Estimation of the wave energy potential on the offshore Mediterranean Sea and propagation toward a nearshore area

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Abstract – This paper presents a study to quantify the availability of wave power in the Mediterranean Sea. Monthly and annual average values of powers are provided, in deep water, for the years 2010 and 2011, based on the elaboration of the data set of the model MED 6MIN - PREVIMER. Through numerical simulation, the data set was propagated from depths of 100 m to coast, taking into account the shoaling, refraction, diffraction, bottom friction and wave breaking processes. In this phase of the study, the methodology was applied only to the stretch of coast between Livorno and La Spezia.

1. Introduction

Currently in the energy sector there is an increasing interest in renewable energy sources and, within this context, the possibilities of producing energy from the waves in the sea is also emerging. The quantification of the availability of such an energy form is the first step to take and constitutes a fundamental element at the base of studies into the practicalities inherent in its conversion to usable forms through the so-called WEC - Wave Energy Converter technologies (Falnes, 2007 and Falcao, 2010).
On a European level, important contributions have been supplied in this sector such as Pontes et al. (1996), OEC (2006), but the Mediterranean has still only received little attention (Filianoti 2000, Vicinanza et al. 2011). This study adds to the knowledge of the availability of energy from the Mediterranean Sea. In addition to the analyses concerning the availability of energy from the wave motion offshore in the whole of the Mediterranean Sea, a procedure has been developed based on a numerical simulation for the detailed analysis of coastal areas with a serviceable depth of less than 100 m which can be useful in the identification of eventual focus zones.

2. Methodology

The analyses of this paper are based on wave data arising from numerical simulation models for wave generation coupled with atmospheric models. The data was provided by IFREMER that has developed a pre-operational system, called PREVIMER, aiming to provide short-term forecasts concerning the coastal environment along the French coastlines bordering the English Channel, the Atlantic Ocean and the Mediterranean Sea.
The data used in the present study arise from the numerical simulation model called MED 6MIN, a WaveWatch III model, with a third-order accuracy propagation scheme in space and time. The weather forecast conditions were provided by Météo-France and covered the twelve hours duration and the following six days. The results are provided in the NetCDF format at 3 hour intervals and the variables are, for example, wave height, period, direction.

The data set analysed covers the whole of the Mediterranean Sea with a resolution of 0.1° in latitude and longitude for a period of 2 year and 9 months, from July 2009 to March 2012.
The formula used to compute the monthly and yearly mean wave power, in the case of irregular waves propagating in deep waters, is reported in eq. (1)

$$P = \frac{1}{64}\frac{g^2}{\pi}\rho H_{mo}^2 T_{m-1,0} \qquad (1)$$

with ρ water density and providing that $H_{m0}=4m_0^{1/2}$ is the significant wave and $T_{m-1,0}=m_{-1}/m_0$ is the mean spectral wave period.
This formula is computed considering, as it is well known, that in case of regular waves the specific wave power is equal to eq. (2)

$$P = \frac{1}{8}\gamma H^2 C_g \qquad (2)$$

with γ *specific weight [N/m³]*

H *wave height [m]*

C_g *group celerity [m/s]*

The irregular waves can be considered as a superposition of an infinite number of regular components and the total power is calculated as the sum of the power associated to any component, according the eq. (3).

$$P = \sum_{i=1}^{\infty}\frac{1}{8}\gamma H^2(f_i)C_g(f_i) \qquad (3)$$

In terms of the frequency spectrum, *S(fᵢ)*, the wave height squared, of each wave components, is expressed as in eq. (4)

$$H^2(f_i) = 8\cdot S(f_i)\Delta f \qquad (4)$$

In the case of deep water the group celerity is computed as in eq. (5)

with g *acceleration of gravity [m/s²]*

π *Pi constant [-]*

f *frequency [s⁻¹]*

Substituting eq. (4) and eq. (5) into eq. (3), eq. (6) is obtained:

$$P = \frac{g\gamma}{4\pi}m_{-1}\cdot\frac{m_0}{m_0} \qquad (6)$$

where

$$m_k = \sum_{i=1}^{\infty} S(f_i)f_i^k\,\Delta f \qquad (7)$$

and so finally eq.(1) is obtained.

3. Results of the wave energy characterization

The spatial distribution of the monthly mean power has been computed and reported in the form of contour maps for each month of a given year (not shown in this paper for brevity). The maximum values of the monthly mean power that resulted in the studied spatial domain have been highlighted in Figure 1 and the localization of the related points is depicted in Figure 2. Moreover, the spatial distribution of the mean power for the years 2010 (Figure 3) and 2011 (Figure 4) has been computed as the mean of the monthly mean powers.

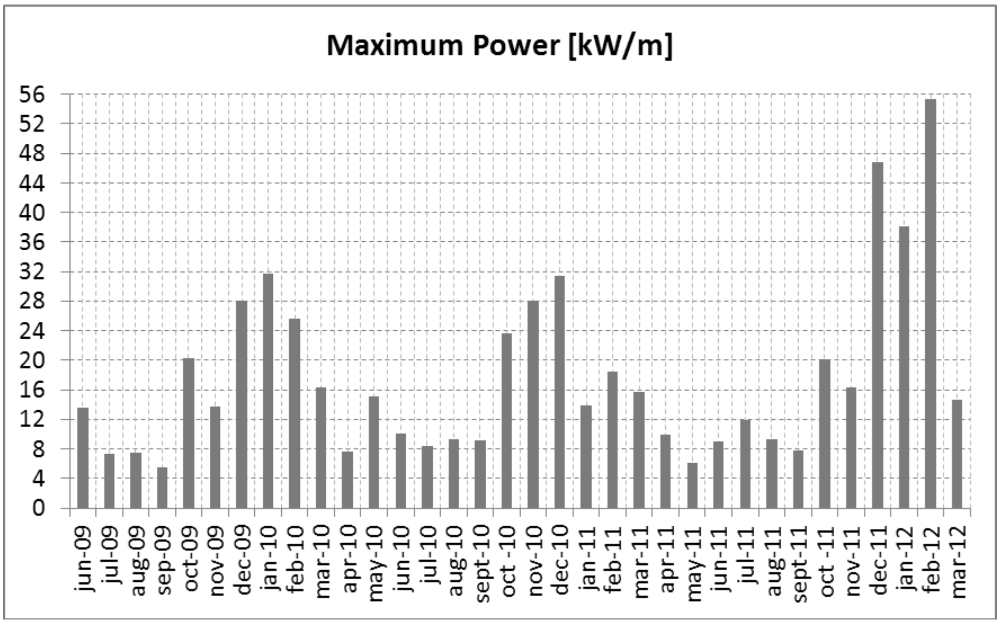

Figure 1: Maximum values of the monthly mean power and its spatial localization as reported in fig 2.

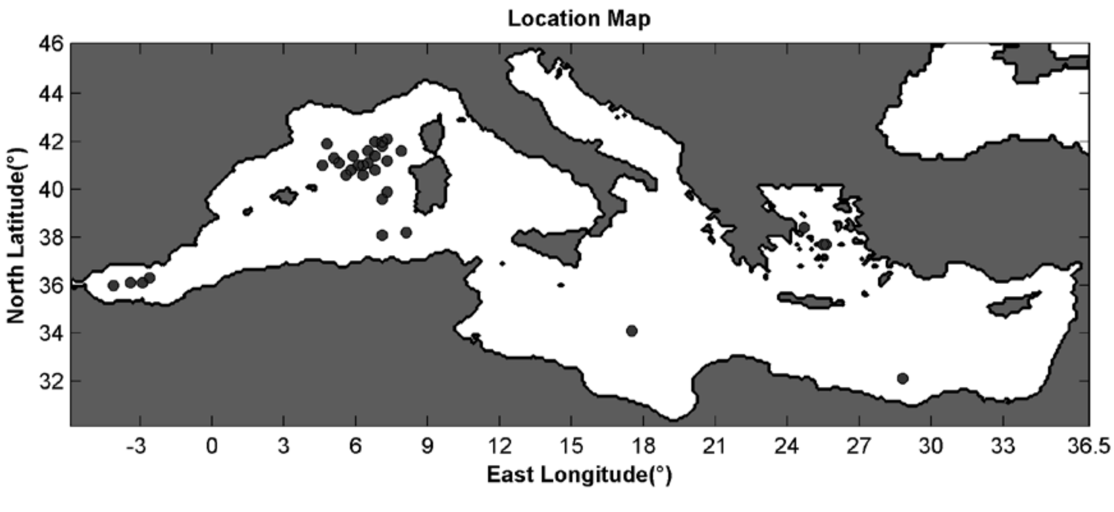

Figure 2: Location map of sea sites characterized by the maximum monthly mean power.

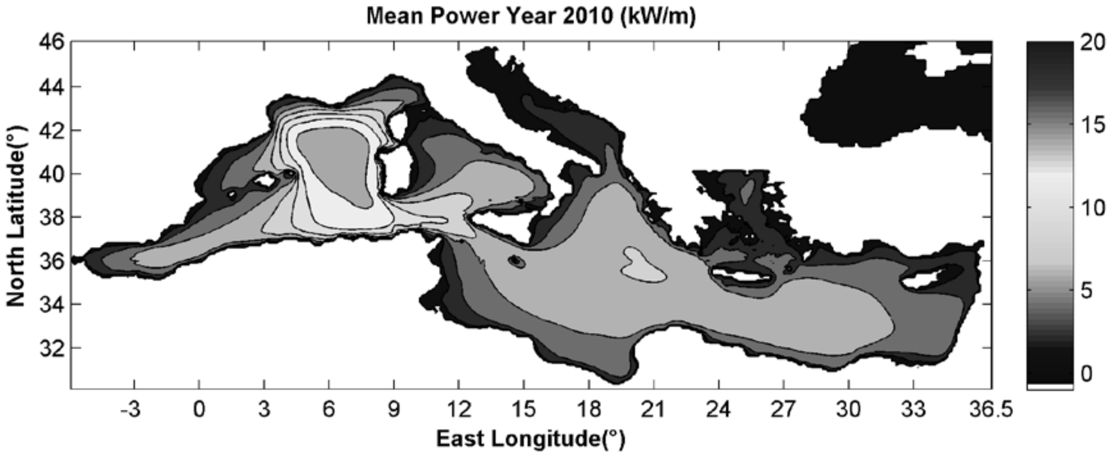

Figure 3:Spatial distribution of the Yearly Mean Power computed by using the data for the Year 2010 [kW/m].

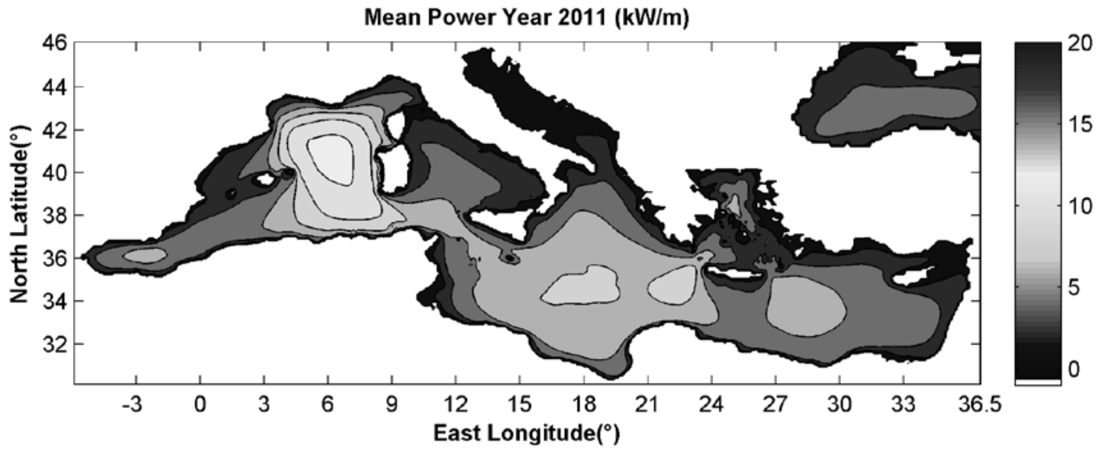

Figure 4:Spatial distribution of the Yearly Mean Power computed by using the data for the Year 2011 [kW/m].

It is worth noting that during the autumn and winter months and therefore in October, November, December, January and February, the maximum monthly mean power in the studied domain is always greater than 20 kW/m (except Nov 09, Jan11 and Feb11).
It is also evident that the most energetic parts of the northern Mediterranean are those on the Western coasts of the islands of Corsica and Sardinia. In this area the maximum annual average power, reaches values equal to 15.8 kW/m for 2010 and 12.8 kW/m for 2011.
For the exploitation of wave energy, supporting infrastructures are necessary (for examples harbours) and so to limit the cabling costs, the distance from the coast should be around 5-10km (Dalton et al., 2009). This topic is of particular interest when studying this resource in coastal waters.
Moreover, the offshore wave energy potential can easily be obtained by means of the analysis of deep water wave data, but the processes affecting waves as they propagate towards the nearshore can modify the wave energy potential, leading to reductions or, sometimes, local enhancements due to focusing mechanisms. Furthermore, due to such mechanisms, the spatial variability of wave energy potential can be remarkable, thus suggesting the need for accurate knowledge for the placing of a pilot plant in order to maximize the harvesting of wave energy.

4. The propagation model

For the numerical simulation of wave propagation, from offshore sites toward coastal sites characterized by water depths of less than 100 m, the Spectral Wave module of the MIKE21 software was used. The MIKE21-SW is a a spectral wind-wave model based on unstructured mesh that allows the simulation of the following physical phenomena: non-linear wave-wave interaction, dissipation due to white-capping, dissipation due to bottom friction, dissipation due to depth-induced wave breaking, refraction and shoaling due to depth variations.
The model is used with the fully spectral formulation, based on the wave action conservation equation, where the directional-frequency wave action spectrum is the dependent variable and with the quasi-stationary mode, where the time is removed as an independent variable and a steady state solution is calculated at each time step.
As offshore boundary conditions the values of wave height, peak period, the average direction and spreading factor, of the six points extracted by the PREVIMER model on a depth of 100 m, were used. The model mesh is flexible with a triangular side of 2000 m in water depths of 100 m to 50 m, a side of 1000 m in water depths of 50 to 30 m, a side of 500 m until the water depth of 20 m and then a triangular side of 300 m (Figure 5).

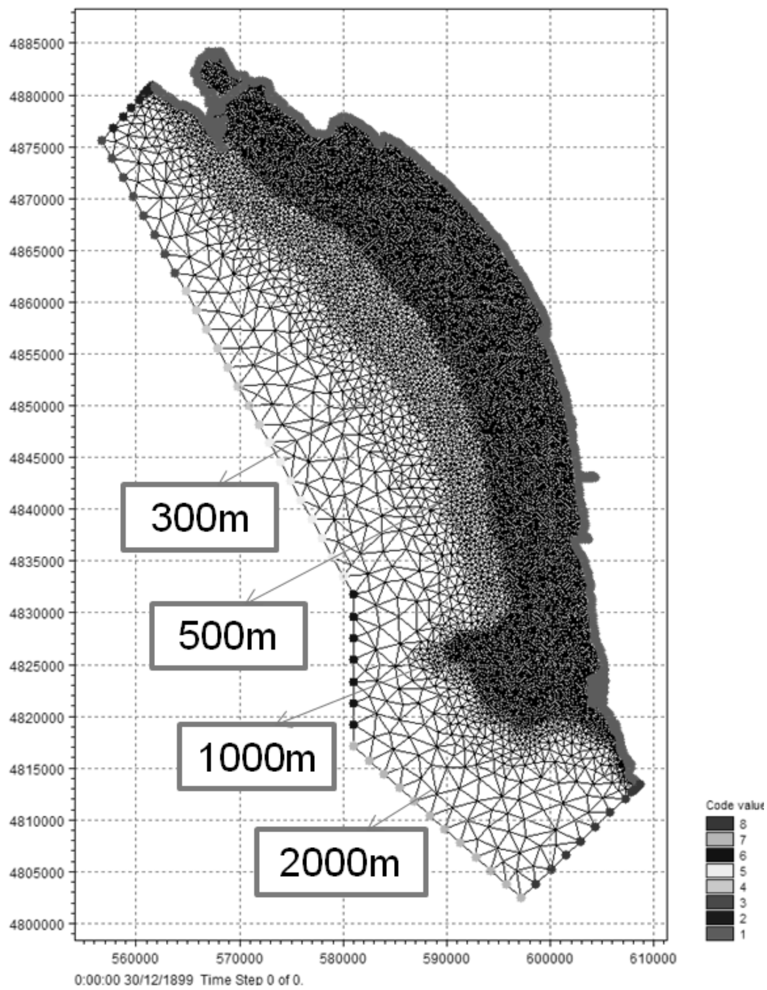

Figure 5:Boundary conditions and resolution mesh.

The model domain is about 60 km x 85 km with a maximum water depth of approximately 100 m (Figure 6).

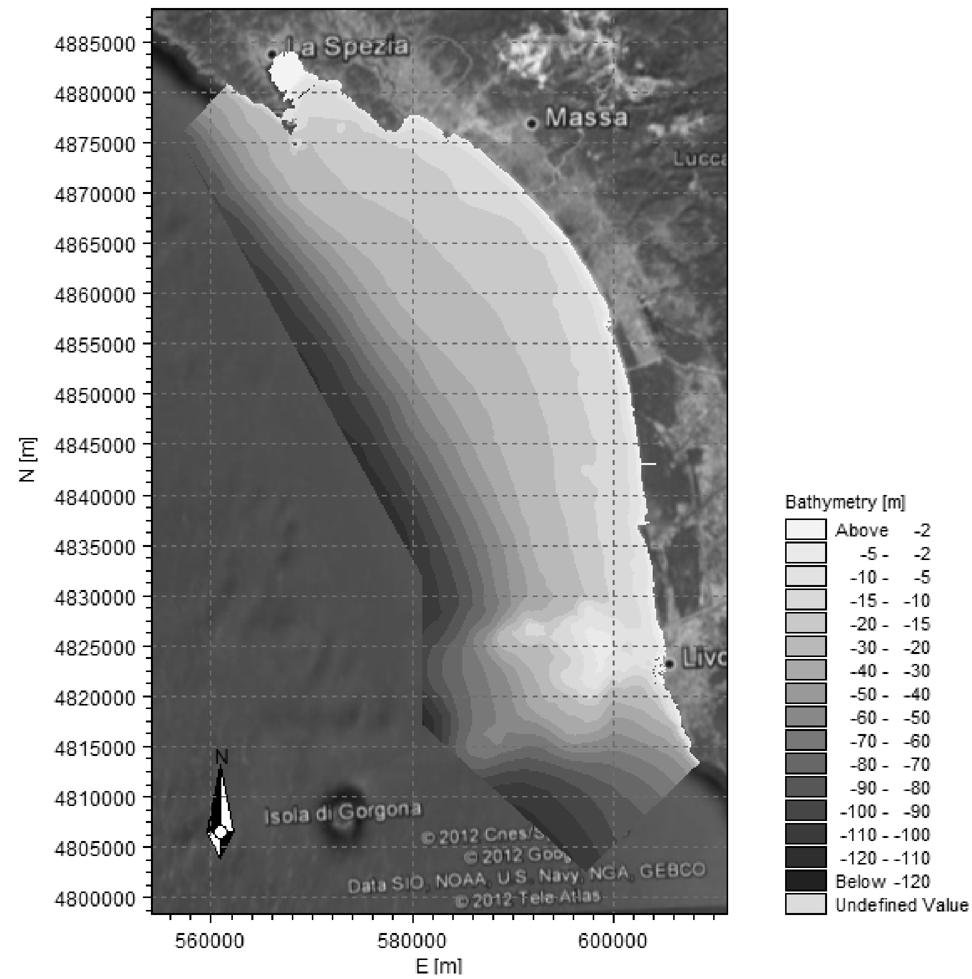

Figure 6:Propagation area bathymetry.

All the time series of the PREVIMER data set (from July 2009 to March 2012) was propagated and a constant value was assumed for the bottom friction equal to 4 cm (Nikuradse formulation) as well as a constant value representing the white capping dissipation source function, equal to 4.5. In output maps were obtained of the variation of the wave height, mean direction and wave power. In fact the MIKE21-SW allows the wave power to be obtained directly as in eq. (8)

$$P_{energy} = \rho g \int_0^{2\pi} \int_0^{\infty} c_g(f,\theta) \cdot E(f,\theta)\, df d\theta \tag{8}$$

where E is the energy density, c_g is the celerity group, ρ is the density of water, g is the acceleration of gravity, f is the wave frequency and θ is the wave direction.

5. Results of the propagation model

The maps of wave power were computed for each time step and fig.7 illustrates an example for one of the most energetic sea states (H_{m0} = 4.2m, T_m = 7.3s, Dir = 240°N) on the 5th of January 2010, hour 18.00 (Figure 7).

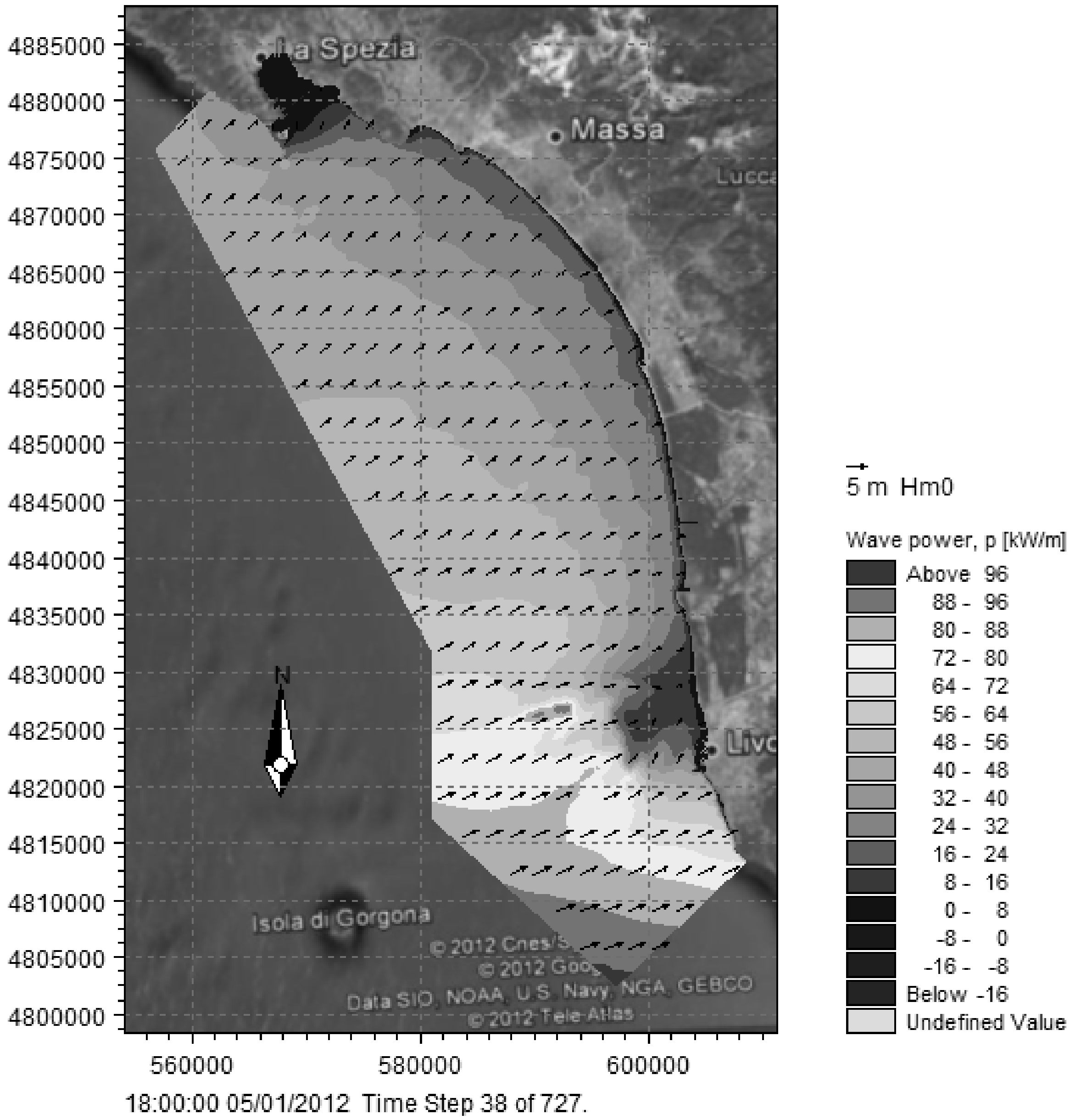

Figure 7:Spatial distribution of the wave power for the 5th of January 2010, hour 18.00 [kW/m] and wave height values (arrows).

Then the monthly mean power for each month was computed from July 2009 to March 2012, and only for the years 2010 (Figure 8) and 2011 (Figure 9), the yearly mean power.

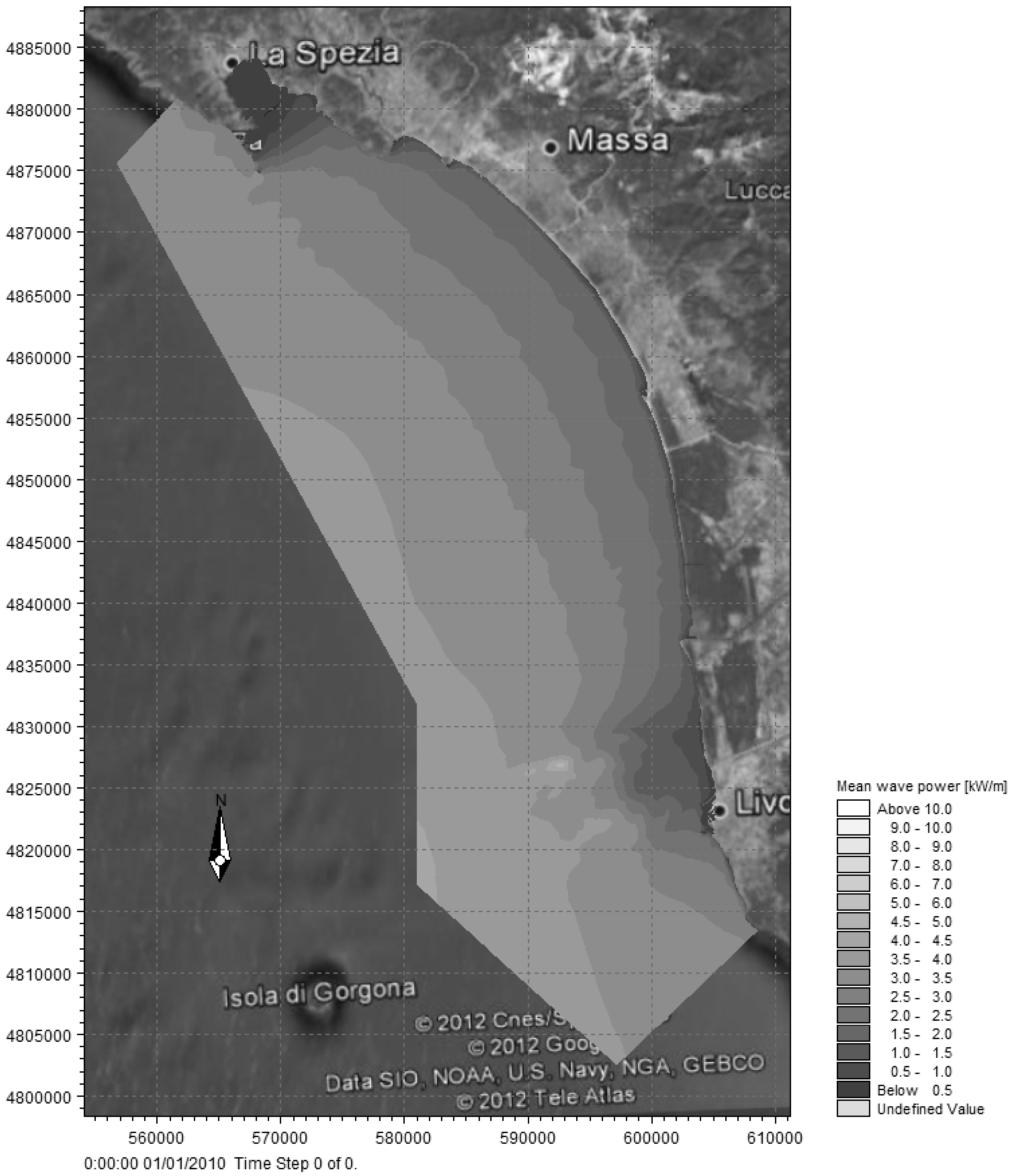

Figure 8: Spatial distribution of the Yearly Mean Power computed by using the data for the Year 2010 [kW/m].

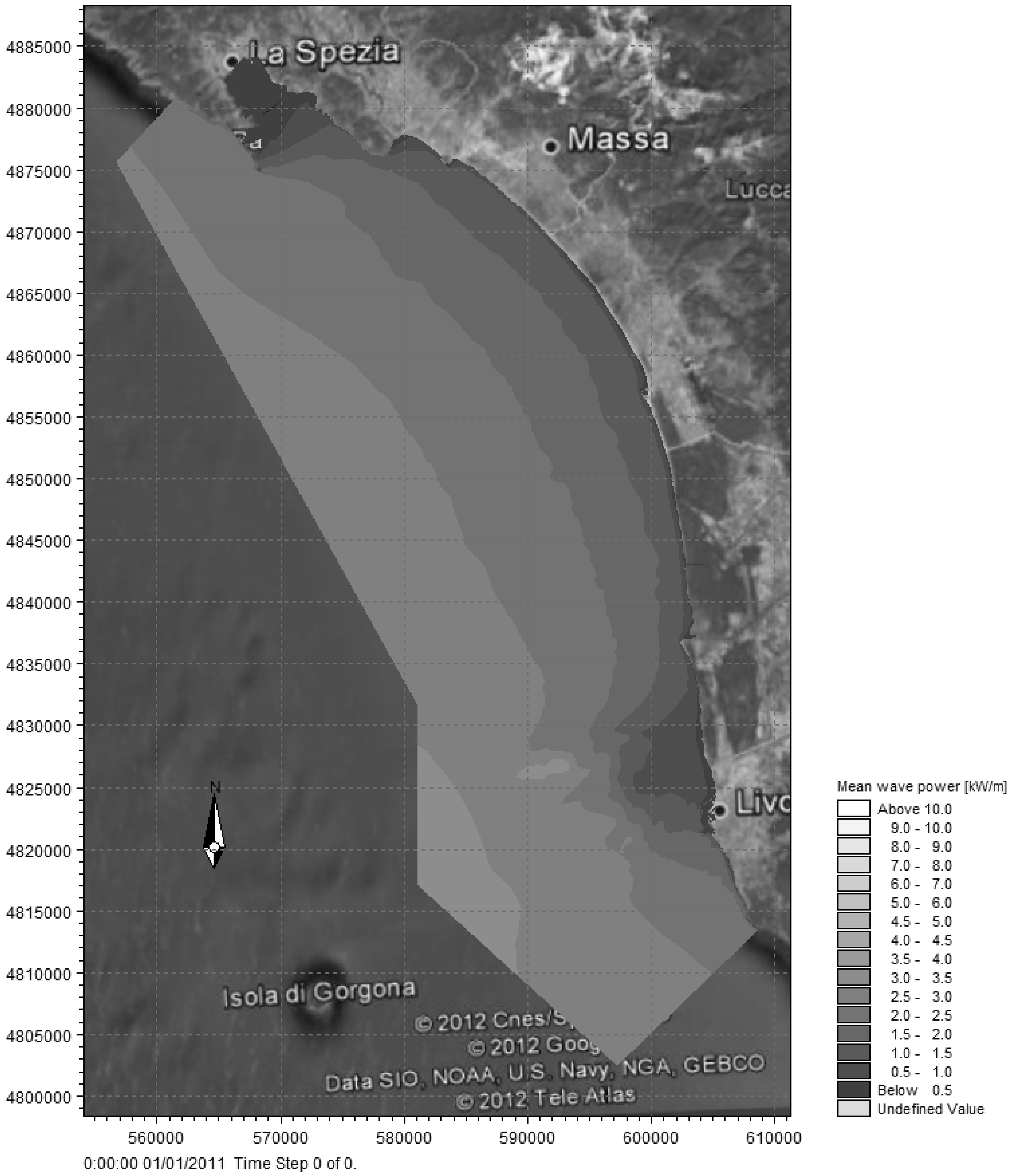

Figure 9: Spatial distribution of the Yearly Mean Power computed by using the data for the Year 2011 [kW/m].

In addition to the above analysis, it was also considered important to analyse the monthly and yearly mean power in 20 different points (Table 1), 10 located in the water depths of 15 m (from 1 to 10) and another 10 in water depths of 50 m (from 11 to 20).

Table 1: Yearly mean values of the wave power in the extracted points.

Point	**Mean Power 2010 [kW/m]**	**Mean Power 2011 [kW/m]**
1	0.97	0.72
2	2.23	1.55
3	2.23	1.61
4	2.21	1.61
5	2.06	1.48
6	2.16	1.6
7	2.28	1.71
8	2.44	1.86
9	*2.89*	*2.23*
10	2.1	1.6
11	3.16	2.51
12	3.16	2.5
13	3.23	2.54
14	3.33	2.61
15	3.4	2.66
16	3.38	2.65
17	3.31	2.6
18	3.36	2.65
19	*3.63*	*2.93*
20	3.07	2.43

At each point the wave roses are also computed (Figure 10).
It is evident that the most energetic points are the 9 in the water depths of 15 m and the 19 in the water depths of 50 m, and these points are located on the Meloria shoals (Secche della Meloria) where a focusing mechanism is affective.

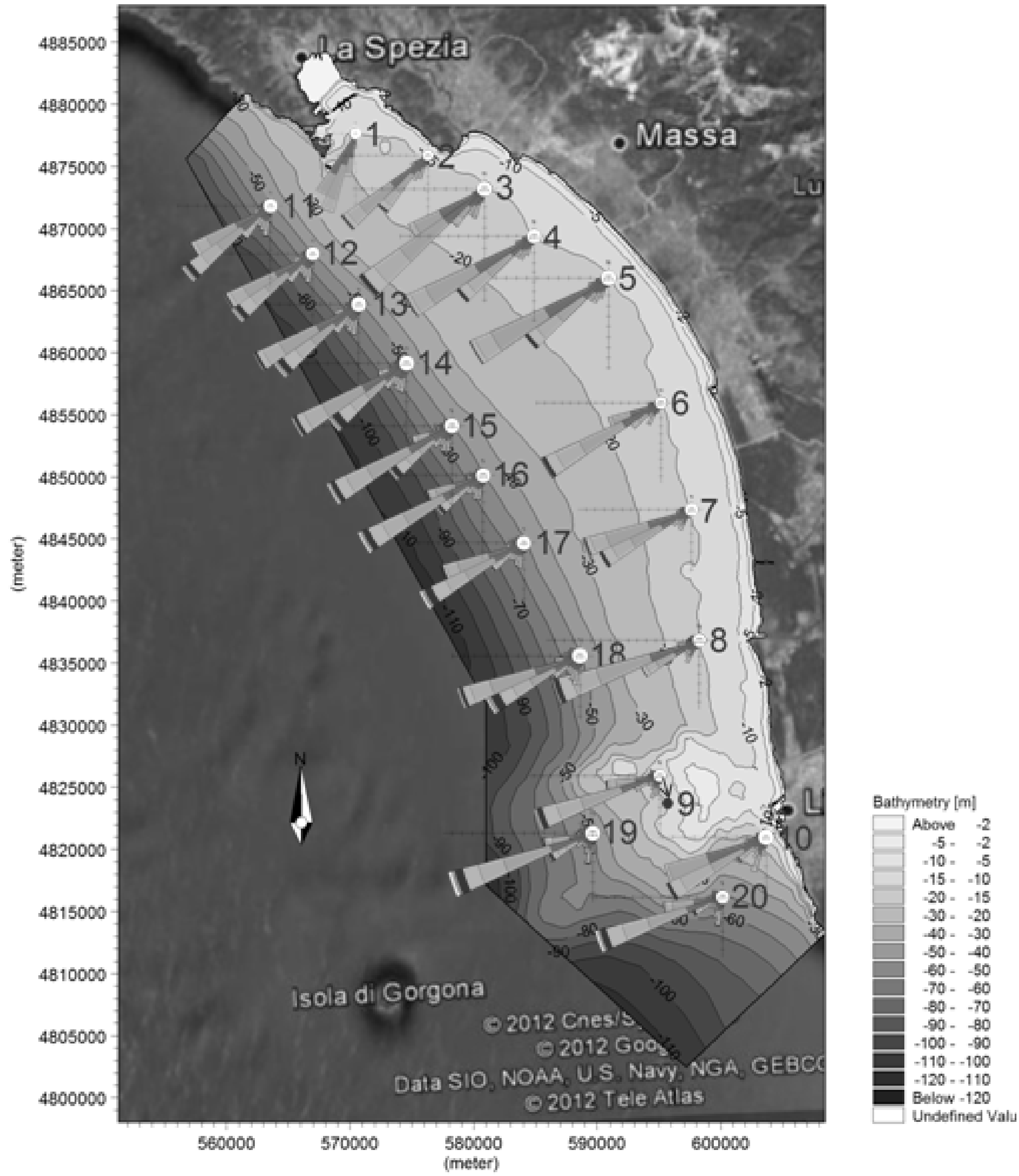

Figure 10: Location and wave rose of the points extracted.

For each month the values of the wave power were computed at all the points in the water depths of 15 m and at all the points in the water depths of 50 m.

In Figure 11 an example for February 2010 is illustrated.

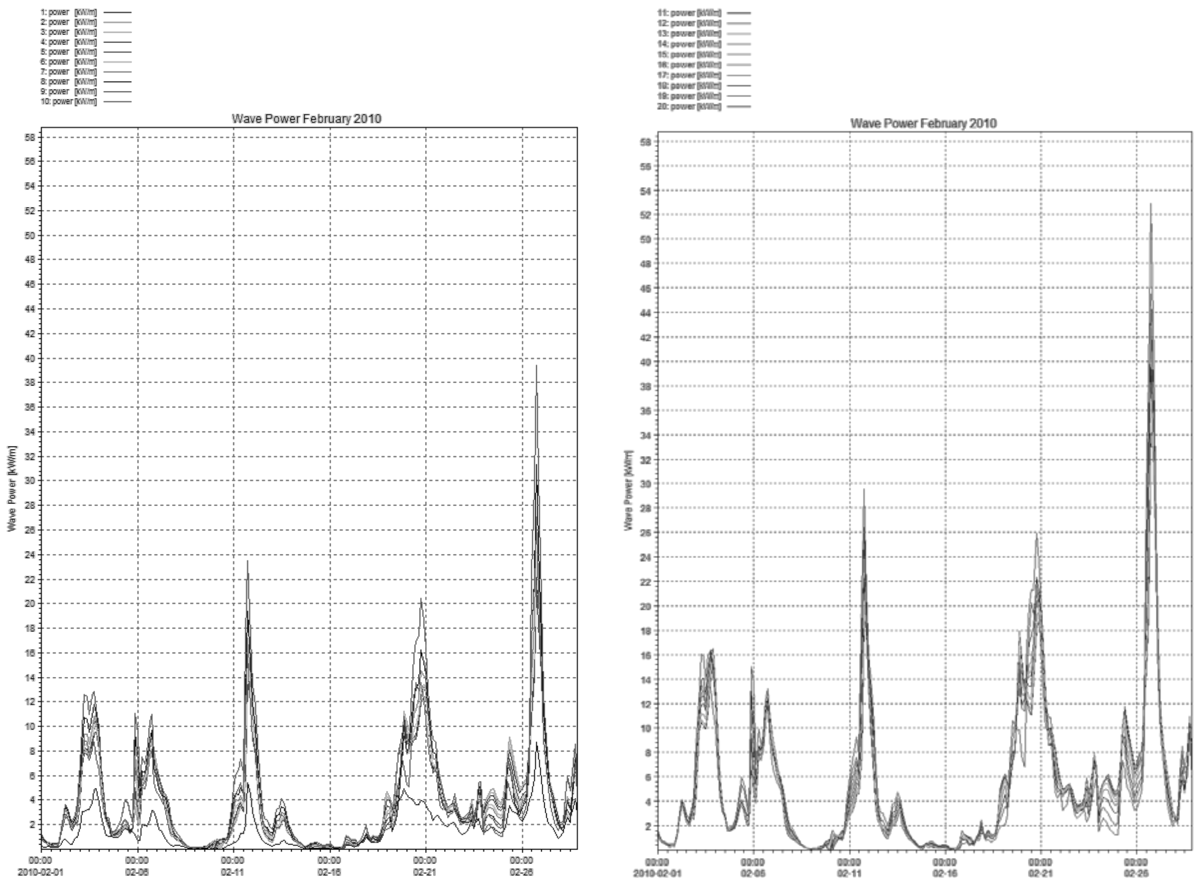

Figure 11: Monthly wave power trend of February 2010 for the points on the 15 m bathymetry (on the left) and on 50 m bathymetry (on the right).

6. Conclusions

This study presents a brief contribution to the knowledge of the availability of wave motion energy in the whole of the Mediterranean sea. The results constitute both an up-date of previous, older studies (Pontes et al. 1996) and a deeper knowledge, in terms of spatial resolution, of wave energy potentials also in respect of more recent studies (Filianoti, 2000, Vicinanza et al. 2011).

With reference to Pontes et al. (1996) it can be confirmed that the area with the most availability of average annual power is that to the West of the islands of Corsica and Sardinia. However, the maximum values supplied in Pontes et al. (1996) for the area of Alghero (5 kWm-1 average annual), are much lower than those obtained from the more recent studies by Filianoti (2000) and Vicinanza et al. (2011) in the same area (9.5 kWm-1 average annual).

These studies are based on data registered punctually from a few wavemeter buoys whereas the present study is based on data coming from numerical simulations (MED 6MIN-IFREMEER), something which has permitted a higher spatial resolution knowledge and so the highlighting of maximum values of up to approximately 15.5 kWm-1 located in other points offshore of the same area.

The analyses are limited to the aspect of the quantitative definition of the energy availability without examining the sustainability of the use of WEC technologies.

Nevertheless, given that evident technical-economical limitations suggest that the potentially exploitable areas for supplying energy to zones inland must be located, amongst other things, between 5-10 km from the coastline, a procedure has been developed based on a second numerical model (MIKE21-SW). This takes as off-shore boundary conditions the output of the MED 6MIN model, permitting the reconstruction, with very precise location definition, of the energy availability of areas close to the coastline with sea-bed depths of less than 100 m. As a first area for testing the procedure a stretch of coastline was chosen between Leghorn and the Gulf of La Spezia. The simulations have highlighted the high spatial variability of the wave energy resource and the formation of hot-spots due to phenomena of focusing in correspondence with areas on the Secche della Meloria (the Meloria shallows). At present, other coastal areas are under examination and the results will be presented in subsequent papers.

7. Acknowledgements

This study constitutes part of the program of the Research Doctorate of Engineer V. Vannucchi, in Civil and Environmental Engineering, at the DICeA, University of Florence.
The authors wish to thank: i) IFREMER for the use of data and in particular Dr Fabrice Lecornu; ii) DHI- Italia for having supplied the availability of the software MIKE21, and in particular Engineer Andrea Pedroncini.
The support of the MARINET Project (EU-FP7, www.fp7-marinet.eu), is gratefully acknowledged.

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