# Analysis of the Wind Field at the Broader Area of Chania, Crete

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*Abstract:* - In this paper the wind field of the broader area of Chania is statistically analyzed. This analysis is based over one year's hourly averaged measurements of the wind speed and direction, obtained from a network of five Automated Meteorological Stations operating in the greater area of Chania. Firstly, a descriptive statistical analysis of wind speed and direction is performed, which includes the availability of data, the calculation of mean wind speeds, monthly and diurnal variations along with the distribution by wind direction. The Weibull distribution function has been fitted to the available data and its two parameters were identified using the maximum likelihood estimation method. The hourly and monthly wind speeds are found to have remarkable variations.

*Key-Words:* - Wind Speed, Wind rose, Wind Energy, Weibull parameters, Weibull distribution, Maximum likelihood method

## 1 Introduction

Over the last few years great interest has been displayed in finding a statistical model (theoretical distribution) that could simulate well the frequency distribution of the wind speed [1][2][3]. This assists in the calculation of the wind energy potential of an area, since the problem of the local turbulence obstructs the application of linear interpolation between two locations with available measurements. In addition, the calculation of the wind energy potential in a country like Greece with great exploitation potentiality is an area of study with special interest. Greece has to make use of its renewable resources, such as wind and solar, not only to meet the increasing energy demand, but also for environmental and sustainability reasons.

In the present study, the wind field of Chania is statistically analyzed based on one-year measured hourly time-series wind speed data. Wind depends on the site characteristics and topography to a large degree, so its variability is stronger in an area such as Chania with its sharp relief and convoluted coastline. The Weibull distribution was used in order to simulate the wind in the area of Chania because of its frequent use in international literature [4][5]. The Weibull function provides a convenient representation of the wind speed data for wind energy calculation purposes. It is important to note that the analysis presented here does not consider extreme wind speed analysis. The preferred method of calculating the Weibull is the most accurate and robust approach, the maximum likelihood estimation method.

## 2 Experimental layout

The city of Chania is inhabited by 53,000 residents, spreading in an area of about 12.6 km$^2$. It is located in a plain, at the base of a large circular shaped Peninsula named Akrotiri. The northern border of the city is defined by the Aegean Sea while the southern part of the plain is constricted by the White Mountains. Four surface automatic meteorological stations (namely PLATANIAS, MALAXA, SOUDA, TEI) were installed and operated from July-20-2004 to September-01-2005, at locations near and around the city of Chania (see Fig.1 and Table 1).

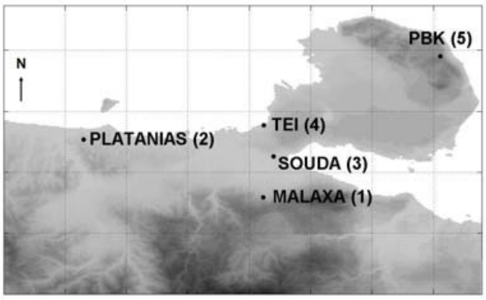


Fig. 1: Experimental Area.

Table 1: Specific Features of Stations

| Station | Longitude | Latitude | Alt (m) | Features |
|---|---|---|---|---|
| PLATANIAS | 24° 03′ 00′′ | 35° 29′ 46′′ | 23 | Rural |
| SOUDA | 23° 54′ 40′′ | 35° 30′ 30′′ | 118 | Urban |
| MALAXA | 24° 02′ 33′′ | 35° 27′ 57′′ | 556 | Rural |
| TEI | 24° 02′ 35′′ | 35° 31′ 09′′ | 38 | Urban |
| PBK | 24° 10′ 20′′ | 35° 34′ 11′′ | 422 | Rural |

Moreover measurements for the same period were contributed from a military facility meteorological station (PBK). All stations are equipped with cup anemometers and wind vanes, installed at a height of 10m above ground, which recorded hourly averaged values of wind speed and direction. The above time period corresponds to a typical meteorological year and the dataset is a statistically suitable sample of the conditions that occur in the area. This was proven after comparing the experimental time series of each station with the 50-year climatological data, obtained from the Climatological Station of the Hellenic Meteorological Service operating in Chania.

## 3 Wind characteristics

Fig.2 represents the monthly mean wind speed values, calculated for all stations and for the entire period.

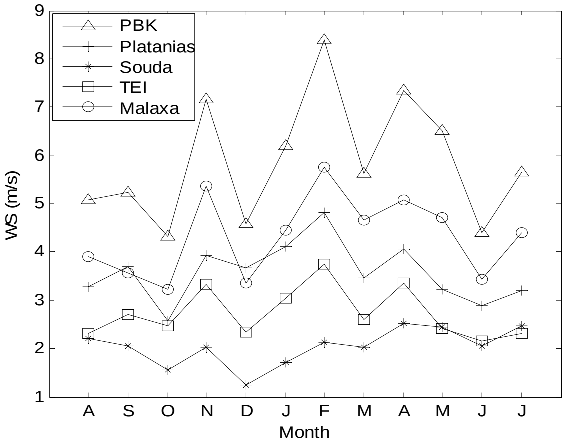


Fig 2: Monthly variation of mean wind speeds.

The mean monthly wind speed for all stations exhibits the same pattern (similar variation) and has pronounced peaks due to the seasonal wind variation. It is observed that the wind field in every station sharply fluctuates from month to month, due to the influence of different factors in each time period. The highest values of mean monthly wind speed of all stations occurred during winter and spring, with the maximum value observed in February for all stations except for Souda which occurs in April. This can be explained by the decrease of the temperature from winter to spring. Such a decrease causes thermal convection and thus, a fraction of the upper air momentum, which moves with higher velocities, is transmitted to the surface layers causing the noticed increase in the mean monthly wind speeds. For all seasons, we notice that Souda station has the lowest values of monthly wind speed and PBK the highest. In general, the seasonal changes of the wind speed in the PBK are well marked, due to its position. The stations showing the most profound and steady winds are the PBK and Malaxa, mostly due to their location and topography. The highest wind intensities in every station were observed from May to September, which is the period that the Etesian winds are predominant in the Aegean Sea.

The wind speed data is usually arranged in the frequency distribution format since it is more convenient for statistical analysis. Therefore, the available time-series data were converted into the frequency distribution format and wind speed measurements are grouped into classes. The mean wind speeds are calculated for each class interval. The annual probability density, derived from the time-series from all stations is presented in Fig. 3.

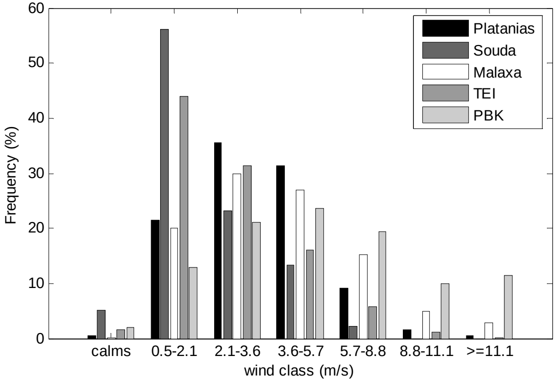


Fig.3: Frequency distribution of wind speeds.

It is apparent from Fig. 3 that: a) all frequencies exhibit the same pattern, with pronounced peaks, which are located in the neighborhood of the mean wind speed, b) in all stations, the peak frequencies are shifted towards the higher values of mean wind speed and c) for all stations, no frequencies occurred for a mean wind speed greater than 11.1m/s. The frequency distributions of the wind speeds help towards answering questions such as: For what amount of time is a wind power plant out of action in the case of lack of wind? What is the range of the most frequent wind speed? How often does the wind power plant achieve its rated output?

Fig. 4 describes the hourly variation of the mean wind speed at the five stations. A clear feature is that the hourly mean wind speed is much higher during day-time than night-time and the wind speed during night-time is almost constant.

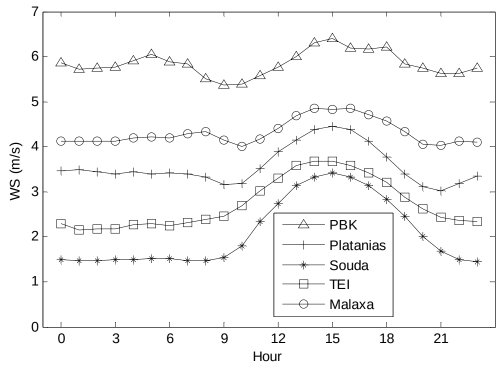
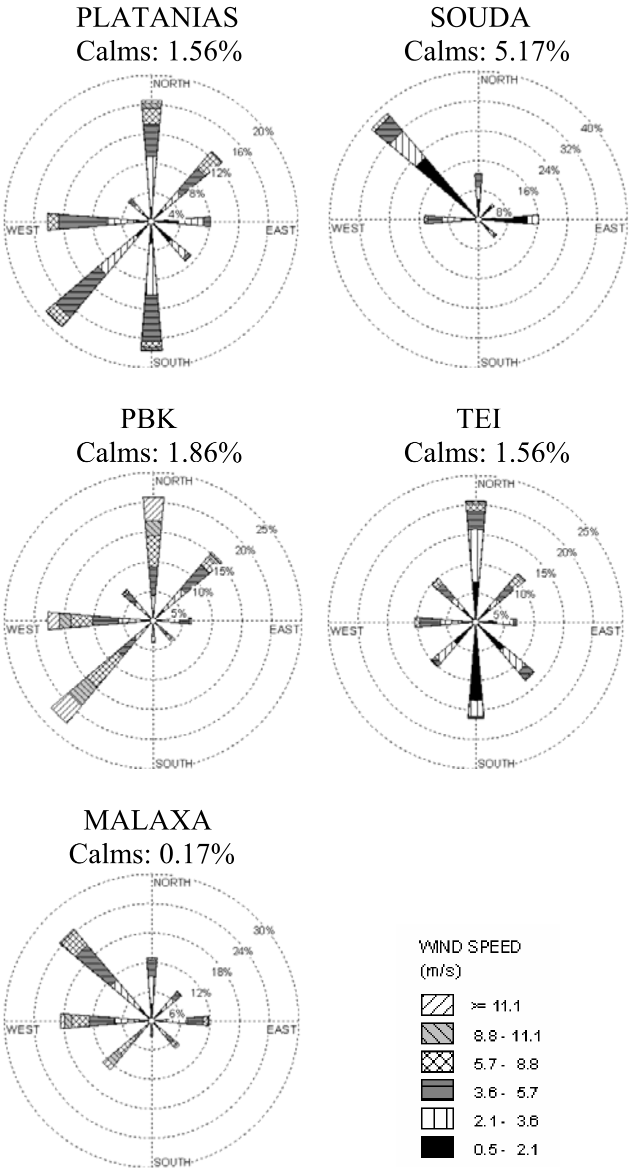


Fig.4: Hourly variation of mean wind speeds.

The hourly mean wind speed variation follows something like a sinusoidal curve which is related to the diurnal variation of stability and momentum mixing over land: an ascending progress of wind speed is observed during the morning hours from 09:00 LST reaching its maximum at midday (14:00 – 15:00 LST) which corresponds to the maximum of the vertical circulation. The entire afternoon is characterized by decreasing wind speed until the minimum mean wind speed is reached at 22:00 LST. The station of PBK is the only exception, exhibiting a second maxima during the first morning hours (05:00 LST). Contrarily, in the evening hours the wind speed is decreasing exhibiting a minimum during the night hours (20:00 – 21:00 LST). Generally speaking, the hourly mean wind speed fluctuates remarkably, and it also varies from site to site. So a careful evaluation should be given according to the wind conditions and the surrounding landforms when wind energy related project is considered. The daily time-evolution of wind speed is quite important for the integration of wind power into the overall energy supply.

The distribution of wind direction is crucially important for the evaluation of the possibilities of utilizing wind power. The distributions of wind speed and direction are conventionally given by wind roses. In Fig.5 the wind roses are displayed for each station for the entire experimental period. In these graphs the wind direction frequency in each of the 8 major classes are displayed, as well as the frequency of each wind speed class per direction. The percentage of calm conditions is also presented. The following features are observed:

- The wind direction varies from station to station due to differential local features (topography, altitude, orientation, distance from the shore, etc.). By performing a general classification, the stations of Souda and Malaxa have mainly a North-Westerly direction, while Platanias and PBK a South-Westerly one.
- Although the wind intensity usually exhibits low values it differs from station to station. The lower values of intensity are found in Souda and TEI stations, while the higher ones are observed in PBK.
- High dispersion of wind directions is observed in Platanias, Malaxa and TEI stations.
- Very low percentages of calm conditions are found in every station. The highest ones being observed in Souda.


PLATANIAS
Calms: 1.56%

SOUDA
Calms: 5.17%

PBK
Calms: 1.86%

TEI
Calms: 1.56%

MALAXA
Calms: 0.17%

Fig.5: Wind-roses for all stations.

## 4 Weibull distribution

The wind speed probability distributions and the functions representing them mathematically are the main tools used in the wind-related literature. Their use includes a wide range of applications, from techniques used to identify the parameters of the distribution functions [6] to the use of such functions for analyzing the wind speed data and wind energy economics [7]. Based on past studies regarding the fitting of the above theoretical distributions to experimental data, the Weibull distribution is proposed as the most satisfactory function for the simulation of wind speed time series [2][8][9]. The fitting of the Weibull distribution to the wind speed data of a station requires the calculation of the parameters of scale c (m/sec) and shape k (dimensionless).

The Weibull distribution family of curves is expressed mathematically by the probability density function f(u):

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{c}\right)^{k}\right] \qquad (1)$$

where k is the dimensionless shape factor, c is the scale parameter in m/sec and u is the wind speed in m/sec. The mean $\bar{u}$ and the variance $\sigma^2$, in terms of k and c may be calculated by using the gamma function Γ,

$$\Gamma(y) = \int_0^\infty e^{-x} x^{y-1} dx \qquad (2)$$

from the following mathematical expressions:

$$\bar{u} = c\Gamma\left(1+\frac{1}{k}\right) \ (3) \qquad \sigma^2 = c^2\left[\Gamma\left(1+\frac{2}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right] \ (4)$$

The Root Mean Square Error (RMSE) has been computed as a measure of the goodness of fit of the Weibull distribution function to the observed data.

In order to estimate the Weibull parameters the Maximum Likelihood Estimation method is applied for wind energy analysis [5][10]. The maximum likelihood estimation (MLE) is widely used to calculate the parameters of theoretical distributions in time series modeling. This method is based on the calculation of the most probable parameters of the distribution that fits the observed data. The shape factor k and the scale factor c of the Weibull distribution are calculated based on the MLE method by using the following estimations:

$$k = \left( \frac{\sum_{i=1}^{n} u_i^{\,k} \ln(u_i)}{\sum_{i=1}^{n} u_i^{\,k}} - \frac{\sum_{i=1}^{n} \ln(u_i)}{n} \right)^{-1} \qquad (5)$$

$$c = \left( \frac{1}{n} \sum_{i=1}^{n} u_i^{\,k} \right)^{1/k} \qquad (6)$$

The Weibull distribution is usually used to describe the wind speed distribution of a given location over a certain period of time, typically monthly or annually. In the present study, the annual Weibull function and its two parameters are derived from the available data, which are shown in Fig.6 and Tables 2 and 3. In Fig. 6, the graphs of the fitted Weibull distributions to the wind speed relative frequency graphs for every station are presented.

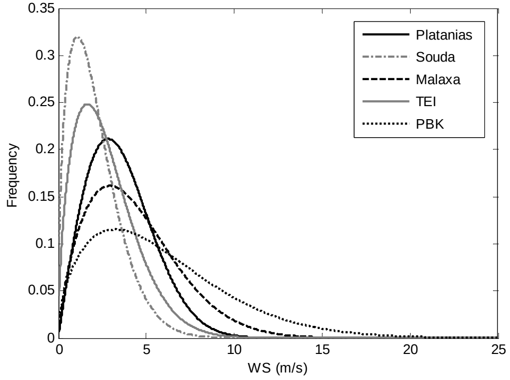


Fig.6: Weibull distributions for the wind speed at each station.

The relative errors of the mean value and the variance result from the comparison the theoretical distribution with the experimental time series. The results for all stations are grouped in Table 2. The agreement of the Weibull frequency distributions with the mean wind frequency distributions was found to be good (at the 90% confidence level), despite the existence of localized flow fields such as sea and land breeze circulations, upslope and downslope winds. The relative errors of the mean value and variance of the Weibull distribution are low for all stations.

As can be seen from the table the values of the scale factor vary between 2.32 and 6.51 m/s, while the values of the shape factor range from 1.48 to 2.00 for the analyzed locations. The values of the shape parameter k and scale parameter c are found to be slightly dependent on local station conditions. Parameter scale values are close to the average wind speeds, indicating that the Weibull distribution is a reasonable fit to the experimental data. The mean wind speed varies from 2.09 m/s in Souda to the maximum of 5.84 m/s in PBK as can be seen in Table 2 owing to the location of the station and its topography.

At this point a few remarks on the accuracy of the resulting values of k and c are in order. Generally, two types of errors can be distinguished: statistical and systematic. First, the initial measurement of the wind speed has an accuracy of 0.5 m/s. It is assumed that this leads to randomly distributed values and eventually to a statistical error in the mean value, which is reduced to a very small figure as it decreases with the square root of the number of observations. Therefore, this statistical error can be discarded. Second, the computational processing of the data leads to systematic errors.

Table 2: Values of the Weibull parameters k and c, Experimental and Theoretical mean wind speed and variance and their relative errors for yearly frequency distributions of the wind speed.

| Station | Weibull parameters | | | Experimental (m/sec) | | | Weibull (m/sec) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | c (m/sec) | k | RMSE | $u_{mean}$ | $\sigma_u^2$ | $u_{max}$ | $u_{mean}$ | $\sigma_u^2$ | Error $u_{mean}$ (%) | Error $\sigma_u^2$ (%) |
| PLATANIAS | 4.04 | 2.00 | $8.44\text{x}10^{-5}$ | 3.57 | 1.89 | 9.13 | 3.58 | 1.88 | 0.28 | 0.53 |
| SOUDA | 2.32 | 1.48 | $3.08\text{x}10^{-4}$ | 2.09 | 1.49 | 7.78 | 2.10 | 1.44 | 0.48 | 3.36 |
| MALAXA | 4.87 | 1.73 | $8.37\text{x}10^{-5}$ | 4.31 | 2.69 | 12.9 | 4.34 | 2.60 | 0.70 | 3.35 |
| TEI | 3.06 | 1.60 | $1.09\text{x}10^{-4}$ | 2.73 | 1.84 | 8.42 | 2.75 | 1.76 | 0.73 | 4.35 |
| ΠΒΚ | 6.51 | 1.53 | $1.63\text{x}10^{-5}$ | 5.84 | 3.94 | 16.68 | 5.86 | 3.90 | 0.34 | 1.02 |

Table 3: Parameter values k and c of the fitted Weibull distributions to the hourly experimental data.

| Hour | Meteorological Stations | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Platanias | | Souda | | Malaxa | | TEI | | PBK | |
| | k | c(m/sec) | k | c(m/sec) | k | c(m/sec) | k | c(m/sec) | k | c(m/sec) |
| 0 | 2.085 | 3.910 | 1.412 | 1.651 | 1.628 | 4.631 | 1.464 | 2.535 | 1.421 | 6.460 |
| 1 | 2.032 | 3.937 | 1.378 | 1.616 | 1.612 | 4.632 | 1.449 | 2.390 | 1.382 | 6.333 |
| 2 | 1.820 | 3.871 | 1.423 | 1.634 | 1.536 | 4.621 | 1.463 | 2.414 | 1.436 | 6.372 |
| 3 | 1.859 | 3.820 | 1.457 | 1.662 | 1.588 | 4.636 | 1.493 | 2.430 | 1.506 | 6.438 |
| 4 | 1.882 | 3.886 | 1.503 | 1.667 | 1.627 | 4.720 | 1.416 | 2.516 | 1.507 | 6.586 |
| 5 | 1.868 | 3.825 | 1.538 | 1.696 | 1.635 | 4.749 | 1.430 | 2.544 | 1.506 | 6.705 |
| 6 | 1.889 | 3.858 | 1.480 | 1.683 | 1.683 | 4.713 | 1.415 | 2.495 | 1.561 | 6.587 |
| 7 | 1.877 | 3.822 | 1.515 | 1.650 | 1.628 | 4.832 | 1.394 | 2.554 | 1.576 | 6.544 |
| 8 | 1.845 | 3.749 | 1.369 | 1.629 | 1.600 | 4.861 | 1.347 | 2.609 | 1.440 | 6.072 |
| 9 | 1.775 | 3.564 | 1.457 | 1.719 | 1.635 | 4.674 | 1.397 | 2.722 | 1.436 | 5.903 |
| 10 | 1.789 | 3.614 | 1.541 | 2.024 | 1.697 | 4.514 | 1.505 | 2.996 | 1.482 | 5.984 |
| 11 | 1.997 | 3.977 | 1.767 | 2.649 | 1.809 | 4.724 | 1.715 | 3.399 | 1.548 | 6.215 |
| 12 | 2.247 | 4.390 | 1.976 | 3.102 | 1.903 | 4.987 | 1.984 | 3.747 | 1.689 | 6.485 |
| 13 | 2.476 | 4.681 | 2.233 | 3.555 | 1.943 | 5.302 | 2.231 | 4.058 | 1.829 | 6.796 |
| 14 | 2.629 | 4.917 | 2.290 | 3.765 | 1.913 | 5.49 | 2.391 | 4.142 | 1.894 | 7.132 |
| 15 | 2.679 | 5.013 | 2.370 | 3.863 | 2.003 | 5.469 | 2.312 | 4.166 | 1.967 | 7.250 |
| 16 | 2.617 | 4.940 | 2.365 | 3.769 | 2.058 | 5.501 | 2.287 | 4.040 | 1.856 | 6.986 |
| 17 | 2.460 | 4.661 | 2.221 | 3.558 | 2.059 | 5.331 | 2.079 | 3.880 | 1.749 | 6.936 |
| 18 | 2.228 | 4.281 | 2.073 | 3.201 | 2.030 | 5.171 | 1.957 | 3.636 | 1.586 | 6.929 |
| 19 | 1.926 | 3.856 | 1.825 | 2.778 | 1.878 | 4.905 | 1.814 | 3.253 | 1.465 | 6.481 |
| 20 | 1.782 | 3.514 | 1.629 | 2.263 | 1.681 | 4.560 | 1.677 | 2.962 | 1.353 | 6.297 |
| 21 | 1.718 | 3.388 | 1.521 | 1.877 | 1.573 | 4.501 | 1.626 | 2.735 | 1.313 | 6.101 |
| 22 | 1.818 | 3.578 | 1.378 | 1.652 | 1.557 | 4.618 | 1.509 | 2.644 | 1.378 | 6.151 |
| 23 | 1.877 | 3.762 | 1.385 | 1.606 | 1.581 | 4.610 | 1.467 | 2.613 | 1.404 | 6.354 |

The Weibull distribution is fitted to the hourly experimental data (see Table 3). The analysis shows that the parameter c follows the general pattern of the hourly mean wind speed of each station (see Fig. 3). For all stations the relevant maximum value of c is observed early at noon.

Table 4 refers to the monthly distributions of the parameters *k* and *c*, showing that the urban stations (TEI and SOUDA) exhibits lower values of the parameters, while the higher values are observed in the rural stations of PLATANIAS, MALAXA and PBK. The values of the scale parameter c are almost proportional (equal) to the mean wind speed, exhibiting a similar seasonal variation. The suitability of the distribution is also judged by the conformity between the observed and the calculated monthly and annually average wind speeds and standard deviation.

The results show that PBK is the most ‘windy’ station, with the largest scale parameter *c*, and its most probable wind speed being 5.8 m/s; Platanias has the most ‘peaked’ Weibull wind distribution with the highest shape parameter *k*, and with its wind speeds tending to be very close to 3.5 m/s (the most probable wind speed).

From the above analysis, an obvious conclusion is that the fitted Weibull distribution function and its two parameters are dissimilar for different locations, even if the sites are geographically proximate. As a result it is very important to choose a suitable site with a wind field sufficient for wind power generation.

Table 4: Weibull monthly parameters c and k, experimental (WS) and theoretical Weibull ($WS_w$) mean wind speeds for each station.

| STATION | PARAMETERS | AUG | SEP | OCT | NOV | DEC | JAN | FEB | MAR | APR | MAY | JUN | JUL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Malaxa | c (m/s) | 4.41 | 4.04 | 3.65 | 6.03 | 3.81 | 5.03 | 6.53 | 5.22 | 5.74 | 5.34 | 3.88 | 5.00 |
| | k | 1.93 | 2.11 | 2.05 | 1.68 | 1.82 | 1.82 | 1.86 | 1.56 | 1.85 | 1.87 | 1.90 | 1.90 |
| | WS (m/s) | 3.89 | 3.57 | 3.22 | 5.37 | 3.37 | 4.45 | 5.76 | 4.66 | 5.08 | 4.72 | 3.43 | 4.40 |
| | $WS_w$ (m/s) | 3.91 | 3.58 | 3.23 | 5.39 | 3.39 | 4.47 | 5.80 | 4.70 | 5.09 | 4.74 | 3.44 | 4.43 |
| Platanias | c (m/s) | 3.70 | 4.18 | 2.91 | 4.43 | 4.15 | 4.67 | 5.43 | 3.90 | 4.59 | 3.64 | 3.27 | 3.61 |
| | k | 2.49 | 2.00 | 2.10 | 2.06 | 2.51 | 1.78 | 2.64 | 1.92 | 1.91 | 2.29 | 2.30 | 2.66 |
| | WS (m/s) | 3.28 | 3.69 | 2.57 | 3.92 | 3.67 | 4.12 | 4.83 | 3.45 | 4.06 | 3.23 | 2.90 | 3.21 |
| | $WS_w$ (m/s) | 3.28 | 3.70 | 2.58 | 3.93 | 3.68 | 4.16 | 4.83 | 3.46 | 4.07 | 3.23 | 2.89 | 3.21 |
| PBK | c (m/s) | 5.66 | 5.87 | 4.73 | 8.08 | 5.14 | 6.78 | 9.47 | 6.29 | 8.20 | 7.31 | 4.91 | 6.37 |
| | k | 1.66 | 1.68 | 1.38 | 1.84 | 1.43 | 1.35 | 2.34 | 1.57 | 1.58 | 1.63 | 1.68 | 1.79 |
| | WS (m/s) | 5.07 | 5.25 | 4.36 | 7.17 | 4.66 | 6.20 | 8.40 | 5.64 | 7.37 | 6.52 | 4.40 | 5.64 |
| | $WS_w$ (m/s) | 5.06 | 5.25 | 4.36 | 7.18 | 4.67 | 6.22 | 8.39 | 5.65 | 7.36 | 6.54 | 4.39 | 5.66 |
| Souda | c (m/s) | 2.48 | 2.31 | 1.74 | 2.26 | 1.40 | 1.91 | 2.38 | 2.23 | 2.83 | 2.73 | 2.28 | 2.77 |
| | k | 1.58 | 1.62 | 1.50 | 1.53 | 1.67 | 1.51 | 1.59 | 1.35 | 1.59 | 1.54 | 1.50 | 1.58 |
| | WS (m/s) | 2.22 | 2.05 | 1.56 | 2.02 | 1.25 | 1.71 | 2.12 | 2.04 | 2.53 | 2.45 | 2.06 | 2.48 |
| | $WS_w$ (m/s) | 2.23 | 2.07 | 1.57 | 2.03 | 1.25 | 1.72 | 2.14 | 2.05 | 2.53 | 2.46 | 2.06 | 2.49 |
| TEI | c (m/s) | 2.60 | 3.05 | 2.74 | 3.76 | 2.67 | 3.41 | 4.25 | 2.94 | 3.75 | 2.70 | 2.44 | 2.62 |
| | k | 1.68 | 1.71 | 1.40 | 1.70 | 2.08 | 1.51 | 2.10 | 1.67 | 1.55 | 1.56 | 1.84 | 1.66 |
| | WS (m/s) | 2.31 | 2.71 | 2.48 | 3.34 | 2.35 | 3.04 | 3.75 | 2.61 | 3.36 | 2.42 | 2.16 | 2.33 |
| | $WS_w$ (m/s) | 2.32 | 2.72 | 2.50 | 3.36 | 2.36 | 3.07 | 3.76 | 2.63 | 3.37 | 2.43 | 2.17 | 2.34 |

## 4. Conclusions

In the present study, hourly averaged measurements of wind speed and direction from five meteorological stations have been statistically analyzed. The data used in the calculations was collected for the purpose of studying the wind field in the broader area of Chania. The probability density distributions have been derived from the observed data and the distributional parameters were identified. The Weibull model has been fitted to the measured probability distributions on an annual and monthly basis. The fitting of the distribution to the experimental data is considered to be satisfactory with low relative errors of the mean value and variance. The values of the scale parameter c exhibit seasonal variations, following the general features of the Chania wind regime.

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