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Spatial and temporal variability of wind speed and energy over Greece

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1. Abstract-Introduction

To appraise the wind potential over Greece we analyse the main statistical properties of wind speed through time. To this end, we use 66 time series from 1932 to 2013 on daily and monthly time scale and examine the spatial variability of wind speed over Greece. To depict the main statistical behaviour and potential of the wind over Greece, maps have been created illustrating the basic statistical characteristics of wind speed on monthly to annual time scale (sections 2-8). Furthermore, we propose a daily stochastic climacogram-based model as well as a reliable probability function. We also estimate the energy production for a given location and wind park, based on the installed turbine's power curve and we compare it with the actual hourly energy output connected to the grid (section 9). Finally, we explore a methodology to simulate wind energy production in a stochastic framework. In that context we generate hourly wind speed synthetic data using a modified Bartlett-Lewis model implemented in HyetosR package, after analysing wind speed for a different site (sections 10-11). The results of our analysis offer an improved overall picture of wind speed variability over Greece and help us clarify to which extent HyetosR package is applicable in the stochastic generation of wind speed time series.

2. Study area and data

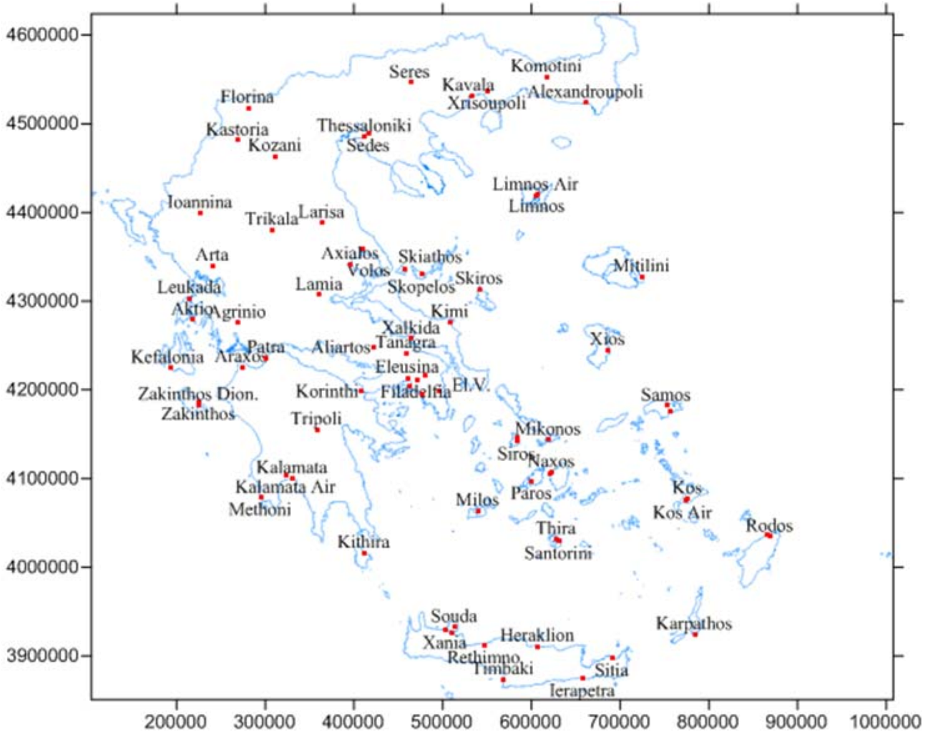

Fig. 1: Data stations that participate in process (Dimakos, 2014).

The above mentioned (Fig.1) depicts data stations used in statistical-stochastic process. Data were extracted from the site: http://www.ncdc.noaa.gov/cdo-web/ which is an open data source site. In many cases observations (Fig. 2) were dated back to 1932, with missing values at the period 1940-1950, due to war in Greece at that period.

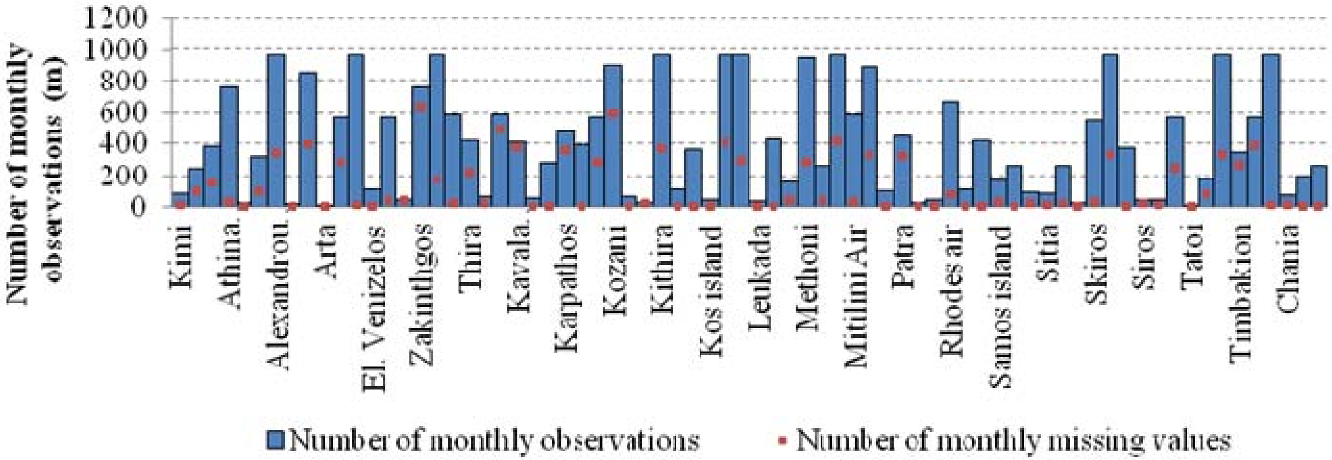

Fig. 2: Number of observations at monthly time scale, along with the missing values at each station (Dimakos, 2014).

3. Mean wind speed (m/s) over Greece

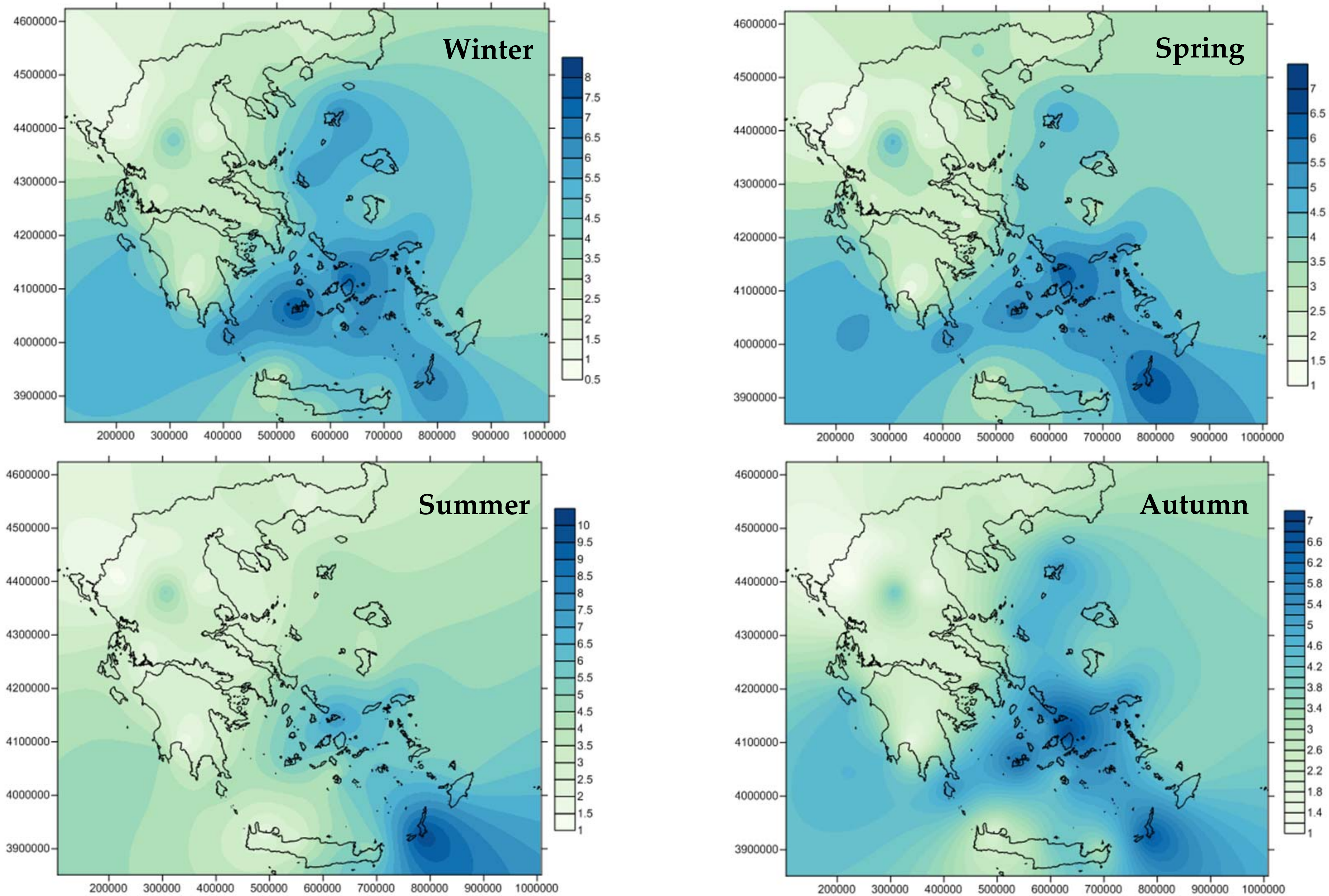

Fig. 3: Seasonal mean wind speed (m/s), over Greece (Dimakos, 2014).

4.Standard deviation of wind speed over Greece

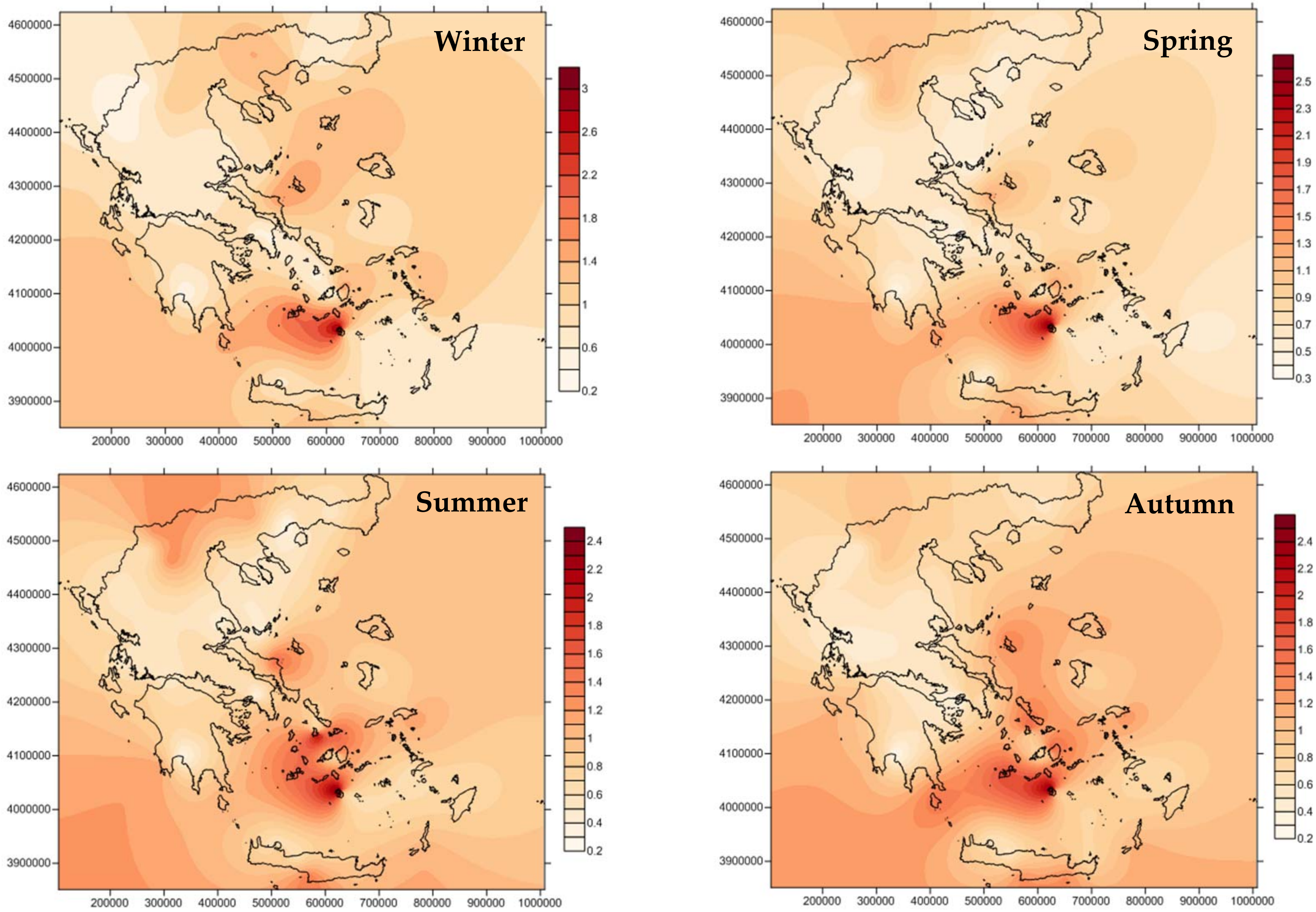

Fig. 4: Seasonal standard deviation of wind speed (m/s), over Greece (Dimakos, 2014).

5. Wind speed and direction over Greece

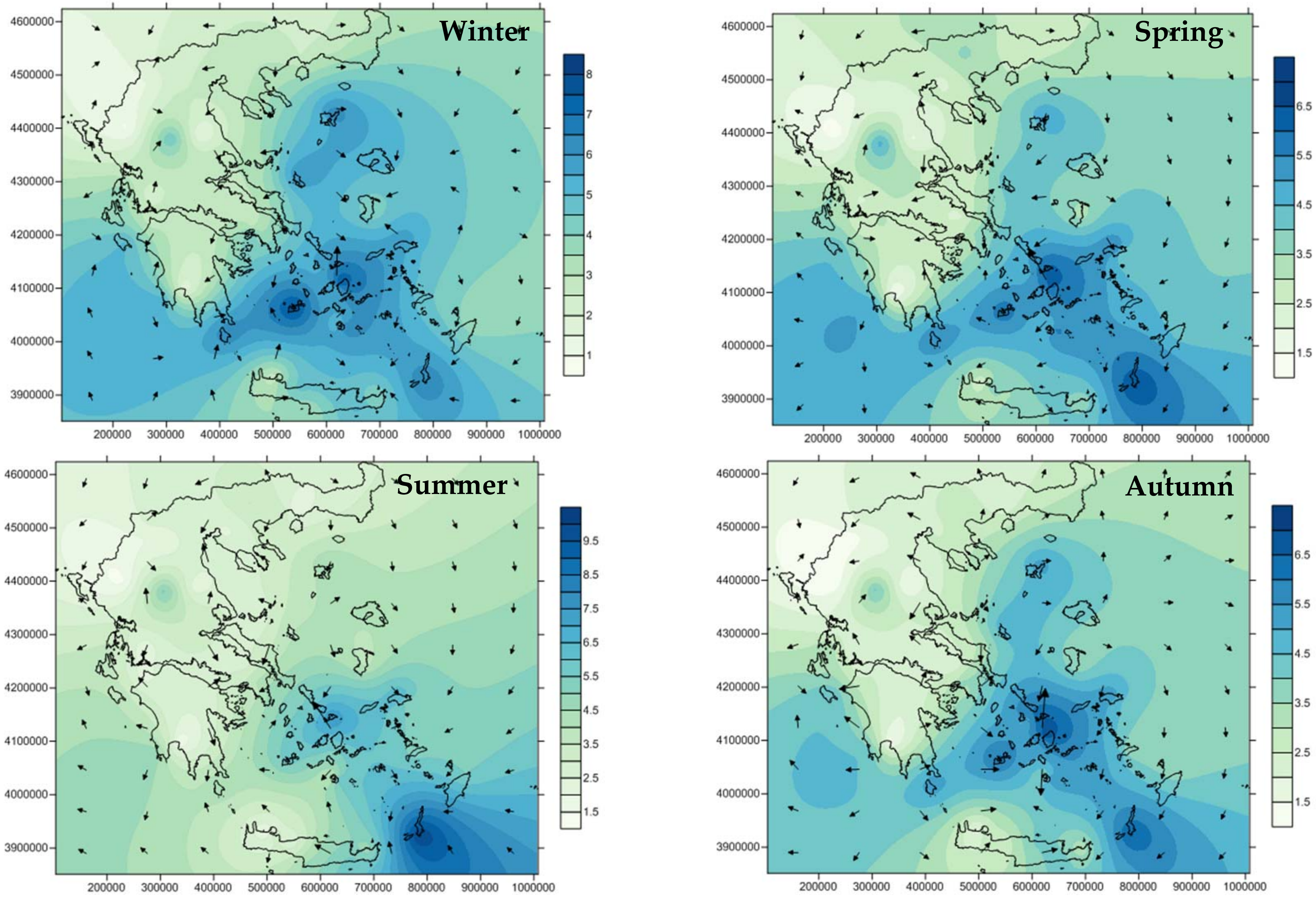

Fig. 5: Seasonal direction of wind speed in degrees (°) over Greece (Dimakos, 2014).

6. Relationships between wind speed and gust

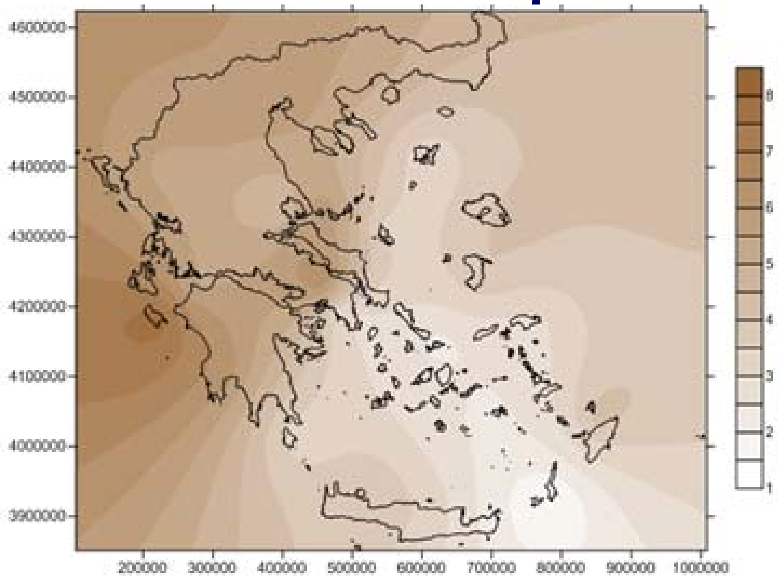

Fig. 6: Ratio of mean gust over wind speed at the same day (Dimakos, 2014).

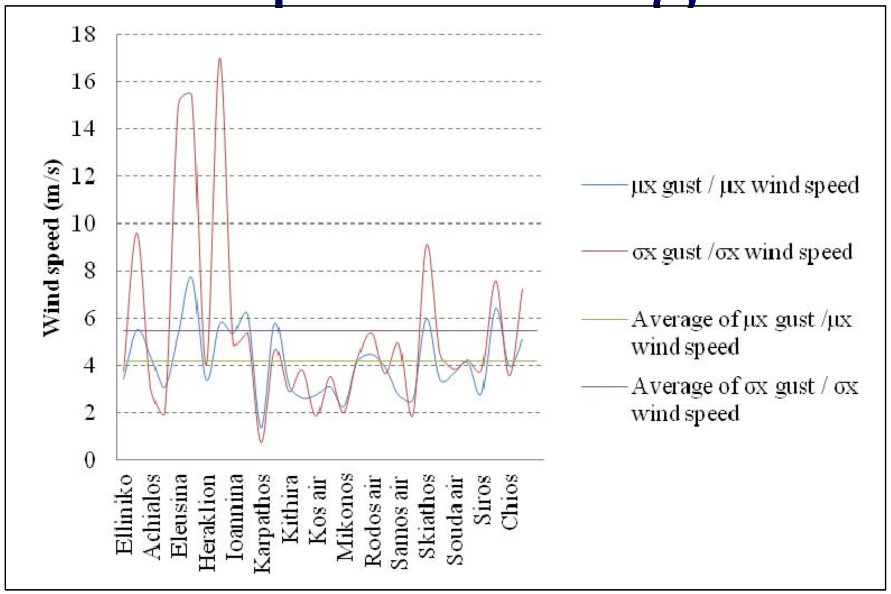

Fig. 7: Mean gust is 2 to 8 times larger than wind speed (Dimakos, 2014).

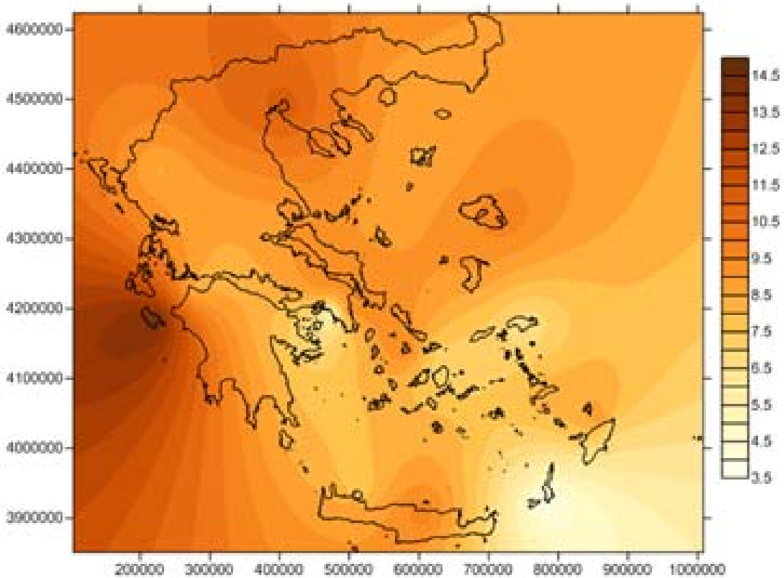

Fig. 8: Difference of mean gust and wind speed at the same day in m/s (Dimakos, 2014).

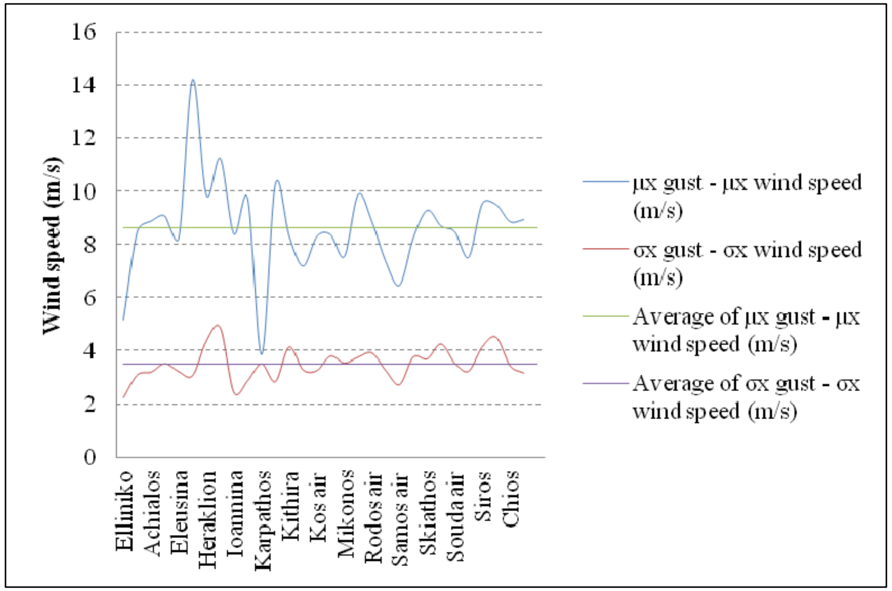

Fig. 9: Range between differences is 4 to 14 m/s (Dimakos, 2014).

7. Modelling wind speed with climacogram

To draw conclusions for the entire country the 10 most representative stations were selected (based on missing values, sample size and spatial dispersion criteria). Climacograms were constructed, from the monthly standardized samples (to remove the wind cyclo-stationarity), in order to investigate the stochastic behaviour of wind speed (e.g. long-term persistence through the Hurst coefficient). They appear to have a relatively similar log-log slope, even at large time scales, which are consistent with a constant value *H = 0.75* for the entire region of Greece (Dimakos, 2014). The aggregated variance was calculated by its classical estimator (Eq. 1, 2) which is shown to be a more reliable estimator than the e.g. autocovariance function (as demonstrated in Koutsoyiannis, 2013).

$$\mathrm{E}[\underline{\hat{\gamma}}(\Delta)] = \eta(\Delta, T)\gamma(\Delta) \tag{1}$$

$$\eta(\Delta, T) = \frac{1 - \gamma(T)/\gamma(\Delta)}{1 - \Delta/T} \tag{2}$$

$\mathrm{E}[\underline{\hat{\gamma}}(\Delta)]$: expected value of the classical estimator of the aggregated variance

$\eta(\Delta, T)$: bias coefficient

T : sample size

Δ : aggregated temporal scale

8. Application (Alexandroupoli station)

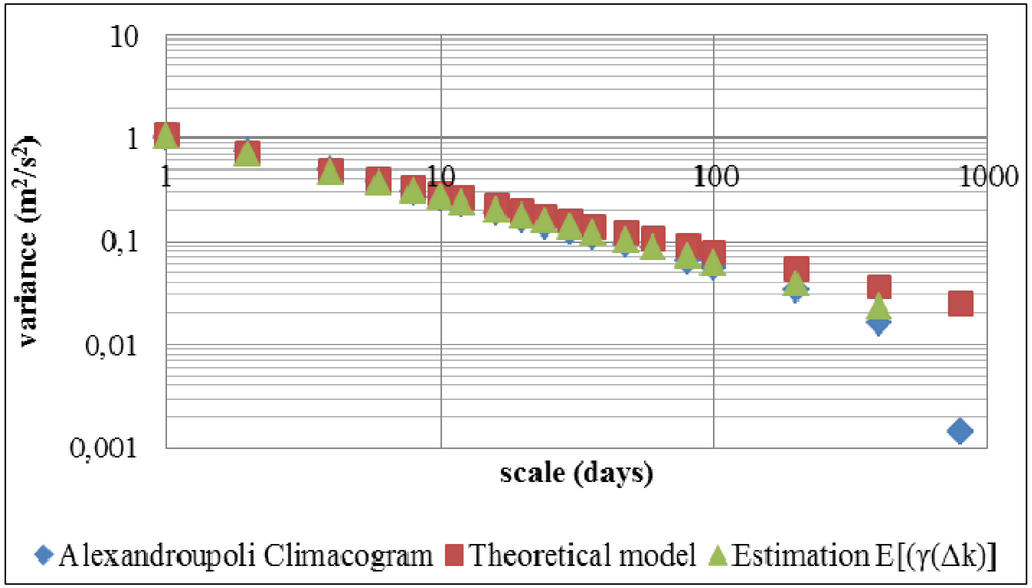

Fig. 10: Fitted the classical estimator of variance to the empirical one (Dimakos, 2014).

Fig. 10 shows the climacogram at Alexandroupoli station (blue diamonds) as well as the aggregated variances from the proposed true model (red squares) $\gamma(\Delta k) = \gamma_0\,(\Delta k)^{-(2H-2)}$, and its expected value (green triangles).

It was observed that the Weibull pdf best fitted to the empirical ones of all the available stations compared to others (e.g. Gamma, Log-Normal). However, this was not the case for the Alexandroupoli station (Fig. 11) where the Log-Normal best fitted the empirical pdf. For the pdf analysis and fitting the Hydrognomon open source software was used.

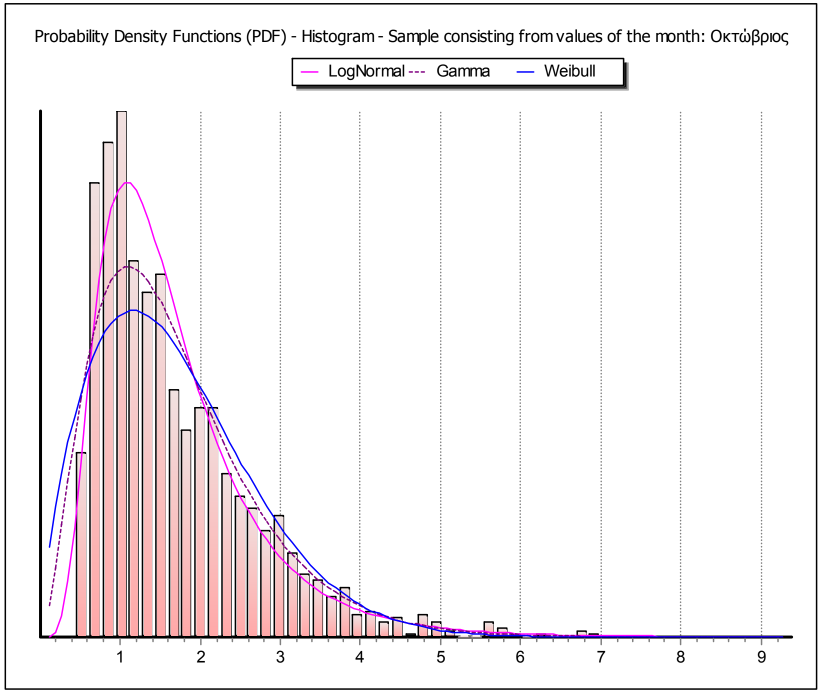

Fig. 11: Fitted probability density functions (pdfs), Dimakos (2014).

9.Comparison between observed and theoretical energy production (in MWh) at Kefalonia

In order to compare theoretical energy output to the actually produced one, we examined 5 years of hourly historical data produced by a wind park connected to the national electrical grid (with a 30 MW installed capacity) and located at the island of Kefalonia in Greece (Pappa, 2014). To estimate the theoretical energy output, historical wind speed data (in m/s) was obtained from the Kefalonia meteorological station, located at distance of 20 km from the wind park. Observed wind speed data were analyzed using MLE to fit the Weibull distribution that seemed to be the most suitable from the examined ones (Mean Absolute Error = 4% of annual mean wind speed).

The wind turbine installed at the specific wind park is type ENERCON E-82. Daily estimated production was determined for both historical and theoretical wind speed data (generated from a Weibull distribution) based on the turbine's power curve.

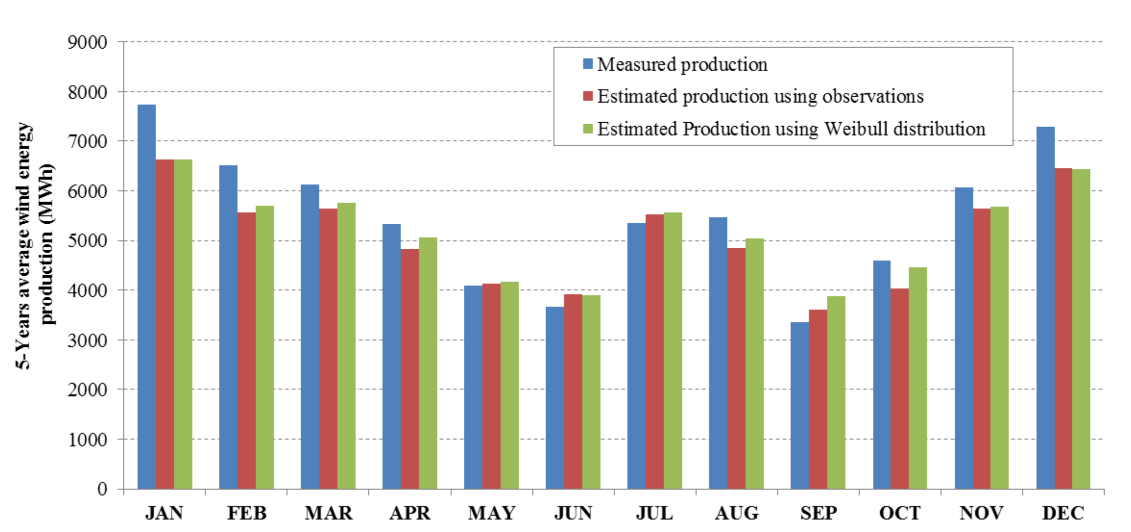

Fig. 12: Comparison between measured and estimated energy production (in MWh), using empirical and theoretical (Weibull) distributions applied to the selected wind turbine power curve (Pappa, 2014).

10. Synthetic time series generation via Bartlett-Lewis model

Model assumptions (like in Rodriguez-Iturbe *et al.*, 1987 for rainfall):

- **Cluster origins**, t_i, occur in a Poisson process, with rate λ
- **Cell origins**, t_{ij}, occur in a Poisson process, with rate β
- **Cell arrivals** terminate after v_i, exponentially distributed (parameter γ)
- **Cell durations**, w_{ij}, exponentially distributed (parameter η)
- **Cell intensities**, x_{ij}, either exponentially or gamma distributed

In the modified version (Rodrigez-Iturbe et al., 1988; Onof & Wheather, 1994), η is assumed gamma distributed, with scale parameter v and shape parameter α, and varies for each cluster, such as the ratios β/η and γ/η remain constant (see in Dimas, 2013).

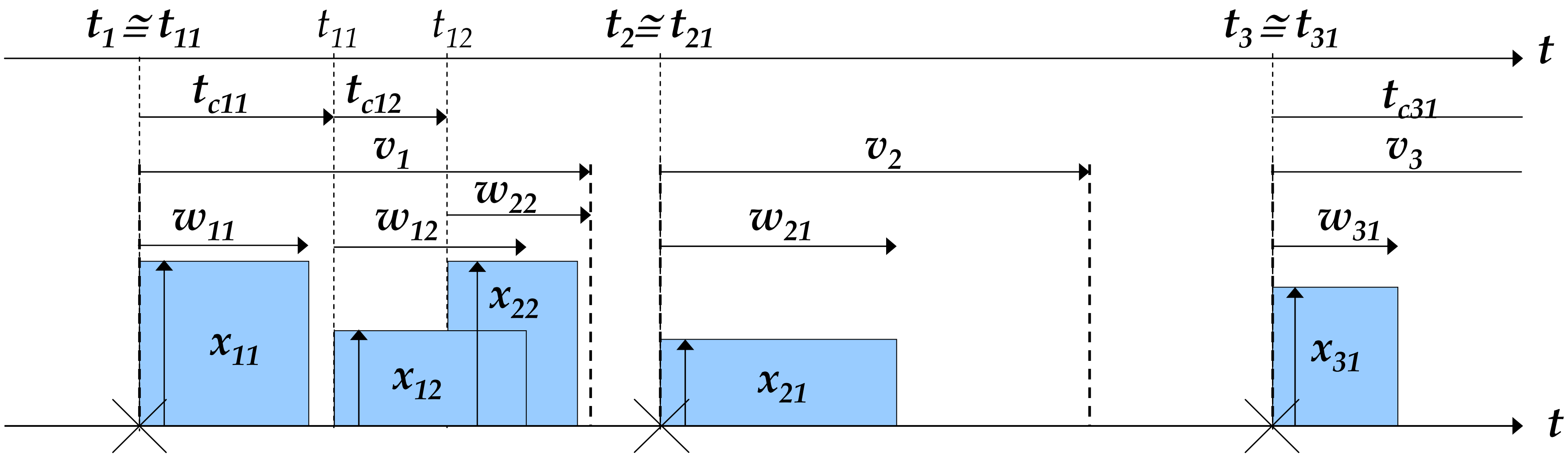

Fig. 13: Mathematical scheme describing the implemented modified Bartlett-Lewis model (Dimas, 2013).

11. Simulation of wind energy production

We generated 10^3 years of hourly wind speed data using a modified Bartlett-Lewis model implemented in **HyetosR.** Historical wind speed data were retrieved from the Kilkis meteorological station (Fig. 14). We note that HyetosR is typically employed for stochastic simulation of hourly rainfall, whose key characteristic is **intermittency** expressed in terms of probability dry (i.e. absence of rain). In this context, the model generates subsequent rainfall events instead of continuous time series. To overcome this characteristic, instead of the original wind speed, w_t, we accounted for the one above threshold, w_0, i.e. $w_t^* = w_t - w_0$, where w_0 is the minimum required value for the activation of the selected wind turbine (7.5 MW, Enercon E-126). Based on its power curve, we calculated the hourly time series of wind energy, as a function of simulated w_t (Fig. 15).

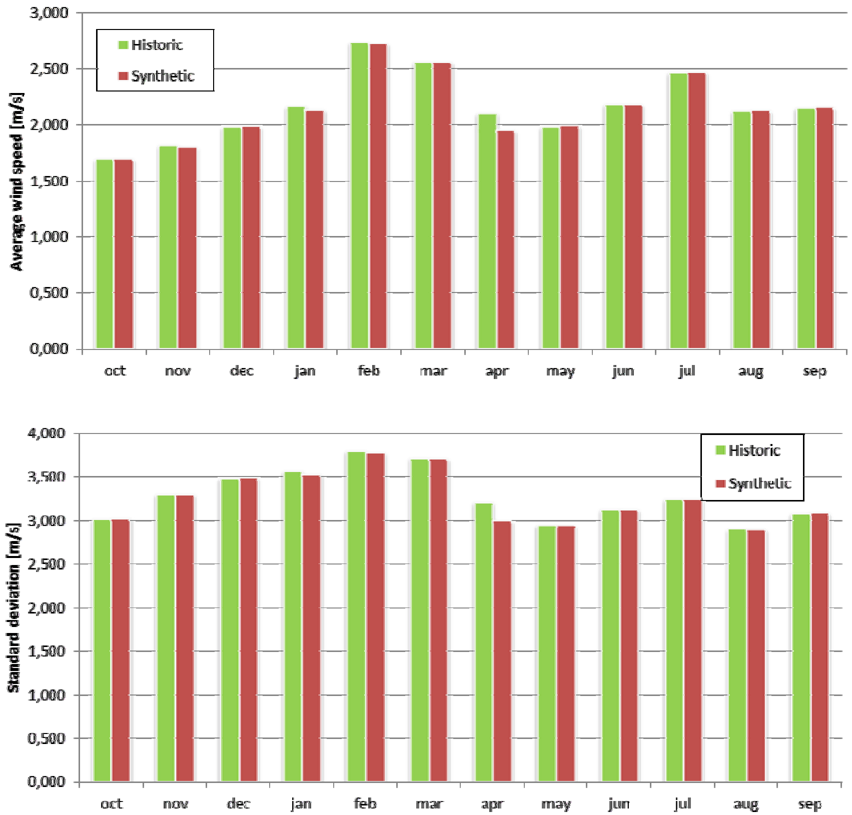

Fig. 14: Comparison of historical and simulated monthly mean values and st. deviations of wind speed (w), Dimas (2013).

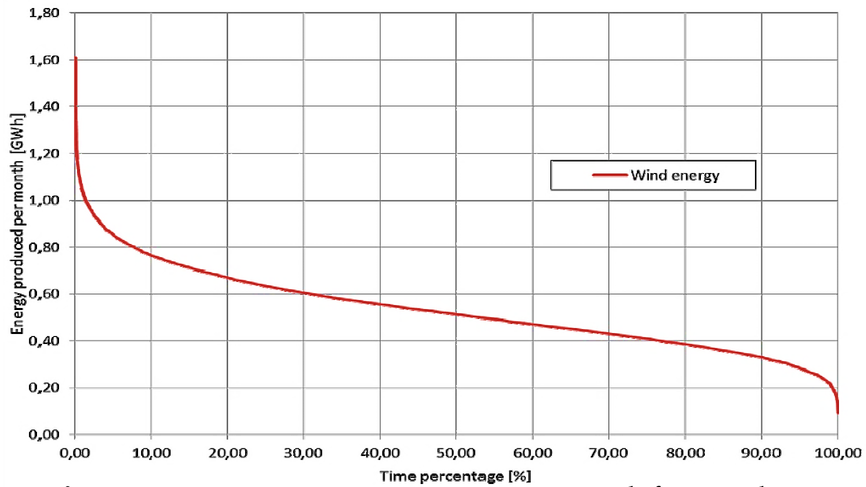

Fig. 15: Duration curves extracted from the simulated wind energy time series (Dimas, 2013).

12. Conclusions

- Over Greece, the wind speed is highest at the central Aegean and specifically during the summer season, with values greater than 10 m/s.
- The dominant wind over Greece is north; specifically, during winter north, northeast and north-west directions dominate at 45% of Greece (in February 58%).
- Wind gust appears to be 2 - 8 times greater than the daily mean wind speed.
- The wind speed process is consistent with long-term persistence with Hurst coefficient almost constant over Greece, with an estimated $H = 0.75$.
- Estimated energy production, derived from wind speed observations fitted to a Weibull distribution (using the MLE) for the site of Kefalonia, appeared to describe efficiently the actually produced energy.
- Synthetic time series at hourly time scale were generated with the Bartlett-Lewis model implemented in **HyetosR**; a case study for the area of Kilkis showed that the model reproduced efficiently the statistical characteristics of historical data.
- The methods applied provide a good framework to describe the large spatial and temporal wind variability, and model the implied uncertainty with respect to the wind energy production and management over Greece.

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