A WIND AND WAVE ATLAS FOR THE MEDITERRANEAN SEA

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ABSTRACT

We describe the procedure followed and the data used for the preparation of an atlas of the wind and wave conditions in the Mediterranean Sea. The two basic sources of data have been the altimeters on board of the ERS-1/2 and TOPEX/Poseidon satellites and the operational wind and wave results of the European Centre for Medium-Range Weather Forecasts. The data have been combined providing a ten year data-set from which both overall and point by point statistics have been derived. The results are critically analysed and suggest an underestimate of the altimeter derived wind speeds in the Mediterranean Sea.

1. INTRODUCTION

Long-term climatological data over the sea are much in demand for a number of reasons, ranging from pure scientific knowledge to the important applications of, e.g., safety at sea and the design of sea structures. Till 15 years ago the only source of long-term data available for a meaningful statistics was the collection of visual observations done from ships at sea. Starting from 1991 two new sources of data began to be available. The launch of ERS-1, and soon after of TOPEX/Poseidon, offered an unprecedented continuous flow of wind speed and wave height measurements. At the same time the improvements in computing power and numerical modelling led to a continuous synoptic description of the wind and wave characteristics at sea.

These two sources offered a wealth of data and today quite reliable statistics exist in the open oceans. However, the situation is less favourable in the inner seas. Here the global meteorological models exhibit a steady underestimate of the wind speeds that in turn leads to an underestimate of the associated modelled wave heights. On the other hand the strong spatial gradients that characterises the basins with a complicated orography, as in our case the Mediterranean Sea, imply that the spatial resolution of the altimeter ground tracks is not sufficient to provide the necessary details. The obvious solution lies in the combined use of the two sources.

The atlas here presented has been commissioned by the French, Greek and Italian Navies via the W.E.A.O. Research Cell. It is the product of several institutions from the three countries. A full description is found in the introductory part of the atlas itself [1], available both in paper and CD interactive formats from the authors. The atlas is based on wind and wave model data from the European Centre for Medium-Range Weather Forecasts (ECMWF) models, appropriately calibrated by means of satellite altimeter measurements. In so doing the systematic space-time coverage, a unique feature of numerical models, is fully exploited and, at the same time, the quality of the data and of the presented results is significantly improved by using the most up-to-date and reliable measurement technique able to cover large sea areas: satellite remote sensing.

2. THE AVAILABLE DATA

2.1. Satellite Data

Wind and wave data are provided by altimeters (wind speed U and significant wave height H_s) and a scatterometer (wind speed and direction). We have made use of the data from ERS-1/2 and TOPEX/Poseidon, available respectively since 1991 and 1992. The altimeter data, made available by Meteo-France, provide point estimates, at about seven kilometre intervals, along the ground track of the satellite. Scatterometer data are available along a wide lateral swath with respect to the ground track, as averages within 25 x 25 or 50 x 50 square kilometre areas. Having been used with data assimilation, hence considered in the ECMWF analysis, the scatterometer data could not be considered for this project. A quality control procedure has been applied to the data, resulting in the elimination of some spurious data.

The significant wave height and the wind speed from TOPEX altimeter have been corrected according to relations deduced from comparisons with buoy measurements [2], [3].

$$SWH_{cor.}=1.052\ SWH_{gdr} - 0.094$$

$$U10_{cor.}= 0.87\ U10_{gdr} + 0.68$$

For TOPEX data, a linear time dependent correction has been applied to the Ku band data in order to correct a maximum bias of 40 cm for cycle 236 (31/01/1999), starting from no correction at cycle 132 (more details in the next section).

The following regression relation from [4], has been used to correct the fast delivery (*fdp*) data of swh for ERS1:

$$SWH_{cor.}=1.32*SWH_{fdp} - 0.72$$

For the ERS-2 FDP swh, the following regression relation from [5] has been applied:

$$SWH_{cor.}=1.09\ SWH_{fdp} - 0.12$$

Once the satellite data were calibrated using results from global studies, a further validation of altimeter data in the Mediterranean Sea has been done using the locally available buoy and altimeter wave data. As there were no extended wind speed data from buoys for the considered period, only H_s data has been compared. To make the following comparison possible, a co-location procedure (time and space) was carried out. This has been done with different approximations for the time and space windowing. The comparison indicated the reliability of the altimeter data, allowing their direct use for the calibration of the model data.

2.2. Model Data

As model data we have made use of the analysis results of the European Centre for the Medium-Range Weather Forecasts (ECMWF, Reading, U.K.), available at 6-hour intervals. The operational meteorological model at ECMWF is spectral, i.e. the horizontal fields are described by a two-dimensional expansion of spherical harmonics truncated at, e.g., 319 (T319). The truncation identifies the model resolution, here defined as half the smallest resolved wave length, used to describe the fields. For T319 it is 40,000/(2 x 319) $\cong$ 63 km. Advection is calculated with a semi-Lagrangian scheme, while the physics is carried out on a reduced Gaussian grid in physical space. The vertical structure of the atmosphere is described by a multi-level hybrid σ coordinate system. The ten metre wind is derived with a boundary layer model from the lowest σ level, 0.997, corresponding to about 30 metres height. A compact description of the model can be found in [6] and [7].

The horizontal resolution and the number of levels with which the atmosphere is described in the model has varied in time. T213 (95 km resolution) and 31 levels were used from 1991 till 1998, when ECMWF passed to T319. This change had a limited effect, because the resolution of the Gaussian grid, used to model the processes in physical space, was not changed. The big step ahead came in November 2000, when the Centre passed to T511 (about 40 km resolution), with 60 levels on the vertical and a 40 km resolution Gaussian grid. Reference [8] has clearly shown how a different resolution implies a different quality of the results. In the Mediterranean Sea this corresponded to an appreciable increase of the wind speeds, a fact to be considered in the evaluation of the calibrated data and of the final statistics.

Since July 1992 the European Centre for Medium-Range Weather Forecasts run, parallel to their meteorological model, a wave model. Similarly to the weather forecast, the aim is to produce a forecast of the wave conditions. The wave model used at ECMWF is WAM, an advanced third generation model developed with the co-operative effort of most of the experts available at the time. WAM considers explicitly all the fundamental processes that affect the evolution of the wave fields. Given the area covered by the model, the input information is provided by the driving wind fields, i.e. at each point by the modulus and direction of U. For the interested reader the two master references are [9] and [10].

As for the wind, the wave fields are available at 6-hour intervals at all the grid points. The wave model for the Mediterranean Sea became operational in July 1992. A 0.5 degree resolution was used in both latitude and longitude, for an overall number of about 950 points. The resolution was later increased to 0.25 degree, for an overall almost 4,000 points.

The information available at any time step of the integration process is represented, at any grid point, by the energy available for each wave component, i.e. by the two-dimensional spectrum $F(f,\theta)$. From this spectrum a number of quantities is evaluated. An integration on directions provides the one-dimensional spectrum $E(f)$, i.e. a description of the energy distribution with frequency. A further integration of frequency provides the overall energy E, from which the significant wave height H_s is derived. Different integrations provide estimates of the mean period T_m, sometimes called energy period, and the mean direction θ_m.

The wind and wave integrated wave parameters available from the ECMWF archive have been retrieved for the Mediterranean area starting from 1 July 1992. The fields are available at 00, 06, 12, 18 UT of each day. The data have been retrieved with 0.5 degree resolution between 6° West and 36° East for longitude, and 30° and 46° North for latitude. This corresponds to a 85x33 point grid, out of which about 950 are sea points.

3. CALIBRATION

To keep the volume of the atlas within reasonable limits, we have considered a reduced number of points with respect to the ones used for retrieving the data from the ECMWF archive. Besides, in some part of the Mediterranean Sea, typically the more open basins, the spatial gradients of the wind and wave characteristics are likely to be more limited than in the smaller basins enclosed by coasts.

Two choices have been made. For the electronic version of the atlas we have chosen 239 points. Most of these are at one degree interval both in latitude and longitude, complemented by some sparse points in the most critical areas. For the printed version the number has been reduced to 129, a subset of the larger choice, obtained selecting one point out of two in each direction, with staggered selection on adjacent lines, again complemented with extra points in some areas.

For each data-set and for each single satellite measurement, e.g. the ECMWF and the TOPEX measured wind speeds, the model data have been interpolated in space and time at the satellite pass time and position. Then, each couple of data (model value and satellite measurement) has been assigned to the closest grid sea point. Similar to what had been done with the retrieved model data**,** this has taken place at 0.5 degree resolution. This has provided for each grid point a sequence of data couples, sparse in time, suitable for a local analysis. For each point the model-sat distribution has been approximated with a best-fit straight line, passing through the origin. An example is given in 0. The slope of the fit provides an estimate of the average ratio between model and satellite data, hence the inverse of the calibration factor to be used (corrected model = model * calibration factor *cal*).

Following what has been said in the previous section, the TOPEX *cal* values are available only at a limited number of positions, more or less along the TOPEX tracks. For each data-set, only points with a number of data larger than 200 have been considered. It was found that a smaller number was leading to occasional local *cal* values clearly out of the physical range.

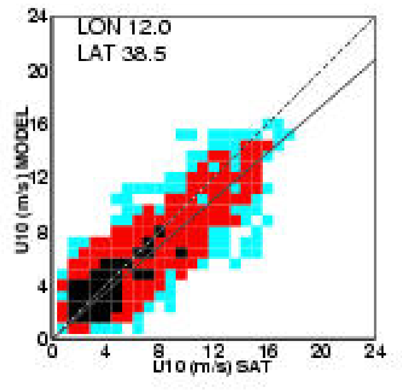

Figure 1. Scatter diagram between model (vertical) and altimeter (horizontal) wind speeds at one grid point in the Mediterranean Sea. The scatter provides an indication of the reliability of the derived calibration coefficient

Even if the TOPEX data, hence the best-fit values A, are available only at part of the points in the Mediterranean Sea (the ones along the ground track of the satellite), to get a general idea of their characteristics we have plotted in 0 the distribution of A for wind speed. Note that the values of A have been multiplied by 100, so that 100 represents in the figures a perfect fit between model and satellite data. By looking at the figure, we recognize at once the substantial underestimate by the model, particularly in the northern parts of the basin. More specifically, strong underestimates, for both wind and waves, are found in the areas with the more complicated geometry, and possibly with a complicated orography in the nearby land. It is easy to identify specific problems in the northern part of the Tyrrhenian Sea, in the Adriatic Sea and in the Aegean Sea.

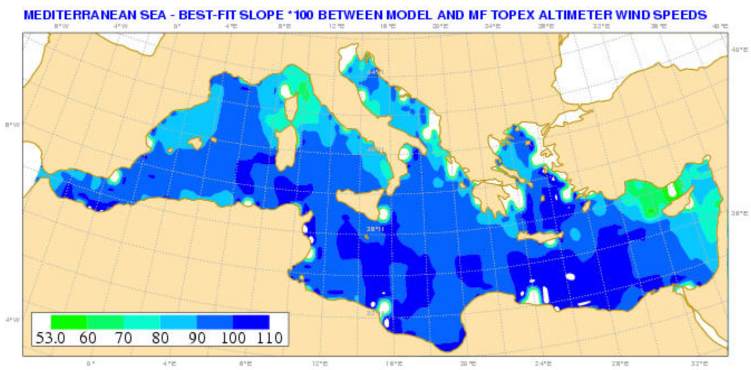

Figure 2. Distribution of the slope of the best-fit lines between model and TOPEX altimeter wind speed values at the various grid points in the Mediterranean Sea. The single values have been multiplied by 100.

Having different instruments measuring the same parameter at different times, we can, in general, expect, on the basis of both statistics and the characteristics of the instruments, to find different calibration factors at the same location. For wave height, following the superior quality of the TOPEX data, one could think of using these data for the final calibration. However, the TOPEX *cal* values are not available at all the grid points we are interested in, because of the sparse distribution of the tracks. On the other hand ERS1-2 provides an almost complete geographical coverage for *cal*. After a careful analysis of the data, it has been decided to use both the sources, weighting them according to their different reliability as derived from the comparison against measured data. The coefficients used for the overall calibration are:

wave height:	TOPEX altimeter	ERS1-2 altimeter
	0.65	0.35

For wind speed the analysis of the quality of data from the different sources has suggested as weighting coefficients:

wind speed:	TOPEX altimeter	ERS1-2 altimeter
	0.60	0.40

Like the scatterometer data in the meteorological model, also the ERS-2 altimeter wave heights have been assimilated into the WAM wave model at ECMWF since 1998. Therefore, as for the scatterometer, we could not use these data for the calibration in the Mediterranean Sea after this date.

Following the procedure outlined above, the single calibration coefficients for wind speed (*calu*) and wave height (*calh*) have been derived at the various grid points. Because the variability of the geographical distributions of *calu* and *calh*, the overall information has been summarised in the calibration coefficients only at the selected points, whose values have been derived with a careful analysis of the values at the surrounding not-considered-for-atlas grid points.

After extracting from the model data the time series, at 6-hour intervals, at all the grid points, they have been calibrated by multiplying the single parameters by the proper calibration factor. As derived from previous experiences [11], an underestimate of H_s does not change appreciably the average wave steepness. Therefore, the wave length changes proportionally to H_s. Given that the wave length varies, at least in deep water, with the square of the wave period (deep water is assumed throughout the Mediterranean Sea), the periods are to be corrected multiplying them by sqrt(calh). No correction has been introduced in direction, as it has long been recognised that both the meteorological and wave model provides a very good description of the overall pattern, hence directions are maintained.

The procedure has been applied separately to the data before and after 20 November 2000, i.e. when the substantial change of resolution in the operational ECMWF meteorological model implied a change of quality of the wind, hence wave fields. Therefore for the first period, we have at disposal 101 months of data, and only 19 for the later one.

4. RESULTS

We give here only a compact description of the results available from the atlas.

The atlas provides synoptic charts and point by point data tables. The charts show the geographical distribution of the mean values of the wind and main wave parameters, plus the probability contours for different U and H_s values. The tables provide bivariate frequency distributions of wind speed and direction, wave height and peak period, wave height and direction, and wave height and wind speed. All these results are provided on yearly and seasonal bases.
As an example Fig. 3 shows the distribution of the mean significant wave heights in winter in the Mediterranean Sea.

5. ANALYSIS OF THE CALIBRATION RESULTS

In this section we analyse the accuracy of the calibrated data, wind speeds and wave heights, in the Mediterranean Sea.

The performance of a model, either meteorological or wave, is not constant in time. It is expected, and indeed found, to vary with a number of conditions, like the meteorological situation. For what we are presently concerned, the main point is that we cannot expect the underestimate we have found in section 3 to be constant in time. When best-fitting the co-located data, this leads to a scatter around the best-fit line, whose amplitude provides an indication of the reliability of the derived calibration coefficients in the different situations.

The corresponding scatter indices (SI= rms error/mean measured value) have been evaluated point by point, and their distribution (see Fig. 4) provides a clear indication of the reliability of the results in different areas.

However, for our present purposes a more interesting result derives from the analysis of the calibrated data. Indeed, looking at the results of the calibration, we find some inconsistency between the wind and wave results. The waves are a direct product of the wind, and any

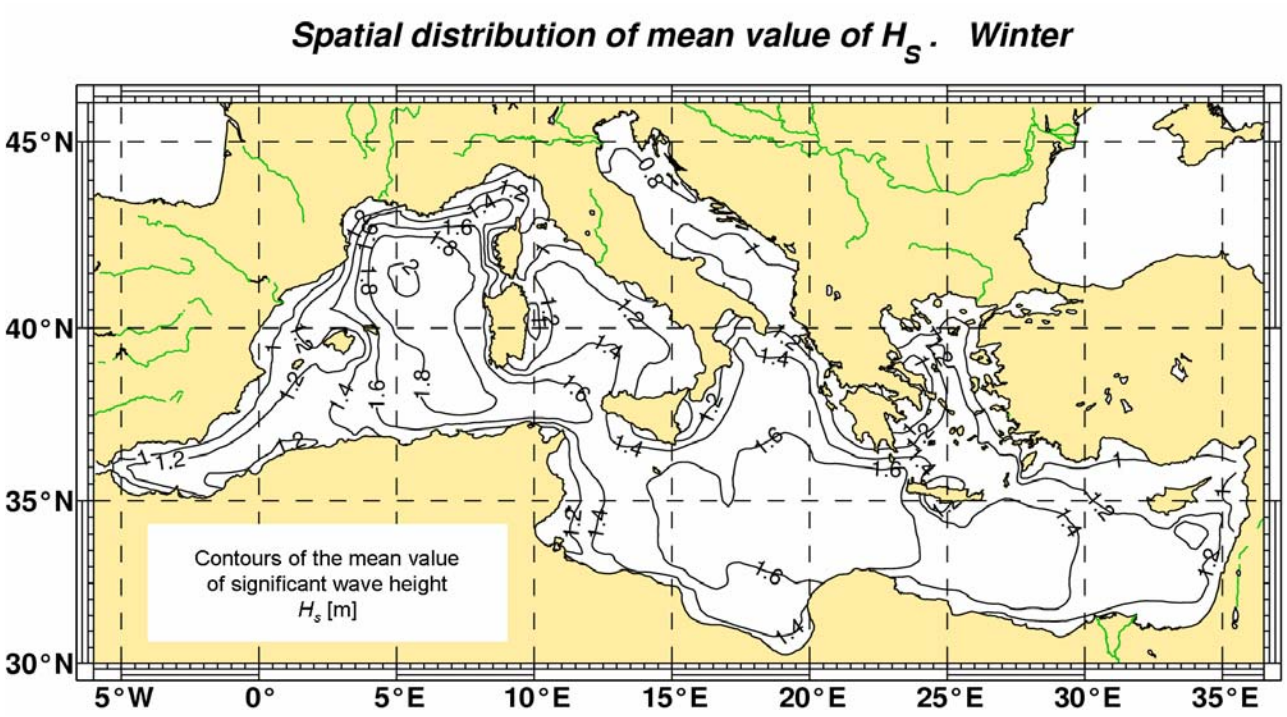

Figure 3. Distribution of the winter mean significant wave heights in the Mediterranean Sea.

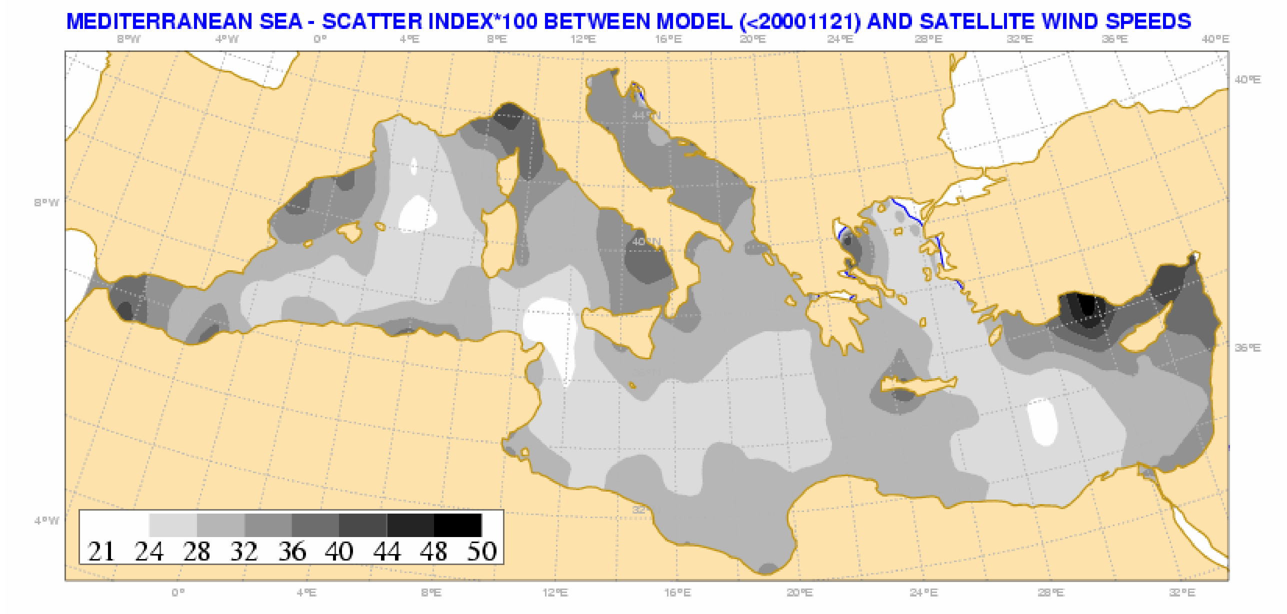

Figure 4. Distribution of the scatter index for the wind speed best-fits.

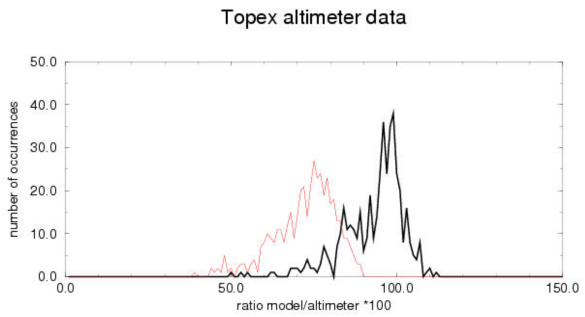

Figure 5. Statistical distribution of the best-fit slopes in the Mediterranean Sea. Thick line for wind speeds, thin line for wave heights.

error in the generating wind field is reflected in the resulting wave field. Therefore the two maps of the calibration coefficients should be expected to show a high degree of consistency. Indeed, this is the case for their geographical distributions in the Mediterranean Sea, but not so for what the values are concerned. This is clearly indicated in Fig. 5, where we show the statistical distribution of the wind and wave best-fit slopes as derived from the calibration procedure. It is evident that the corrections for wind are much lower than what one could guess using the ones for waves. In other words, the calibrated wind speeds are too low with respect to the calibrated wave heights. As a further verification we have hindcast one year of wave data using the same version of the WAM model used at ECMWF and as input the calibrated wind fields. The resulting wave heights were lower than the calibrated ones by about 10%. In principle, this could be due to an error in the wave model, that could underestimate the wave heights. However, apart from the ample evidence in the literature (see [10], [12] and [13]), the monthly statistics ECMWF provides on the operational performance of the WAM model (typical bias of a few per cent on a global level) clearly shows that the problem is not connected with this model. Given the relationship between wind speed and wave height, the H_s errors suggest a wind speed error of the order of at least 5%. Our overall conclusions on the calibration are the following.

We believe we have obtained what can be considered as the best dataset of wind and wave data presently available in the Mediterranean Sea. However, some characteristics and limitations of the data should be kept in mind. For both wind and waves the slope of the best-fit lines grows markedly moving southwards, across the basin. The largest errors are found along the northern coasts, larger where the smaller basins are characterised by a marked orography.

The accuracy of the best-fit slopes, hence of the calibration coefficients, can be derived from the scatter of the data around the best-fit lines. The calibration coefficients for wind and waves are not fully consistent to each other. Given the verified general reliability of the wave results, the suggestion is that the altimeter derived wind speeds, hence the correspondingly calibrated model data, are too low by about 5%.

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