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Study of the offshore wind and its propagation inland of the northern zone of the Yucatan Peninsula, Eastern Mexico

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ABSTRACT

A preliminary study of the wind characteristics of the northern zone of the Yucatan Peninsula, Eastern Mexico was undertaken for offshore and coastal sites using data measured from three measurement sites. Ten minutes averages of wind speeds, wind directions and ambient temperatures at two different heights were recorded from data measured over a year. The usual wind statistics analysis was undertaken to evaluate the atmospheric stability and the relation between the offshore and onshore winds. The results were compared with the models previously proposed by Monin-Obukhov and by Hsu.

1. INTRODUCTION

The winds in the offshore environment have better characteristics for wind energy applications than winds in inland flat regions because offshore winds tend to show less variability, there is reduced turbulence intensity that can fatigue turbine components and offshore wind speeds are normally higher due to a lower surface roughness. However, these potentially better wind conditions need to be evaluated as the benefits are to some extent offset by higher installation, operation and maintenance costs for wind farms in offshore environments. One alternative option is consider the wind conditions at a coastal site which may benefit from some of the features of an offshore site but is far more accessible in terms of installation, operation and maintenance.

Among the factors affecting wind speeds in mainly flat coastal regions are the latitude of the site, differences between the air and sea temperatures, water depth and distance from the coastline. The flow of winds over a coastal discontinuity face changes in roughness, availability of heat and moisture which alter the turbulent mixing and momentum transfer creating different stability conditions offshore and onshore sites and influencing the wind profile behaviour [1]. By means of data measured from an offshore wind farm in Denmark, Barthelmie studied the changes in the onshore and offshore stability and their impact in the wind profile [2].

Barthelmie and Palutikof [3], introduced a couple of methods to predict wind speeds at offshore coastal regions using an empirical approach and a solution with the internal boundary layer theory. On the other hand, McQueen and Watson [4], studied different methodologies to predict the offshore wind speeds concluding that more research should be undertake to evaluate the impact of the atmosphere stability on the sea-land discontinuity conditions.

The research presented in this paper is focused in to identify the directional and diurnal patterns of the winds over the north-West of the Yucatan Peninsula, to classify the stability stages of the atmosphere over the measurement period and to evaluate the correlation between the offshore and onshore winds. Three strategic locations have been chosen around the North-West coast of the Yucatan peninsula. Two stations are located at coastal sites and one station is located 6.4km offshore. Ten minutes averages of ambient temperature and wind speed and direction at two different heights were recorded during a full measurement year in each study site.

2. STUDY REGION

Three measurement stations were installed on communication towers at the North-West of the Yucatan Peninsula: one offshore (API) and two onshore (CHM and TCP) as can be seen below in the map and the tower images of the Figure 1. A couple of ambient temperature and wind speed and direction sensors were installed at two different heights in each site oriented in the east directions, see TABLE 1. The data measured every two seconds was averaged every ten minutes during a period of one year.

Figure 1. Locations of the three measurement sites at the North-West coast of the Yucatan Peninsula.

The distances from the measurement tower to the coastline as well as the relevant distances between every site are listed in TABLE 1.

TABLE 1. Sensors heights for each site, distances between the sites and distances between each site and the coast line.

Sites ID	Distances [km]				Sensors heights [m]	
	Coast	API	CHM	TCP	Low (Lo)	High (Hi)
API	6.400	-	-	-	15	30
CHM	0.410	10.720	-	35.990	20	40
TCP	0.330	28.850	-	-	20	50

3. MEASURED PATTERNS

The ten minutes recorded data was classified by wind directions in 16 directional sectors of 22.5 angular degrees each one. Figure 2 shows the frequency of the winds through the directions for the three study sites. The directional patterns are very similar with a small amount of winds from the sector from SSW to WNW and the higher concentrations around NE-ENE and ESE-SE sectors.

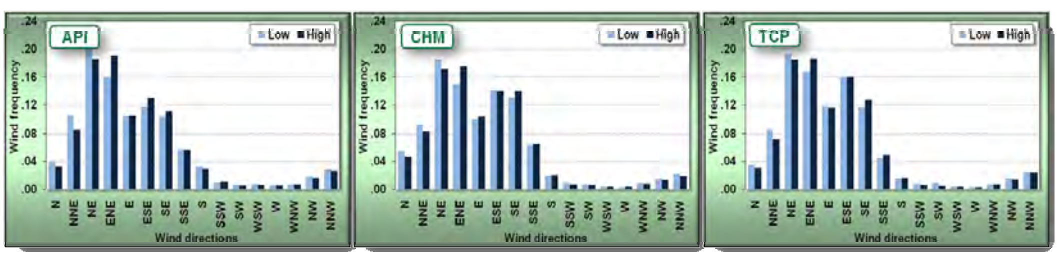

Figure 2. Directional distributions of wind speeds for each study site at both measurement heights (Low and High).

Figure 3 present the directional behaviour of the wind speed ratio around the directional sectors. It can be appreciated that the wind speed ratio around the WSW sector is disturbed by the mast position mainly at API and TCP sites. This effect has not a particular influence for the presented research because as was presented in Figure 2, less than 1% of the winds arrived to each site from this direction.

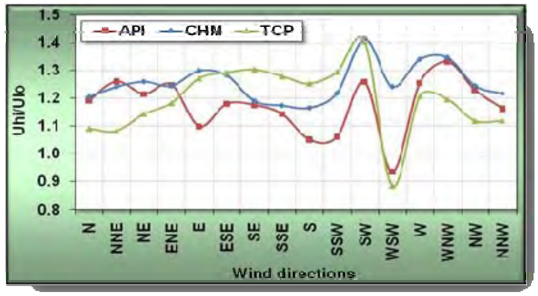

Figure 3. Directional behaviour of the wind speeds ratio at both heights for each study site.

To represent the diurnal patterns, the hourly averages were computed to generate the daily profiles for the wind speed and wind direction shown in Figure 4. A clear pattern was present with higher speeds around 5:00 pm in the afternoon and a relative flat profile during the night time. The daily wind directions reflected that the increase in the wind speeds is related with winds coming between the E and S sectors.

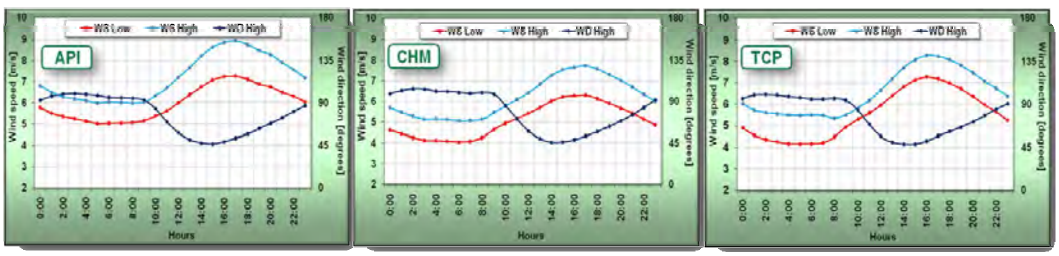

Figure 4. Diurnal patterns of wind speed (WS) and wind direction (WD) for each study site at both measurement heights (Low and High).

Considering that the coastline is approximately orientated along the east-west line and in order to study the correlation between the offshore and onshore winds, the recorded data was regrouped in four directional zones: North (with the sectors NW,NNW,N,NNE,NE), East (with the sectors ENE,E,ESE), South (with the sectors SE,SSE,S,SSW,SW) and West (with the sectors WSW,W,WNW). Then, the onshore sites were paired with the offshore one as API-CHM and API-TCP and synchronized in times and dates to obtain the wind distribution for each directional zone, see Figure 5 below.

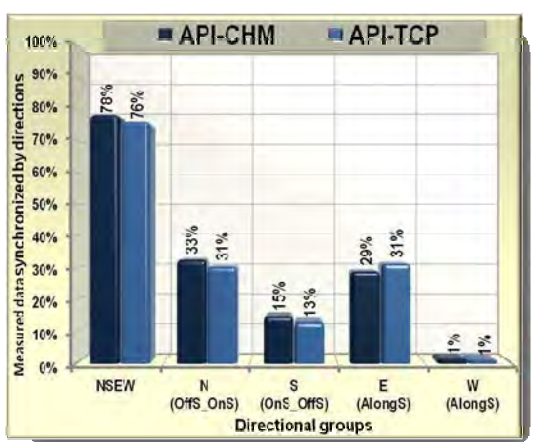

Figure 5. Distribution by directional zones of the data synchronized by times and dates for the pairs of offshore-onshore sites.

4. ATMOSPHERIC STABILITY

The stability of the atmosphere can be means of the Obukhov length L in the stability classes reported by van Wijk [5] as can be seen below in TABLE 2.

TABLE 2. Stability classes

Classes	L [m]	z/L (z=20)	z/L (z=15)
very stable	0 < L < 200	z/L > .1	z/L > .08
stable	200 < L < 1000	.1 > z/L >.02	.08 > z/L >.02
near-neutral	1000 < L < –1000	.02 > z/L > -.02	.02 > z/L > -.02
unstable	–1000 < L < –200	-.02 > z/L >-.1	-.02 > z/L >-.08
very unstable	–200 < L < 0	z/L < -.1	z/L < -.08

A relation to compute the Obukhov length L was proposed by Businger [6] and Högström [7] in terms of the gradient Richardson number R_i at height z', see equation (1) below.

$$L=\begin{cases}\left(\dfrac{z'}{R_i}\right) & R_i<0\\[2mm] \dfrac{z'(1-5R_i)}{R_i} & 0<R_i<0.2\end{cases}\qquad \text{where}\quad z'=\frac{z_{Lo}-z_{Hi}}{\ln\left(\frac{z_{Lo}}{z_{Hi}}\right)} \tag{1}$$

Equation (2) presents an expression to compute the gradient Richardson number from ambient temperatures and wind speeds measured at two different heights (z_{Lo} and z_{hi}). This expression is valid at the height z' showed in equation (1) which was proposed by Larsen [8]. The differences in height, virtual temperature and wind speed are represented by z, T_v and u while C_p and g are the specific heat of air at constant pressure and the gravity acceleration respectively.

$$R_i(z')=\frac{\frac{g}{\bar{T}}\left(\frac{\Delta\bar{T}_v}{\Delta z}+\frac{g}{C_p}\right)}{\left(\frac{\Delta\bar{u}}{\Delta z}\right)^2} \tag{2}$$

Thus, the frequency of the stabilities classes was computed for each site and is presented in Figure 6. This result shows that the atmosphere in all the study sites behaves mainly very unstable and unstable during the study period.

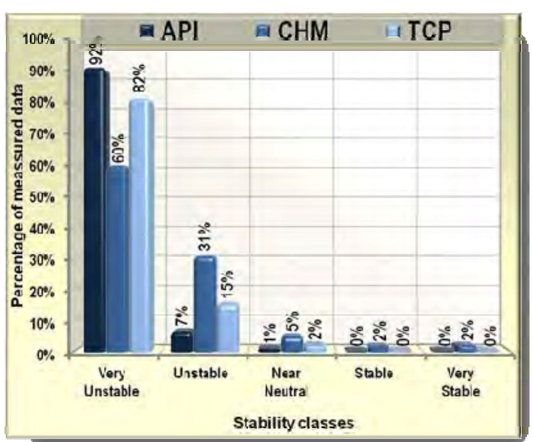

Figure 6. Distribution of stability classes presented in each study site.

In order to compare the measured values with the theoretical wind speed profile, the Monin-Obukhov similarity theory can be used:

$$u(z)=\frac{u_*}{k}\left[\ln\left(\frac{z}{z_0}\right)-\Psi_m\left(\frac{z}{L}\right)\right] \quad (3)$$

In the equation (3), k is the von Karman constant and the wind speed u at height z is represented as a function of the friction velocity u_*, roughness length z_0 and Obukhov length L. $\psi_m(z/L)$ is the stability function which considering the results of the Figure 6, just need to be calculated for unstable classes with the equation (4), formulated by Businger [6]. In this equation the empirical parameter was evaluated by Högström [7] as 19.3.

$$\Psi_m = 2\ln\left(\frac{1+\Phi_m^{\,2}}{2}\right) - 2\tan^{-1}(\Phi_m) + \frac{\pi}{2} \quad \text{where} \quad \Phi_m=\left(1-\gamma\frac{z}{L}\right)^{1/4} \quad (4)$$

Then, the theoretical wind speeds ratio between high and low heights can be calculated by the relation show in the equation (5). The roughness length z_0 was estimated at API site as 0.0003, at CHM site as 0.015 and at TCP site as 0.003.

$$\frac{u(z_{HI})}{u(z_{Lo})}=\frac{\ln\left(\frac{z_{HI}}{z_0}\right)-\Psi_m\left(\frac{z_{Lo}}{L}\right)}{\ln\left(\frac{z_{Lo}}{z_0}\right)-\Psi_m\left(\frac{z_{Lo}}{L}\right)} \quad (5)$$

Finally, the ratio of the wind speeds measured for each site was binned every 0.01 value of the stability parameter z/L, where z was taken as the lower height for each site. Figure 7 shows the measured and the Monin-Obukhov (MO) theoretical ratio of the wind speeds as function of the stability parameter "z/L" for all the directional zones, Figure 7(a), and for the winds coming from offshore to onshore (North zone), Figure 7(b).

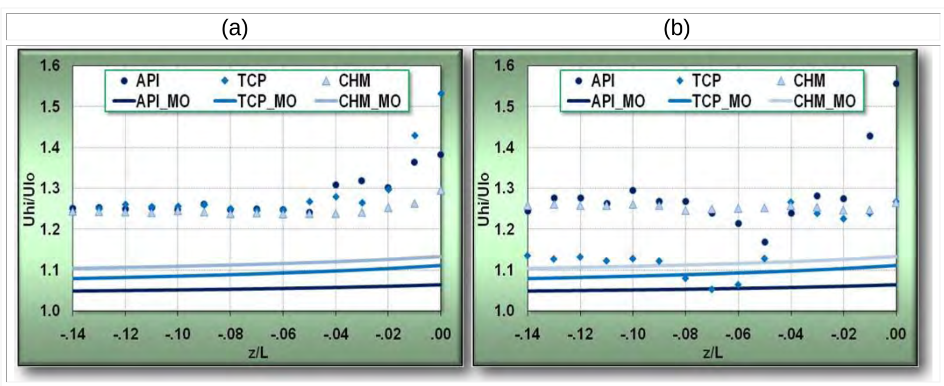

Figure 7. Behaviour of the wind speed ratio between high and low measurements as function of the stability parameter z/L. (a) for all directional zones, (b) for the winds coming from offshore to onshore.

As can be seen the measured values of the shear are appreciably higher than those predicted by MO similarity theory, particularly for values of z/L greater than -.05 which is the region of unstable and near neutral stability. Figure 6 showed that CHM site presented the major concentration of winds in near neutral and unstable conditions and its measured profile is closer in shape to the MO profile in Figure 7. It can also be appreciated greater dispersion when just data from the North zone is considered, around 33% of the data (Figure 5). At this stage of the research just a filter for the wind speeds has been applied to avoid non homogenous and non-stationary flow conditions which are no properly described by the Monin-Obukhov similarity theory. Lange et al. [9], applied additional filters for wind direction, temperature, stability parameter and friction velocity to obtain measured profiles closed to the MO theory. In the next stages of the presented research these additional filters will be also apply to identify the causes of the high shears showed in Figure 7.

5. OFFSHORE-ONSHORE CORRELATION

An extrapolation to 10m height was applied to the measured values of each site to allow a direct comparison with the empirical model proposed by Hsu [4,10] which predict the wind speeds offshore (U_{sea}) from the onshore ones (U_{land}). Figure 8 shows the correlation between the offshore and onshore wind speeds for each pair of sites (API-CHM and API-TCP) in the three main directional zones (North, South and East). The West zone was not study because just 1% of the measured data comes from this zone, see Figure 5. Linear interpolations were applied to the measured data without enforcing them to pass through the (0,0) point. This was made because the Hsu model does not include this condition.

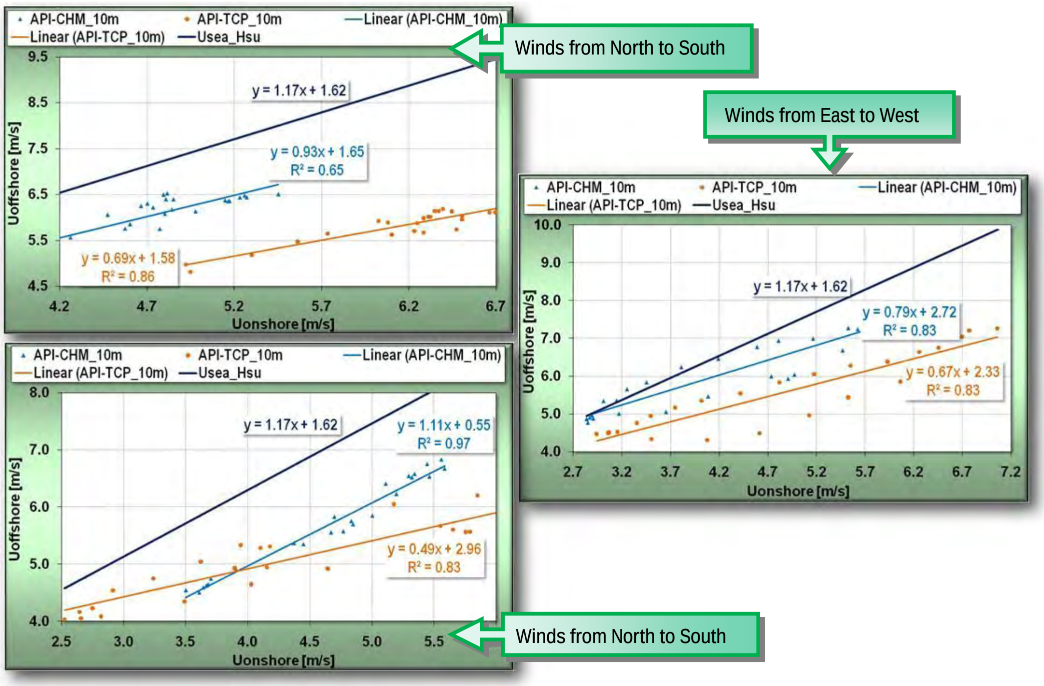

Figure 8. Correlation between the winds speeds measured for the pairs of sites API-CHM and API-TCP. The model proposed by Hsu has been also included.

CONCLUSIONS

A first analysis of the atmosphere stability has been presented in order to identify its impact in the wind profile at the North-West of the Yucatan Peninsula. The results presented showed much greater values than would be expected for the wind shear of the onshore and offshore wind speeds. In addition, the rate of increase in wind shear at near neutral conditions is greater than predicted by MO theory. This requires further investigation and additional filters should be applied to ensure homogeneous and stationary flow conditions in the measured data.

The Hsu model over predict the wind speeds on the API site producing better results in some of the study sites for lower wind speeds conditions.

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