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Evaluation of high resolution wave simulations with SAR-observations and estimation of the wave power spatial and temporal distribution

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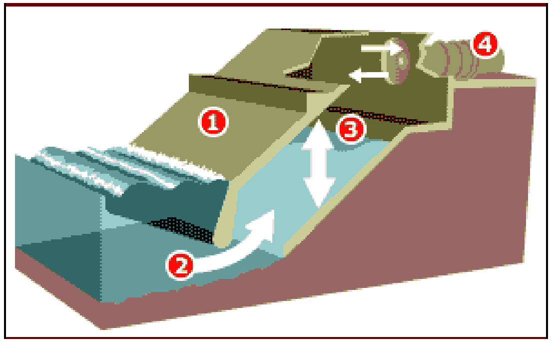
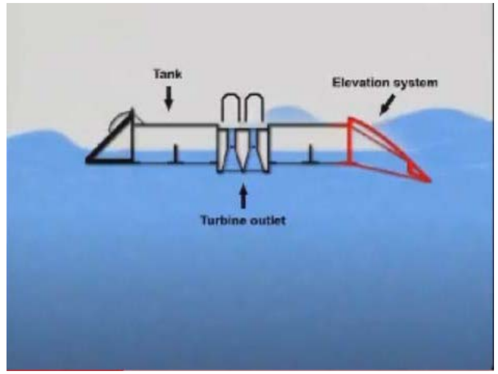
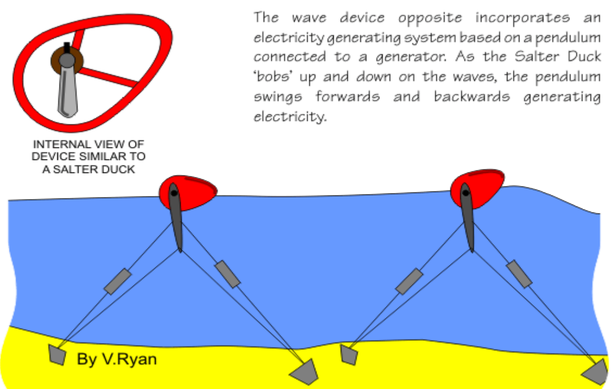
Renewable Energy Resources - Wave Energy

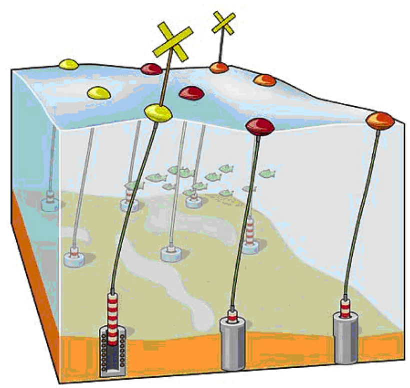
- Over the last years, the use of renewable resources for energy production is receiving increased attention as a result of the threat posed by climate change and the strict environmental policies regarding the production of greenhouses gases.
- Within this framework, wave energy (the energy that can be captured by sea waves) is a promising alternative energy resource with critical advantages:
    - Low variability (easier integration to the general grid)
    - High predictability
    - Good seasonal load for the most energetic seas (NW Europe)
    - It can be produced even in the case of low winds by exploiting the swell component of waves
    - Ocean energy technologies produce no emissions of harmful pollutants or greenhouse gasses

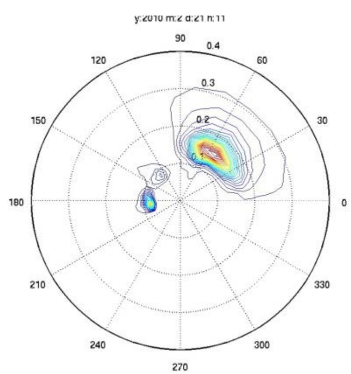
What kind of information the energy production industry needs ?











Wave Energy is dependent on the joint distribution of Significant Wave Height (H_s) and Wave Energy Period (T_e):

$$P_w = \frac{\rho g^2}{64\pi} H_s^2 T_e \quad [W/m]$$

Different types of WECs are suitable to different combinations of wave height and period.

The use of the full wave spectrum is critical for the estimation of the wave energy potential over deep and shallow water areas:

$$P_W = \rho g \int_0^{2\pi} \int_0^{\infty} c_g(f,h) E(f,\theta) \, df \, d\theta$$

where c_g is the group velocity:

$$c_g(f,h) = \begin{cases} \frac{g}{4\pi} f^{-1}, & \textit{for deep water} \\ \sqrt{gh}, & \textit{for shallow water} \end{cases}$$

Wave Resource Assessment-Methodology

- Resource mapping
- Resource analysis identifying areas where “hot spots” of high intensity exist
  - Mean wave conditions (Hs, T, θ) – 10 year mean values
  - Spatial and temporal variability of wave parameters at different time scales
    - Inter-annual
    - Seasonal
    - Monthly
  - Statistical measures for the asymmetry and the impact of non frequent values of the analysis results
  - Multivariate distribution fitting
- Analysis taking into account constraints such as bathymetry, distance from shore, marine structures, local commercial activities, fisheries, military areas, ship routes, etc.

Wave Resource Assessment-Numerical Models

- Difficulties in obtaining wide coverage (spatial and temporal) of **observed wave data** over sea areas.
- The main tool for accurate environmental predictions is today the use of **Numerical Weather Prediction** (NWP) models that simulate successfully the general weather conditions with average accuracy reaching 80-90%.
- Such models are able to provide accurate short or long term forecasts for environmental parameters that are crucial for wave energy estimation:
  - Wave Height and Direction
  - Swell Height and Direction
  - Wave Period
  - Extreme Values

Wave Resource Assessment-Resource Mapping

The EU Projects

Marina Platform *(http://www.marina-platform.info/)* and

E-Wave *(http://www.oceanography.ucy.ac.cy/ewave/)*

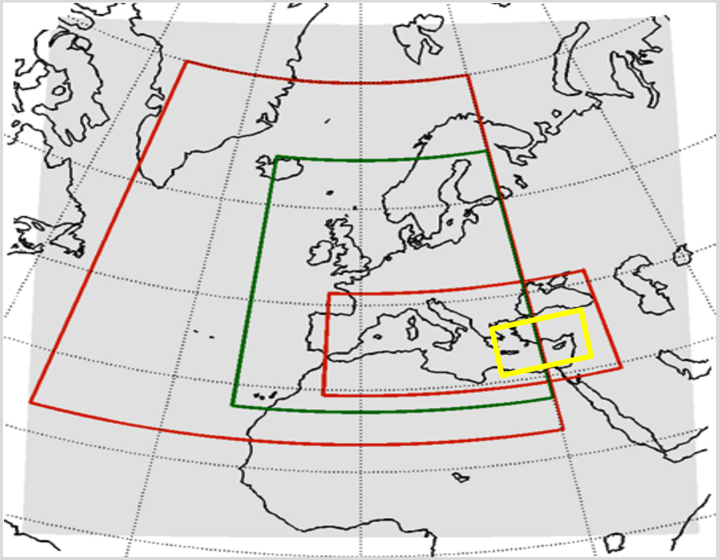
focus on the monitoring and exploitation of the wave energy potential over the Atlantic and Mediterranean coastline of Europe.

A 10-year (2001-2010) high spatial and temporal resolution reanalysis data-set was derived for wind, wave and tidal parameters providing a wealth of information for marine resource assessment for the entire coastline of Europe.

MARINA PLATFORM

E-WAVE

The models used



Atmospheric model Characteristics	SKIRON
Horizontal Resolution	0.05° x 0.05°
Initial and Boundary Conditions	High Resolution Reanalysis (15x15 Km)
Vertical Levels	45 (up to 50hPa)
Output at:	10, 40, 80, 120, 180 m a.s.l
Timestep	15 sec
Full set of meteorological variables - every 1h	

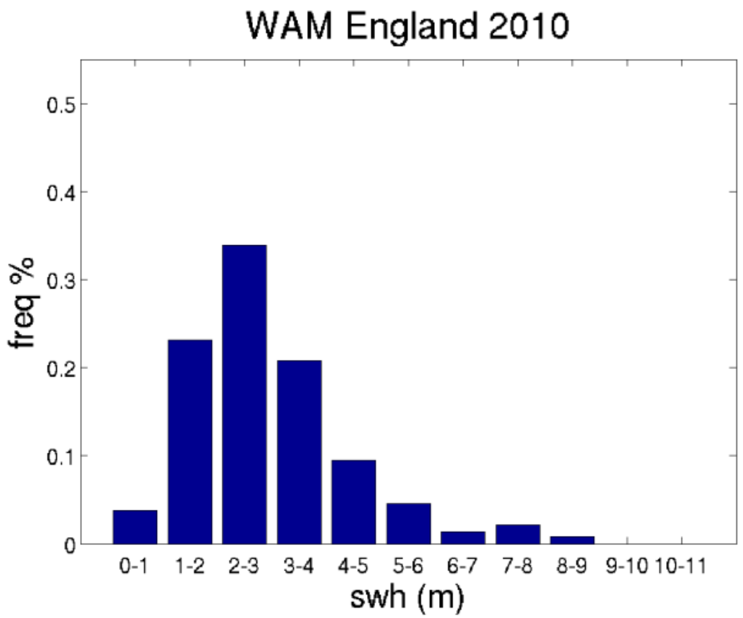
Wave model Characteristics	WAM ECMWF CY33R1 Marina Platform	WAM ECMWF CY33R1 E-WAVE
Model's domain	20–75°N, 50°W–30°E	30 – 41°N, 15°–37°E
Horizontal Resolution	0.05° x 0.05° (1601 x 1101 grid Points)	1/60 °x 1/60° (1.667 km approximately)
Frequencies	25 (min 0.055Hz)	25 0.0417-0.54764Hz logarithmically spaced
Directions	24 (equally spaced)	24 (equally spaced)
Timestep	45 sec	45 sec

- The wave model includes **data assimilation systems** that can utilize satellite altimetry data.
- A **new advection scheme** (Corner Transport Upstream) has been adopted providing a more uniform propagation in all directions
- The **maximum wave height** is estimated by means of the probability distribution of sea surface elevation

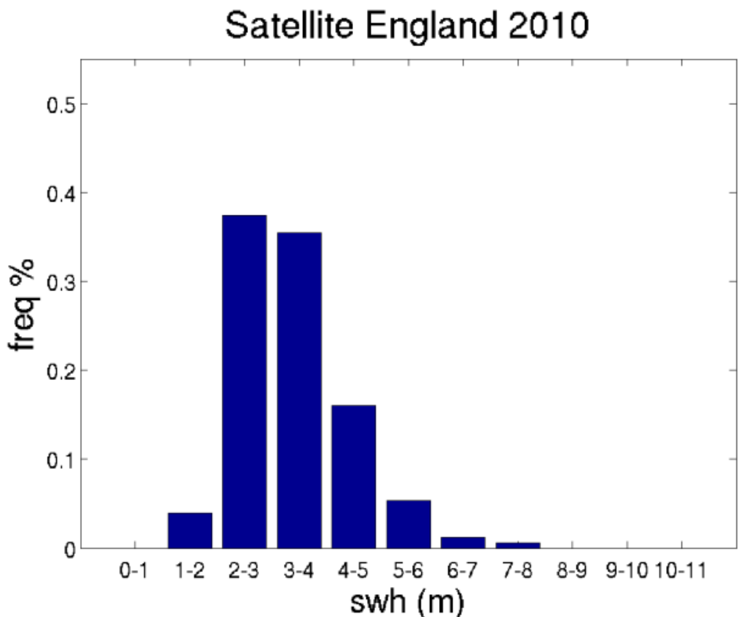
Seasonal evaluation against ASAR records

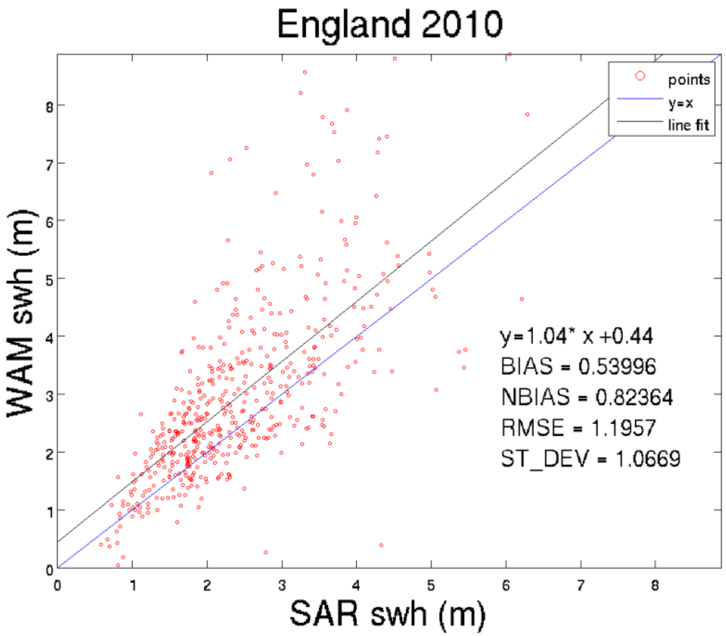
UK Atlantic coastline

Model results



SAR records





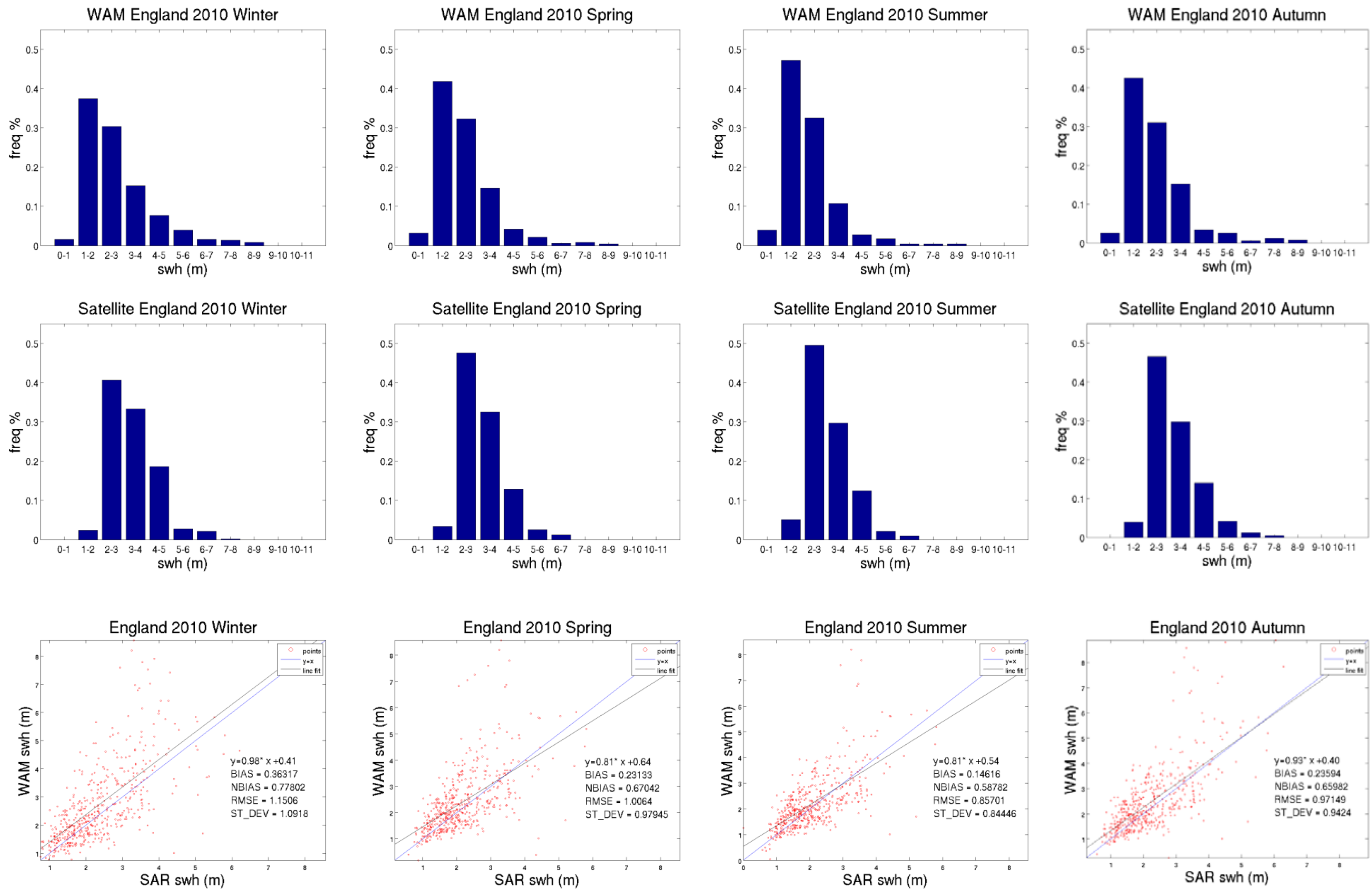
Seasonal evaluation against ASAR records

UK Atlantic coastline

	Dec – Feb	March – May	June – Aug	Sep - Nov

WAM

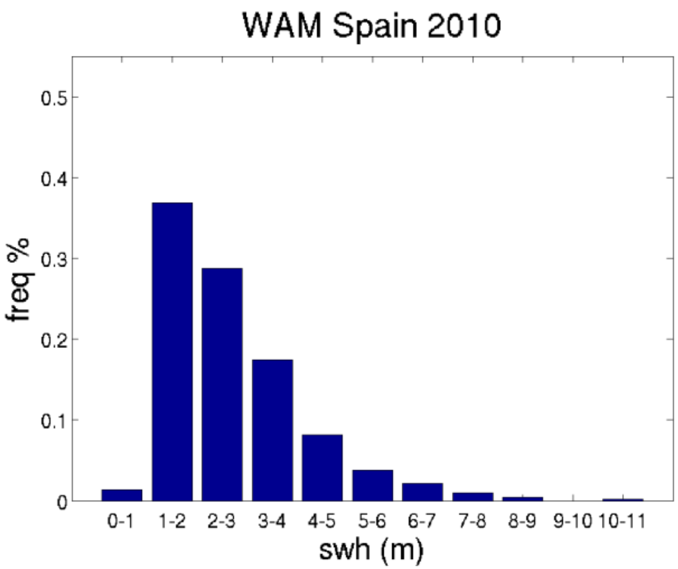
SAR



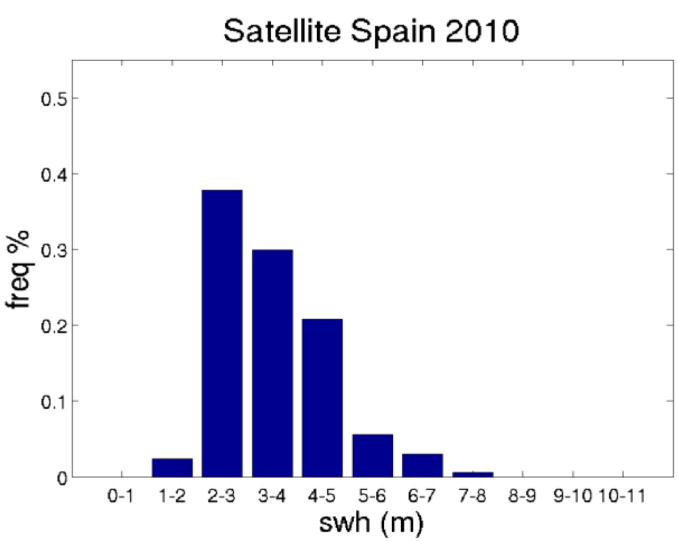
WAM evaluation against ASAR records (annual)

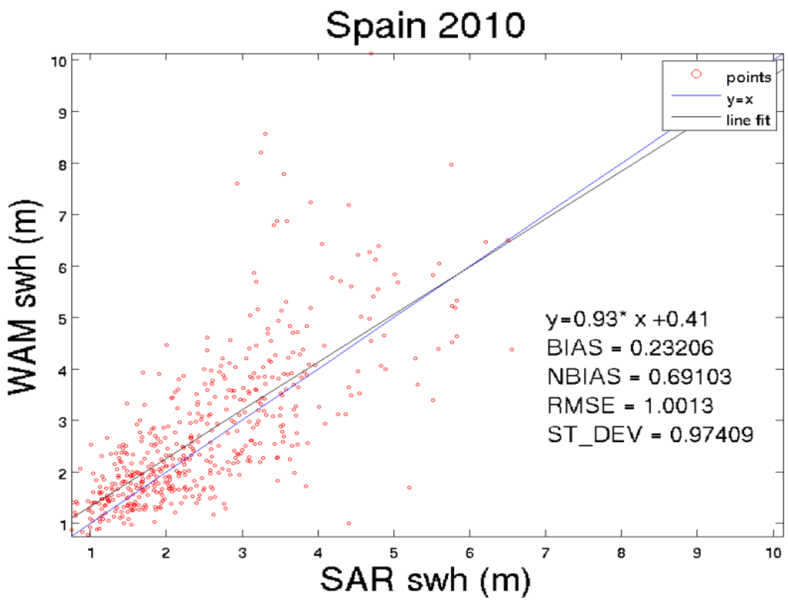
Spanish Atlantic coastline

Model results



SAR records





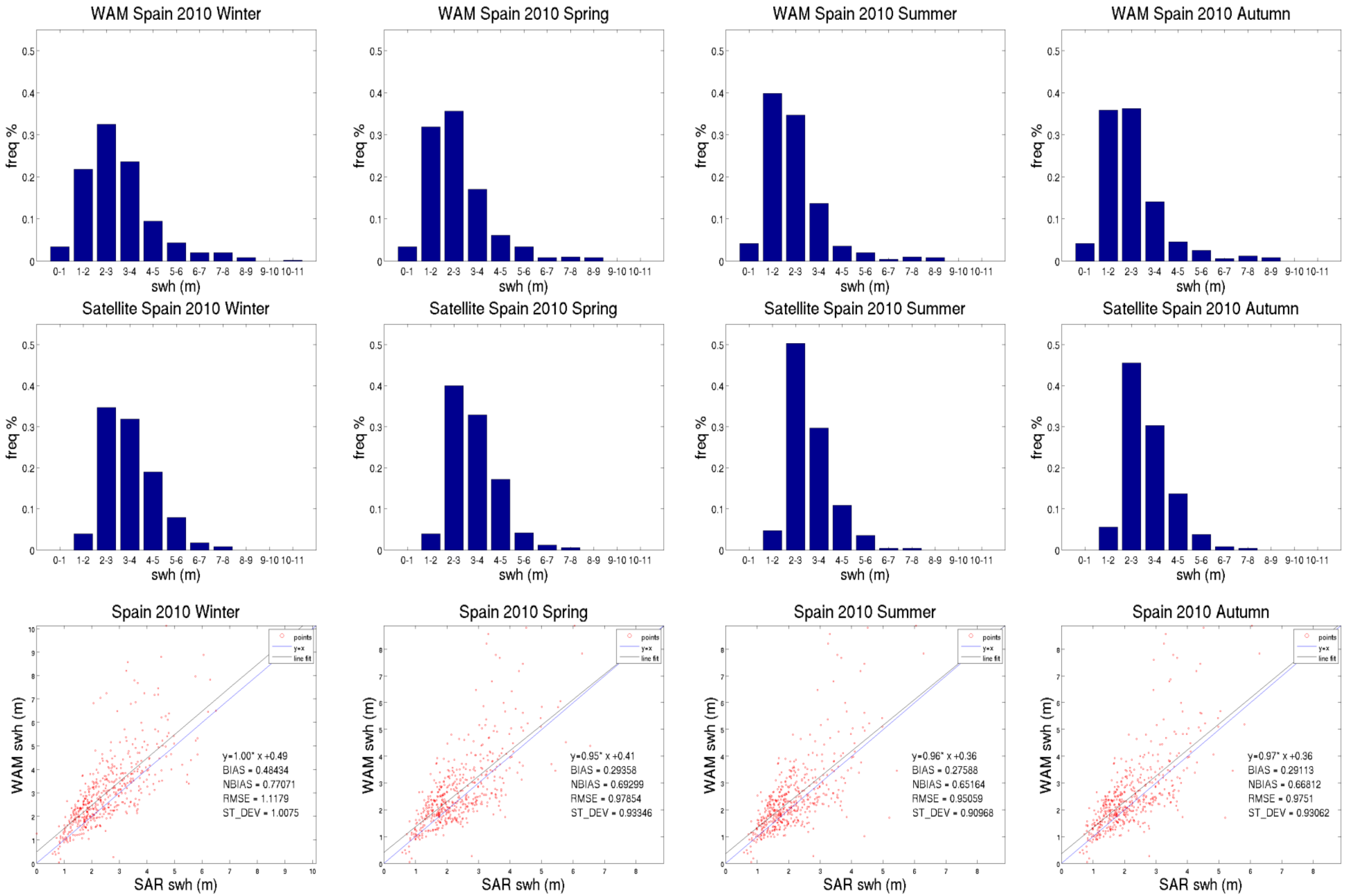
More uniform correlation between WAM modeled data and ASAR records is recorded over the Atlantic Spanish coastline

Seasonal evaluation Spanish Atlantic coastline

Dec – Feb | **March – May** | **June – Aug** | **Sep - Nov**

WAM

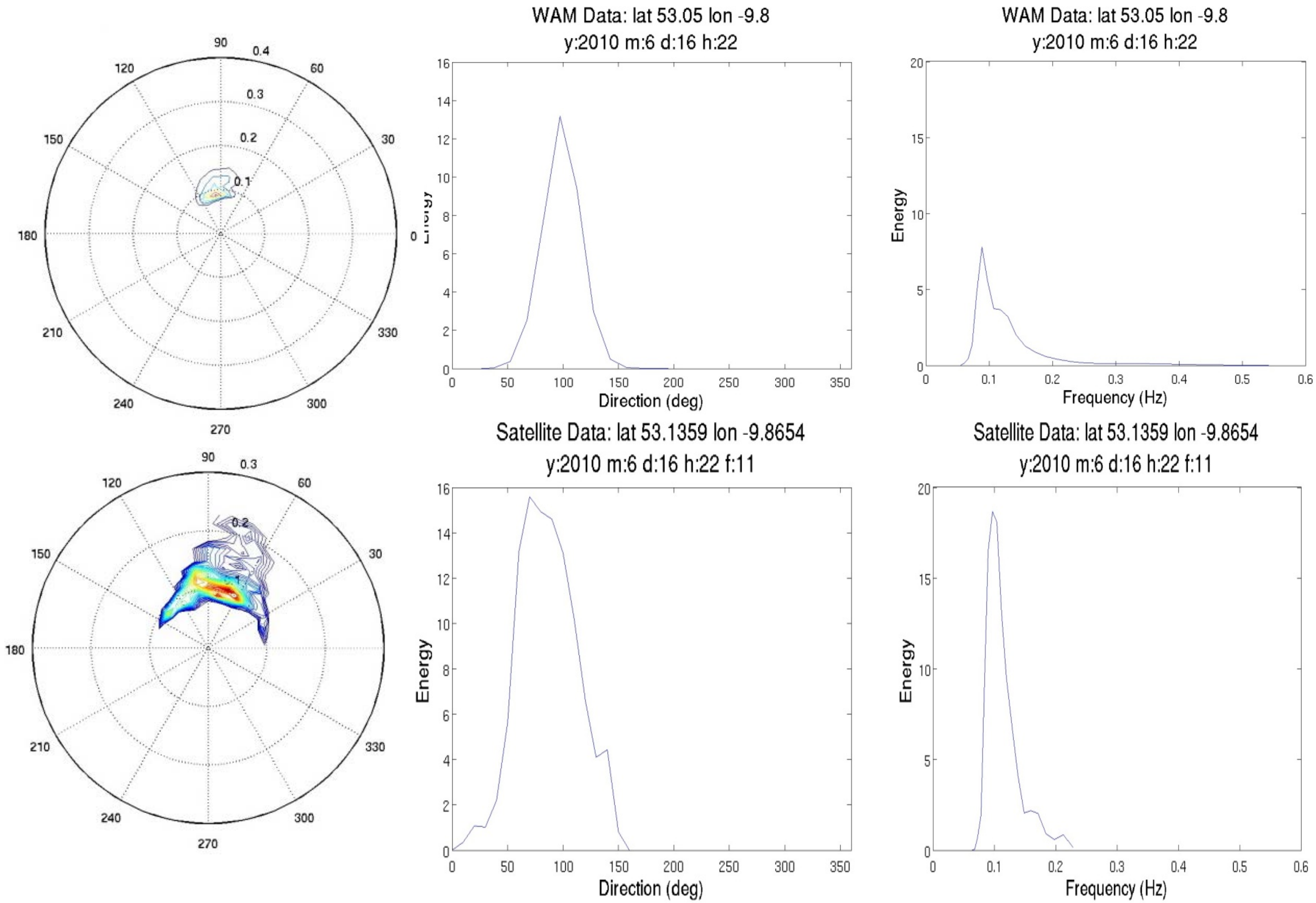
SAR



Evaluation based on the full wave spectra

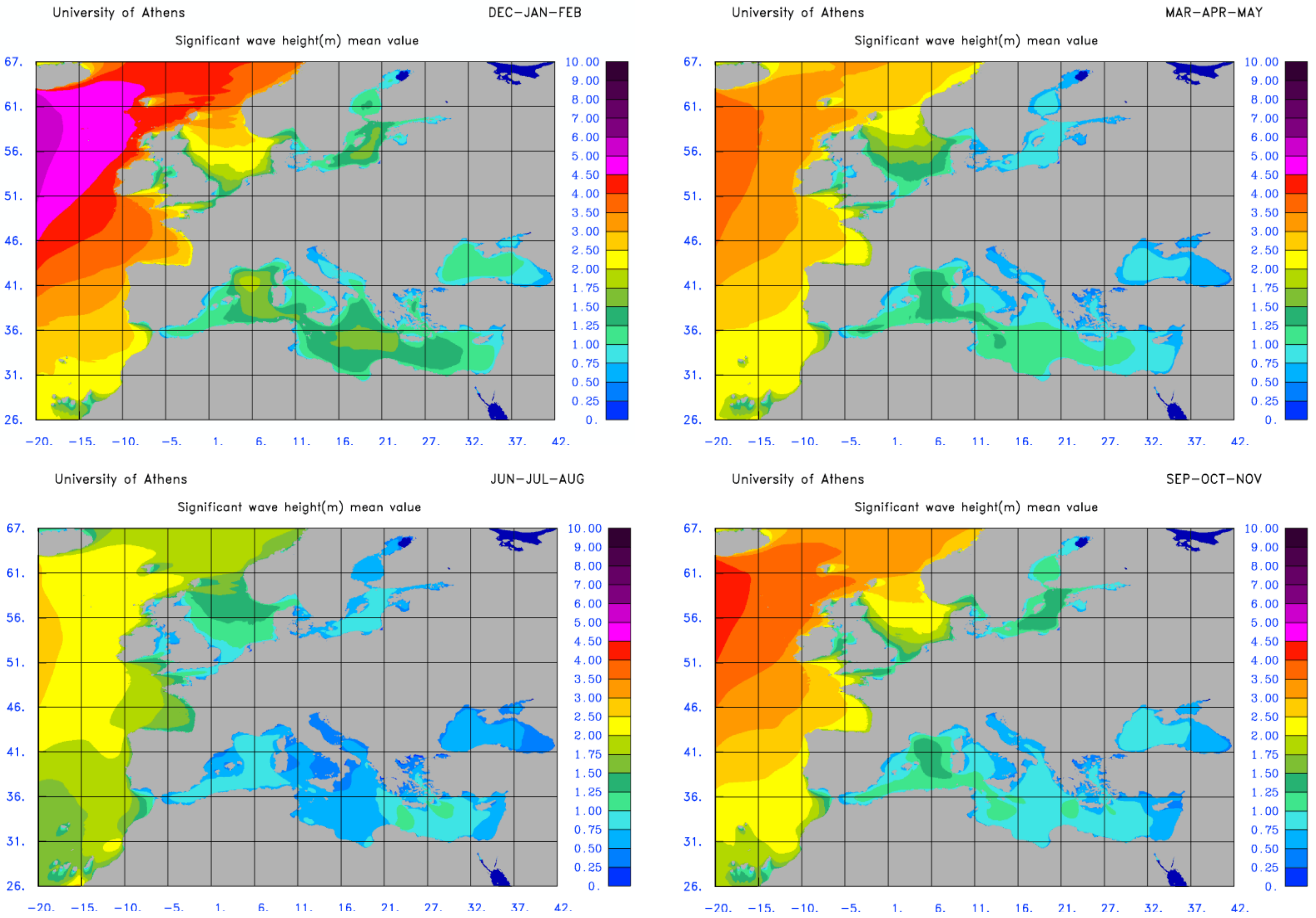
WAM

SAR

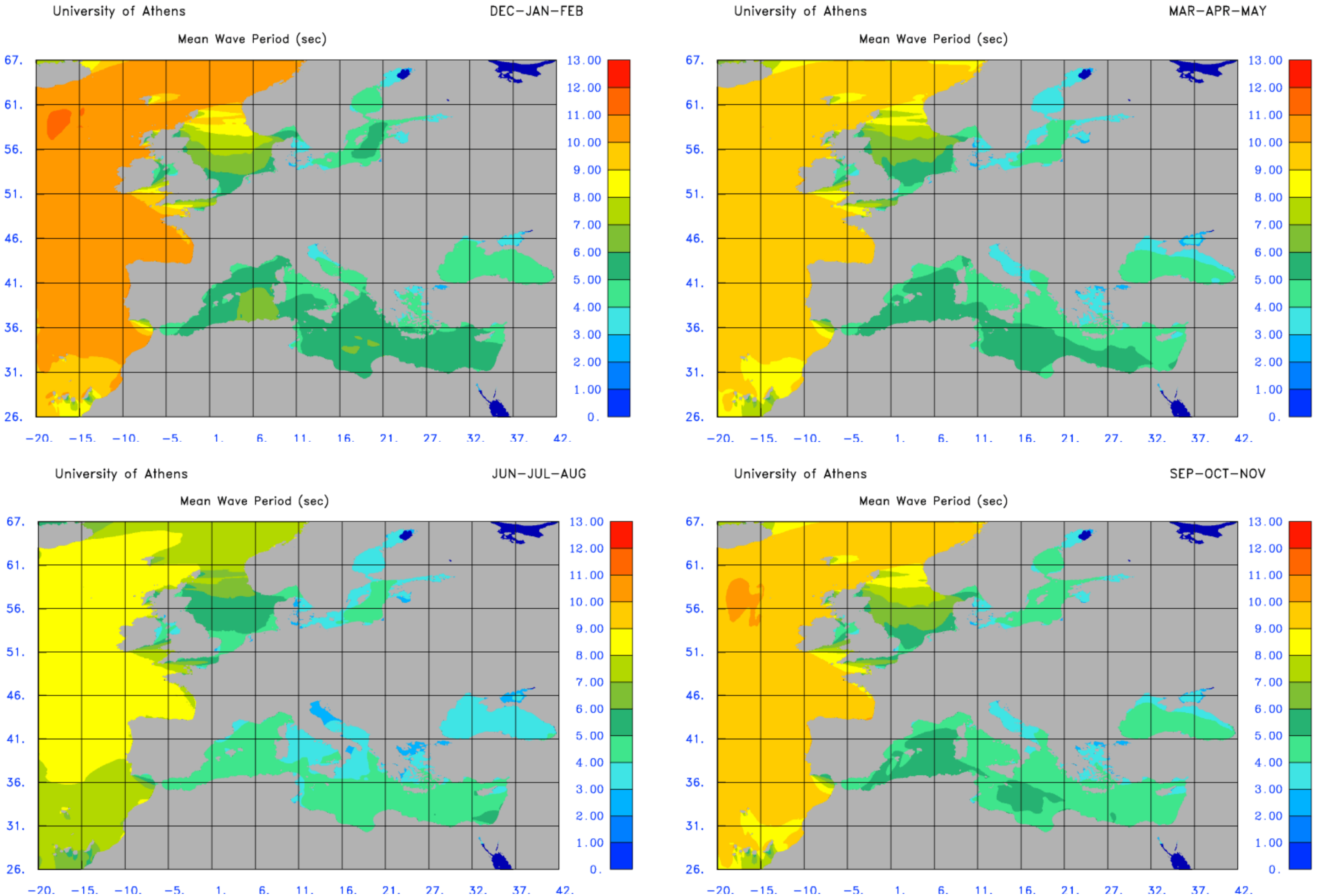


The frequency band of the SAR records is steeper than the corresponding model results while the directional distribution of modeled and recorded data are comparable

Seasonal Distribution of Significant Wave Height

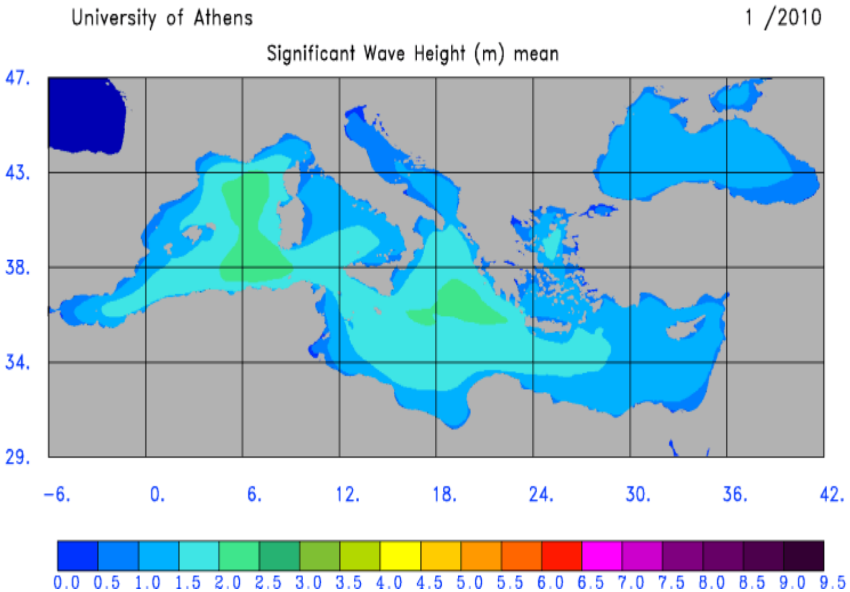


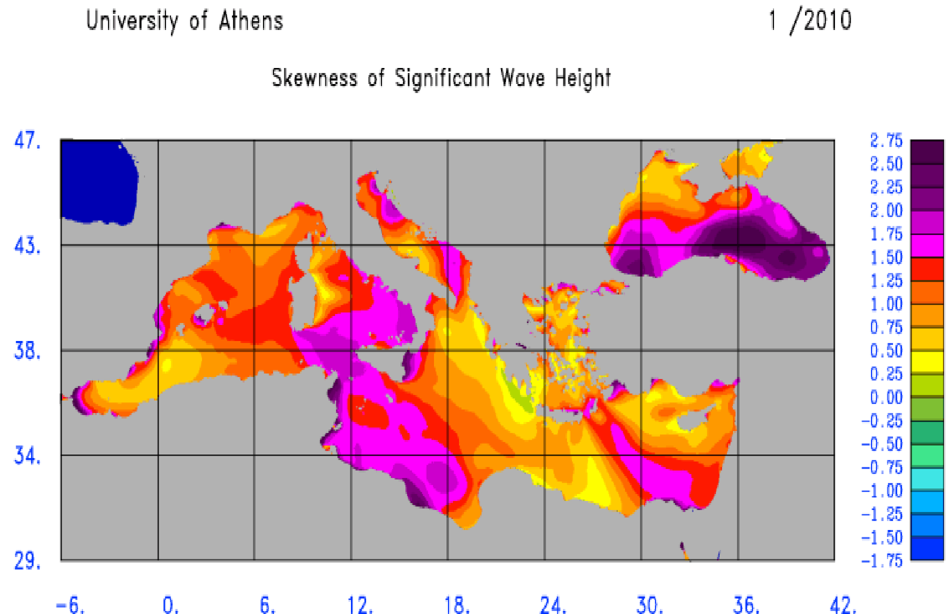
Seasonal Distribution of Wave Period

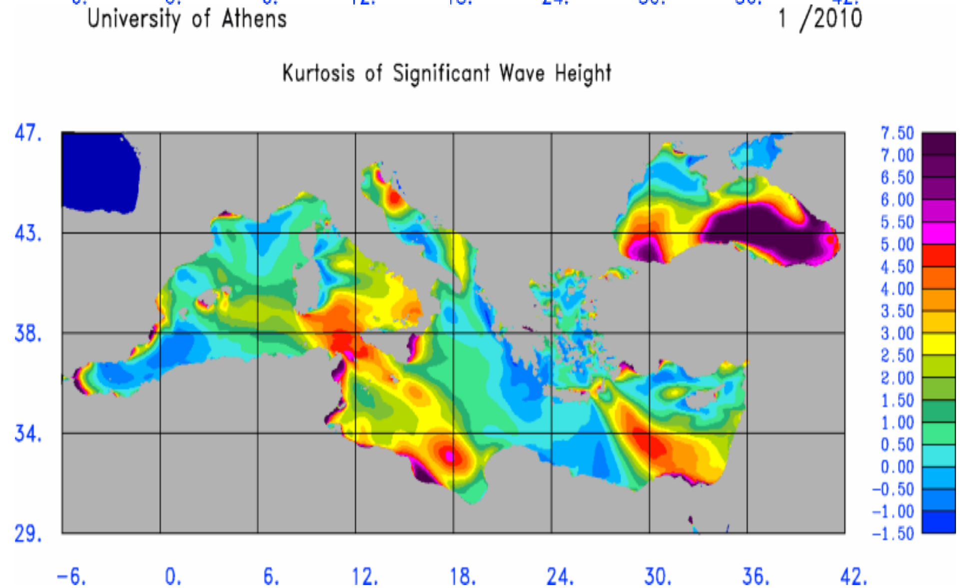


Wave climatology: Is it enough for supporting efficiently the resource assessment?

Monthly variability of the Mean Hs in Med Sea



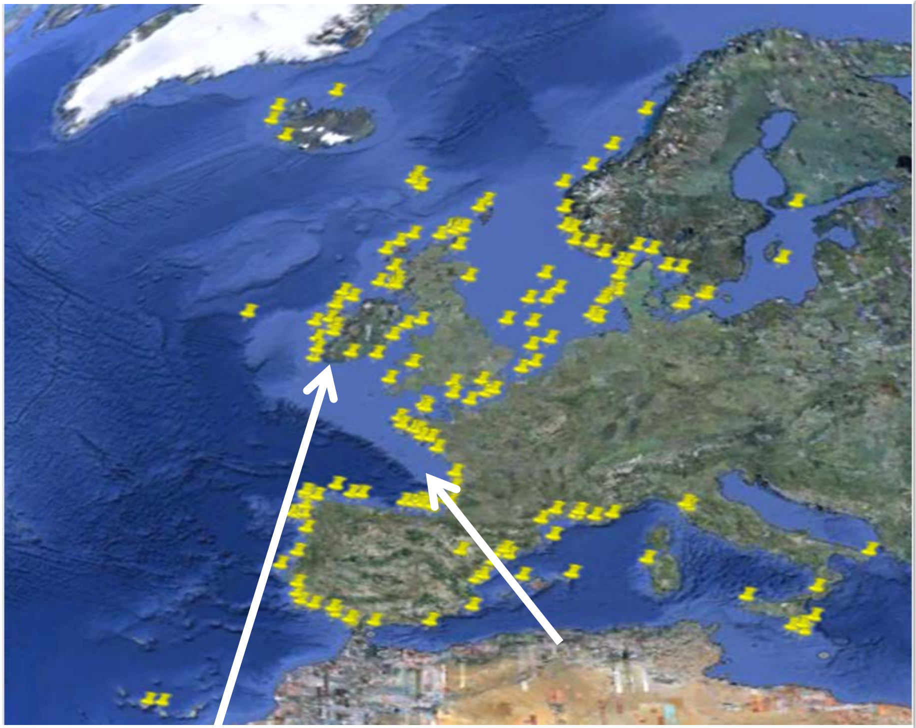


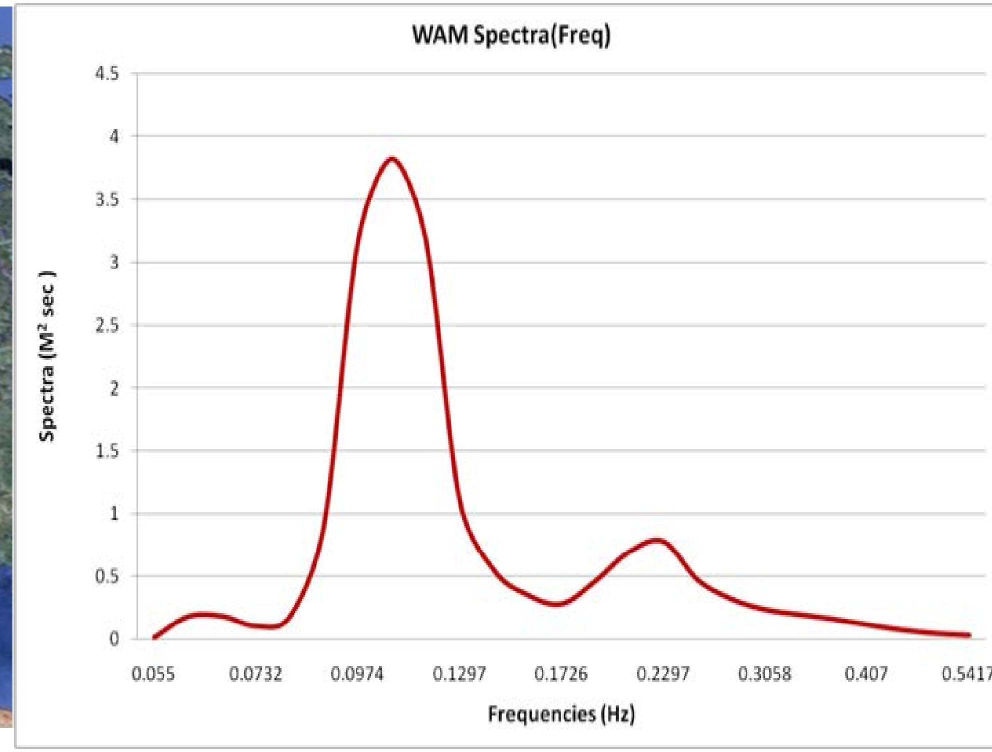


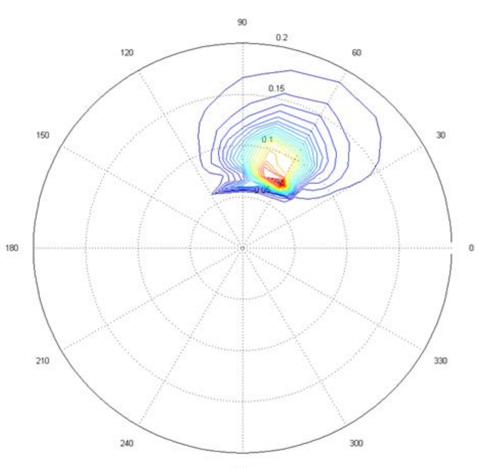
Statistical measures for the **asymmetry** and the **kurtosis** of the data could be essential

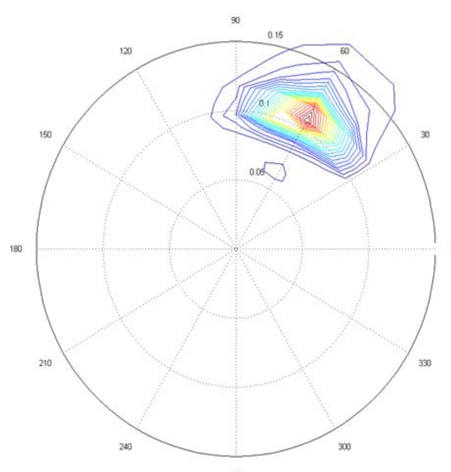
- **Skewness** (3rd standardized moment) provides information for the tails of the distributions
- Areas with potential impact from extreme values can be spotted based on the **kurtosis** (4th standardized moment)

On site statistical analysis



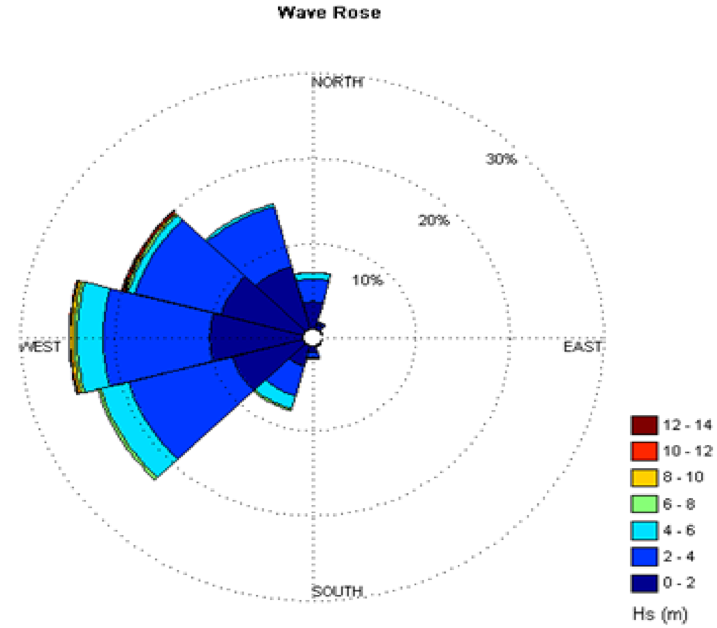


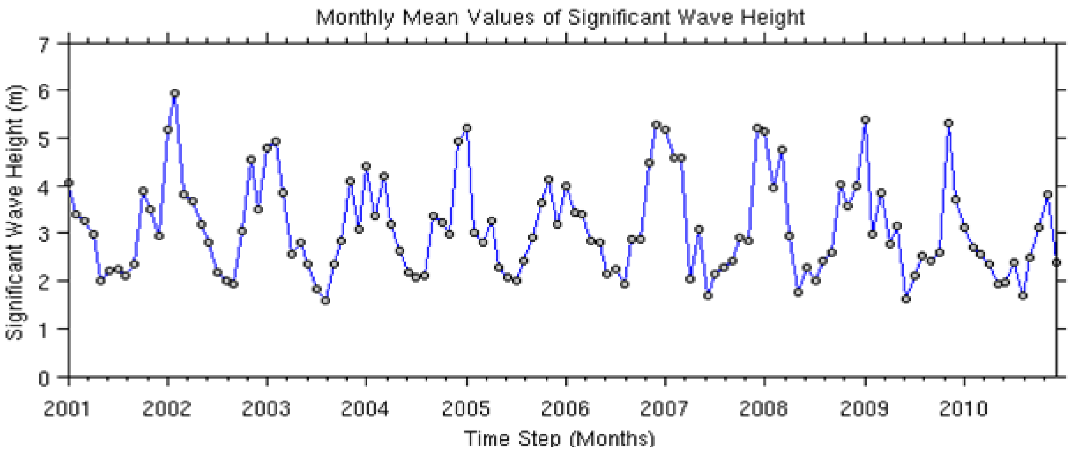


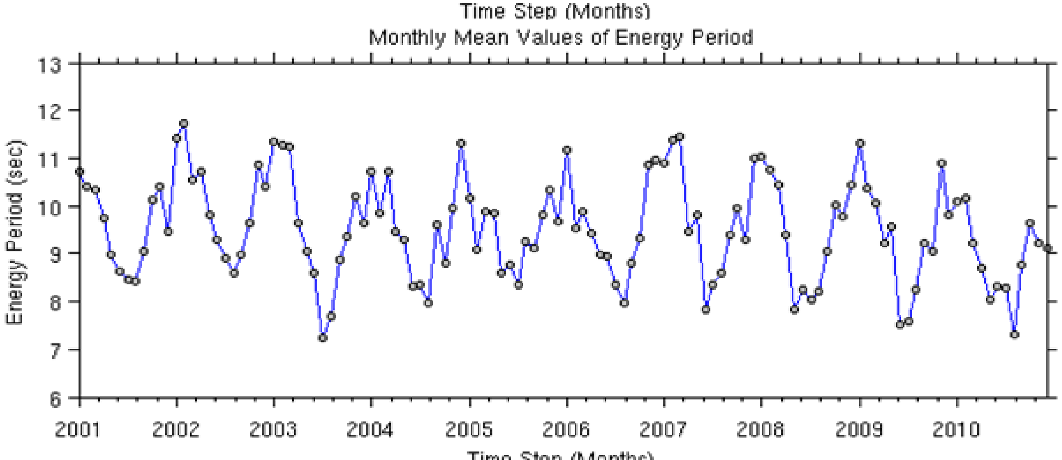


For a set of preselected points of interest along the coastline of Europe, the full wave spectrum derived without adopting any preselected standard forms, like e.g. JONSWAP, has been stored to provide the full package of information needed

On site statistical analysis

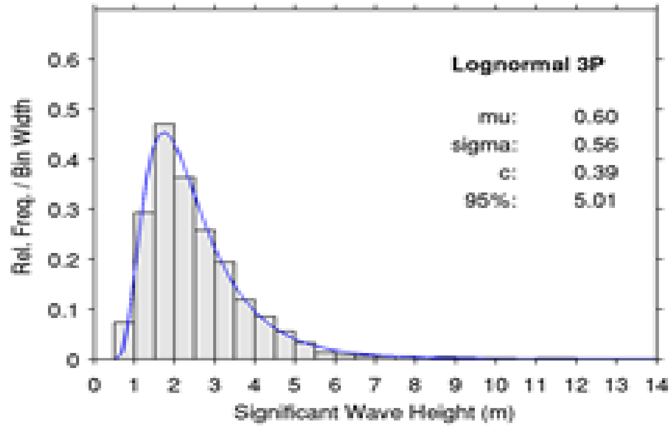


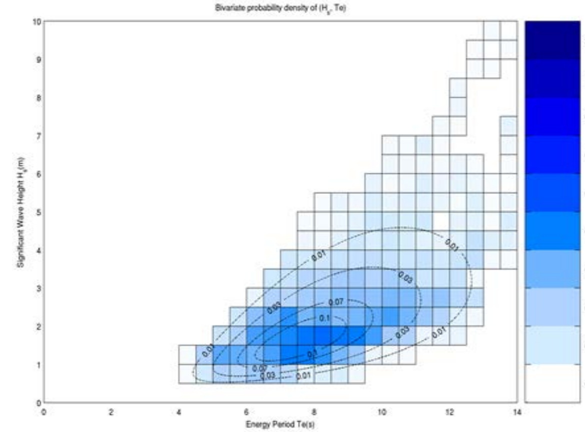


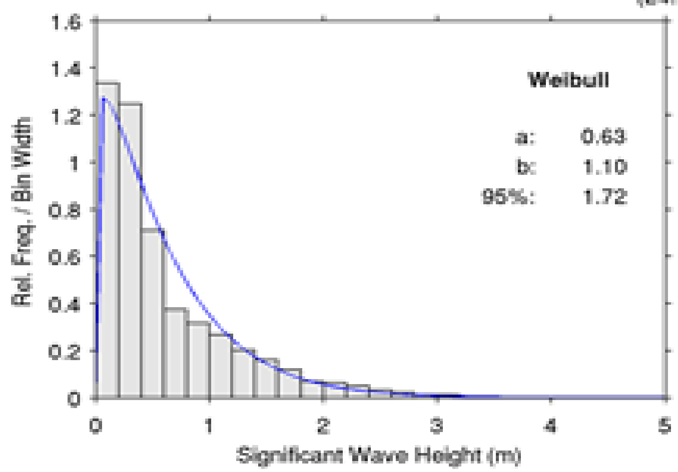


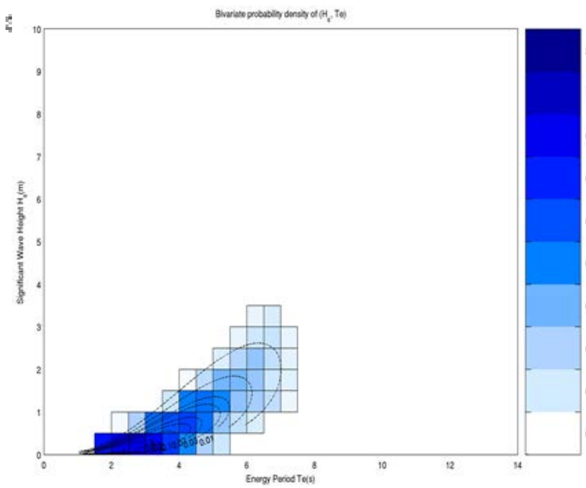
- The **time distribution** of crucial parameters over the whole 10-year study period may reveal trends and (seasonal or other) periodicities
- The directionality of the local wave parameters could characterize the wave climate of the area under study

On site statistical analysis





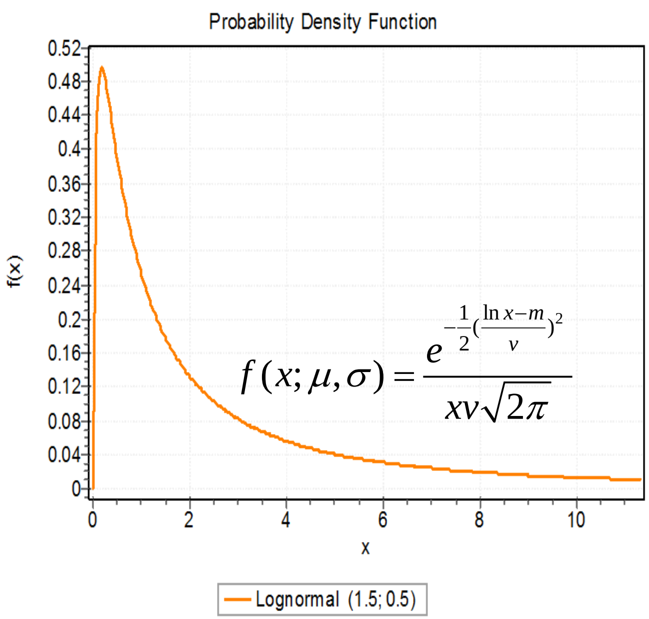


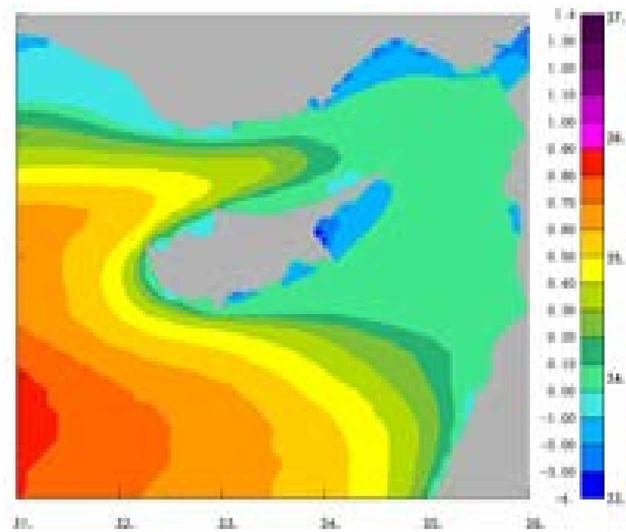


- The optimal distribution with its corresponding parameters are spatially dependent and not predefined/fixed by any way
- Weibull distribution could be a good choice for fitting wind speed and significant wave height values but Lognormal 3P provides an interesting alternative with even better convergence.
- Thresholds for extreme values are equivalently estimated by the two PDFs as the corresponding 95-percentiles.
- The joint Hs/Te distribution is a statistical information of **primary importance** for wave resource characterization
- Different local wave climatology is depicted in the bivariate plots

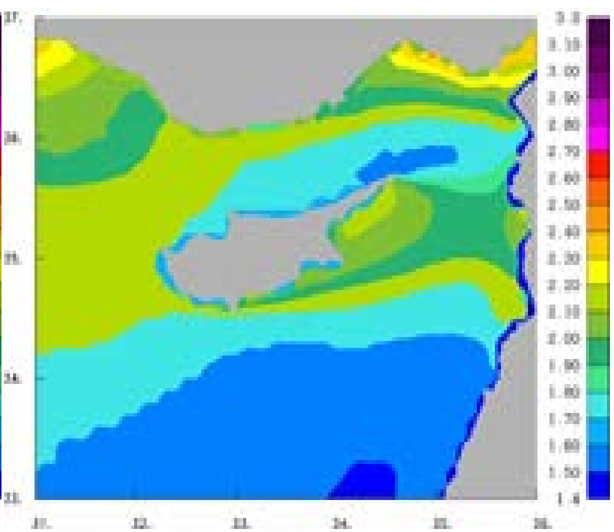
Wave Power Potential distribution

- The wave energy potential can be also analyzed by a PDF fitting point of view.
- In the present work, 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.
- **<u>The corresponding parameters have a non trivial spatial distribution</u>** and provide information of potential value for grid designers and researchers.



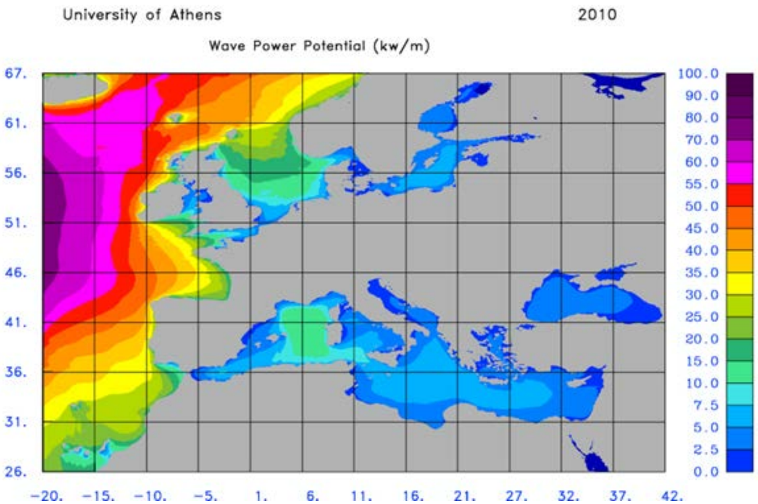


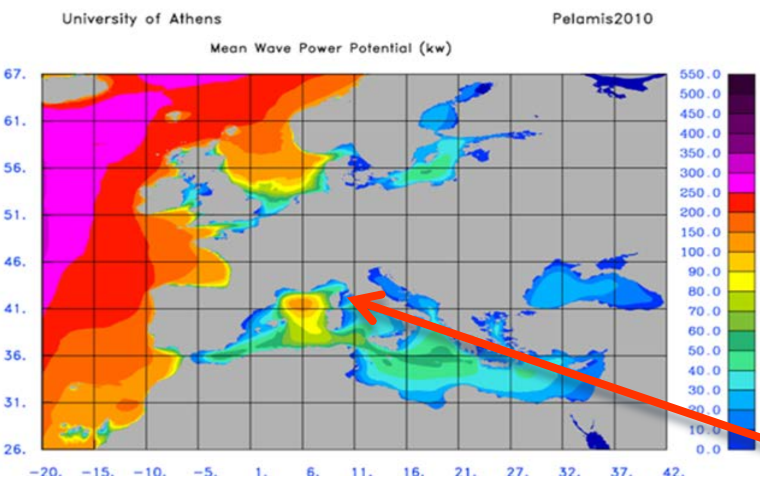
Lognormal m-parameter



Lognormal v-parameter

Energy Potential Mapping





The available potential for Wave Power in deep water is defined as:

$$P_w = \rho g \int_0^{2\pi} \int_0^{\infty} f^{-1} E(f,\theta) df d\theta = \frac{\rho g^2}{64\pi} \mathrm{H}_s^2 T_e \quad [W/m]$$

is considered by the research and technical community as an important tool for monitoring the wave power potential.

The **theoretical approach** can be **misleading** since no constrains relevant to the converter used are taken into account

The **actual power** that can be extracted **is dependent on the available technology**.

The use of (Hs/Te) Power Transform Matrices could be utilized and (Hs, Te) - surfaces should be developed

Pelamis – Power Transform Matrix (generic performance): output in kW

Significant Wave Height Hsig – m \ Wave Period – Tpow (s)	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10	10.5	11	11.5	12	12.5	13
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.0	0	22	29	34	37	38	38	37	35	32	29	26	23	21	0	0	0
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	47	42	37	33
2.0	57	88	115	136	148	153	152	147	138	127	116	104	93	83	74	66	59
2.5	89	138	180	212	231	238	238	230	216	199	181	163	146	130	116	103	92
3.0	129	198	260	305	332	340	332	315	292	266	240	219	210	188	167	149	132
3.5	0	270	354	415	438	440	424	404	377	362	326	292	260	230	215	202	180
4.0	0	0	462	502	540	546	530	499	475	429	384	366	339	301	267	237	213
4.5	0	0	544	635	642	648	628	590	562	528	473	432	382	356	338	300	266
5.0	0	0	0	739	716	731	707	687	670	607	557	521	472	417	369	348	328
5.5	0	0	0	750	750	750	750	750	737	667	658	586	530	496	446	395	355
6.0	0	0	0	0	750	750	750	750	750	750	711	633	619	558	512	470	415
6.5	0	0	0	0	750	750	750	750	750	750	750	743	658	621	579	512	481
7.0	0	0	0	0	0	750	750	750	750	750	750	750	750	676	613	584	525
7.5	0	0	0	0	0	0	750	750	750	750	750	750	750	750	686	622	593
8.0	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	690	625

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

Some Concluding Remarks

- **The estimation of the wave energy available potential is not as straight forward as in wind power case being directly dependent on two wave parameters (Hs-Te).**
- **The lack of a dense observational network over sea areas poses further difficulties revealing the increased role that satellite data may have.**
- **Numerical wind/wave models, with optimization post processes, is considered as a good approach.**
- **The suitability od an area for wave energy exploitation cannot be based on a Yes/No answer.**
- **The local wave characteristics and the corresponding energy potential should be analyzed on <u>different time scales</u> and by employing statistical indexes measuring not only averages but also the <u>variation</u>, <u>asymmetry</u> and <u>potential impact of extreme values</u> as well as the 1 or 2-D <u>optimally fitted distributions</u>.**
- **The use of SAR information could be critical in energy estimation and monitoring since the wave directional spectrum gives full-package information avoiding averaging and/or smoothing over frequencies and directions.**
- **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.**

Acknowledgements

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