Wave energy resource and its conversion efficiency along the coast of Argentina

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Abstract— **The paper presents an evaluation of the wave energy potential output along the Argentine coast.**

With its almost 5000 km of coastline, Argentina provides an ideal scenario for the exploitation of this renewable energy. Unfortunately, no direct (buoy) wave data are available in this area, so the analysis has been carried out by using WAVEWATCH III and WAM hindcast data produced respectively by NOAA Marine Modeling and Analysis Branch (available from 1979 to 2009) and by European Centre for Medium-Range Weather Forecasts (ECMWF) ERA-Interim project (available from 1979 to present). The model grid points nearest the coast have been considered, for each of them a statistical analysis of the average yearly energy has been performed, and the differences between the two systems have been evaluated. Satellite altimeter tracks have been used to validate the model results. Results show that for different points the mean yearly potential power is about 14 kW/m, with peaks of about 18 kW/m. A further – and often neglected aspect – is that the spectral distribution of the wave energy in a given site is of paramount importance since the Wave Energy Transformation Index (IWET) for all sort of devices depends on the wavelength. By making use of ECMWF public data the Wave Energy Potential is evaluated separately for the total Significant Wave Height (SWH or Hs) and for its wind wave SHWW (Significant Height of Wind Wave) and swell component SHTS (Significant Height of Total Swell). Results are important for any wave energy planning or design activity.

Keywords—**Argentine coast, swell, wave energy potential, wave model data, wind wave.**

I. INTRODUCTION

THE evaluation of wave energy potential of sites, offshore and along the coast, is an all-important tool for planning of Wave Energy systems, so that it is only natural that the literature on the subject should be extremely large. A clear picture of this problem is given by the results of both EMEC (The European Marine Energy Resource) [1] and EquiMar [2] research programs. No review of the existing references can however be complete, and in the following we shall only briefly quote some of the past work in order to highlight the complexity of the task and the variety of the possible approaches.

Most of the approaches are based on making use of the archived data of the many spectral wave models available all over the world. Such models are generally run by national and international meteorological offices or by private companies. In many instances, where direct (usually buoys) wave measurements are not available, model recorded data have been used either as stand-alone or as supplement as described e.g. in [3].

For instance an early work by Defne et al. [4] deals with the energy potential along the East Coast of the USA by making use of buoy data – which are numerous enough in that area. Reference [4] is also interesting since the authors make use of recorded spectral wave data to determine the effect of using significant wave height and period for power calculation.

Model data (generally ECMWF Centre for Medium-Range Weather Forecasts analysis or re-analysis, and NOAA-National Center for Environmental Prediction) are however the most commonly used sources. Many authors also fit ("nest") a higher resolution wave propagation model, taking the output spectra from large scale model as boundary conditions, with the objective to take into account the effect of the coastal morphology and of the near-shore bathymetry.

Such is the approach taken to carry out coastal energy potential evaluation for the Italian Island of Sardinia [5] and for many other locations all over the world [6-13]. Reference [14], where the wave climate in the Mediterranean Sea was examined, is particularly interesting since it makes extensive use of both buoy and satellite data to calibrate and correct model results. A similar procedure was used in [15] to study the Irish Wave climate.

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Another remarkable work, which dealt with the energy potential around India, is described by Sannasiraj and V. Sundar [16] who made use of ten years (1993 to 2002) WAM (WAve Model) generated wave data, and took into account the influence of the seasons: in their case Monsoon and non-Monsoon seasons.

Reference [17] reports the use of ten years ECMWF data, validated against buoy measurements in two different intervals in the Persian Gulf. The annual, seasonal and monthly variations of wave characteristics and seasonal wave energy are evaluated.

In [18] and [19], authors while carrying out a wave energy assessment along one of the coasts of Sicily, pointed out that wave energy devices should be optimized for each particular wave climate, if an acceptable efficiency is to be attained.

Reference [20], where wave energy potential in various Mediterranean spot is evaluated, shows also the importance of the economical aspects, in particular in connection with the use of point devices.

In [21] and [22] the assessment of potential wave energy is carried out in two mild wave climate locations in Calabria (Southern Italy), by making use of ECMWF data validated against Italian Wave Buoy Network (RON - Rete Ondametrica Nazionale) and UKMO (United Kingdom Met Office) data. Their work is particularly interesting in that they analyse the performance of thirteen types of offshore WECs, and consider hypothetical, but realistic user demands. They also consider the spatial arrangement of wave energy devices in order to minimize possible park (shadowing) effects.

While this consolidated practice has certainly lead to a great improvement of the knowledge of wave energy potential around the world, its applications should be carefully evaluated. It should not be forgotten that not all Wind/Wave models are equal; even though the basic energy balance equations are universal, the parametrization, the procedures, the resolution, and above all the data assimilation techniques all differ, and often in a significant way. This problem has been examined elsewhere: e.g. by MacKay et al. [23], [24] who dealt with the uncertainty deriving from both the use of historic data and from the variability of the wave climate. A somewhat similar problem was considered in [25], in the context of extreme value of Hs but it can be extended to all applications

The possible answer to this problem at the current stage of the technology is, on the one hand to make use of more than one source of the many existing modelling systems, and on the other hand to cross-check the results with any available experimental data which should be available.

II. METHODOLOGY AND DATA

As stated above the methodology for wave energy assessment is generally well established. The main data sources are the various institutions that produce daily weather and wave forecast by running global models. There are numerous producers, both public and private, of such data and most of them provide their archived wave data for all the points of the computational grid, at a given time interval.

Even assuming that modern modelling technique are similarly advanced, the adequacy of such data to the objective is however debatable since many factors influence the quality of the results, and not all these factors are known to the users.

The first and foremost aspect is of course the source of the wind data: a wave simulation system is only as good as the weather forecast systems behind it. Besides, even assuming an accurate weather system, no matter how accurately the wind is computed or how high the spatial and temporal model resolution is, the frequency with which the wind is fed to the wave module is of paramount importance.

A further, perhaps even more important aspect, is the way measured data are incorporated (“assimilated”) into the computation: modelling system cannot be expected to provide reliable information unless a regular assimilation is carried out with data from “ground truth”, i.e. generally buoy wave meters and satellite radars (altimeters).

If an accurate and consistent climate study is required, there is no guarantee that a single data source will prove adequate. A good strategy, which has been followed in this work, should involve the comparison between two or more data providers, and possibly the cross checking of whatever ground truth is available.

In this work, which is aimed at assessing wave energy potential off the coasts of Argentina, the authors have made use of the two most widely diffused wave modelling archives, i.e. the NOAA-NCEP Climate Forecast System Reanalysis (CFSR) dataset (in the following: NOAA) and the ECMWF ERA-Interim archive (in the following: ECMWF), while some ground truth data have been obtained from a number of Jason-1 Phase A satellite passages. NOAA data are on a 0.5° grid and data are available at 3 hours interval for 31 years (1979 to 2009), ECMWF same grid are available at 6hours interval for 39 years (1979 to 2017).

Fig. 1 illustrates the computational grids and the points near the coast that have been used for the assessment.

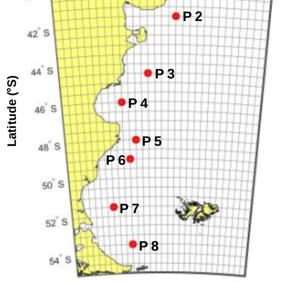


Fig. 1. Computational grid, common to NOAA and ECMWF.

Exact point locations are reported in Table I.

TABLE I
POINT LOCATIONS

Points	Latitude (° S)	Longitude (° W)
P 1	39.5	59.5
P 2	41.5	61.5
P 3	44.5	63.5
P 4	46.0	65.5
P 5	48.0	64.5
P 6	49.5	65.0
P 7	51.5	66.5
P 8	53.5	65.0

No wave buoy data are available along the coasts of Argentina. Some validation, however can be carried out by making use of altimeter satellite data, as for instance in [14] and [15].

Jason-1 Phase A (from 2002 to 2009) altimeter data were used for this work. In the study area there were 12 different tracks (see Fig. 2) including cycles from 1 to 260 with a total of 2773 valid passages.

Fig. 3 shows the correlation graphics between satellite altimeter and model Hs data.

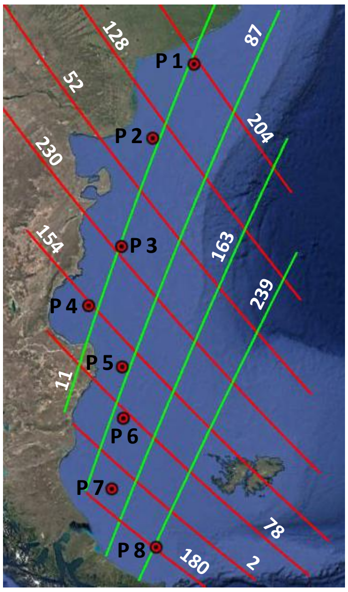


Fig. 2. Available tracks for Jason-1 Phase A. Phase A extends from 2002 to 2009 with a total of 2773 valid passes in the study area.

The deep water potential energy flux (expressed in W/m) is easily evaluated by the classical formula [7]:

$$P = \frac{\rho\, g^2\, H_s^2\, T_e}{64\,\pi} \tag{1}$$

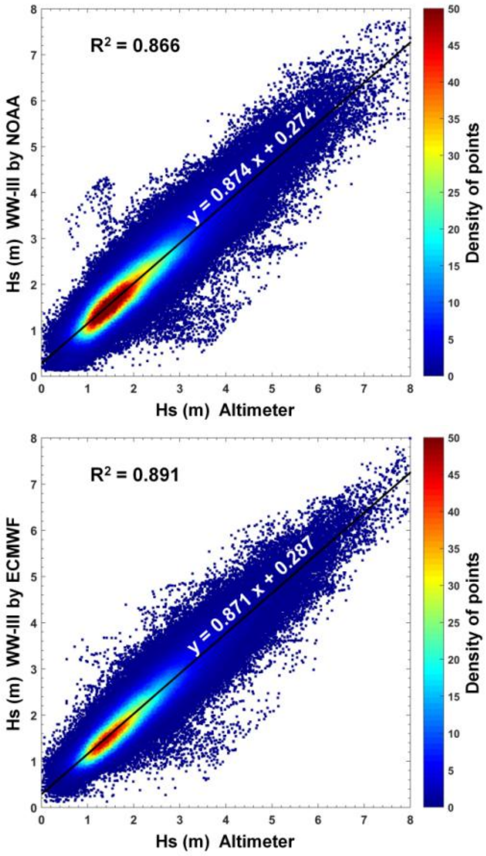


Fig. 3. Correlation between Significant Wave Height as measured by Jason-1 Phase A satellite altimeter and computed respectively by NOAA (top) and ECMWF (bottom) wave models.

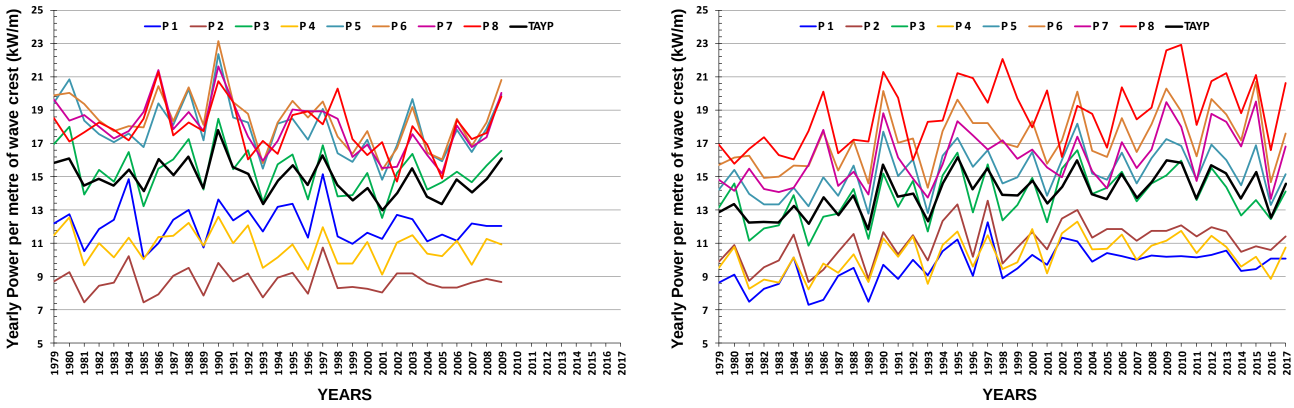
where H_s is the Significant Wave Height and T_e is the “energy period”. T_e is a conventional value that in principle depends on the wave spectrum [26], and it usually not specified in the dataset archives. It must therefore be estimated from other variables (e.g. mean or peak period). Evaluating this relation is beyond the scope of this study, so we use the same relation, valid for a standard JONSWAP spectrum, as used in [26] and reported in (2):

$$T_e = 0.9 T_p \tag{2}$$

A first result is the computation of the Average Yearly Power per metre of wave crest for each grid point considered (AYP_n) as well as the Total Average Yearly Power (*TAYP*) for both databases (Fig. 4), where *TAYP* is defined as AYP_n averaged over the total N (in this case N = 8) points considered:

$$TAYP = \frac{1}{8}\sum_{n=1}^{8} AYP_n \tag{3}$$

It is also useful to compare the two sets of values, as in Fig. 5, which correlates the respective *GAYPn*, i.e. the AYP_n averaged over the whole measurement period available for each point *n*.



(a) (b)

Fig. 4. Average Yearly Power *AYPn* for each coastal grid point and Total Average Year Power *TAYP* (black lines) from NOAA (a) and ECMWF (b)

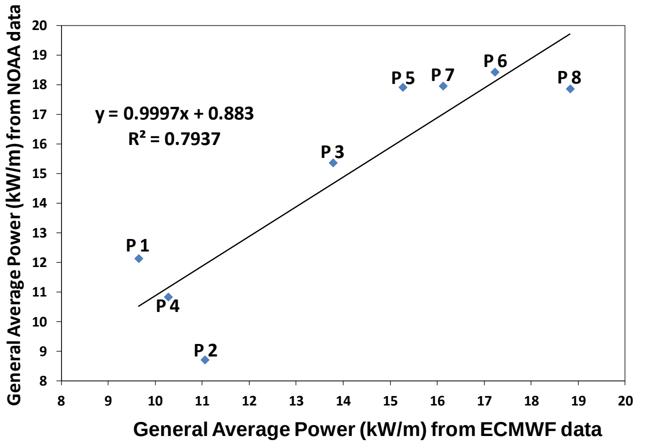


Fig. 5. Correlation between Correlation between general average GAYPn as computed with ECMWF and with NOAA sources.

The general correlation is quite acceptable; however more interesting results can be obtained by comparing some statistics for the yearly potential power. Table II reports Minimum Yearly Power (*MinYP*), Maximum Yearly Power (*MaxYP*), *GAYP* and Standard Deviation Yearly Power (*StDYP*) for each point and for Total Average Yearly Power (*TAYP*) from both the data sources which have been considered.

Table III reports the ratio between ECMWF and NOAA values reported in Table II.

It appears that ECMWF consistently underestimates most of the statistics in comparison with NOAA. Moreover, also the dispersion of the data (Ratio between the two Standard Deviation = 1.15) seems to be higher for ECMWF than for NOAA.

One of the causes could be the different time sampling of the results: 6 hours for ECMWF, 3 hours for NOAA. The influence of the sampling time interval on the skill of wind/wave modelling suites on producing reliable statistics has indeed been examined by different authors: [27], [28] [29] and [30].

Data from ECMWF, moreover, provide useful information, besides the total Hs and the average period Tm. Based on the wave spectrum, the total energy is divided into two component, related respectively to the wind waves (Significant Height of Wind Wave Hsw and peak period Tpw) and swell (Significant Height of Total Swell Hss and peak period Tps) [31].

Since the performance of most – if not all – the wave energy devices, is heavily dependent on the wave length, it makes sense to consider the potential energy separately according to (1) and (2) for the two ECMWF wave components.

TABLE II
SIGNIFICANT STATISTICS OF THE WAVE POTENTIAL POWER FOR EACH POINT AND FOR TAYP FROM BOTH DATA SOURCE

	ECMWF				NOAA			
Points	*MinYP* (kW/m)	*MaxYP* (kW/m)	*GAYP* (kW/m)	*StDYP* (kW/m)	*MinYP* (kW/m)	*MaxYP* (kW/m)	*GAYP* (kW/m)	*StDYP* (kW/m)
P 1	7.32	12.26	9.64	1.08	10.12	15.16	12.13	1.13
P 2	8.66	13.55	11.05	1.17	7.46	10.75	8.71	0.74
P 3	10.84	16.59	13.78	1.48	12.52	18.48	15.37	1.41
P 4	8.23	12.29	10.27	1.10	9.14	12.58	10.83	0.92
P 5	12.77	18.16	15.27	1.40	14.81	22.36	17.92	1.63
P 6	14.33	20.70	17.22	1.69	15.42	23.15	18.43	1.64
P 7	13.67	19.50	16.12	1.66	15.17	21.63	17.96	1.54
P 8	15.80	22.89	18.83	2.00	14.70	21.27	17.87	1.46
TAYP	11.84	16.15	14.02	1.21	12.98	17.80	14.90	1.05

TABLE III
RATIO OF SIGNIFICANT STATISTICS IN ACCORDING TO DIFFERENT SOURCES

	ECMWF/NOAA			
Points	*MinYP Ratio*	*MaxYP Ratio*	*GAYP Ratio*	*StDYP Ratio*
P 1	0.72	0.81	0.79	0.96
P 2	1.16	1.26	1.27	1.58
P 3	0.87	0.90	0.90	1.05
P 4	0.90	0.98	0.95	1.20
P 5	0.86	0.81	0.85	0.86
P 6	0.93	0.89	0.93	1.03
P 7	0.90	0.90	0.90	1.08
P 8	1.07	1.08	1.05	1.37
TAYP	0.91	0.91	0.94	1.15

Results for the Total Yearly Average Power (*TAYP*) are shown in Fig. 6.

It appears that the sum of the power produced by the two components separately is less than the power computed with the whole wave system. This is obviously due the influence of the Te "energy period". This is however a comparatively minor issue. The main point is that, due to the influence of the wave period on the efficiency of any Wave Energy device, making use of a single Hs and Te may lead to important errors on the estimate of all the potential energy estimates for any site.

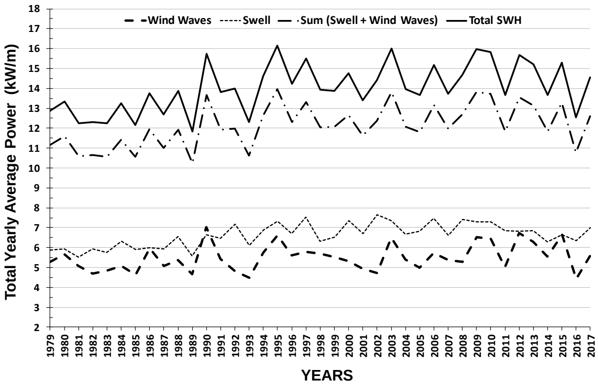


Fig. 6. Totally Yearly Average Power (*TAYP)* computed according to ECMWF data with wind wave only, swell only, sum of the two and total.

III. CONCLUSION

An assessment of wave energy potential on points off the coast of Argentina has been carried out by introducing a number of innovations to the now more or less standard approach for this kind of computations.

In the first place, we have made use of two different sources of wave data: the NOAA-NCEP Climate Forecast System Reanalysis (CFSR) and the ECMWF ERA-Interim Archive. By comparing the results thus obtained, some differences have emerged between the two set of results.

Even though form a practical point of view the difference is not too high (about 5%), probably due to the good quality standards of the two institutional sources, it is enough to suggest caution. From this point of view, another possibility of validation is provided from the now widely and publicly available satellite altimeter tracks, which yield reliable measurements of the Significant Wave Height all over the world and for many years. An example of this approach has been followed and reported in the paper.

A final, and possibly more important, aspect which has been highlighted in the paper is that the Significant Wave Height and some kind of average period are not adequate to properly characterize the potential energy of a site. Given the strong dependence of the efficiency of most Wave Energy Devices on the wave period, it is obviously necessary to take into account the spectral distribution of the incoming waves. A first and practical approach to this problem is to make use of the separate "swell" and "wind wave" data which are nowadays available in some data archives (such as for instance ECMWF). The results show that, at least for an open and wide oceanic environment such as the coast of Argentina, the influence of swell is important and has to be taken into account when performing a potential wave energy assessment.

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