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SEA-WAVE HEIGHT MEASUREMENTS IN THE OPEN LIGURIAN SEA COMPARED WITH WAVE AND SEA–SALT AEROSOL FORECASTS

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ABSTRACT

Wave height measurements in open sea are often collected through remote sensing techniques, such as, among the others, SAR and HF radar systems, due to the difficulty of managing any device with extension in deep waters [1].
On the contrary, several other methods, including wave buoys, pressure and acoustic water level sensors, upward-looking ADCPs, are usually employed to monitor and estimate ocean waves in shallow waters.
The paper deals with long-term and continuous measurements of wind waves data in deep open sea collected by the W1-M3A observing system [2], moored in the Central Ligurian Sea with a specifically developed acoustic-based new prototype.
The estimates provided by the system have been compared with Wave Wacht III model forecasts and with Sea Salt Aerosol model outputs achieving a good correlation between in situ measurements and model outputs.

1. INTRODUCTION

Ocean wave time series have been always considered extremely useful and interesting for scientific purposes, public safety, and engineering applications. Coastal erosion analysis and prevention, integration of data for weather forecasting, analysis of offshore structures behaviour with respect to the sea heave, and complementary information to safely operate off shore navigation are only some of the applications related to the sea waves.

There is also a growing interest into scientific application of wave measurement and estimate in order to improve the forecast capability of coupled ocean-atmosphere models and to increase knowledge of the physical phenomena controlling the air-sea interactions that has implied, in recent years, great efforts in studying the effects of waves, sea-state and wind.
This work describes the technology, based on the joint use of an array of acoustic altimeters (echosounder), developed to obtain wave estimates from the W1-M3A observatory and reports some results related to the comparison of in-situ wind and wave measurements with wave models.
The contemporary availability of wave height and wind speed observations in open ocean has been also helpful for understanding the impact of wind and wave on ocean-atmosphere interactions and, consequently, for example, on sea-salt aerosol production. For this reason, the paper also presents the results of the comparison between wave estimates and sea-salt operational forecasts in the open Ligurian Sea.

2. METHODOLOGIES AND DATA

In situ ocean wave and wind speed time series have been collected by the off-shore W1-M3A observing system moored in the center of the Ligurian basin, approximately 75 km far from the coast, exposed to winds and waves without any shield by the surrounding orography. The off-shore platform is based on a stable spar buoy with the capability to measure a complete set of meteorological parameters, water column physics and bio-geochemical data down to 40 meter depth, wave estimates and snapshots of the sea-state using the on board camera installed at an height of about 8 m from the sea level. All the data and the images are collected on hourly basis and available in near-real-time by means of both satellite and GSM links.
The buoy was specifically designed as a stable measuring platform for air-sea interaction research: its

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design (e.g., total mass, unity buoyancy at the sea level, and dumping disk) allows for negligible sensitivity to sea heave and height.

Even if the buoy was not conceived as a wave measuring platform and cannot be considered as a classical wave meter buoy, a new methodology has been developed in order to estimate significant waves height, period and direction.

The proposed method is based on the use of an array of echosounders installed along the buoy body at 10m depth in an upward looking configuration (Figure 1).

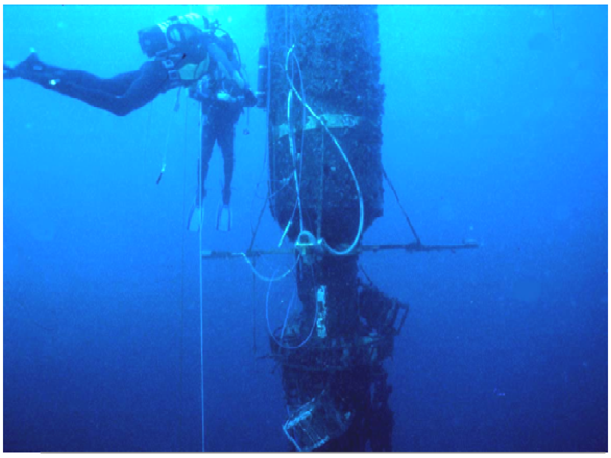

Figure 1. The acoustic-based wave meter system deployed on the W1-M3A observing system.

The directional array is mounted on three supports at 120° apart, and the used echosounders have a beam width of 6° at 3dB point and 5 mm of resolution.

The echosounder's transducer is a circular piston whose radiation pattern is shown in Figure 2 (transducer radius *a*=17.2 mm, *ka*=36.68). The narrow beamwidth provides a small footprint on the sea surface (about 1 m wide) and the length of the supports assures that footprints are sufficiently separated to acquire different profiles of the same sea surface.

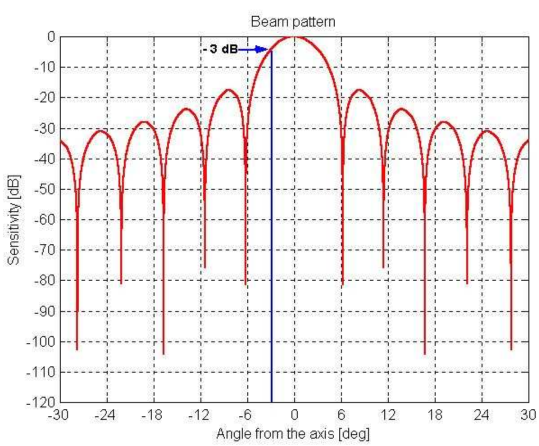

Figure 2. Radiation pattern of the transducer.

The profiling of the sea surface is carried out by emitting a single vertical sound beam toward the sea surface and measuring the time delay of the first significant echo within the sea surface backscatter (by assuming a sound speed *c*=1473 m/s constant for the entire water column). In order to avoid interference of an echosounder return by the others, each ping (and consequently each sample acquisition) is delayed with respect to the others by few milliseconds.

The onboard acquisition system collects the time series by the three echosounders for 5 minutes each hour at 2Hz. At the same time and with the same sampling frequency the time series related to the motion of the buoy (inclination and acceleration) are collected together with a snapshot of the sea state (Figure 3).

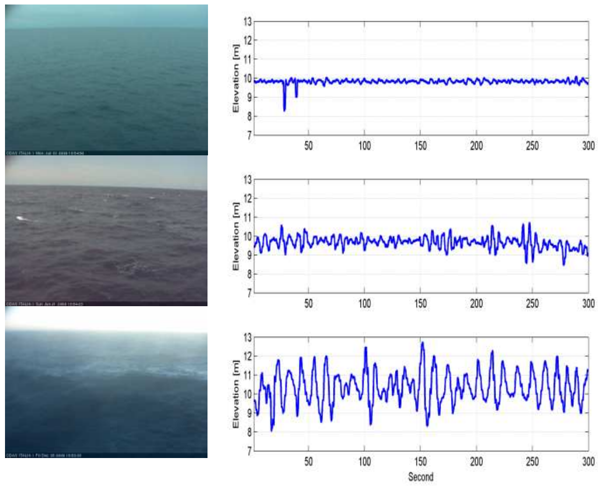

Figure 3. Examples of three time series acquired by the echosounders with the corresponding sea state as captured by the on board camera.

1.1. Wave model data

The wave estimates provided by the W1-M3A observing system have been compared to the operational forecasts obtained using the Wavewatch III (WW3) model.

The forecasts have been collected from an operational center producing the wave field at 0.02 degree of resolution in the Ligurian basin and the comparison has been carried on the basis of several sea state classes for the wave height and period.

The model is forced with the wind field generated by the WRF-NMM model and also the forcing wind classes are used in the comparison in order to evaluate the quality of the model and its skill in accurately reproducing the wave field in a semi-enclosed basin as the Ligurian Sea.

1.2. Sea-salt forecasts

The wave measurements collected by the mentioned buoy have been also used to test the DREAM-Salt prediction model [3][4].

Indeed, the action of wind over the sea surface is the main factor responsible for the production of sea salt in open ocean. When the wind speed increases and the energy of the wind becomes too much to be absorbed by waves, waves start breaking and producing whitecaps. As soon as sea-salt aerosol (SSA) reaches the first air layer above the sea surface, about 1/3 of the mean wave height, the droplets exchange with atmosphere an amount of heat and moisture, leading to a decrease in size of sea droplets.

Sea salt aerosol forecasts are provided by the DREAM-Salt prediction system at the Tel-Aviv University that outputs daily predictions of 3-D distribution of SSA over the Mediterranean with 0.3 degrees horizontal resolution, 24 vertical levels, and eight particle size bins ranging from 1 to 8 μm.

Forecasts are made once a day and for the 72 hours ahead. The model includes parameterizations of all the main processes in which sea-salt aerosol is involved, such as generation, transport, wet and dry deposition (http://wind.tau.ac.il/salt-ina/salt.html).

3. DATA ANALYSIS AND RESULTS

The collected time series are statistically processed onboard to estimate wave parameters (i.e., height, period and direction).

The basic assumption is that under stationary conditions of the sea state the model of the height of the sea is a stationary and ergodic stochastic process with zero mean. However, the statistical description of sea waves is possible only if the model is supposed to be a Gaussian process [5]. Standard statistical parameters, such as wave height, period and direction, are computed on the basis of the spectral density features of the acoustic profiles [6][7].

The time series of the three echosounders are quality controlled in order to identify spikes and outliers and then they are spline interpolated in order to recover the signal integrity.

After a trend removal and a bandpass filtering, the power spectrum is computed to estimate several wave parameters.

Under the hypothesis of planar wave defined as

$$z = E(x, y, t) = E(t) = \sum_{m=1}^{N_w} A_m \cos(w_m t - \varphi_m) \quad (1)$$

the directional array, based on equilater – triangular acoustic altimeters array (Figure 3), allows for the estimation of the wave height as well as of the Direction-Of-Arrival (DOA) [8].

When the planar wave passes through a couple of two separated altimeters indexed by i and j, a time delay is generated between the sensors according to the following vectorial expression

$$\tau_{(i,j)} = \underline{x_{(i,j)}} \cdot \underline{k} \quad (2)$$

Three distinct altimeters pairs can be formed, hence it is possible to group all the pair wise equations into matrix to obtain the following expression

$$\underline{\tau} = \underline{X} \cdot \underline{k} \quad (3)$$

By computing the time delays, the propagation vector can be estimated by solving the following least squares pseudoinverse equation

$$\underline{\hat{k}} = (\underline{X^T X})^{-1} \cdot \underline{X^T} \hat{\tau} \quad (4)$$

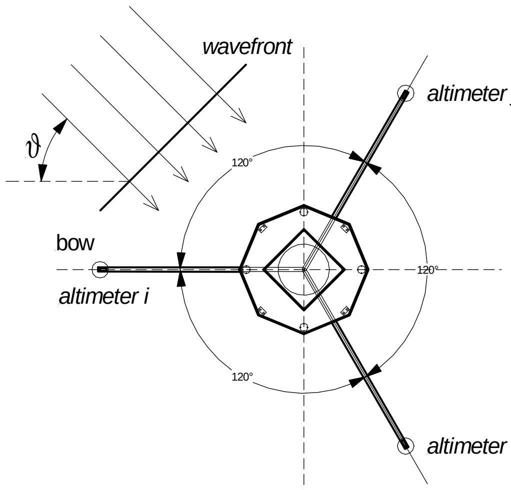

Figure 3. Sketch of the directional array composed by three echosounders (i, j, l) deployed on the W1-M3A observing system.

The algorithm allows us to detect sensor failures under the hypothesis that the failed sensor is still producing signal. If there is a failure, the triangularity condition couldn't be satisfied, thus

$$x_{(i,j)} + x_{(j,l)} + x_{(i,l)} \neq 0 \quad (5)$$

The proposed algorithm has been validated during the Ligurian Air Sea Interaction Experiment (LASIE) [9] carried out in the period June-July 2007 when a Datawell Directional Waverider was deployed about 4 km far from the W1-M3A observatory.

During the experiment, both the buoys collected 769 data, including 23 cases of very rough sea and 356 cases of smooth sea.

Table 1 represents all the available dataset subdivided into classes based on the Douglas Scale of the sea state.

Comparing the estimates provided by the W1-M3A observing system and the Datawell Waverider we obtained successful results for wave height, period and direction with a correlation coefficient of 0.97 for the wave height and 0.99 for wave period (Figure 4).

Table 1. Statistics of the events occurred during the LASIE test period.

Sea State	Sign. Wave Height [m]	Nr. of Events
0	0.0	0
1	0.0 – 0.1	0
2	0.1 – 0.5	356
3	0.5 – 1.25	247
4	1.25 – 2.5	143
5	2.5 – 4.0	23
6	4.0 – 6.0	0
	Total	**769**

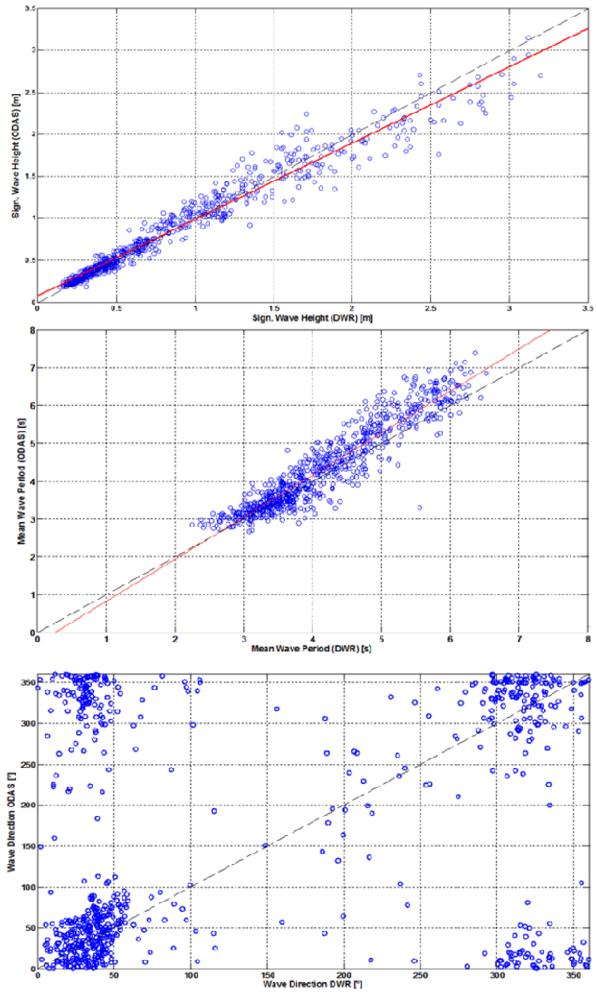

Figure 4. Scatter plots of (top) significant wave height, (middle) wave period and (bottom) wave direction between the W1-M3A observing system (ODAS) and the waverider buoy (DWR).

Through the carried out analysis it was also possible to derive the best fitting for the period and the wave height data between the estimates from the buoy and the measurements collected by the waverider buoy.
The resulting calibration linear curve (Table 2) has been applied to the data in order to obtain e more accurate estimates of wave properties from the W1-M3A platform.

Table 2. Coefficients for the calibration curve for the W1-M3A wave height and wave period measurements.

Parameter	Offset	Slope
Sign. Wave Height	0.08	0.91
Wave Period	-0.29	1.11

Wave estimates provided by the W1-M3A observing system have been used to test the performances of the Wavewatch III model forecasts from 1st of March 2011 up to 13th of November 2011.
Wavewatch III model wave forecasts are operationally produced by the Environmental Agency of the Tuscany Region (ARPAT) and available every 3 hours. We compared the wave estimates extracted at the buoy position with the in-situ observations subdivided for sea state classes and by mean of statistical indices.

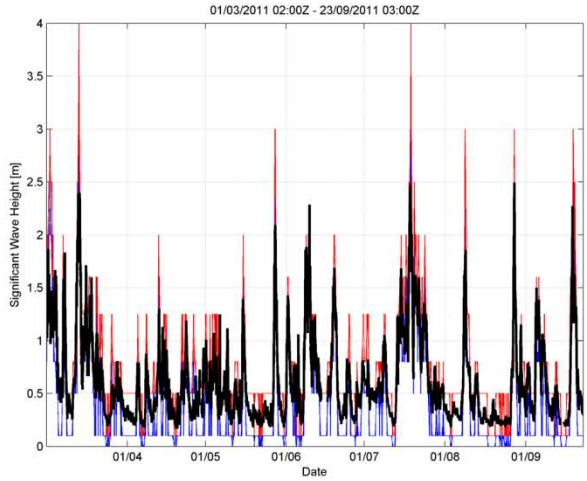

Figure 5. W1-M3A wave height estimates (black line) superimposed to the sea state class limits of the WW3 model output (upper limit in red; lower limit in blue).

More in details we considered the BIAS, the Mean Absolute Error (MAE), the Mean Normalized Gross Error (MNGE) and the Anomaly Correlation (AC) between model output and buoy observations.

$$BIAS = 1/J \sum_{j=1}^{J} (P_j - O_j) = 0.001\ m$$

$$MAE = 1/J \sum_{j=1}^{J} |P_j - O_j| = 0.164\ m$$

$$MNGE = 1/J \sum_{j=1}^{J} {|P_j - O_j|}/{O_j}\ \% = 0.298\%$$

$$AC = \frac{\sum_{j=1}^{J}(P_j - M_o)(O_j - M_o)}{\left[\sum_{j=1}^{J}(P_j - M_o)^2 \sum_{j=1}^{J}(O_j - M_o)^2\right]^{1/2}} = 0.891$$

being P_j the model output, O_j the W1-M3A estimates and M_o their average.
From the carried out analysis we noticed a clear overestimation of the model for wave higher than 2m and an underestimation for calm sea state and a good correlation between the forecasts and the in-situ observations.

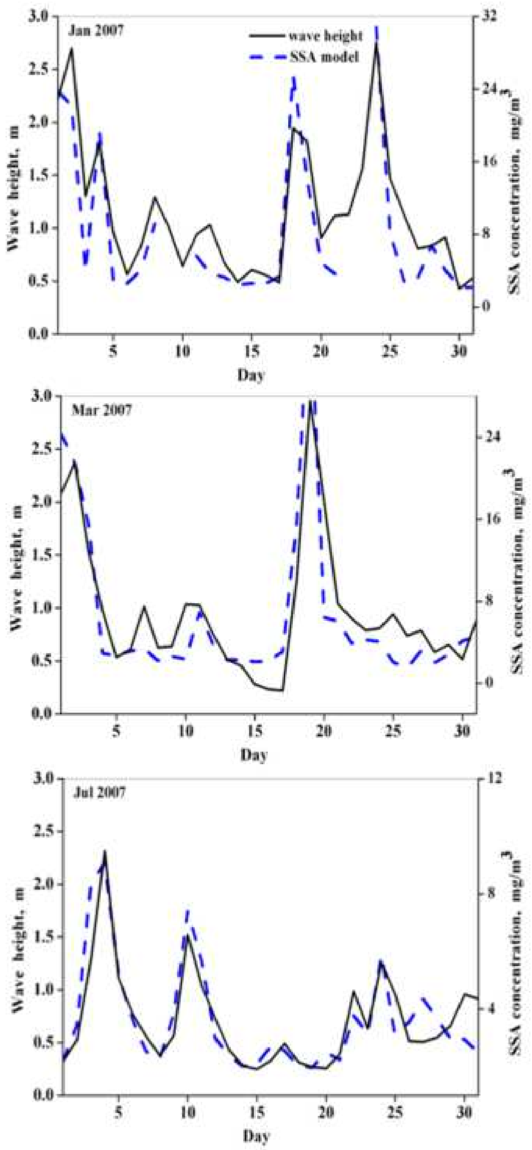

Figure 6. W1-M3A wave height compared with sea-salt model outputs for January, March and July 2007.

Wave height data acquired by the W1-M3A observing system are very useful to study the production of sea-salt aerosol. Moreover the capability of the buoy to take snapshots of the sea state in the meantime of the echosounders acquisitions allowed us to verify the presence of whitecaps.
Wave measurements acquired in 2007 have been used to test the DREAM-Salt prediction model in cooperation with Tel-Aviv University.
The analysis carried out in this study shows a good agreement between the day-to-day behavior of modeled SSA concentration and in-situ measurements of wind speed and wave height in the open sea and the good visual correlation between the modeled SSA concentration and the corresponding presence of whitecaps (Figure 6).
On 20th of March 2007, the estimated wave height was about 3 m, the corresponding wind speed was 14 m/s, and the model output was over 24 mg/m^3 showing a very good correlation with the rapid increasing of wave height. The snapshot took by the W1-M3A observing system showed rough sea with some whitecaps.
The same behaviour occurred on 4th of July 2007 when the significant wave height estimated from the buoy was over 2 m, the wind speed was 9 m/s and the model output was 9 mg/m^3. The corresponding photo took by the camera installed onboard the W1-M3A observing system showed rough sea with presence of whitecaps.
It is noteworthy the good correlation with SSA model outputs also in calm period, like the 15th of July 2007 when the W1-M3A platform measured a wave height of 0.3 m, a correspondent very low wind speed (0.3 m/s) and the model estimated only 0.2 mg/m^3.

4. SUMMARY AND CONCLUSIONS

Several methodologies have been developed in the literature to estimate wave characteristics for open sea and coastal studies.
In both framework the difficulties to acquire data also with rough sea increased the use of data provided by satellite and, in the meantime, gave rise to a growing interest in autonomous system capable to measure in continuous way and in all meteo-marine conditions.
The methodology proposed in this paper answered to this issue, since the developed wave system is working without taking care of the adverse weather conditions and allowed long term sea waves monitoring.
More in details, a directional array of echosounders has been installed on the W1-M3A observing system, an open ocean laboratory moored in the Ligurian Sea on a sea bed of 1220 m.
A new algorithm has been developed in order to obtain wave characteristics derived from the time series acquired by the array of echosounders using spectral analysis and the direction of arrival theory.
Data provided by the new wave package that include also accelerometer and inclinometers data to correct the acoustic measurements for the buoy motion, has been compared with a classical wavemeter buoy, a Datawell Waverider, in 2007. Indeed, in 2007 during the LASIE experiment, the two buoys were far only 4 km each other and during the testing period of two months, wave heights spanning from 0.3 m up to 3 m were recorded.
The achieved results are very encouraging for what

concern both the wave height and wave period: from statistical analysis a correlation coefficient of 0.97 and 0.99 was obtained, respectively.

Good results have been also accomplished in the comparison performed for wave direction even if a more variability has been obtained.

The data acquired with the new system have been also compared to the Wavewatch III model forecasts produced by the Environmental Agency of the Tuscany Region (ARPAT) and available every 3 hours.

From statistical point of view, we obtained an anomaly correlation of 0.89 and a mean gross error of 0.3%, with a bias of only 0.001 m.

The comparison carried out showed an over estimation of the model for wave higher than 2m and an underestimation for calm situations.

The capability of the buoy to collect in the same time both wind speed and wave estimate and to take snapshots of the sea state, allowed to test the DREAM salt prediction model in cooperation with Tel-Aviv University.

The analysis performed showed a good agreement between the day-to-day behavior of modeled SSA concentration and the measurements collected by the buoy.

Furthermore, the availability of the photos taken by the camera installed on board the W1-M3A observing system, allowed us to verify the good visual correlation between the modeled SSA concentration and the corresponding presence of whitecaps.

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