{1/4} \quad \textbf{(3)}$$

Under stable atmospheric conditions $(z/L>0)$ [20], the expression of $\psi(z/L)$ is given by the equation (4).

$$\psi_m(Z/L)=-5(Z/L) \quad \textbf{(4)}$$

The method used to determine the Monin-Obukhov length which characterizes the state of stability of the surface layer is based on the expression from the studies by Monin and Obukhov [19] and is given by the equation (5):

$$L=-=\frac{u_*{}^3T_0}{\kappa g\,\mathrm{cov}(w,T)} \quad \textbf{(5)}$$

Where $\mathrm{cov}(w,T)$ represents the covariance of the vertical wind component (w) and the ambient air temperature, g is gravity, T_0 the average temperature. Based on Cauchy-Schwarz inequality which is based on the mathematical properties of the covariance, we have determined $\mathrm{cov}(w,T)$. So we have [21]:

$$\left[\mathrm{cov}(w,T)\right]^2\le\sigma^2(w)\sigma^2(T) \quad \textbf{(6)}$$

Where $\sigma^2(T)$ is air temperature variance and $\sigma^2(w)$, the variance of the vertical wind component. According to[21], the standard deviation of the vertical wind component $\sigma(w)$ can be estimated from the parameter $\sigma(v)$ which is the standard deviation of the horizontal wind component:

$$\sigma(w)=0.45\sigma(v) \quad \textbf{(7)}$$

Where v is the horizontal wind speed recorded by the anemometer at 10 m from the ground. Results obtained using the equation (5) during day cycle were used to characterize the stable or unstable atmosphere conditions. Table 1 shows the various classes of atmospheric stability according to Obukhov length.

Table 1: Atmospheric stability class according to Monin-Obukhov length[21]

Stability class	Monin-Obukov length (m)
Very stable	$0 < L < 200$
Stable	$0 < L < 1000$
Neutral	$\left\|L\right\| > 1000$
Instable	$-200 < L < 0$
Very instable	$-1000 < L < -200$

The friction speed and the roughness length given by equations (8) and (9) respectively can be determined according to the various classes of the atmosphere stability by changing the variable and using the equation (1)[21]:

$$u^* = \kappa P \quad \textbf{(8)}$$

$$z_0 = \exp\left[-\left(\frac{H}{P} + \psi\left(\frac{z}{L}\right)\right)\right] \quad \textbf{(9)}$$

The equation (1) therefore becomes:

$$V_h = P\ln\left(z_h\right) + H \quad \textbf{(9)}$$

3.1.2- The Power Law

This law was proposed by **G. Hellman** and is based on experimentation. This method is easier to use in general for engineering studies[21] and therefore enables to address difficulties encountered in the use of the log-linear law in terms of input parameters [22],[23] ,[24]. Then, we have:

$$\frac{v_h}{v_1} = v_1\left(\frac{z_h}{z_1}\right)^{\alpha} \quad \textbf{(11)}$$

Where v_1 is wind speed at 10 m and α wind shear coefficient. It depends on the atmospheric stability and roughness [10] and provides information on the variations in wind intensity according to the altitude. With the equation (11), α can be determined by logarithms properties[21]:

$$\alpha = \frac{\ln\left(v_2\right) - \ln\left(v_1\right)}{\ln\left(z_2\right) - \ln\left(z_1\right)} \quad \textbf{(12)}$$

According to the studies by Huang (1979) [25] reported by [26], wind shear coefficient varies according to unstable and stable atmospheric conditions. It is expressed by equations (13) and (14), respectively

$$\alpha_{insta} = \frac{\left(1-16\left(Z/L\right)\right)^{-1/4}}{\ln\left(\left(\eta-1\right)\left(\eta_0+1\right)/\left(\eta+1\right)\left(\eta_0-1\right)\right) + 2Arc\tan\left(\eta_0\right)} \quad \textbf{(13)}$$

$$\eta = \left(1-16\left(Z/L\right)\right)^{1/4} \text{ et } \eta_0 = \left(1-16\left(Z_0/L\right)\right)^{1/4}$$

$$\alpha_{sta} = \frac{1+5\left(Z/L\right)}{\ln\left(Z/Z_0\right) + 5\left(Z/L\right)} \quad \textbf{(14)}$$

Based on the power and logarithmic laws, parameters α, P and H are determined by to a monthly and annual adjustment of data. With the values taken by these parameters, we therefore deduce the best wind speed adjustment equations at altitude through statistical error estimation tests.

3.1.3. The model validation test

Statistical tests of the square root of the mean square error (RMSE) and of the mean absolute value (MAE) were used to assess the errors made by the prediction. These indicators are the most used and the model is better when

ISSN: 2277-9655
Impact Factor: 5.164
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they are close to zero[21]. Using equations (15) and (16), we can assess the errors between the measured speeds and the estimated speeds [33],[21] :

$$RMSE = \left(\frac{1}{n} \sum_{i=1}^{n} (p_i - f_i) \right)^{1/2} \quad \textbf{(15)}$$

$$MAE = \frac{1}{n} \sum_{i=1}^{n} \left| (p_i - f_i) \right| \quad \textbf{(16)}$$

Where p_i represents the observations, f_i the various estimates or forecasts, and $n$the total number of wind speed observations.

4. RESULTS AND DISCUSSIONS

4.1 Vertical wind speed profile

Graphs in Figure 2 show the curves for adjusting the vertical profile of wind speed for a typical day on a monthly basis according to the power and logarithmic laws for the Ouahigouya site. The values of parameters A and B obtained after monthly adjustment are presented in Table 2. The adjustment coefficients (α, A, B) obtained varies from one month to another. The analysis of Figure 1 shows that the vertical profile of the wind speed adjusted by the power law and the logarithmic law corresponds to the measurements whatever the time of the year with a slight gap between both laws at altitudes between 20 m and 40 m. RMSE and MAE coefficients values obtained and summarized in Table 3 are low. These low values therefore lead us to validate these various adjustment equations based on the model of the power law and the logarithmic law as models for extrapolating the wind speed on the Ouahigouya site. These two laws can therefore be used to model the profile of the vertical wind speed on our study site as reported by the studies of [27],[21].

Table2: Parameters to adjust the log-linear law and the power law on the Ouahigouya site.

	J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**An.**
A	1.53	1.58	1.77	1.52	1.39	0.99	0.88	0.85	0.86	1.44	1.26	1.56	1.65
B	-1.19	-0.96	-1.54	-0.72	0.18	1.35	1.25	0.44	0.23	-1.28	-1.00	-1.39	-1.69
α	0.44	0.41	0.46	0.39	0.31	0.22	0.21	0.28	0.35	0.46	0.50	0.50	0.50
z_0	2.17	1.84	2.39	1.61	0.87	0.25	0.21	0.59	1.24	2.37	2.72	2.76	2.82
u_*	0.61	0.63	0.70	0.60	0.55	0.39	0.35	0.34	0.34	0.57	0.50	0.62	0.66

Figure 3 shows the annual adjustment curve for the vertical wind profile by applying both laws and the adjustment equations. The estimation errors (RMSE; MAE) on an annual basis between both laws and data measured are 8.10^{-16}; 1.10^{-16} and 9.10^{-16} ; 6.10^{-16}, respectively for the power and logarithmic laws. These low values show that both laws are also relevant for estimating the annual vertical wind profile on the study site.

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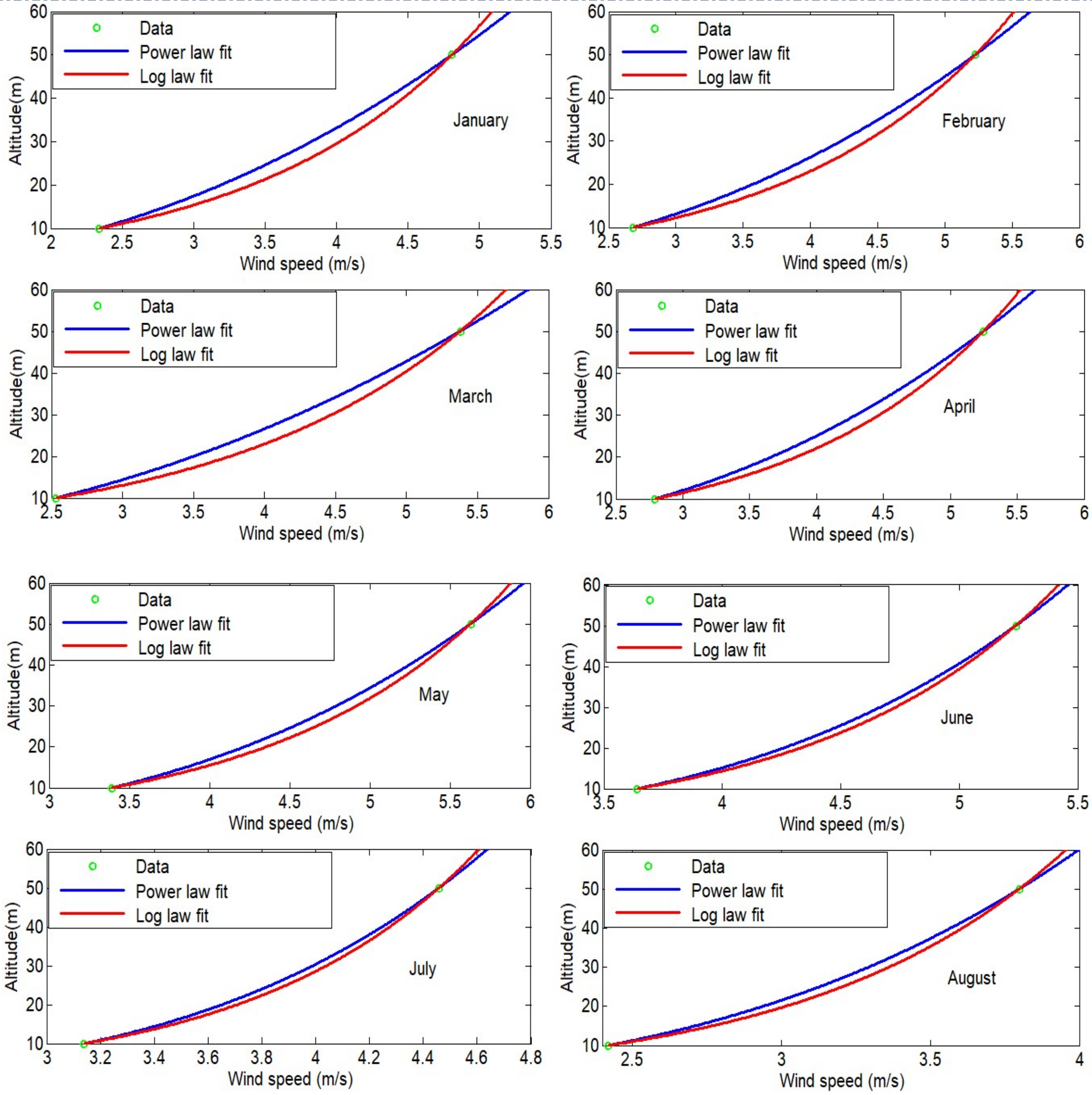

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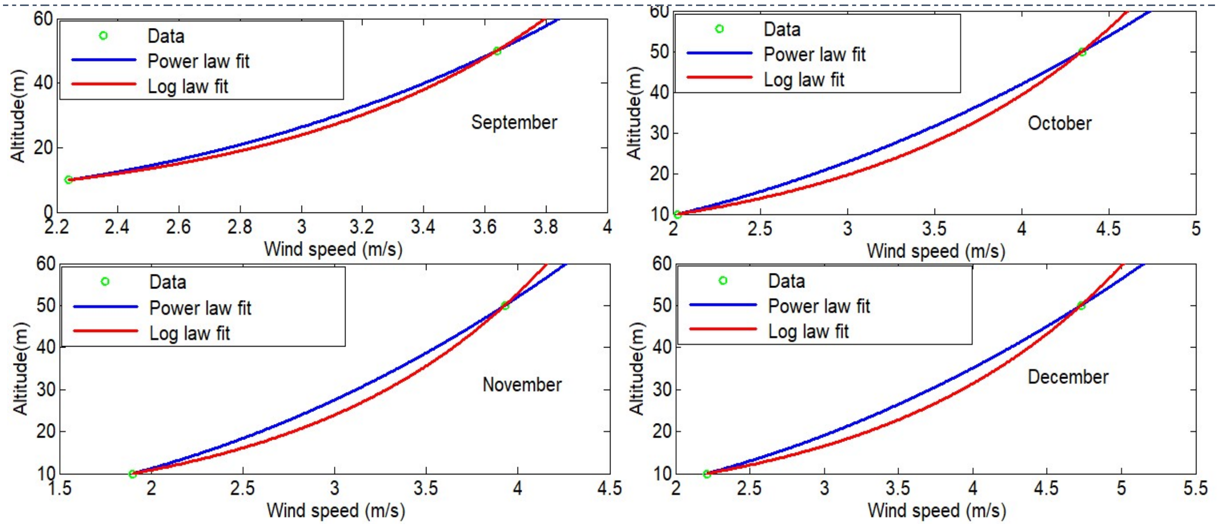

Figure 2: Adjustments of the vertical profile of wind speed on a monthly basis from January to December on the Ouahigouya site (2006-2016).

Table 3: The square root of the mean square error (RMSE) and the mean absolute error (MAE) for the various laws corresponding to the extrapolation range 10–50m (2006–2016).

	Power Law		Logarithmic Law	
	RMSE (10^{-12} m.s^{-1})	MAE (10^{-12} m.s^{-1})	RMSE (10^{-12} m.s^{-1})	MAE (10^{-12} m.s^{-1})
January	0.0001	0.0001	0.001	0.001
February	0.001	0.001	0.0001	0.0008
March	0.0006	0.0004	0.002	0.002
April	0.0006	0.0004	0.001	0.001
May	0.0007	0.0002	0.001	0.001
June	0.001	0.001	0.0006	0.0004
July	0.0003	0.0002	0.0006	0.0004
August	0.0004	0.0001	0.0006	0.0004
September	0.0006	0.0004	0.0007	0.0006
October	0.0008	0.0008	0.0009	0.0006
November	0.0007	0.0007	0.001	0.0009
December	0.001	0.001	0.001	0.001
Annual	0.0008	0.0001	0.0009	0.0006

ISSN: 2277-9655
Impact Factor: 5.164
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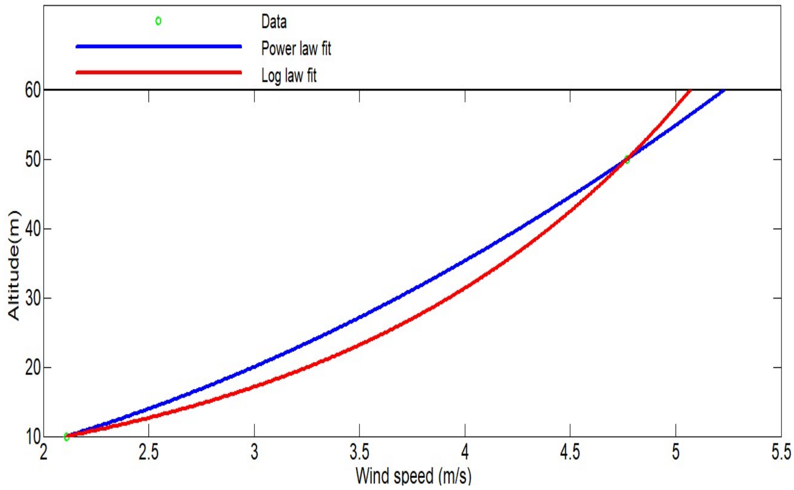
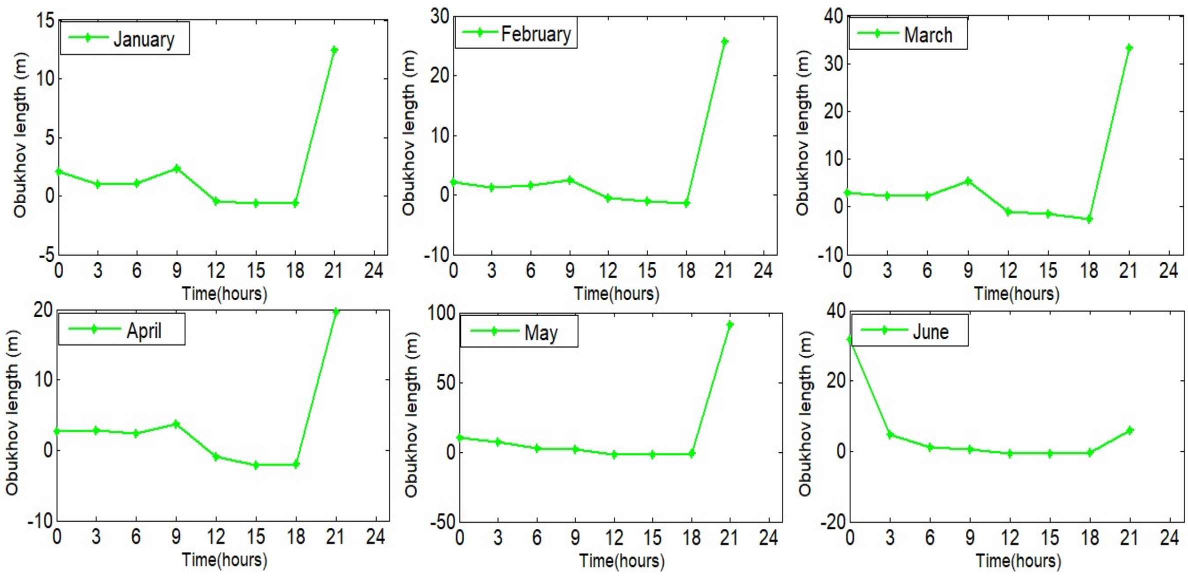


Figure 3: Adjustments of the vertical profile of wind speed on a monthly basis from January to December on the Ouahigouya site (2006-2016).

4.1.4 Vertical Profile of diurnal and nocturnal wind cycle

Figure 4 shows the variation in Obukhov length during its diurnal and nocturnal cycles. Obukhov length is determined by equation (5). Referring to Table 1, the analysis of graphs in this figure shows that from 10 a.m. to 6 p.m. atmosphere is generally unstable. For the other periods of the day, it is stable. These results are confirmed by a large number of studies such as those of [21] which show that the atmosphere is unstable during the day. Based on these observations, the average vertical profile of the wind of the diurnal cycle is between 10 a.m. and 6 p.m. and the average profile of the night cycle between 6 p.m. and 10 a.m. From the power law that requires fewer parameters (equations (11), (12)), wind shear coefficient and wind data recorded at 10 m from the ground, we can determine the profiles by extrapolation according to the atmospheric stability conditions. Table 4 summarizes the shear coefficients values according to the atmospheric stability conditions.



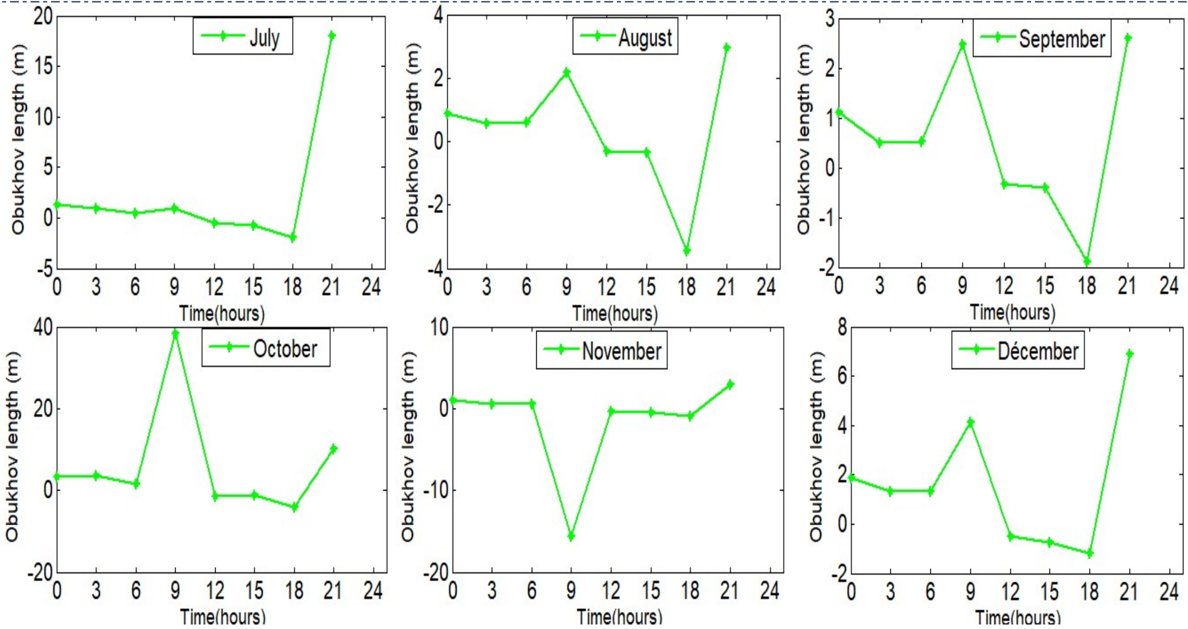


Figure 4: Variation of the day and night cycles of the Obukhov length for a typical day on a monthly basis for the Ouahigouya site (2006-2016).

Table 4: Shear coefficients values according to atmospheric stability conditions

Months	J	F	M	A	M	J	J	A	S	O	N	D	Annual
Instable	0.53	0.47	0.58	0.43	0.30	0.16	0.15	0.24	0.36	0.57	0.65	0.65	0.67
Stable	0.56	0.50	0.61	0.46	0.33	0.19	0.18	0.27	0.39	0.60	0.68	0.68	0.7

Table 4 presents the shear coefficient values according to atmospheric conditions on a monthly and annual basis at the study site. Analysis of this table reveals two major observations. On the one hand, the values of the shear coefficient are higher under stable atmospheric conditions than under unstable conditions whatever the period of the year. On the other hand, the maximum values are recorded during the months of the dry season while the minimum values in the rainy season. This trend is due to a greater mixing of the air (turbulence) above the ground, which makes that the shear is lower in rainy seasons than in dry season where there is less mixing of the air near the ground (turbulence removed) during the rainy season.

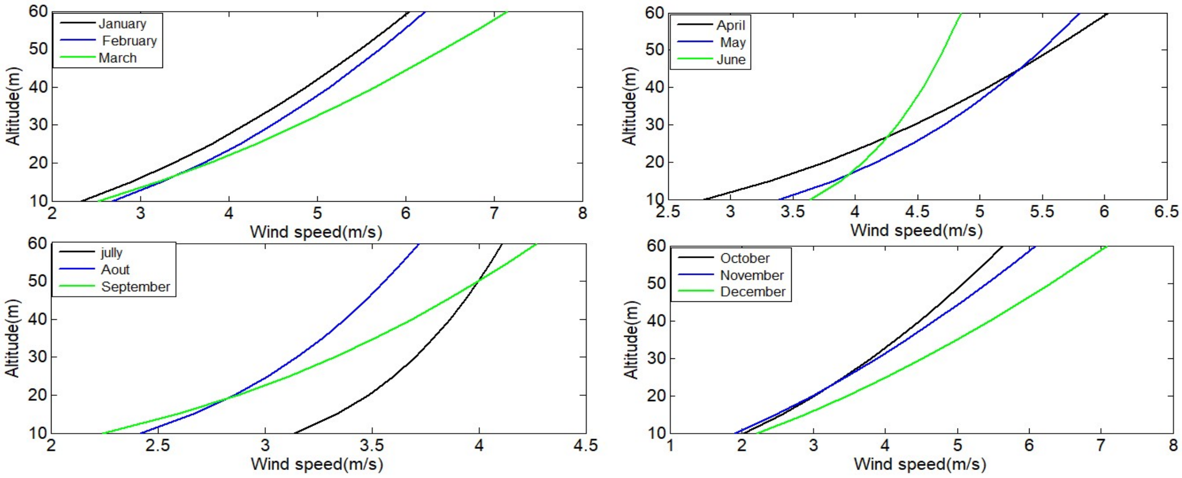


Figure 5: Average vertical wind speed profile on a monthly basis under unstable atmospheric conditions

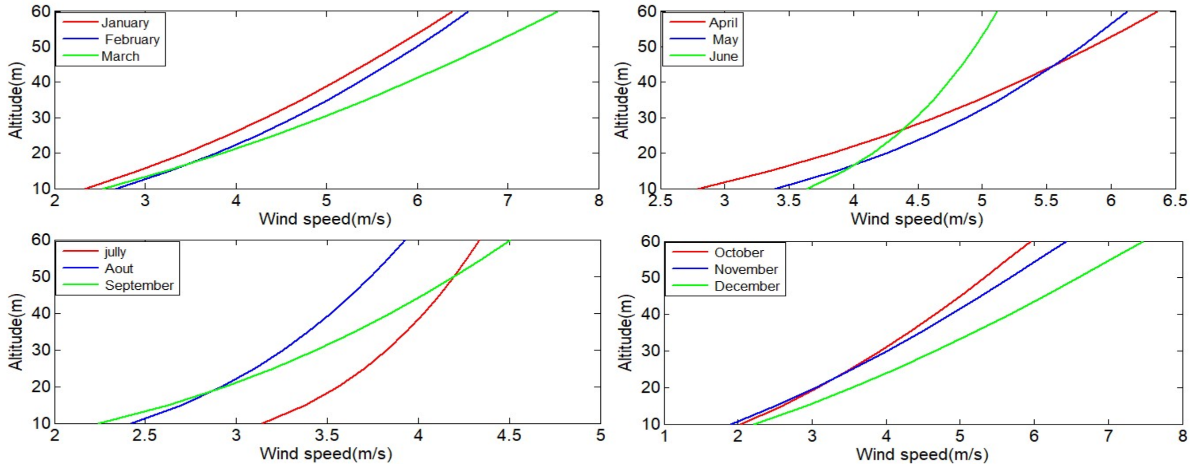


Figure 6: Average vertical wind speed profile on a monthly basis under stable atmospheric conditions

Figures 5 and 6 show the average vertical wind speed profiles during the periods of atmospheric instability and atmospheric stability, respectively. Under these conditions, the windiest months correspond to a good part of the dry season with peaks in March and December. These average speed peaks are estimated at 6.43 m/s and 6.29 m/s respectively during the unstable period. As for the stable period, the values are 6.75 m/s and 6.60 m/s, respectively. The minimum wind speed values are recorded during in July, August and September. They are estimated at 3.99 m/s; 3.56 m/s; 3.99m/s, for the unstable period, respectively. On the other hand, values of 4.19 m/s; 3.73 m/s and 4.19 m/s are recorded during the stable period. These speed values therefore constitute basic data for any investor in wind energy sector and represent a decision-making aid tool for the development of this energy source in the Ouahigouya region.

5. CONCLUSION

In this study, wind and temperature data from Burkina Faso National Meteorological Agency as well as those from NASA were used to determine the vertical wind speed profile. The power and logarithmic law models were therefore assessed for unstable and stable atmospheric conditions. The power law model was used to extrapolate the vertical profile during the unstable and stable periods of the atmosphere from data measured at 10 m from the ground. The main results of our study are summarized as follows:

- The power and logarithmic laws perfectly adjust the average speed data.
- At the study site, the atmosphere is generally unstable between 10 a.m. and 6 p.m. and stable over the rest of the day. Average annual shear coefficients of the wind during the day and night cycles are estimated at 0.67 and 0.7, respectively.
- Lastly, the average vertical wind speed profiles during unstable conditions (10h-18h) and stable conditions (18h-10h) are determined by extrapolation from the wind speed measured at 10m from the ground using the power law which requires few parameters compared to the logarithmic law. The average wind speed in unstable atmospheric conditions is estimated at 6.43 m/s for the windiest month (March) and at 3.56 m/s for the least windy month (August) at 50 m from the ground. Under stable atmospheric conditions, the average wind speed is estimated at 6.75 m/s for the windiest month (March) and 3.73 m/s for the least windy month (August) at 50 m compared on the ground.

These results could therefore be used by investors in the wind energy sector for optimal exploitation of this energy source in the Ouahigouya region. Therefore, the vertical profiles developed for the study site need to be refined by measurements at several altitude levels.

6. ACKNOWLEDGMENTS

The authors of this paper sincerely thank the Burkina Faso National Meteorological Agency of (ANAM) for having made the data available to them, data which were used to carry out this research work.
The ISP, Uppsala University, Sweeden os gratefully acknowledged force their support to project BUFO1

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