Mathematical and physical models for the estimation of wind-wave power potential in the Eastern Mediterranean Sea

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Abstract. A new system developed for the accurate estimation of wind and wave power potential in the area of Eastern Mediterranean Sea is presented in this work. Numerical simulation models in conjunction with statistical techniques are utilized. The numerical systems used are based on high resolution models able to resolve in detail the evolution of the environmental parameters that affect the wind-wave power potential. Moreover, dynamical statistical tools (Kalman filters) and recent advances in a relatively new branch of mathematics the Information Geometry are proposed for the bias correction in the modeled data.

Keywords: Wind and wave power, numerical modeling, Kalman filters, Information Geometry.

1 Introduction

In the last decades, the estimation and monitoring of renewable energy resources are in the front line of interest of the scientific and technical community worldwide since a variety of important issues that surpass the borders of pure scientific research are affected. In the present work a high resolution study for the wind and wave energy potential is presented for the area of Eastern Mediterranean Sea focusing especially in the Levantine Basin and the Aegean Sea area. An integrated atmospheric-wave modeling system is utilized and ten year (2001-2010) simulation runs are performed. Observations from different sources (meteorological stations, buoys and satellites) are assimilated into the models for improving the initial conditions used ([3], [6]). The relevant outcomes are analyzed by means of a complete statistical system employing conventional statistical measures, probability distribution fitting tools, as

E. Pardo-Igúzquiza et al. (eds.), Mathematics of Planet Earth, 5
Lecture Notes in Earth System Sciences, DOI: 10.1007/978-3-642-32408-6_123,

well as postprocessing modules based on Kalman filters for the elimination of possible systematic biases. For the latter, new advances obtained from the Information Geometry framework are utilized providing new ideas on the way that the discrepancies between model and observed data should be measured.

2 The modeling systems employed

Two state of the art atmospheric models are employed performing simulations for a ten year period (2001-2010): The Skiron/Eta regional forecasting system ([5]) and the open source atmospheric model WRF ([9]). The former has been developed at the University of Athens by the Atmospheric Modeling and Weather Forecasting Group. It is based on the Eta/NCEP model and consists of a full physics non-hydrostatic model with sophisticated convective, turbulence and surface energy budget scheme. The horizontal resolution used for the present study was 0.05 x 0.05 degrees covering the whole Mediterranean region while 45 vertical levels up to 50hPa have been utilized. Initial and boundary conditions are obtained from a high-resolution reanalysis (15 x 15 Km). On the other hand, the WRF model has been a collaborative partnership between NCAR, NOAA-NCEP, US military laboratories and Universities. It is a numerical weather prediction system suitable for a broad spectrum of applications from meters to thousands of kilometers. For the present study a horizontal resolution 0.02 x 0.02 degrees over the area of interest have been applied with 35 vertical levels up to 50hPa. Initial and boundary conditions are obtained from the GFS high-resolution reanalysis (15 x 15 Km).
The wave parameters that are necessary for the estimation of wave power monitoring are simulated by the wave model WAM ([7]). This is a third generation wave system that solves the wave transport equation with-out any presumptions on the shape of the 2d (frequencies/angular) wave spectrum. For the present study, the ECMWF version, CY33R1 ([2]), has been adopted. The horizontal resolution used for the wave model's simulations were 1/60x1/60 degrees, while the wave spectrum was discretized in 25 frequencies and 24 directions.
The estimation of the wind and wave power potential over the areas of interest is based on the following formulas:

$$P_{wind} = \frac{1}{2} p v^3 \quad [W] \qquad P_{wave} = \rho g \int_0^{2\pi} \int_0^{\infty} f^{-1} E(f,\theta) df d\theta = \frac{\rho g^2}{64\pi} \mathrm{H}_s^2 T_e \quad [W/m] \tag{1}$$

([8]) where p stands for the wind and ρ the water density, v for the wind speed, $E(f,\vartheta)$ denotes the two dimension wave spectrum, Hs the significant wave height, Te the wave period and g the gravity acceleration.
In addition to the above modeling systems and targeting to the elimination of biases that numerical simulation systems usually exhibit when focusing on local applications, a postprocess module has been developed. It is based on a non-linear version of Kalman filter ([3]) that estimates the bias of the modeled data as a polynomial of the modeled parameter:

$$y_i = a_{0,i} + a_{1,i} \cdot m_i + a_{2,i} \cdot m_i^2 + a_{3,i} \cdot m_i^3 + \ldots + \varepsilon_i \tag{2}$$

where m_i denotes the direct output of the model and y_i the corresponding bias. The estimation of the involved covariance matrices ([3], [6]) is based on new techniques that have been developed within the framework of Information Geometry. The latter recognizes the distributions of modeled and corresponding recorded data as statistical manifolds categorized in non-Euclidean spaces ([1]). In this context, the underlying geometry may differ significantly from the classical one and the distances between the data sets – the discrepancies of the models – are estimated by minimum distance curves (geodesics) avoiding simplifications adopted by the classically used least square methods. A detailed presentation of this approach can be found in [4].

3 Statistical Analysis – Results.

The statistical analysis of the modeled results for the wind/wave power outputs and the environmental parameters that affect their evolution, is based on a variety of statistical measures including average values, deviation and asymmetry measures as well as the kurtosis (the fourth moment of the data), providing information for the most frequent values, their expected deviation but also for the exposure of the data under study to extreme events. On the other hand, the model outputs and the corresponding observations have been studied by a probability density function (pdf) point of view: This approach gives the full package of information and is further exploited in order to estimate the discrepancies between modeled and observed data using techniques of Information Geometry, as mentioned in the previous section.
Some indicative results are presented in figures 1, 2. The former depicts the 10-year main wave statistical parameters over the Cyprus sea areas, while the latter provides the full package of the statistical analysis at a point in Aegean Sea (Cyclades islands).

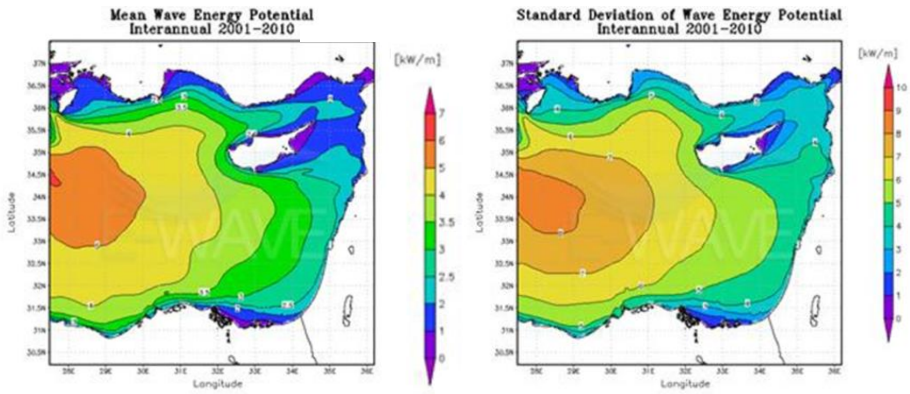

Figure 1. Mean values and deviation of wave energy potential in the Levantine Basin

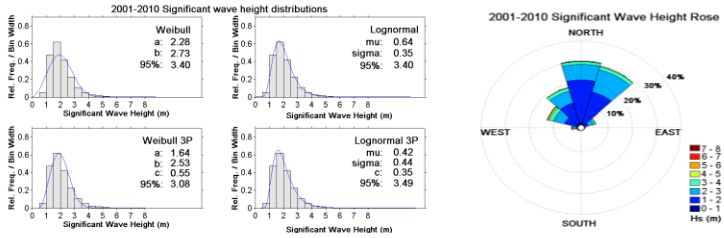

Figure 2.The analysis of the significant wave data for a central Aegean point

The south-western sea area of Cyprus seems to keep the primary role in wind and wave power potential being exposed to long period waves (swell) that favor rather smooth evolution of the wave power with low exposure to extreme events and available amounts of energy even in the absence of winds. On the other hand, the Aegean Sea is a wind dominated area where the wind and wave power potential are closely related.

Acknowledgment. This work has been supported by the Research Program "Development and application of new mathematical and physical models for monitoring the wind and sea wave energy potential" funded by the Greek Secretariat of Research and Technology.

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