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EastMed Symposium Agenda
Regional Cooperation in Eastern Mediterranean Sea Research
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THE FRAMEWORK

• Renewable energy resource assessment is a primary target today for EU Member States especially under the warnings of the scientific community concerning global warming and the new framework set by the recent economic crisis

• Analyses and studies focusing on more than one “clean” energy sources are of particular interest since different questions/problems can be addressed:
  • Monitoring the renewable energy potential spatially and temporally
  • Quantifying and reducing the variability of the available energy supporting the optimal integration to the general grid
THE FRAMEWORK

• Demands in this framework are becoming more and more important for both designing and operational phases.

• Regularly, data sets and analysis supporting this type of activities are not available from the existing governmental agencies, such as Met Offices.

• Such information can be provided only by specialized groups with interdisciplinary type of knowledge and tools based on state-of-the-art monitoring equipment and numerical systems.
• In the present work recent actions/projects on the monitoring and analysis of wave energy potential with particular emphasis to the area of Eastern Mediterranean Sea are discussed.

• A hybrid/multi-parametric approach is adopted based on
  - high resolution numerical atmospheric-wave modeling and
  - non-conventional statistical techniques
Wave Energy – A new challenge

- It’s easier adopted to the general grid due to its continuous behavior.
- Wave power may be produced even in the absence of local winds by exploiting swells.
- Ecological damages or consequences appear negligible.
- Wave energy has the potential to meet a significant proportion of Mediterranean Sea energy demands:

  The International Energy Agency states that ocean energy has a potential to reach 3.6 GW of installed capacity by 2020 and close to 188 GW by 2050.

  The global wave power resource has been estimated as around 2.1 TW.

New technologies allow the exploitation of the energy from waves, currents and sea surface winds.
Mathematical and Physical Models for the Estimation of Wave Energy Potential

Wave Power Estimation

The available (theoretical) Wave Energy Power density potential is estimated by

\[ P_w = pg \int_0^{2\pi} \int_0^\infty f^{-1} E(f, \theta) df d\theta = \frac{pg^2}{64\pi} H_s^2 T_e \quad [W/m] \]

where

\( E(f, \theta) \) is the 2-dimensional wave spectrum,
\( H_s \) the significant wave height and
\( T_e \) the mean energy wave period.

This was the main target of three recent European projects:
Wave Power Estimation

The tools

- State of the art *atmospheric-wave prediction system* targeting at the high resolution monitoring/estimation of the sea state characteristics, essential for the energy potential.

- Novel advanced *statistical systems* for the local adaptation of the results of the models and the estimation of energy distribution.
The models used

**Atmospheric model SKIRON**

- Horizontal Resolution: 0.05° x 0.05°
- Time-step: 15 seconds
- 45 vertical levels up to 50 hPa
- Initial and boundary conditions:
  - High-resolution reanalysis (15x15Km)
- Output at: \{10, 40, 80, 120, 180\} m
- Full set of meteorological variables

**Wave Model WAM**

- Domain: (20–75°N, 50°W–30°E)
- Resolution: 0.05° x 0.05°
- Number of frequencies: 25
- Minimum frequency: 0.055 Hz
- Number of directions: 24
- Grid points: 1601 x 1101
- Spectral output at selected locations
- Integrated parameters at every grid point: Hs, Te, Swell, Maximum wave
The numerical models used: The new parallel version of the wave model WAM

- The OC-UCY in cooperation with the UOA/AM&WFG has adopted the latest version of the new WAM model from the ECMWF (parallel version).
- A new advection scheme (Corner Transport Upstream) has been adopted providing a more uniform propagation in all directions.
- For the E-wave project the wave model’s domain cover the whole east Med region in order to capture all the swell information that could reach the study area (Levantine Basin).

<table>
<thead>
<tr>
<th>Wave model Characteristics</th>
<th>WAM ECMWF CY33R1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model’s domain</td>
<td>East Mediterranean (30N – 41N, 15E – 37E)</td>
</tr>
<tr>
<td>Study area</td>
<td>Levantine</td>
</tr>
<tr>
<td>Horizontal Resolution</td>
<td>1/60 x 1/60 degrees (0.01667 km approximately)</td>
</tr>
<tr>
<td>Frequencies</td>
<td>25 (range 0.0417-0.54764Hz logarithmically spaced)</td>
</tr>
<tr>
<td>Directions</td>
<td>24 (equally spaced)</td>
</tr>
<tr>
<td>Timestep</td>
<td>45 sec</td>
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</tbody>
</table>
Wave Model Direct Outputs

- Significant Wave Height & Direction
- Maximum Expected Wave Height
- Swell Height and Direction
- Wind driven wave height and Direction
- Mean & Peak Wave Period
- Wind Speed & Direction at sea level
- Wind and Swell frequencies for the two dominant spectrum components
- Full wave spectrum at selected grid points
Evaluation of the wave predictions

The evaluation results against independent observations from a wave buoy at the eastern coast of the Mediterranean (area of Hadera port, Israel) prove excellent accuracy of the modeling system.

<table>
<thead>
<tr>
<th>Stats</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Bias (m)</td>
<td>-0.09</td>
</tr>
<tr>
<td>RMSE (m)</td>
<td>0.32</td>
</tr>
</tbody>
</table>
Evaluation of the wave predictions

The evaluation results against independent observations from a wave buoy and against available satellite records prove excellent accuracy of the modeling system.

<table>
<thead>
<tr>
<th>Test Case</th>
<th>WAM – Buoy</th>
<th>WAM – Satellites</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean BIAS</td>
<td>RMSE</td>
</tr>
<tr>
<td>Test Case 1</td>
<td>0.05</td>
<td>0.16</td>
</tr>
<tr>
<td>Test Case 2</td>
<td>0.28</td>
<td>0.33</td>
</tr>
<tr>
<td>Test Case 3</td>
<td>0.10</td>
<td>0.29</td>
</tr>
<tr>
<td>Test Case 4</td>
<td>0.19</td>
<td>0.42</td>
</tr>
</tbody>
</table>
Wave Resource Assessment-Methodology

Resource analysis identifying “hot spots” areas
- Wave conditions (Hs, T, θ)
- High spatial and temporal resolution statistical analysis
- Temporal variability of wave parameters at different time scales
  - Annual
  - Seasonal
  - Monthly
- Statistical indexes for the asymmetry and the impact of non frequent values
- Multivariate distribution fitting
Wind – Wave climatology

• The results obtained from a 10y high resolution simulations provide important information for the wind-wave climatology of the areas under study.
• Estimations can be made on the spatial and temporal distribution of wind-wave power potential.
Wind – Wave climatology

- The wind speed keeps interesting values over Aegean Sea even in summer due to the etesian winds.
- The areas of increased interest are located over the two sides of Crete and in a central tunnel crossing the Aegean from north to southeast.
- The significant wave height is considerable even in the west parts of Greece due to the prevalence of swell, coming from central and southern parts of the Mediterranean Sea.
- The swell dominated southwestern areas of the Greek seas seem to keep the primary role in wave energy potential.
Wind - Wave climatology: Is it enough for supporting efficiently the resource assessment?

More statistical measures should be taken into account

**Statistical measures** for the **asymmetry** and the **kurtosis** of the data could be essential

- **Skewness** (3rd standardized moment) provides information for the tails of the distributions
- Areas with potential impact from extreme values can be spotted based on the **kurtosis** (4th standardized moment)
The results of the E-Wave project indicate higher values for the two sea state parameters (Hs and Te) that mainly affect the wave energy estimation, in the west and south offshore Cyprus EEZ.
The impact of extreme/non-frequent values of the sea state is limited, as revealed by the low kurtosis (4th statistical moment) values.
The use of the E-wave project results for the wave energy potential combined with other area characteristics, as for example the bathymetry, provide information of added value to the decision makers and the industry involved in the energy sector.
Wave Power Mapping using the characteristics of specific wave platforms

The use of Hs/Te power transform matrices are utilized for estimating the wave power potential over the Marina Platform domain (Hs, Te) - surfaces are developed and compiled into the 10y-data base.

Some classical myths are shaken down:

Pelamis can be used in Med Sea too.

The Med coast of France seems to be comparable with the most energetic Atlantic coastline, a trend not visible in the theoretical resource.
On site statistical analysis

The time distribution of crucial parameters over the whole 10y study period may reveal trends and (seasonal or other) periodicities.
On site statistical analysis

- Weibull distribution could be a good choice for fitting wind speed and significant wave height values but Lognormal 3P provides an interesting alternative with even more better convergence.

- Thresholds for extreme values are equivalently estimated by the two pdfs as the corresponding 95-percentiles.
Different local wave climatology is depicted in the bivariate plots describing the joint probability distribution of Hs and Te; a statistical information of primary importance for wave energy estimation.
Wave Power Potential distribution

- The wave energy potential can be also studied by a probability distribution fitting point of view.

- For the present study, a series of independent statistical tests proved that the Lognormal distribution optimally fits the modeled data.

- Equally good fit can be also succeeded by the Generalized Extreme Value pdf.

- The corresponding parameters have a non trivial spatial distribution and provide information of potential value for grid designers and researchers.
The new Wave Model WAM – Evaluation study of the Wave Currents Interaction with applications to wave power prediction

A decrease of the mean wave period is noticed as a consequence of the use of sea surface currents as a forcing in the wave model. These changes result in reduced wave power potential.

<table>
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<tbody>
<tr>
<td>Hs(m)</td>
<td>Energy Per(s)</td>
<td>Peak Per(s)</td>
</tr>
<tr>
<td>Mean</td>
<td>1.08</td>
<td>5.89</td>
</tr>
<tr>
<td>St. Dev.</td>
<td>0.78</td>
<td>1.47</td>
</tr>
<tr>
<td>Var. Coeff.</td>
<td>0.74</td>
<td>0.25</td>
</tr>
<tr>
<td>St. Error.</td>
<td>0.04</td>
<td>0.08</td>
</tr>
<tr>
<td>Skewness</td>
<td>1.76</td>
<td>0.43</td>
</tr>
<tr>
<td>Kurtosis</td>
<td>5.86</td>
<td>2.41</td>
</tr>
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</table>
Operational predictions of wave energy potential

An online operational wave energy system has been coupled with the CYCOFOS WAM and is available at:

www.oceanography.ucy.ac.cy/cycofos/offshore.html
Bias analysis and correction

- Numerical wind/wave models may result to systematic (or not) biases due to
  - intrinsic difficulties of the models in simulating subscale phenomena
  - local area’s peculiarities.

- Main ways out:
  - Assimilation
  - Optimization of the outputs of the models by using statistical techniques (MOS methods, Kalman filters)
  - The minimization of a “cost-function” that governs the evolution of the error is needed.
Bias analysis and correction

Kolmogorov-Zurbenko Filter:
An iterative moving average aiming at the removal of high-frequency variations in the initial data.

\[
x_i^1 = \frac{1}{2q+1} \sum_{j=-q}^q x_{i+j}^0, \quad MA = (2q+1)
\]

\[
x_i^2 = \frac{1}{2q+1} \sum_{j=-q}^q x_{i+j}^1
\]

Kalman Filter:
Simulates the temporal relation between observational and forecasted values and improves the latter at a following time.

\[
y_i^0 = a_{0,i} + a_{1,i} \cdot m_i + a_{2,i} \cdot m_i^2 + \ldots + a_{n-1,i} \cdot m_i^{n-1} + \varepsilon_i
\]

\[
y_i^0 = H_i[x^e(t_i)] + \varepsilon_i
\]

\[
x^e(t_{i+1}) = x^e(t_i) + \eta(t_i)
\]
Optimization of the wave predictions

- Mathematical post-processes based on Kalman filters have been utilized supporting the adaptation of the numerical models to the local area characteristics and the elimination of possible systematic biases.

WAM outputs, Kalman improved forecasts and the corresponding buoy wave observations
Kalman combined with assimilation

Available Observations and WAM forecasts are used by the filter to produce a new improved forecast.

This is assimilated during the forecasting period improving significantly the assimilation impact in time and space.
Apart from the real observations assimilated (blue solid line) within the assimilation window, the improved, via the filters, forecasts of the model (dashed line) are assimilated inside the forecasting period as artificial observations.

The assimilation impact is extended to the whole forecasting period (area of test case: California, USA)
Bias analysis and correction

- Recent advances in Statistics and Differential Geometry (Information Geometry) suggests that the use of distribution fitting should be taken into account.

- The family of two parameter Weibull distributions 
  \[ p(x; \xi) = \frac{\alpha}{\beta} \left(\frac{x}{\beta}\right)^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \]

  form a statistical 2-dimensional manifold with Fisher information matrix

  \[ G(\alpha, \beta) = \begin{bmatrix} \alpha^2 \beta^2 & \frac{\beta (1 - \gamma)}{\beta (1 - \gamma) + 6(\gamma - 1)^2 + \pi^2} \\
    \frac{\beta (1 - \gamma)}{\beta (1 - \gamma) + 6(\gamma - 1)^2 + \pi^2} & \frac{6(\gamma - 1)^2 + \pi^2}{6\alpha^2} \end{bmatrix} \]

- This matrix defines the inner product, and therefore the geometrical framework, in which the Weibull manifolds are categorized.

- This distance should be minimized instead of using least square methods (classical Euclidean Geometry).


Bias analysis and correction

Monthly satellite and WAM values as elements of the Weibull distributions statistical manifold
Bias analysis and correction

The minimum distance between two elements $f↓1$ and $f↓2$ of a statistical manifold $S$ is defined by the corresponding geodesic $ω$ which is the minimum length curve that connects them.

Geodesics are obtained as solutions of 2$^{nd}$ order differential systems:

$$ω↓i ↑′′ (t) + \sum_{j,k=1}^{\text{n}} Γ↓jk↑i(t) ω↑j ↑′ (t) ω↑k ↑′ (t) = 0, \quad i=1, 2, \ldots, n.$$ 

under the conditions $ω(0)=f↓1$, $ω(1)=f↓2$.

The coefficients $Γ↓jk↑i$ are defined by the Fisher information matrix and, therefore, are directly affected by the shape and scale parameter that the data under study better fit.

An example for the area of Med Sea. The ode system becomes:

$$ω↓1 ↑′′ = -0.82 ω↓1 ↑′ 2 + 0.65 ω↓1 ↑′ 2 - 0.02 (ω↓2 ↑′ 2) ↑′ 2 = 0$$

$$ω↓2 ↑′′ = -0.77 ω↓1 ↑′ 2 + 0.77 ω↓1 ↑′ 2 - 0.32 (ω↓2 ↑′ 2) ↑′ 2 = 0$$

under the conditions $ω↓1 ↑(0)=3.43$, $ω↓2 ↑(0)=2.30$, $ω↓1 ↑(1)=2.82$, $ω↓2 ↑(1)=2.35$.

In the plot the numerical solution spray of geodesics emanating from (3.43, 2.30) is given including the one to (2.82, 2.35) that gives the minimum length curve connecting the satellite observations with WAM outputs.
Extreme wind/wave conditions

**Extreme wind/wave values estimation**

The credible estimation/forecast of potential non-frequent/extreme values for environmental predictions is of critical importance for a number of applications.

Extreme Conditions can be described by different approaches:

- 95\textsuperscript{th} percentiles of Significant wave height after fitting the data on a Probability density Function (e.g. Weibull, Weibull 3 parameters, Lognormal 2/3 parameters).
- The maximum expected wave height.
- 50 year return period of Significant Wave Height, Wind Speed.
Weibull distribution could be a good choice for fitting wind speed and significant wave height values but Lognormal 3P provides an interesting alternative with even better convergence.

Thresholds for extreme values are equivalently estimated by the two pdfs as the corresponding 95-percentiles.
Estimation of the 50-year return period of significant wave height and wind speed

For this analysis at least 10-year long-term data are required

- Periodic Maximum Method (PMM): based on the 95% confidence intervals
  \[ X_{\uparrow \downarrow T} \pm 1.96 \sigma(X_{\uparrow \downarrow T}) \]
  of the Generalized Extreme value distribution (GEVD)
  \[ F(X) = \exp\{- (1 - \alpha(X - \beta)) \} \]

- Peak Over Threshold (POT): based on the 95% confidence intervals
  \[ X_{\uparrow \downarrow T} \pm 1.96 \sigma(X_{\uparrow \downarrow T}) \]
  of the Generalized Pareto Distribution (GPD)
  \[ F(X) = 1 - (1 - k(X - xo)/A)^{1/k} \]

Results for wind speed

Results for Hs

<table>
<thead>
<tr>
<th>H_{s}^{50} \pm 1.96 \sigma (m)</th>
<th>PMM</th>
<th>POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>5.6±1.4</td>
<td>6.5±1.7</td>
</tr>
<tr>
<td>(b)</td>
<td>9.8±1.8</td>
<td>10.9±2.0</td>
</tr>
<tr>
<td>(c)</td>
<td>5.2±1.0</td>
<td>6.2±1.4</td>
</tr>
<tr>
<td>(d)</td>
<td>5.6±1.0</td>
<td>6.3±1.0</td>
</tr>
</tbody>
</table>
Forecasting maximum wave height at selected sites based on high resolution hindcast wave modeling and local adaptation techniques

The maximum wave height is modeled by the significant wave height and the local mean wave period based on a statistical approach:

\[ H_{\text{max}} = \alpha H_s + F(T_m) \]
Concluding thoughts

• The estimation of wave energy potential is not always straightforward. The characterization of an area as suitable for renewable energy exploitation can not be based on a Yes/No answer.

• The lack of a dense observational network over sea areas poses further difficulties revealing the increased role that numerical simulation systems keep.

• Numerical wind/wave models, supported by optimization post processes, provide an excellent way out.

• The local wind/wave characteristics and the corresponding energy potential should be analyzed on different time scales and by employing statistical indexes measuring not only averages but also the variation, the asymmetry and the potential impact by extreme values as well as the corresponding optimally fitted distributions.

• The specific characteristics of the technology that will be employed for the translation of the wave energy to power are crucial and should be taken into account.