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Coastal Engineering 53 (2006) 613 – 627

Coastal Engineering
An International Journal for Coastal, Harbour and Offshore Engineers

www.elsevier.com/locate/coastaleng

The calibration of wind and wave model data in the Mediterranean Sea

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Received 4 August 2005; received in revised form 22 December 2005; accepted 22 December 2005
Available online 3 March 2006

Abstract

Three sources of long-term wind and wave data are available in the Mediterranean Sea: numerical models, satellites and buoys. We make use of the overall information to obtain calibrated decadal time series at a large number of points, distributed at 0.5° intervals. We discuss the accuracy of the three sources and point out the errors that affect the accuracy of the final results.

Keywords: Surface wind speed; Wave height; Mediterranean Sea; Calibration; Time series

1. Aim of the study

Long time series of meteorological and oceanographic parameters, in particular wind and waves, are required for many obvious purposes. These range from the assessment of climatology to the more immediate needs of oceanographic and coastal engineering.

Historically, there are four sources of data available in the sea: visual observations, buoys and platforms, satellites, and numerical models. No one succeeds in providing the accurate and distributed data requested for a sufficiently long period. Our aim is to describe how such a result has been obtained for an inner sea, namely the Mediterranean Sea, making use of the information from the different available sources. In particular, we focus on the calibration of the model data making use of satellite data.

After a short description of the area of interest (Section 2), we continue in Section 3 discussing the available sources and the accuracy of the related data. In Section 4, we describe how the different sources have been combined to provide more complete and better results. The calibration and the geographical distribution of the results are discussed in Sections 5 and 6.

2. The Mediterranean Sea

The parameters we consider in this work are wind speed and direction (at 10-m height) and the significant wave height, period and direction. The area where we focus our attention is the Mediterranean Sea, extended from 6° West to 36° East longitude, and from 30 to 46° North latitude. At its west end, it is connected with the Atlantic Ocean via the Strait of Gibraltar. This narrow connection only affects appreciably the wave climate in the close-by Alboran Sea, and it is often neglected in local wave modelling.

The Mediterranean Sea is mostly surrounded by mountain ranges (see Fig. 1) that affect and often control the local climate. Notwithstanding its large dimensions, 3600 × 1700 km, the complicated geometry of the coastline splits the sea into a number of sub-basins of different size. Some areas, like the east side of the Adriatic Sea and most notably the Aegean Sea, are characterised by a large number of islands.

Deep water conditions hold everywhere, with the exception of the Northern Adriatic Sea, the Sirte Gulf on the African coast, and the areas close to the mouth of the big rivers, e.g., Ebro and Nile.

3. The sources of data

In this section, we discuss the characteristics of the different sources of data used in the present work.

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0378-3839/$ - see front matter
doi:10.1016/j.coastaleng.2005.12.006

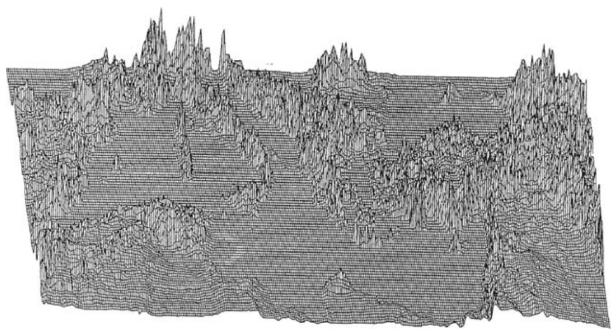


Fig. 1. The orography bordering the Mediterranean Sea.

3.1. Visual observations

Taken from ships of opportunity, this has been for a long time the only source of information for wind and wave data in the open sea. Many decades of data exist, and a full generation of atlases has been based on these data, see, e.g., Ocean Wave Statistics by Hogben and Lamb (1967) and Global Wave Statistics by Hogben et al. (1986). However, this approach has clear limitations and there are substantial errors potentially present in the reported data, particularly in stormy conditions, the situation end-users care more about. Graham (1982, 1983) and Soares (1986), among others, discuss in details the problem. For the purpose of an atlas, a major limitation of the visual data is given by their preferential distribution along the most common maritime routes, and by the tendency of the ships to avoid the stormy areas, in so doing substantially biasing the statistics that can be derived. Finally, a direct inspection shows the relatively low number of data in the Mediterranean Sea, particularly in its more enclosed sub-basins, where, as we will soon see, we face serious problems with the model data.

Given the availability of alternative data, that, combined in an optimal way (see later sections), provide a good accuracy and a complete coverage in space and time, no use has been made of the visual estimates during this work.

3.2. Buoy and platform data

Surface following buoys are the most common instrument used to collect wave data in the sea. Because of mooring constraints, the local depth can vary from about 10 m to a few hundred metres. Different kinds of buoys exist, the simplest, and oldest ones, providing only the surface elevation, the more complete ones providing also information on the sea surface slopes, or lateral motion or acceleration. Properly analysed (see the classical paper by Longuet-Higgins et al., 1963; Kuik et al., 1988), these data allow an estimate of the main wave parameters (significant wave height H_s, mean and peak period T_m, T_p) and the related directional information (mean direction θ_m, mean directional spread, curtosis and skewness, for each frequency band). More sophisticated methods (e.g., Long, 1980; Donelan et al., 1996) provide also information on the full 2D spectrum.

These buoys are continuously in operation, the timing of records being only a strategic decision at the recording station, on land or on a close-by oil rig. Typically, the records are taken at 3-h intervals at synoptic times (00, 03, 06,... UT), the intervals being reduced in case of severe or interesting events.

A substantial number of these buoys is in operation in the Mediterranean Sea, the larger sets being located along the coasts of Italy and Spain. In some cases, the buoys are equipped with meteorological instruments, especially anemometers, but this is true only for a small fraction of them. Wind data are available from two French buoys, moored in the gulf of Lion (since late 2001) and offshore Nice (since 1999).

Wind and wave data are often collected also from large structures, typically oil rigs. In our case two of these deserve a special mention. One is the fully equipped large spar buoy, presently moored in more than 1000 m of depth in the Ligurian Sea, at 43° 48.90 North and 09° 08.80 East (Bozzano et al., 2004). The other one is the oceanographic tower of ISMAR (Cavaleri, 2000), in 16 m of depth, 15 km off the coast of Venice in the Northern Adriatic Sea. Both provide a full set of meteorological and oceanographic parameters.

3.2.1. Errors

Wind data from buoys are usually of good quality. The wind recorded at the oceanographic tower is affected by the presence of the structure. However, these data have been corrected, both as wind speed and direction, on the basis of the tests done in a wind tunnel (Cavaleri et al., 1985).

Wave measuring buoys are accurate instruments, and the related error for the significant wave height H_s is usually estimated at a few percent. Uncertainty on the single data derives also from the sampling variability of the surface, particularly in the spectral shape. The accuracy of the reported peak periods is further limited by the resolution of the frequency distribution.

In the high H_s range the buoys have a tendency to slip around the highest crests, in so doing introducing a negative bias in the estimate of the higher values.

3.3. Satellite data

After the short parenthesis of Geosat, operated from 1986 till 1989, satellite data began flowing-in in 1991 with the launch of ERS1, followed one year later by Topex/Poseidon, and in 1995 by ERS2. These satellites have on board an altimeter (ERS1–2 and Topex) and a scatterometer (ERS1–2). Full description of the characteristics of the instruments can be found in the specialised literature, see, e.g., Duchossois (1991) and Fu et al. (1994). For our present purposes it suffices to list the available data. The altimeter provides wind speed and wave height at seven km intervals (once a second) along the ground track of the satellite. The scatterometer is the most complete source of wind data (speed and direction), the data being available all along the width, a few hundreds kilometres, of the swath on one side of the satellite. In more recent years more data have become available, e.g., from JASON (since

2002) and QuikSCAT (since 1999), but they do not extend enough in the past to be considered for our present purposes.

The data we have used from ERS1–2 and Topex have different characteristics. The former ones are fast delivery products, i.e. made available in almost real time, so that they can be used, if necessary, for data assimilation in numerical models. On the contrary the Topex data are delivered several days after the pass, which allows a better quality check and more accurate measurements.

The ERS1–2 and Topex data differ from each other also for another characteristics. Although varied in time, ERS1–2 have been flying mainly with a return period of 30 days. This implies that the adjacent ground tracks at different passes differ by less than 1° in longitude, corresponding to about 80 km in the Mediterranean Sea. This provides a wide uniform coverage of the basin (see Fig. 2), but with relatively few data at each point, one datum every 30 days. On the contrary Topex has been following an orbit with a 10 day period. This triples the number of data per point with respect to ERS1–2, at the expenses of tripling also the distance between adjacent tracks, now about 240 km in the Mediterranean Sea. This may not be so important in the wide spans of the oceans, and indeed the large amount of information has allowed the compilation of exhaustive atlases. A good example is provided by Young (1999a). However, in an enclosed basin with a complicated geometry, hence strong spatial gradients, such distance leaves many sections of the sea without enough data for a proper analysis.

Another limitation of the satellite data is their lack of continuity. The intermittency implied by the orbit makes the data suitable for climatic studies (within the just mentioned limits about spatial resolution), but it excludes any possibility of deriving high frequency time series at a given location, as it is possible with the buoys.

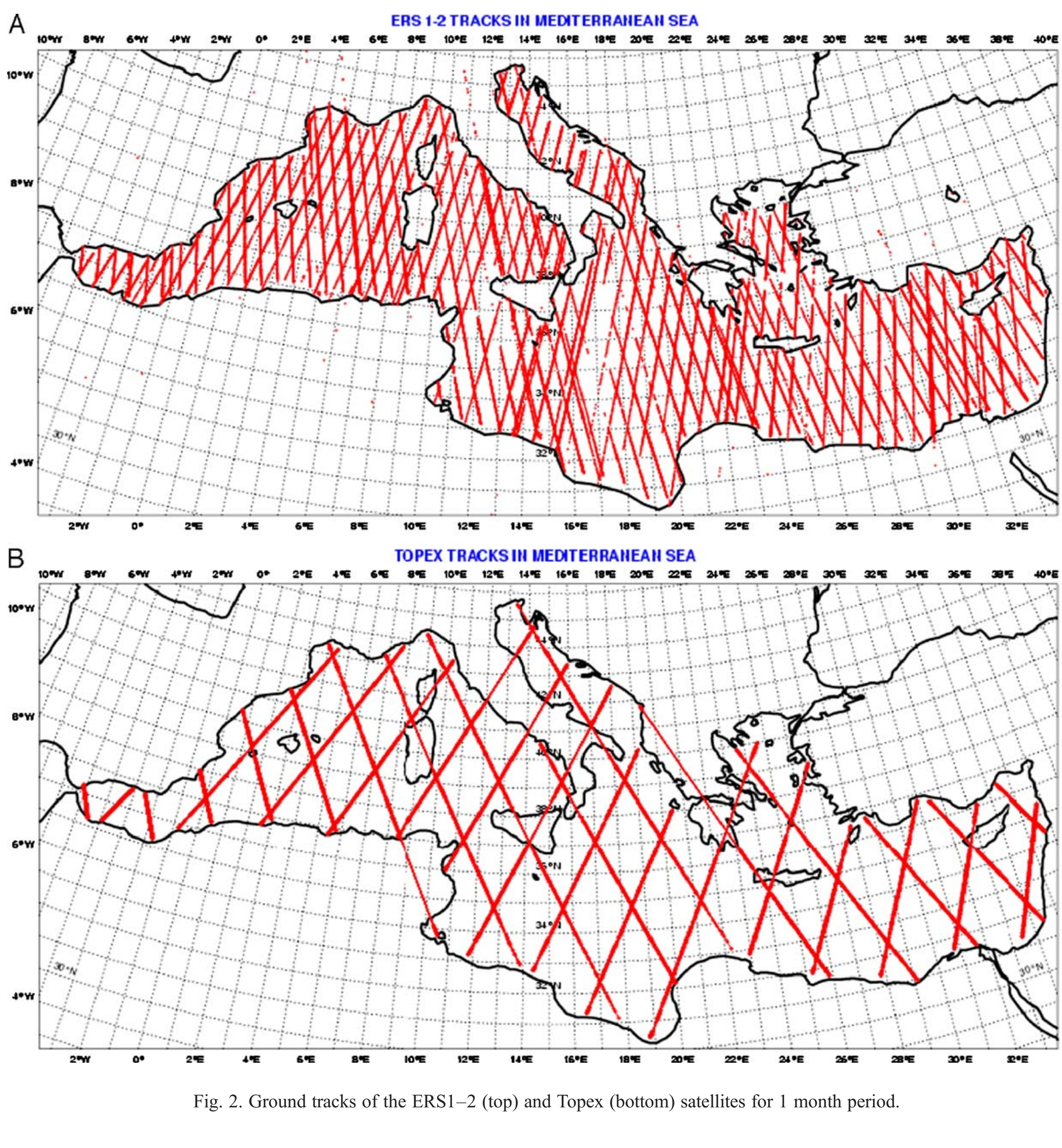


Fig. 2. Ground tracks of the ERS1–2 (top) and Topex (bottom) satellites for 1 month period.

3.3.1. Errors

The official accuracy of the wind speeds and wave heights derived from the altimeter are (see Duchossois, 1991; Fu et al., 1994):

	Wind speed, U_{10}	Wave height, H_s
Topex	2 m/s	10% or 50 cm (whichever the better)
ERS1–2	2 m/s	10% or 50 cm (whichever the better)

The original data exhibit an intrinsic variability that is partly damped by averaging sequential single measurements (10 or 20 per second) into a single datum, 1 per second, as already mentioned. However, a lot of variability is still visible in the final data (see, e.g., Abdalla and Cavaleri, 2002). The unanswered question is if this variability is instrumental or a characteristic of the fields. Most likely both the hypotheses are true, the instrumental relevance decreasing when we move to lower frequencies (longer distances).

Because of a limitation in the altimeter software of ERS2 in the "Fast Delivery" stream, the one operational centres care more about, the instrument was providing minimum wave heights of 1–1.2 m, also when the actual wave height was lower (see, e.g., Janssen et al., 1997; Greenslade and Young, 2004).

The wind speeds derived from the altimeter are not reliable at very low wind speeds, the threshold for useful data being 2 m/s. The retrieval algorithm also loses reliability in the very high value range, above 20 m/s, in connection with the different physics involved in the sea surface processes.

Altimeter measured significant wave heights become unreliable at very large values, above 20 m. Such situations are not present in the Mediterranean Sea.

The altimeters and the scatterometer cannot measure close to the coasts because of the interference with land. This depends on the dimension of the footprint of the remote signal, a few kilometres for the altimeter, a few tens of kilometres for the scatterometer. Besides, when the satellite is flowing towards offshore, once entered in the marine area, the altimeter requires some time to work properly again. This implies that the related wind speed values are not available till 25–30 km off the coasts, and not fully reliable till 50–100 km offshore.

3.4. Model data

Many different institutions run global atmospheric and wave models, producing daily forecast and analysis worldwide. However, in general these models, and in particular the wave ones, do not have a resolution high enough to describe with sufficient accuracy the fields in the enclosed basins, like the Mediterranean Sea. For this reason some of these institutions, which have a particular interest in this basin and/or in the surrounding areas, run locally also a limited area version of their models, nested in the large-scale ones.

Indeed, it turns out that several sources of information are presently available for the Mediterranean Sea. The list includes the U.K. Meteorological Office (UKMO), the European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, UK), Meteo France, and the U.S. Navy Oceanographic Center. The condition of having data available on the whole Mediterranean Sea for a full decade limits the choice to the first two institutions. Our final choice was dictated by several considerations. UKMO has been running locally higher resolution limited area meteorological and wave models. However, while ECMWF runs an advanced third-generation wave model (to be soon described), UKMO is still running a second generation one, also using a much lower number of frequencies. This may introduce errors in swell advection and in the evaluation of the wave periods. Besides, for a long time the boundary of the limited area UKMO meteorological model, nested in the global one, was at 30° latitude. While this reflected the focus of interest on the U.K. isles, it implied that in the Mediterranean Sea, at least in its most southern part, the limited area model could not develop the details associated in principle with its resolution. Finally, the UKMO data are available only on a commercial basis, while the ECMWF ones can be obtained freely or for a limited fee, depending if the purpose is or is not purely scientific.

The above conditions have led to choose ECMWF as the source of the data to be used for this study. In the following paragraphs, we give a brief description of the models used at the Centre and of the available results, also pointing out the inherent potential errors.

3.4.1. The ECMWF meteorological model—wind data

The operational model at ECMWF is spectral, i.e. the horizontal fields are described by a two-dimensional expansion of spherical harmonics truncated at, e.g., 511 (T511). The truncation identifies the resolution, here defined as half the smallest resolved wave length, used to describe the fields. For T511 this is $40{,}000/(2\times511)\cong 39$ 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 physical parameterisations describe the basic physical processes connected to radiative transfer, turbulent mixing, subgrid-scale orographic drag, moist convection, clouds and surface soil processes. The prognostic variables include wind components, temperature, specific humidity, liquid/ice water content and cloud fraction. Parameterisation schemes are necessary in order to properly describe the impact of subgrid-scale mechanisms on the large scale flow of the atmosphere. Forecast weather parameters, such as the 2-m temperature, precipitation and cloud cover, are computed by the physical parameterisation of the model. The 10 m wind, U_{10}, is derived with a boundary layer model from the lowest σ level, 0.9976 of the surface pressure, corresponding to about 20 m height. A compact description of the model can be found in Simmons (1991) and Simmons et al. (1995).

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 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 39 km resolution), with 60 levels on the vertical and a 40 km resolution Gaussian grid. This implied a substantial improvement of the quality of the results (Cavaleri and Bertotti, 2003). In particular, in the Mediterranean Sea this led 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.

3.4.1.1. Errors. The model data at very low wind speeds are not reliable because the situation is dominated by sub-grid processes. This is particularly true close to land, an obvious example being the land–sea breezes.

In the coastal areas, the model winds are unreliable because of the dominant influence of orography, not properly represented in the meteorological model because of its limited resolution (95 km for T213, 39 km for T511). Also the limited accuracy with which the actual coastline is represented in the model introduces errors in the coastal wind fields.

In offshore blowing conditions the winds are strongly underestimated, much more than off the coast. This problem is not yet completely understood, but dominant roles are likely to be played by the orography and by the modelling of the marine boundary layer (see Cavaleri and Bertotti, 2004).

There is a marked tendency to underestimate the peak wind speeds. This is probably connected to the resolution of the model, but the non-correct parameterisation of the physical processes active in heavy storm conditions is likely to play a role.

3.4.2. The WAM wave model

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 in the late 1980s with the co-operative effort of most of the experts available at the time. The two master references are WAM-DI Group (1988) and Komen et al. (1994). Only a brief description, sufficient for the purposes of this paper, is given here. The interested reader is referred to the above references for full description and explanation.

The model stands on the spectral description of the sea surface, i.e. at all the points of the grid covering the area of interest the wave conditions are represented as the superposition of a finite, but large, number of sinusoidal components, each characterised by frequency f (Hz), direction θ (flow, degrees cwrgn), and height h (m), hence energy F, proportional to h^2. The evolution in time and space of the whole field is governed by the so-called energy balance equation

$$\frac{\partial F}{\partial t} + c_g \cdot \nabla F = S_{\text{in}} + S_{\text{nl}} + S_{\text{dis}}$$

where the left-hand terms represent the time derivative and the kinematics of the field, and the right-hand ones the physical processes at work for its evolution. More specifically: $\partial/\partial t$ is the derivative with respect to time, c_g is the group speed, ∇F represents the spatial gradient of the field.

Once the area covered by the model has been defined, the input information is provided by the driving wind fields, i.e. by the modulus and direction of U_{10} (wind speed) at each grid point. More specifically, U_{10} is used, together with the wave conditions existing at that time at that point, to evaluate the friction velocity, hence the surface stress connected with the actual transfer of energy S_{in} from wind to waves.

The term S_{dis} summarises the energy loss by the various dissipation processes at work. For all practical purposes the only dissipative term of significance in deep-water is white-capping, i.e. the breaking that appears at the crest of the waves under the action of wind. More processes appear when the waves enter a shallow water area, the two most prominent ones being bottom friction and depth induced breaking.

The fourth-wave nonlinear interactions S_{nl} represent the conservative exchange of energy between the different wave components that takes place continuously during the evolution of the field.

All the above processes are represented in the WAM model via their proper equations. The model is numerically integrated using a semi-implicit scheme for the source functions, while for the advection and refraction terms in the energy balance equation a first-order upwind scheme is used. Because of requirements for numerical stability, the integration time step depends on the grid resolution, being typically 20 min for 0.5°, 15 min for 0.25° resolution.

3.4.3. The WAM model operational at ECMWF

Two versions of the WAM model have been operational at ECMWF, one for the global ocean and one for the Mediterranean Sea. The reasons for doing this are the maximum resolution allowed for the global version because of computer power limitations, and the contemporary requirements to go to a higher resolution to properly describe the geometrical characteristics of the Mediterranean basin.

The wave model for the Mediterranean Sea became operational in July 1992. A 0.5° resolution was used in both latitude and longitude, for an overall number of about 950 sea points (WAM considers only sea points in its description of the basin). The resolution was later increased to 0.25°, for an overall of almost 4000 points.

The original wave model for the Mediterranean Sea included the area between 6° West and 36° East in longitude, and 30° and 46° North in latitude. The area was later extended to include the Baltic Sea. In the Fall of 1998, a much more extended version was made operative. It includes the North Atlantic Ocean, the Barents Sea, the Baltic Sea, the Mediterranean Sea, and the Black Sea. The resolution is still 0.25°, but only in the latitude direction. For each latitude a different number of points has been used in the longitude direction, uniformly distributed at 27.5 km distance, more exactly at a distance corresponding to 0.25° in the latitude direction. This implies that the grid points are staggered and some further manipulation is required during the computation of advection.

The number of frequencies has been kept constant for a long time at N_f=25, with f_1=0.04 Hz and f_{n+1}=1.1 $\cdot f_n$. N_d=12 uniformly spaced directions have been used. These have been later increased, respectively, to 30 frequencies and 24 directions.

3.4.4. The results available at ECMWF

The information available at any moment 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 a number of quantities are 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 on 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 related formulas are given below.

$$E(f) = \int F(f,\theta)\mathrm{d}\theta.$$

The n-th order moments of the frequency spectrum are defined as

$$m_n = \int E(f)f^n\mathrm{d}f$$

from which

$$H_s = 4\sqrt{m_0}$$

$$T_m = \frac{m_{-1}}{m_0}$$

$$\theta_m = \tan^{-1}\frac{\int\int F(f,\theta)\sin\theta\mathrm{d}f\,\mathrm{d}\theta}{\int\int F(f,\theta)\cos\theta\mathrm{d}f\,\mathrm{d}\theta}.$$

Note that in numerical applications the integrals are substituted by finite summations.

The integral wave parameters available from the ECMWF archive, together with the corresponding surface wind data, have been retrieved for the Mediterranean area for a decade starting 1 July 1992. The fields are available at 00, 06, 12, 18 UT of each day. The data have been extracted with 0.5° resolution between the geographical limits present in the first version of the model at ECMWF, i.e. between 6° West and 36° East for longitude, and 30° and 46° North for latitude. This corresponds to a 85 × 33 point grid, out of which about 950 are sea points.

3.4.5. Errors

The model wave data are not reliable at combined low wave heights and periods because associated to light winds. Given (see above) that these are not reliable, a similar uncertainty follows also for the corresponding wave heights.

In connection with the underestimate of the wind speeds (see above), the model has a tendency to underestimate the wave heights in the Mediterranean Sea. This tendency is more marked at the peaks of a storm.

The wave data have a lower reliability close to the coasts because of the already mentioned poor accuracy of winds in these conditions. Besides, if the wind is blowing offshore the wave data can be substantially wrong till at least 50, most likely 100, km from the coast, because of the errors in the driving wind field (see above) and the approximation in the definition of the coastline due to the resolution of the wave model grid. The latter point is even more true during the first years considered for this analysis because of the 0.5° resolution used at the time. Because of the three different grids used at different times (see above), some coastal grid points have been alternatively considered land or sea.

The first integration algorithm used in the WAM model led to an underestimate of the wave heights in the early stages of wave generation, typically in the first 100–200 km off the coasts in offshore blowing wind conditions. This algorithm was corrected in December 1996 (Hersbach and Janssen, 1999).

4. The combined use of data from different sources

To summarise the situation outlined in the previous section, we have wind and wave data available from:

- buoys (meant as any locally measured data in the sea): accurate, frequent (typically at 3-h intervals), but limited in number, very sparse and mostly close to coasts,
- satellites: good accuracy, except for very low and high values, continuous, but very intermittent at a given location, difficulties in working close to coast,
- numerical models: continuous in space and time, full information (wave spectrum), but often underestimated in the enclosed basins.

Somehow the three sources are complementary to each other. It is obvious that the best possible results can be obtained only through the combined use of the whole available information. The background information is given by the models. Their results have been calibrated on the base of the satellite data, after having verified the satellite reliability against the buoy data. The buoy data have been used to verify the quality of the calibrated model data. Finally, a triple co-location analysis, buoy-satellite-model, has been performed. We describe in sequence these different steps.

4.1. Satellite data

The calibration of the satellite microwave instruments, altimeter and scatterometer, has been repetitively done in the open ocean (see, e.g., the recent paper by Challenor and Cotton, 2001). Given the different conditions in the large open spaces, mainly swell dominated, and in the enclosed seas, wind sea dominated, a local validation would seem a good idea. However, the scarcity of suitable data off the coast, particularly during the decade chosen for our purposes, made a validation of the altimeter wind speeds not possible. The scatterometer could not be considered for reasons to be explained in the next section. Note that a long-term source of wind data does exist in the Northern Adriatic Sea, East of Italy. The oceanographic tower of ISMAR (formerly ISDGM, see Cavaleri, 2000), fully

Table 1
Best-fit slopes between altimeter and buoy measured wave heights at different locations in the Mediterranean Sea (see Fig. 6 for their position)

	Alghero	Mazara	Spezia	Monopoli
Topex	1.01	–	–	–
ERS1–2	0.97	0.97	0.98	0.99

operational since the 1970s, had been used for the absolute calibration of the ERS1 altimeter (see Francis et al., 1993). However, its position relatively close to the coast (15 km), the limited dimensions of the sub-basin, combined with the restrictions from the orbit, excluded its direct use for the validation of the altimeter wind speeds.

The situation is somehow more favourable for the wave height. There is a large number of locations in the Mediterranean Sea where waves conditions are recorded on a routine basis, mostly by surface following buoys. For our purpose of a long-term validation and later analysis, the most relevant data set is provided by the Italian network of buoys, available since 1989 and distributed along the coasts of the Italian peninsula (their position is discussed later in detail in Section 6, see Fig. 6). Notwithstanding the large time span, a decade, for which both the buoy and altimeter data are available, in practice the proximity of the buoys to the coast, the large gradients present in the fields, the restrictions from the orbit, the exclusion of the very low wave heights, rather frequent in the Mediterranean Sea, substantially reduce the number of co-located values at each buoy position (50 km distance was allowed between the positions, while the buoy data were interpolated in time to fit the time of the satellite pass). The derived best-fit slopes, altimeter versus buoy, for the locations where the number of pairs exceeded 100, are given in Table 1.

Our immediate conclusion is that the differences from the ideal unitary values do not justify a different calibration of the altimeter wave heights. It is of interest to note that, with one exception, the stations where a comparison was possible face West, the direction where most of the storms come from. Finally, we note the different best-fit slopes for the Topex and ERS1–2 data at Alghero. Both these points will be soon discussed.

4.2. Model and satellite data

The calibration of the model data implies a long-term comparison between the corresponding model and satellite data available at, or better around, each grid point. This will indicate the correction to the model data needed at that point. Our model data are available at 0.5° intervals. So each grid point is considered as representative of an area 0.5 × 0.5° centred on it.

For each satellite datum, at given time and position, the corresponding model value has been obtained with a double linear interpolation between the four surrounding grid points and a linear time interpolation between the previous and following field values (available at 6-h intervals). This has provided a co-located pair (model-satellite), then assigned to the closest grid point. Close to land, the interpolation was limited to the surrounding sea points.

For each grid point this has provided a sequence of pairs of data, whose distribution has been best-fitted with a straight line passing through the origin. Equal weight has been given to both the sources. The slopes *s* of the best-fit line is the estimate of the average ratio between model and satellite data, hence the inverse of the calibration factor cal = 1/s to be used (calibrated model values = model values × cal).

An example of the performance of the ECMWF meteorological model in the Mediterranean Sea is given in Fig. 3. The 61001 buoy wind data, recorded off Nice, between France and Corsica, are available only for the last part of the considered decade, but the comparison clearly shows the substantial underestimate by the model, also when run with an increased resolution, T511. We chose this example, rather than a direct comparison against the altimeter data, to show later on versus an independent source the effect of the calibration. Note that, as already mentioned, the buoy is not in the best position for a direct comparison against satellite data.

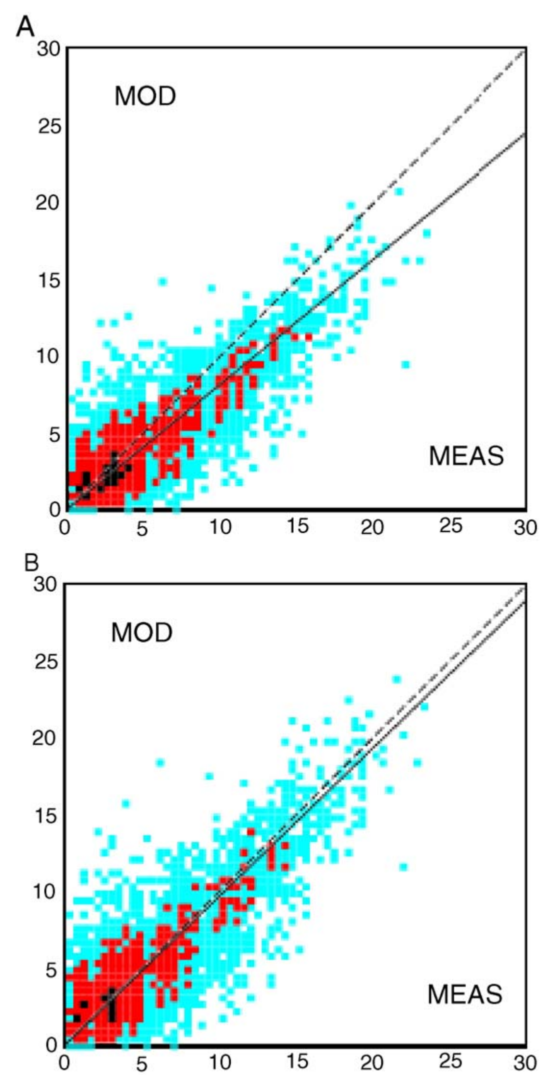


Fig. 3. Scatter diagrams and related best-fit lines between model and buoy measured wind speeds offshore Nice. Upper panel: model data. Lower panel: calibrated model data.

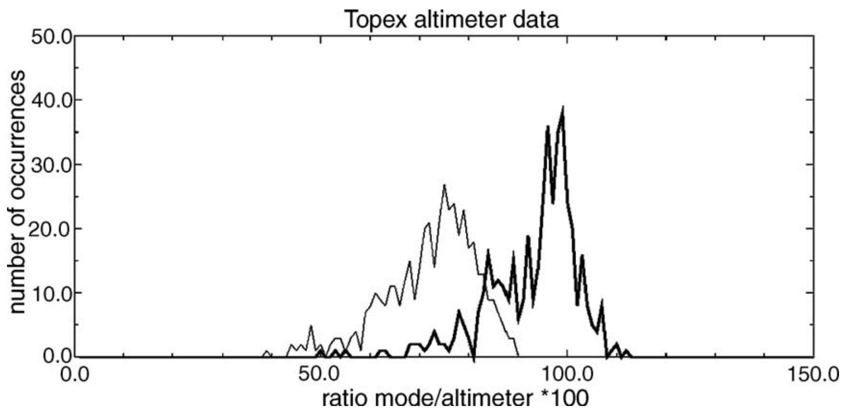


Fig. 4. Statistical distribution of the best-fit slopes between model and Topex altimeter data in the Mediterranean Sea. The thick line refers to wind speed, the thin one to wave height. The slopes have been multiplied by 100.

As mentioned in the previous section, the ERS1–2 ground tracks are dense enough so that most of the grid points have a number of co-located pairs. The minimum number of pairs required to consider the best-fit slope was 100. It was found that a smaller number could occasionally lead to local cal values clearly out of the physical range.

Due to the more distant ground tracks, the TOPEX pairs were available only at a subset P of the grid points, more or less distributed along the ground tracks. The value at any intermediate point Q has been derived with a double linear interpolation, in latitude and longitude directions, from the closest P's. with a weight inversely proportional to the distance from Q. A similar procedure has been followed for the ERS1–2 altimeter data. The overall results for TOPEX are summarised in Fig. 4, where we have plotted the overall statistical distribution of the *s* values for the Mediterranean Sea, for both wind speed U_{10} and wave height H_s. There is an evident average underestimate of both U_{10} and H_s by the models. The values for U_{10} are peaked almost on unity (representative a perfect model on the average), with a long tail towards lower values. Values as low as 0.5 are found. The values for wave height are much lower. No value is larger than one, all being lower than 0.90, with a peak at about 0.75, and values as low as 0.4.

Once the geographical distributions of the best-fit values are analysed, we find some scatter between neighbouring points, also in areas where the large space available would suggest a rather smooth distribution. This is associated to the randomness implicit in the procedure, the data used for best-fit at close-by points being potentially associated to different events, while the behaviour of the models is not constant in time. This is reflected also in the scatter of the data around the best-fit line of the single distributions. The implications will be discussed in Section 7. Therefore, the overall distribution has been smoothed with a weighted average with the close-by points, the original values retaining a 0.5 weight.

From the different instruments, i.e. the Topex and ERS1–2 altimeters, we must derive a single calibration factor cal at each grid point (separately for wind speed and wave height). This implies to weight the information received from the two instruments. Young (1998) did a thorough analysis of the wind speed and wave height measurements from the Geosat, Topex and ERS-1 altimeters. Although in this study he proposed calibration relationships to be applied to the raw satellite estimates, he reported a general good agreement with the buoy data (see also Young, 1999b). In our case we have seen above (see Table 1) that there are indications of a possible slightly different performance of the instruments from Topex and ERS-1. This is better highlighted by comparing the two corresponding sets of best-fit slopes, both for wind and waves. This is done in Fig. 5, showing the two derived scatter

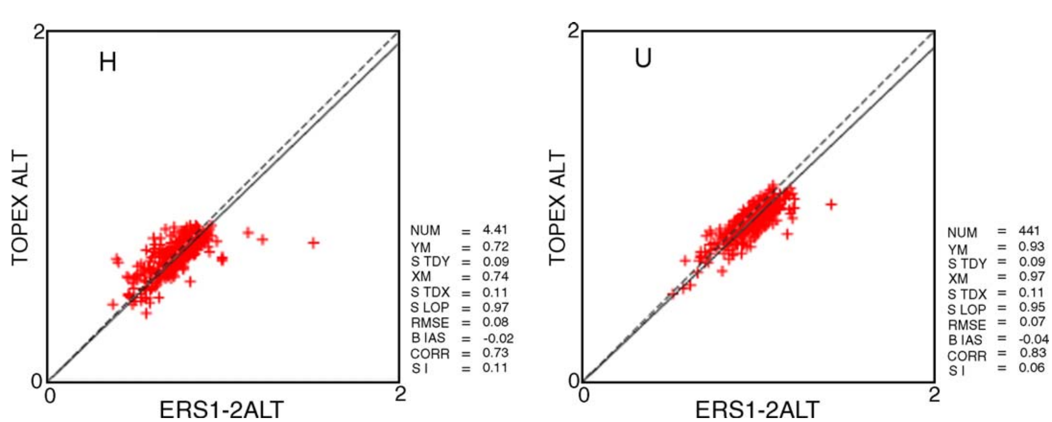


Fig. 5. Scatter diagrams between Topex and ERS derived underestimates (slopes) of the model results. Left panel: wave height. Right panel: wind speed.

diagrams, left panel for wave heights, right panel for wind speed. Each mark corresponds to one grid point where we want to do the calibration. From the figure, we see that the ERS derived slopes are on the average 3% larger than the Topex ones for wave height and 5% larger for wind speed. A similar analysis has shown the ERS wind speed slopes to be larger by 2% with respect to the scatterometer.

To obtain an objective estimate of the weight to be given to the two different sets of coefficients, we have made use of the triple co-location analysis. We intercompare co-located, in space and time, altimeter, buoy and model data. The analysis (see Mandel, 1964; Stoffelen, 1998; Janssen et al., 2003; a short description is given in Appendix A) provides the regression constants of the three possible combinations (altimeter versus buoy, etc.) and an estimate of the error present in each of the three sources. The analysis has been done only for wave height at the eight locations shown in Fig. 6 (described later), as we do not have enough locally measured wind data. For our present purposes, using the same sets of model and buoy data, we have done the analysis separately for Topex and ERS1–2, and we have looked for the altimeter relative errors with respect to those of the model and the buoys, assumed to be constant in the two sets. The results are shown in Table 2, where we provide also the scatter index SI of the altimeter data. On the basis of these results and of the errors listed in the previous section, we have elected to use the following weights: Topex 0.65, ERS1–2 0.35. Of course, if one datum is missing, the other one is accepted by default with unitary weight.

Table 2
Error (%) and scatter index SI of the altimeter data with respect to those of model and buoys (average)

Altimeter	Error (%)	SI
ERS1–2	0.82	0.17
Topex	0.35	0.13

The data are wave heights at the eight locations shown in Fig. 6.

By far the most complete source of measured wind data on the sea is the scatterometer, providing along its swath a two

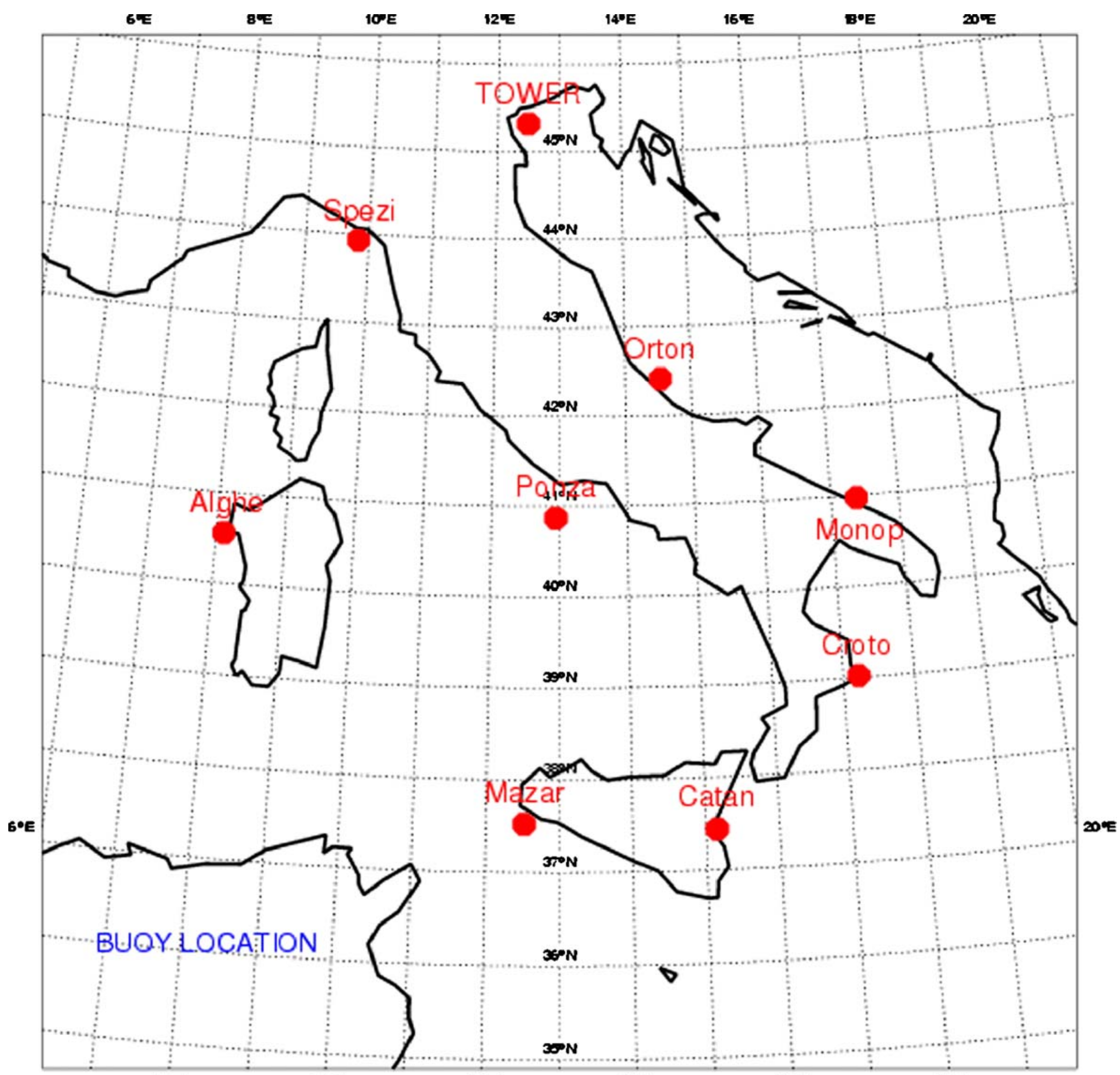


Fig. 6. Locations of the eight long-term measuring buoys around Italy. Also the location of the ISMAR oceanographic tower is shown, at the northern end of the Adriatic Sea.

dimensional view of the fields. However, for our present interests there is a fundamental problem with these data. The meteorological models rely heavily on the measured data made available in almost real time to produce the best analysis, before starting with the new forecast. This is done with data assimilation, i.e. correcting the model estimates on the basis of the measured data. The scatterometers have been, and still are, one of the main sources of information for the meteorological models.

In principle, this would not be a problem, as we are looking for the best possible data. However, the correction done with data assimilation does not affect the whole field of wind speed at the same extent. Its influence is relevant in the area of the measurements, gradually fading when moving away from it. This implies that the resulting modelled wind fields do not have the same accuracy at all the locations. It is higher at the point where and when measured data have been available, lower otherwise. This is already a source of variability in the quality of the data. However, the crucial point is that, when we compare modelled and scatterometer wind speeds, this happens to be exactly at the times and locations where the model had already been corrected. In other words, the comparison is biased, and it does not represent the actual quality of the general model data. It follows that we cannot use the scatterometer data for a long-term correction of the wind data set we have at disposal. Indeed, this information is still extremely useful in studying the overall fields, but it is not so for our present purpose of a general calibration.

The same is true for the ERS1–2 altimeter data. At ECMWF the ERS2 altimeter wave heights have been assimilated into the Mediterranean WAM wave model since 1998. Therefore, as for the scatterometer, we cannot use these data for the calibration in the Mediterranean Sea after this date.

There is another problem using the ERS2 wave height data. We have mentioned (see previous section) a permanent malfunctioning of the altimeter, when measuring the wave heights. Whichever the sea state, the reported measured data are almost always above 1–1.2 m. Therefore, the low wave height data are biased towards higher values. At ECMWF this was realised in 1996, with a consequent bias of the ECMWF analysis data available from the archive. Because the H_s correction done when assimilating the ERS2 altimeter data was reflected also in the correction of the period, this is biased as well.

Summarising, the situation is the following:

– the scatterometer data cannot be used for calibration,
– the ERS2 wave height data cannot be used for calibration after 1998,
– we know that the analysis data used for the atlas are biased towards higher values in the low H_s range.

The exclusion of the scatterometer data from the calibration procedure implies that no discussion is possible on wind direction. On the other hand, a direct comparison between model and wave directions from buoys shows that the WAM model captures well the structure of the fields. The problem is the underestimate of the wave height. Given that in an enclosed basin the wave characteristics are strongly associated with those of the driving wind fields, we make the assumption that no correction is required for the wind and wave directions.

Therefore, for the actual calibration, we can make use of the following data:

– wind speed, Topex and ERS1–2 altimeter data,
– wave height, Topex altimeter data; ERS-1 altimeter data, i.e. till 1995; ERS-2 altimeter data, only for sufficiently large wave heights, and only till 1998.

As already mentioned, the weighting coefficients for Topex and ERS1–2 have been taken as 0.65 for Topex and 0.35 for ERS1–2. Of course, when one source is missing, the other one gets a unitary weight.

5. The calibration

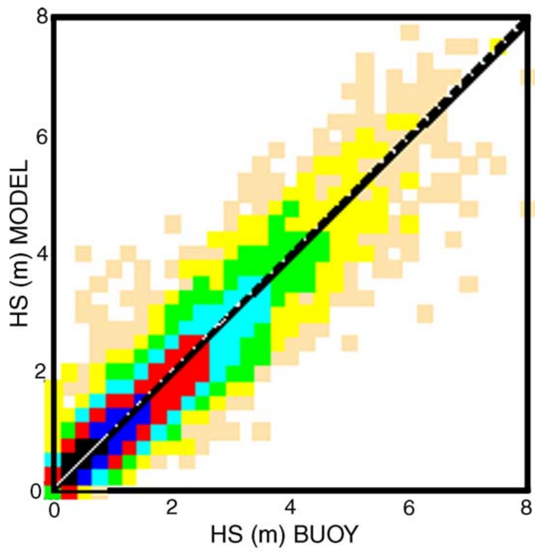
Following the procedure outlined above, the single calibration coefficients for wind speed (calu) and wave height (calh) have been derived at the various grid points. After extracting from the model data the single point time series, at 6-h intervals, they have been calibrated by multiplying the single parameters by the proper calibration factor. As derived from the physics of the process (see, e.g., Komen et al., 1994), from the limited importance of swell in an enclosed sea and a direct comparison with the buoy data, an underestimate of H_s implies also an underestimate of the wave period, in such a way that the average wave steepness does not change appreciably. 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, these are corrected multiplying them by sqrt(calh). As specified in the previous section, no correction is introduced in direction. Therefore, the final time series have been obtained multiplying the above quantities by:

–H_s	calh
–Dir$H$	no correction
–T_p	sqrt(calh)
–T_m	sqrt(calh)
–U	calu
–Dir$U$	no correction.

This 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.

6. Validation of the results

In this section, we analyse the accuracy of the calibrated wind and wave data, in the Mediterranean Sea. First, neglecting the satellite data, we compare calibrated values at specific



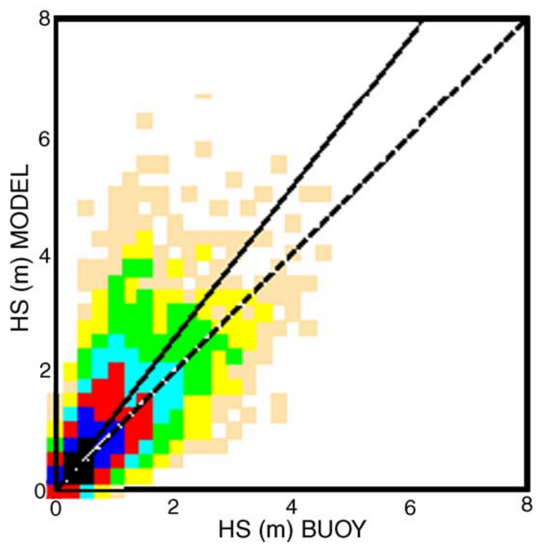


Fig. 7. Scatter diagrams between calibrated wave height data at Alghero (upper) and Monopoli (lower) and the corresponding buoy data. See Fig. 6 for their position.

positions with the corresponding measured data, where they are available.

The lower panel of Fig. 3 shows the comparison between the model calibrated and the buoy recorded wind data offshore Nice. The improvement is evident.

The extended series of buoy measured data allows a more thorough verification for wave height. We have focused on the eight long term measuring buoys (since 1989) available around the Italian peninsula (De Boni et al., 1993; see Fig. 6). For the analysis it is convenient to split the buoys in two groups: the well exposed ones, off a coast facing West (A = Alghero, Ponza, Mazara), and the ones either facing East or located in the more enclosed Ligurian and Adriatic seas (B = Spezia, Catania, Crotone, Monopoli, Pescara). Two examples, one for each set, are given in Fig. 7 (Alghero and Monopoli). The difference is clear. At Alghero most events come from the open west sectors, the coast has a limited effect on the local wave fields, and a reliable calibration is possible. On the contrary, at Monopoli the orientation of the coast and the limited extent of the Adriatic Sea frequently imply strong spatial gradients. Besides, the buoys are often much closer to the coast than the nominal distance in the model. In the latter case the minimum fetch, when the wind is blowing from land to sea, is connected to the grid step resolution. The consequences are the overestimate of the calibrated data with respect to the buoy and the large scatter that characterises the distribution.

The general results are summarised in Table 3, where we report the best-fit slope and the scatter index for the eight buoys. Apart from Spezia and Catania, we see that in group B three out of five stations have very large slopes, while the scatter index SI shows a clear distinction between the two groups.

The question arises if the scatter is simply a consequence of the variable quality of the model data, different from one event to the next one, or it is due also to the buoy data. Again, this can be established using a triple co-location analysis, among altimeter, model and buoys. The results, using the Topex data, are given in Table 4, where we have averaged the wave height rms errors and the corresponding scatter indices SI separately for groups A and B. The largest error, both as rms and SI, is associated to the buoys. This should not be surprising, because the buoy is the only one of the three sources that provides an estimate of the significant wave height H_s at one specific point. As such, although extended in time, it has non-negligible confidence limits. On the contrary an altimeter provides an estimate over a large area, 1 km wide or more, depending on the sea conditions. The model output is essentially an average over a grid mesh, in our case 0.25 × 0.25°, roughly 600 km^2 in the Mediterranean Sea. Of course, on top of this there is the accuracy of the source (instrument or model). This is reflected in the larger values of the model with respect to the altimeter.

Table 3
Best-fit slope and scatter index SI between calibrated and buoy wave heights at the eight locations shown in Fig. 6

(A) Well exposed			(B) Not well exposed		
Station	Slope	SI	Station	Slope	SI
Alghero	0.98	0.32	Spezia	1.05	0.50
Ponza	0.99	0.42	Catania	1.00	0.53
Mazara	1.03	0.34	Crotone	1.28	0.74
			Monopoli	1.21	0.51
			Pescara	1.28	0.74

Table 4
Average rms error and scatter index SI of the three sources of data, Topex altimeter, model and buoys, at the eight buoys shown in Fig. 6

Stations	rms error			SI		
	Altimeter	Model	Buoys	Altimeter	Model	Buoys
(A) Well exposed	14	20	37	13	14	25
(B) Not well exposed	17	25	32	14	17	27

7. Critical analysis of the results

In this section, we discuss in details the various sources of errors that may affect the calibration of the wind and wave data throughout the basin. In the previous section, we have provided estimates of the overall error at eight buoy positions. This is not possible in general (buoys are scarce and often not well representative of the surrounding area), and we have to argue on the base of the known characteristics of the altimeter and the model, and of the obtained results.

In Section 3, we have listed the various sources of data and pointed out the main errors present in each source. In particular, we have mentioned a number of errors that may affect the calibration. They concern mainly the measurements by the satellites and the different capability of the models to respond to different situations. These errors lead to the large scatter we find around the best-fit line at each specific location. This is also the reason why we find an unrealistic spatial variability of the calibration coefficients that has forced us to smooth their geographical distribution. This procedure makes sense in the large sub-basins, where we have no reason to expect large spatial gradients. It becomes debatable close to the coasts or in complicated areas where a large spatial variability is a natural implication of the local geometry. However, having a natural variability superimposed to the one derived from the calibration, particularly in areas where the models show the largest errors, we are not able to distinguish among the various sources of variability.

The variability increases along the northern coasts of the Mediterranean Sea. The reason is that the whole European coast is characterised by a marked orography (see Fig. 1). As most of the storms that affect the Mediterranean Sea come from the northern sectors, the marine areas along the northern coasts are on the lee of the mountains. We have already mentioned that, when flying offshore, the wind speed altimeter data are not accurate up to the specifications in the first few tens of kilometres off the coast. Assimilated in the meteorological model, their error is transmitted also to the wave field.

We can have an idea of the consequent uncertainty of the final estimate of the calibration coefficients by considering the scatter index SI of the single best-fits. The distributions of the SI values in the Mediterranean Sea, for U_{10} and H_s, are given in Figs. 8 and 9, respectively. This information is essential to assess the reliability of the final results, and it should be considered when deriving statistics from the calibrated time series.

We have to consider also the systematic errors. Their single influence is hidden, because in general we can only see their overall effect. The relevance of a specific error can be identified when this error has been corrected at a certain date. This is the case with the results of the WAM model in the first 100–200 km off the coast. In this range, with the wind blowing from land to sea, the previous integration scheme was biased towards low values. As already discussed in a previous section, this was corrected in the operational model in December 1996. Therefore, before this date, all the short fetch data have a permanent error in the low value range. Given the directions most of the storms come from, this is particularly true along the northern coasts of the Mediterranean Sea.

In principle, the systematic errors are taken into account with the calibration. However, this is not always true for two reasons. In the just mentioned example, the bias is more marked in the low wave height range (early stages of generation off the coasts). When fitting a best-fit line to the data, the slope depends on the whole set, and therefore only a partial correction to the low range data is introduced, disrupting at the same time the fit to the larger values. This is reflected in the variability of the ratio model/measurements. This is also the case for the continuous upgradings of both the meteorological and wave models at ECMWF. We can take into account the most substantial changes, as done for the passage to T511 in November 2000. However, it is not possible to split the calibration into a number of small periods, because the resulting reliability would be too low. Indeed, this is partially the case for the period November 2000–June 2002. With only 19 months at disposal, and a substantial decrease of the percentage of data available from the satellites, the results for this period have a lower reliability than for 1992–2000.

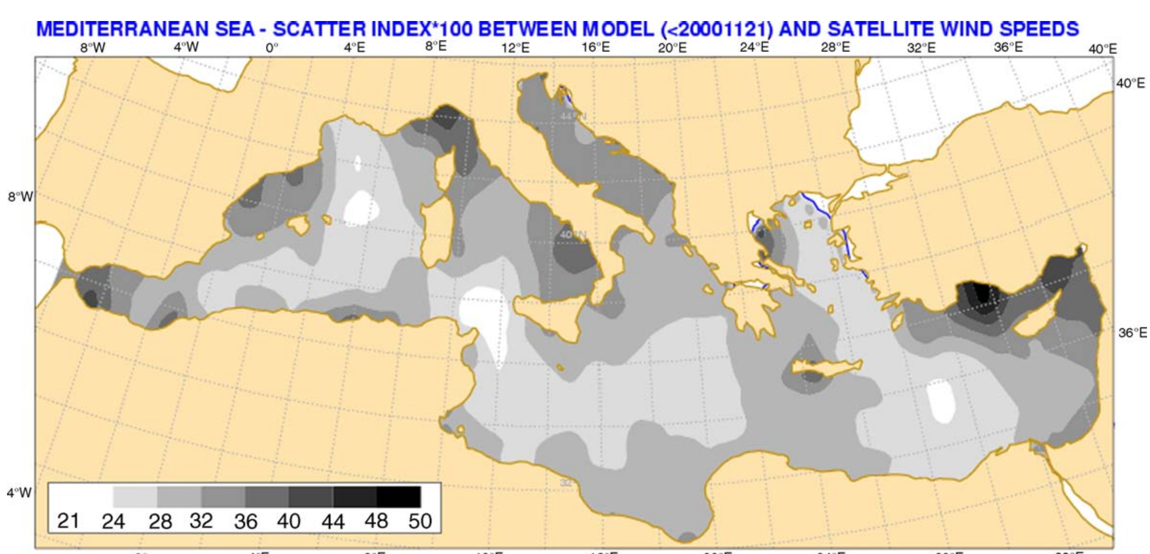


Fig. 8. Distribution of the scatter index SI (×100) for the fits between model and altimeter wind speeds in the Mediterranean Sea.

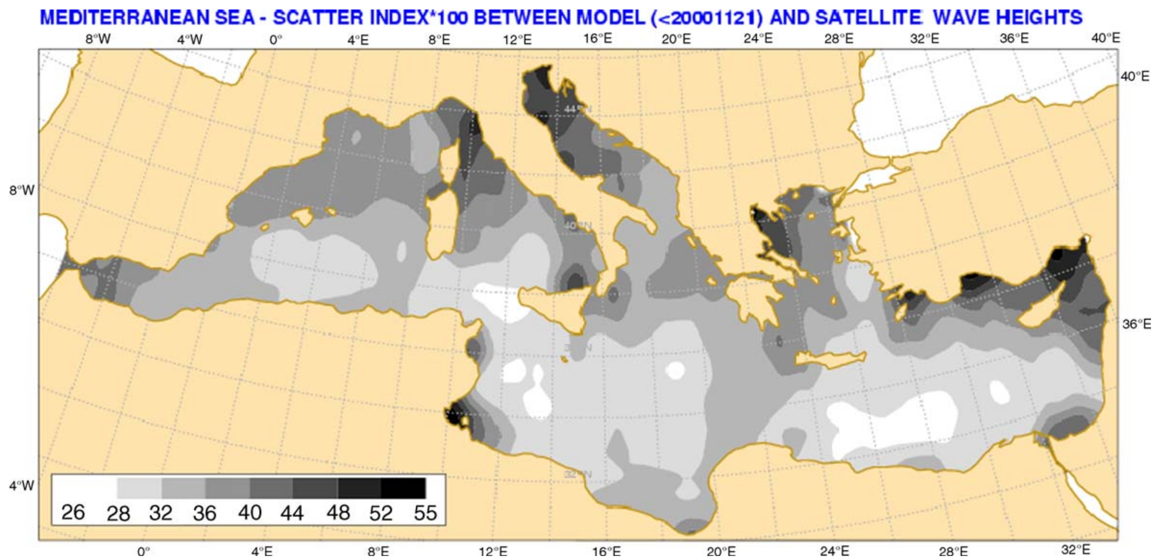


Fig. 9. Distribution of the scatter index SI (×100) for the fits between model and altimeter wave heights in the Mediterranean Sea.

The Mediterranean model is presently run with 0.25° resolution. In principle, we could have extracted the archive data with the same interval. However, the data are not available with this interval for the whole period considered, as ECMWF moved from a 0.5° to a 0.25° resolution Mediterranean wave model in 1995. Besides, this would have drastically decreased the number of co-located pairs at each grid point, further increasing the uncertainty of the single fits. Therefore, we would have not gained anything for the final results. A better spatial resolution would have been achieved close to the coasts. However, as we have pointed out, this is also the area where we have often the largest errors, and the improvement would have been only apparent.

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 error in the generating wind field is reflected in the resulting wave field. Therefore, the two maps of the calibration coefficients are expected to show a high degree of consistency. Indeed, this is the case for their geographical distributions in the Mediterranean Sea, shown in Fig. 10 for the wind speed and Fig. 11 for the wave height. For both wind and waves, higher corrections are required along the European coasts and Turkey. However, the actual figures are not fully consistent. The corrections for wind are much lower than what one could guess from the ones for waves. In other words, the calibrated wind speeds are too low with respect to the calibrated wave heights. Indeed, this could be due to an error in the wave model that could underestimate the wave heights. However, it is amply accepted in the literature (see Komen et al., 1994; Janssen, 1998; Swail and Cox, 2000) that the error of a sophisticated wave model, as it is the case with WAM, is substantially lower than those of the generating wind fields. As a matter of fact, the distribution of the wave heights in a basin, compared to the locally

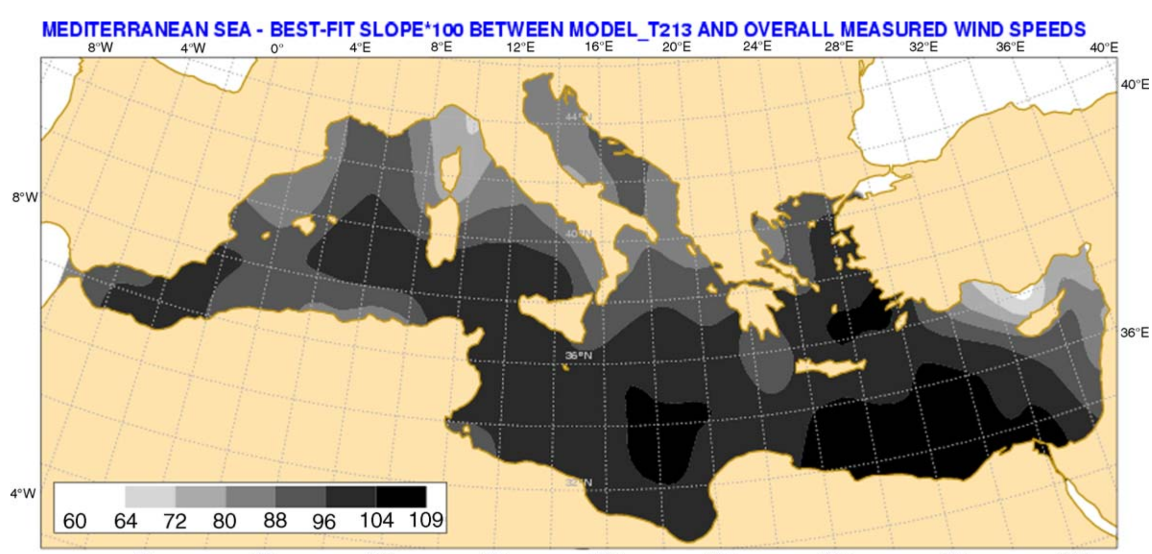


Fig. 10. Distribution of the best-fit slopes (×100) between model and altimeter wind speeds in the Mediterranean Sea.

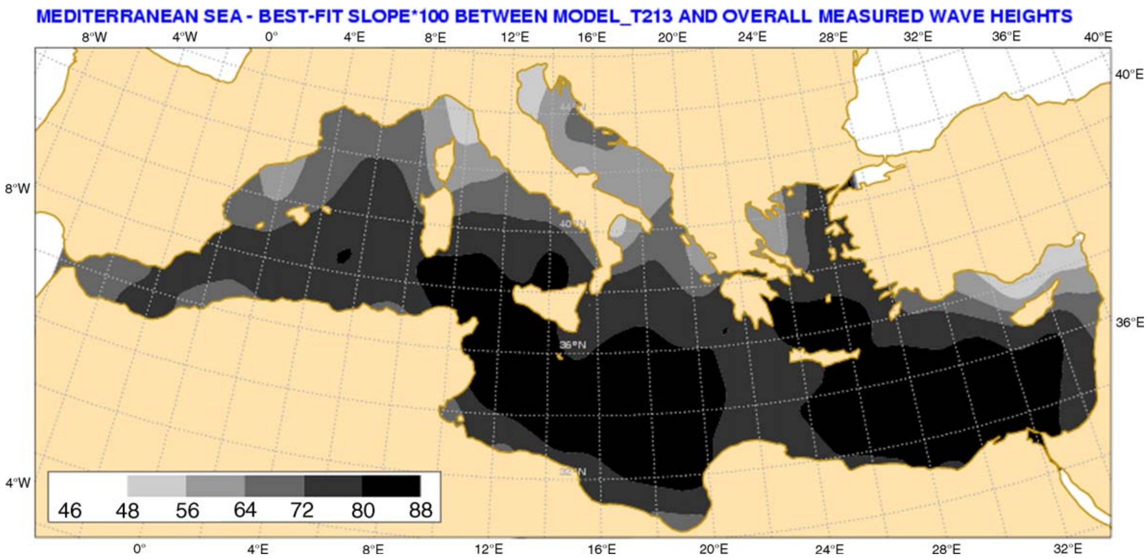


Fig. 11. Distribution of the best-fit slopes (×100) between model and altimeter wave heights in the Mediterranean Sea.

available measurements, is one of the best ways to judge the quality of the input wind fields. Therefore, the inconsistency we have noted, of the order of at least 5%, is not expected to be a product of the wave model.

After the previous critical analysis of the results, our overall conclusions on the calibration are summarised in the following.

We believe we have obtained what can be considered as the best extended data set 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. Maps have been provided showing the distribution of the scatter index (a non-dimensional measure of the rms error) in the basin for both wind speed and wave height.

Out of the three sources of data, altimeter, model and buoys, where all of them are available the altimeter shows the smallest error. The largest one is given by the buoys.

The data in the lower range of wave heights are the least reliable ones. This is due to an error in the wave model before a certain date and to a problem with the corresponding measurements by the ERS2 altimeter.

The calibration coefficients for wind and waves are not fully consistent to each other. The calibrated wind speeds are low by at least 5% with respect to the calibrated wave heights.

Appendix A. The triple co-location analysis

The following text is a slightly modified summary of the description provided by Janssen et al. (2003).

We consider three sources of data concerning the variable T. Each set of three "measurements" is co-located, i.e. the three data are taken at the same time and position. We assume that the data are related to the truth T as

$$X = \beta_x T + e_x$$

$$Y = \beta_y T + e_x$$

$$Z = \beta_z T + e_x \tag{A1}$$

where the β's are the calibration constants and the e's represent the uncorrelated errors of the measurements. It follows that

$$\langle e_x e_y \rangle = \langle e_x e_z \rangle = \langle e_y e_z \rangle = 0 \tag{A2}$$

where the $\langle\rangle$ indicate the average over a sufficient number of available data. From (A1), we can derive

$$e_x/\beta_x - e_y/\beta_y = X/\beta_x - Y/\beta_y$$

$$e_x/\beta_x - e_z/\beta_z = X/\beta_x - Z/\beta_z$$

$$e_y/\beta_y - e_z/\beta_z = Y/\beta_y - Z/\beta_z. \tag{A3}$$

With a simple manipulation and taking (A2) into account, we obtain

$$\langle e_x^2 \rangle = \langle (X - \beta_x Y/\beta_y)(X - \beta_x Z/\beta_z) \rangle$$

$$\langle e_y^2 \rangle = \langle (Y - \beta_y X/\beta_x)(Y - \beta_y Z/\beta_z) \rangle$$

$$\langle e_z^2 \rangle = \langle (Z - \beta_2 X/\beta_x)(Z - \beta_z Y/\beta_y) \rangle. \tag{A4}$$

Hence, we get an estimate of the variance of the error in each source. However, the results depend on the still unknown calibration constants β's. Without any further information, we can only reach an estimate of the relative calibrations, e.g., X with respect to Y, and so on. We arbitrarily choose X as a reference. Then the calibration constants for Y and Z may be obtained using neutral regression (Marsden, 1999). It follows that

$$\beta_y = (-B + \mathrm{sqrt}(B^2 - 4AC))/2A \tag{A5}$$

where $A = \gamma\langle XY\rangle$, $\gamma = \langle e_x^2\rangle/\langle e_y^2\rangle$, $B = \langle X^2\rangle - \gamma\langle Y^2\rangle$, and $C = -\langle XY\rangle$. β_z is obtained replacing Y with Z.

Of course the definition of β_y and β_z affects the estimate of $\langle e_x^2\rangle$, $\langle e_y^2\rangle$, $\langle e_z^2\rangle$. Therefore, an iteration procedure is required between (A4) and (A5) that rapidly converges to a several digit accuracy.

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