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Comparison of wind and wave measurements and models in the Western Mediterranean Sea ☆

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Abstract

We have hindcast the wind and wave conditions in the Mediterranean Sea for two one month periods. Four different meteorological models and three different wave models have been used. The results have been compared with satellite and buoy wind and wave observations.

Several conclusions concerning both the instruments and the models have been derived. The quality of both wind and wave results has been assessed. Close to the coasts high resolution, nested wave models are required for sufficient reliability.

A wave threshold analysis suggests a sufficient reliability only off the coast, with a substantial decrease for low wave heights.

Keywords: Wind; Waves; Meteorological models; Wave models; Satellite data; Buoy data

1. Introduction

The knowledge of wave conditions, either as climatology or short-term forecast, is critical for all human activities at sea, including shipping, fishing, oil extraction and naval operations. The development of wave models has been very fruitful over the past few decades and wave forecasts are now quite reliable in the open ocean. Because wave models compute the wave field from surface winds, mostly provided by atmospheric models, this progress was made possible by advances in weather forecasting and remote sensing of winds over the oceans. The reliability of wave models has been achieved also thanks to the many efforts of space agencies to provide wave height measurements with space-borne range altimeters, in particular on the ERS-1 and -2 satellites, Topex, Jason, Envisat, Geosat and Geosat-follow on, as well as Word Meteorological Organization member countries exchange of in situ observation from wave buoys. Current efforts to improve global wave forecasting is essentially driven by these continuous observations and the theoretical developments on the generation and evolution of wind waves.

However, this effort may not resolve all the problems encountered in coastal areas or enclosed basins where waves have different characteristics due to their local generation. In the Mediterranean, wind forecasts are usually not as accurate as in the open oceans (Cavaleri and Bertotti, 2003, 2004). Many studies have highlighted the fact that winds in the Mediterranean are usually underestimated by coarse global models. However, because of the limited amount of data, it is still unclear how good the wave models are and how much they can still be improved when using good quality winds. For low wave

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heights in particular, altimeters rely on the time-delay of sea echoes between wave crests and troughs to make the measurements, and these echoes are time-gated in a way that corresponds to a vertical resolution of typically 0.4–0.5 m. Therefore in these conditions they are unable to define properly the wave height. In situ measurements are also scarcely available due to the sparsity of the measurement locations and to the many local authorities that gather measurements for their own needs without any connection to the WMO that may be able to distribute the data.

The present work aims at defining the accuracy and identifying biases of wave forecasting models in the western Mediterranean. This knowledge will allow a more informed use of wave model output and hopefully provide new evidence to support modifications in the parameterisations used in the models. These results can likely be generalized to other enclosed basins and some coastal areas. Because these results depend largely on the quality of the wind fields, the accuracy of the wind models is also discussed. The diagnosed behaviour of the models will be used in further studies to improve the wave model parameterization, and the dataset described will be used as a benchmark for these further improvements.

2. General outline of the test

The wave model results depend to a comparable extent on the accuracy of two models, meteorological and wave ones, working in series. In practice, when comparing measured and modelled wave data, it is not straightforward to decide where the discrepancies come from.

Two methods can be followed to sort out this ambiguity. One obvious solution is to compare both wind and wave model data with all the available measurements. The efficiency of this method is limited by the sparsity and intermittency of the measured data, while wave conditions depend on the integral in time and space over the previous wind fields. Alternatively, we can cross-compare the results obtained using several meteorological and wave models. Doing so, we highlight the possible deficiencies of one model, suggesting where to act for correction.

We have used both approaches. We have defined two periods, one month each, during which the wind and wave conditions covered the range of interest. We have collected a large amount of wind and wave measured data, both from satellites (altimeters and scatterometer) and from buoys and one platform. The wind and waves during the two periods have been simulated using four different meteorological models and three wave models, using all the possible combinations. This has provided an unprecedented dataset, whose analysis provides an assessment of the performance of the single models. The two chosen periods are:

- 1st–31st October 2002,
- 28th January–28th February 2003,

characterized by both mild conditions and severe storms.

In the following first we describe (Section 3) the dataset of the collected measured data. In Section 4 we mention the meteorological and wave models used for the test, and in Section 5 the general method followed for the analysis. Section 6 describes briefly the wave conditions and the relevant events during the two test periods. The data analysis is done in Section 7 for the wind and in Section 8 for the waves. In Section 9 we discuss our results, then summarized in the final Section 10.

3. Datasets description

We consider in situ observations from a variety of buoys and an oceanographic tower. Most of the buoys are located close to the coast. Only a few ones are moored in deep water. Their location is shown in Fig. 1. More specifically:

- In Italy the tower, managed by ISMAR-CNR, and the buoys, ODAS managed by ISSIA-CNR and the other ones part of the national buoy network (RON), are located at:
  CNR tower (close to Venice), Punta della Maestra (Po estuary), La Spezia, Ancona, ODAS (Ligurian Sea), Civitavecchia, Ortona, Alghero, Ponza, Monopoli, Capo Comino, Cortone, Cetraro, Cagliari, Palermo, Mazara, Catania.
- In France, managed by Météo-France and Centre d'Etudes Techniques Maritimes et Fluviales (CETMEF):
  Nice, 61001 (offshore of Nice), 61002 (Gulf of Lion), Marseille, Cap Corse, Porquerolles,
- In Spain, managed by Puertos Del Estado and the Xarxa d'Instrumentacion Oceanografica I Meteorologica (XIOM) de Catalunya:
  Rosas, Cabo Begur, Palamos, Tordera, Llobregat, Tarragona, Cap Tortosa, Mahon, Capdepera, Valencia, Alicante, Cabo de Palos, Cabo de Gata (two buoys, one in shallow water the other in deeper water), Malaga, Alboran, Ceuta.

Wave observations used here are restricted to wave heights that we consider to be equally well estimated from the various instruments. Quality control is routinely done on the data of each instrument, getting rid of the obviously wrong values. No smoothing averaging was used. Wind information is also available at four of these locations, namely Lion 61002, Nice 61001, ODAS and the CNR tower.

Besides in situ data, we use space-borne altimeter-derived wave heights and wind speeds from ERS-2 (European Space Agency) and Jason (CNES-NASA). These data are available along the satellite ground tracks and correspond to an average over 6–7 km along those tracks, with repeat cycles of 35 and 7 days, respectively (Fig. 2). Winds from the altimeter are derived from the radar cross section, and wave heights (Gourrion, 2000) using empirical neural network fitting of co-located wave

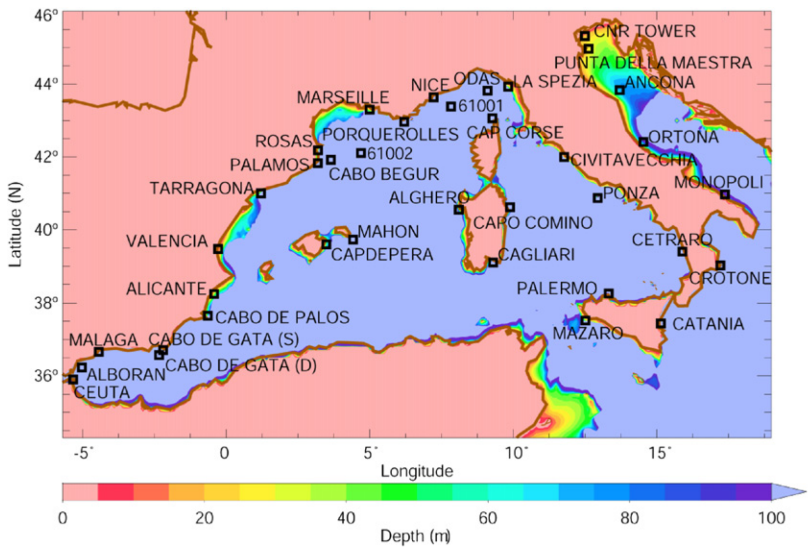

Fig. 1. Model bathymetry and location of buoys in the Western Mediterranean Sea.

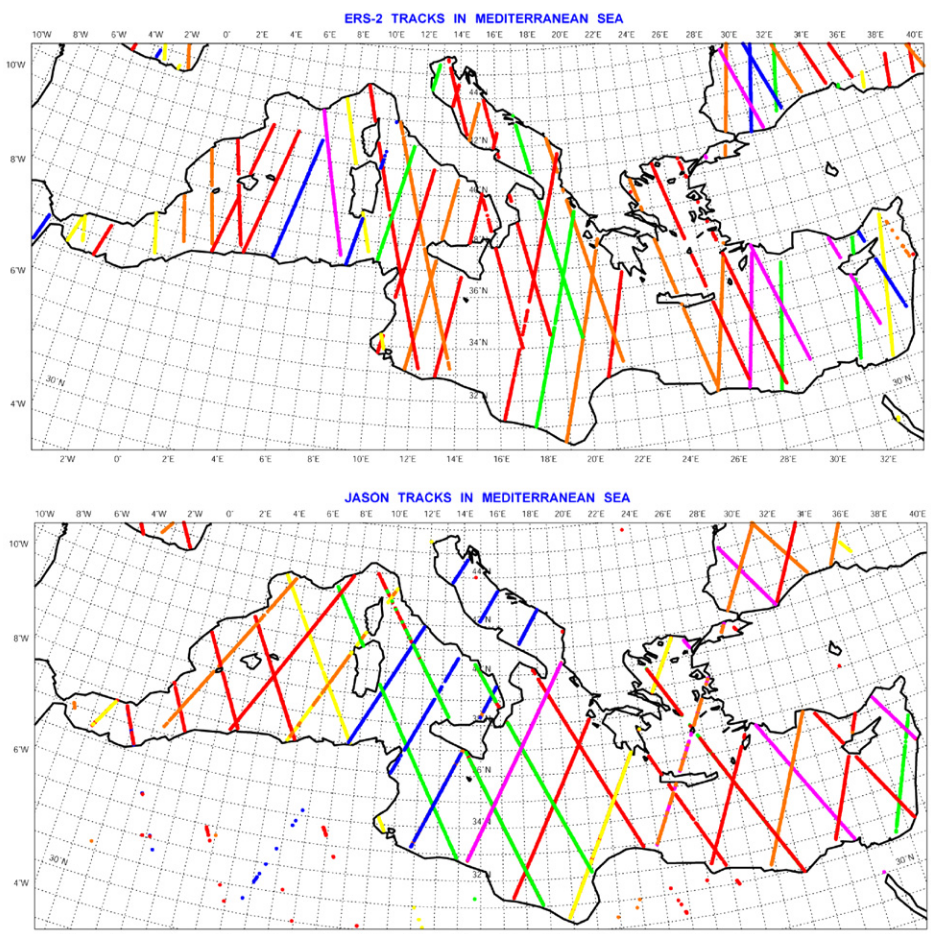

Fig. 2. Ground tracks of ERS-2 and Jason for February 2003. The lines show where data are available.

height measurements to satellite data. Fast Delivery (FD) data have been used. The data have been corrected according to calibration derived from extended comparisons with sea truth derived from buoy measurements (Challenor and Cotton, 1997; Queffeulou, 1996).

We also use SeaWinds wind measurements from the QuikSCAT satellite, operated by NASA, and provided by CERSAT as Level 2B products. These Ku-band scatterometer winds are gridded at 25 km resolution along the 1800 km wide swath of the satellite, with 2 passes per day (ascending and descending). The data include wind speed and direction. Over each pixel of this along-track grid, the wind vectors are determined by the combination of 2–4 individual radar cross section measurements of the ocean surface under various angles of incidence.

4. Wave model set-up and wind fields

Three wave models were used in the present work, using the same bathymetry, provided by SHOM, and the same spatial resolution (0.1° of latitude and longitude):

- An improved version of WAM "Cycle 4" (see Janssen, 2004), using the discrete interaction approximation (DIA) for the wave–wave interactions, a quasi-linear wind wave generation term (Janssen, 1991) and a dissipation based on Komen et al. (1984) adjustment of Hasselmann's (1974) pulse model for wave dissipation. The differences between this version and the widely used WAM Cycle 4 are essentially restricted to numerical aspects. Furthermore, the global wave model at ECMWF is coupled to the atmospheric model. However, the model set up used here is the uncoupled version of the same code.
- VAG is the model currently in operation at Météo-France, and is based on a "second-generation" parameterization of the wave–wave interactions together with wind generation and dissipation formulations equivalent to the WAM Cycle 4 model (Guillaume, 1987; Fradon, 1997; Fradon et al., 2000; Lefèvre et al., 2003).
- Wavewatch III (version 2.22, hereafter called WW3) is the current model operational at the National Center for Environmental Prediction (NCEP, see Tolman et al., 2002) and at the Fleet Numerical Meteorology and Oceanography Center (FNMOC, see Wittmann, 2002). It uses a wind input source term fitted to numerical simulations by Chalikov and Belevich (1993); for wind over waves, a dissipation that acts separately on the wind sea and the swell (Tolman and Chalikov, 1996) and a tuned (i.e. reduced) DIA for non-linear interactions, together with different numerical schemes for integration and propagation.

It may seem out of date to use also a second generation model. However, we believe it is interesting to compare its results with those from WAM and WW3 to pinpoint advantages and disadvantages of the different models.

All models were run with a directional resolution of 15°. The frequency grid is the same for WAM and WW3, starting at 0.05 Hz and using 30 frequencies logarithmically spaced with a relative intervals of 0.1 from one frequency to the next. This grid spacing is imposed by the DIA. VAG uses only 12 frequencies uniformly distributed over the same frequency range.

The models were "spun up" for 24 h, from 00 UTC on the 1st October and 28th January, and run for about one month, until 00 UTC on 1st November 2002 and 1st March 2003, respectively. Winds were not interpolated in time and therefore changed in a step-wise fashion with the interval of the wind output (e.g. 0 h, 3 h, 6 h ...). Results from the models are used in the periods 2nd October to 1st November and 29th January to 1st March. The models were forced with wind fields from four sources:

- ALADIN (limited area model operational at Météo-France, ALADIN Int. Team 1997), wind forcing every 3 h, short-term forecast (+3 to +12 h). The horizontal resolution is about 10 km.
- COAMPS (limited area model operational at FNMOC), wind forcing every hour (except for the run with VAG), short-term forecasts (+1 to +12 h). The horizontal resolution is 27 km.
- ARPEGE (global model operated by Météo-France, Courtier et al., 1991) wind forcing every 3 h, short-term forecasts (+3 to +12 h). The horizontal resolution is about 25 km for the Western Mediterranean Sea.
- ECMWF winds, from the operational model, wind forcing every 6 h, analysis. The horizontal resolution is about 40 km.

All the short-term forecasts started at 00 and 12 UT. It must be noted that ALADIN is nested into ARPEGE, and that ARPEGE and ECMWF are actually the same model, developed jointly, but run with slightly different settings, and in a different operational context. Finally ECMWF is the only model where the QuikSCAT data are assimilated. The altimeter winds are not assimilated in any of the considered atmospheric models.

The model data domain covered the area from 30°N to 46°N, and from 6°W to 36°30′E. Since the ALADIN area is restricted to 35°N and 17°E (low and right border, respectively), the ALADIN wind fields were complemented by ARPEGE in the not covered area, allowing the generation of waves also in the Eastern Mediterranean.

5. Methods

Model outputs were produced every 3 h and compared in the following sections to remote sensing and in situ observations. In the latter case the model outputs are taken at the closest grid point, which should be at most 6 km away, and for the corresponding time. In a few cases where the closest point was on land the model output was instead taken at the next closest point with a water depth corresponding as closely as possible to the water depth at the buoy location. Measurement points are in general in deep enough water, compared to the wavelength of the observed waves, to be considered in deep water anyway.

For remote sensing data, the model output was interpolated in space with a bilinear interpolation, and in time. In all cases, co-location files were used to compute statistics and produce scatter diagrams by binning the model-observation co-locations with the observed and predicted values.

The statistical parameters used below are the slope of the regression line through the origin, the rms error, the normalized error (rms error divided by the mean observed value), and the scatter index (standard deviation of the data with respect to the best-fit line, divided by the mean observed value). We essentially focus on the slope which indicates the presence of biases and the scatter index that gives indications about typical scatter around this bias. However, it must be noted that, having removed the bias from the scatter index, very strong underestimations will generally cause a small scatter index, so that we tend to emphasize more the slope in our comments. To summarize, for low biases (typically, slopes between 0.90 and 1.1), the best indication of model quality is the scatter index, while for larger biases the scatter index cannot be interpreted directly in terms of "quality".

For our analysis in this paper we have chosen to focus on only a few of the possible model combinations. We have considered the output of the WAM model driven by the different winds. Alternatively we have considered the output of the different wave models, all driven by the ALADIN winds. All the other combinations provided results consistent with the ones reported here.

6. General conditions

The two periods were chosen for their different wave conditions. October 2002 is dominated by small waves (1 m or less) with a couple of moderate storms. Notable events include:

- 7, mistral (measured wave height at Alghero is up to 3.5 m),
- 9–10 westerly wind events in the Alboran sea (H_s up to 3 m at Cabo de Gata),
- 12 to 13, mistral (H_s up to 4.6 m at Alghero),
- 18, westerly wind in the northern part of the basin (H_s up to 3.2 m at Nice 61001),
- 23–24, as on 18, following a general strong westerly flow in the entire basin on the 22 (H_s up to 2 m at Cabo de Gata).
- 28, mistral (H_s up to 4 m at Alghero).

February 2003 had major storms:

- 29–30 January–1st February, 3 sequential mistral storms peaked on 29/01, 30/01 and 1/02, with recorded wave heights up to 5 m at Alghero for each event,
- 4, the largest mistral storm covering most of the western Mediterranean, with observed waves up to 6.5 m at Cetraro.
- 17–18, two noticeable easterly wind events in the north of the basin, with more than 3 m waves during these 2 days at 61001 (offshore of Nice) and on the east of Sicily (the buoy at Catania did not transmit during the peak of the storm)
- 25 to 28, south-easterly winds dominating the end of February with recorded wave heights above 2 m at Palamos and 61002 (Lion) and a peak of 4.6 m at Palamos on 26.

7. Models performance: wind fields

Wind fields from the models can be compared to remote sensing (QuikSCAT scatterometer, and ERS-2 and Jason altimeters) and to in situ data to evaluate their quality. The comparison is made in terms of the best-fit slopes and the scatter indices.

Fig. 3 shows the diagrams between the four wind models (ALADIN, COAMPS, ARPEGE, ECMWF) and the corresponding QuikSCAT data for October (2002; we will not repeat the year). Table 1 summarizes the results of all the comparisons for the same period. Table 2 does the same for February. Fig. 4 shows the scatter diagrams between model and Lion 61002 data for October. Fig. 5 does the same for February, but limited to ALADIN and COAMPS at the tower.

7.1. Models versus buoys

Of the four locations where measured wind data are available, we classify Lion 61002 as open sea, Nice 61001 and ODAS as open sea, but potentially affected by the nearby orography, and the tower (see Fig. 1) as coastal, in a rather difficult situation (mountains in the north and east directions, at some tens of kilometres distance).

We see from Fig. 4 and from Tables 1 and 2 that, on average, in the open sea the higher-resolution models, ALADIN, COAMPS and ARPEGE, perform rather well. The results are consistently better when the meteorological conditions are more defined and winds are stronger (in February the mean ALADIN wind speed was 7.65 m/s, in October 5.56 m/s). The results degrade drastically at the tower (Fig. 5), where the underestimation ranges from 20% to 40%. These figures are probably slightly in excess because the wind is here measured at 18 m height and because of the influence of the structure.

The coarsest model, ECMWF, shows a consistent underestimation of the wind speed, from 5%–10% at exposed locations to 40% at the tower. This figure is consistent with the previous results by Cavaleri and Bertotti (1997) in the Adriatic Sea and by Quentin (2002) in the Gulf of Lion. In general the wind speeds by ECMWF are 10% lower than those by the other three models.

7.2. Models versus satellites

The comparison between model and satellite wind data is somehow more erratic. Granted the different areas covered by the instruments, when compared to models, the Jason data lead to a statistics comparable to the one from the

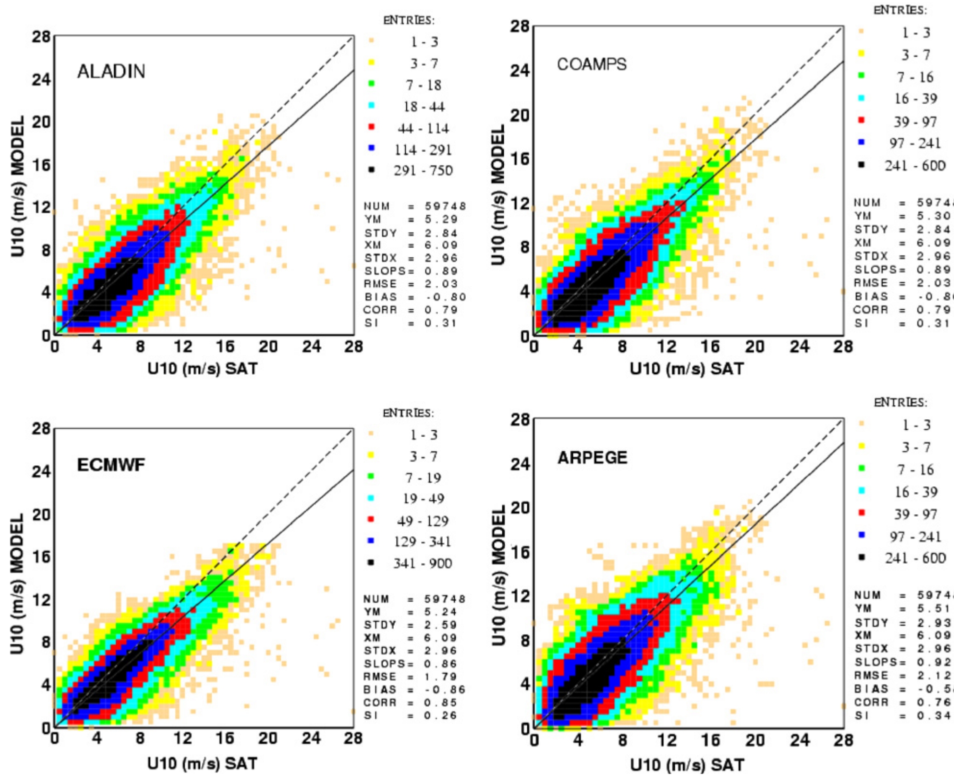

Fig. 3. Comparison of QuikSCAT wind speeds with wind fields (ECMWF analysis and short term forecasts from ARPEGE, ALADIN and COAMPS) for October 2002.

Table 1
Statistics of the comparison between the four wind model data and the measurements from satellites and buoys

October 2002	ALADIN		COAMPS		ARPEGE		ECMWF	
Jason	**0.94**	0.31	**0.98**	0.33	**0.92**	0.31	**0.92**	0.25
ERS-2	**1.10**	0.34	**1.12**	0.37	**1.09**	0.35	**1.03**	0.28
QuikSCAT	**0.89**	0.31	**0.89**	0.31	**0.92**	0.34	**0.86**	0.26
Lion 61002	**1.06**	0.22	**1.02**	0.32	**1.09**	0.33	**0.95**	0.20
Nice 61001	**1.03**	0.47	**0.89**	0.50	**0.92**	0.62	**0.91**	0.41
CNR Tower	**0.69**	0.42	**0.65**	0.46	**0.58**	0.50	**0.59**	0.42

See Fig. 1 for the location of the buoys. The period considered is October 2002. For each wind source the best-fit slope (model against measured data, bold) and the scatter index SI are given.

Table 2
As Table 1, but for February 2003

February 2003	ALADIN		COAMPS		ARPEGE		ECMWF	
Jason	**0.92**	0.25	**0.94**	0.30	**0.91**	0.24	**0.87**	0.22
ERS-2	**1.03**	0.30	**1.08**	0.32	**1.01**	0.28	**0.96**	0.25
QuikSCAT	**0.89**	0.24	**0.88**	0.24	**0.92**	0.28	**0.84**	0.21
Nice 61001	**0.99**	0.25	**0.97**	0.38	**0.91**	0.20	**0.85**	0.31
Lion 61002	**0.99**	0.19	**1.01**	0.20	**1.01**	0.18	**0.89**	0.14
CNR Tower	**0.80**	0.26	**0.67**	0.33	**0.66**	0.33	**0.60**	0.30

buoys. However, the ERS-2 data always show much lower wind speeds, except at the CNR tower. Combined with the buoy statistics, this suggests that the ERS-2 wind speeds are underestimated by more or less 10%. A similar result was found by Cavaleri and Sclavo (2006) who, calibrating the ECMWF wind and wave model data against altimeters in the Mediterranean Sea, found an inconsistency in the calibrated data, the wind speeds being systematically too low to justify the corresponding wave heights. As the latter ones were verified against buoy data, the result was explained with a permanent underestimation of the altimeter wind speeds. The altimeter algorithms were derived from calibration campaigns in the swell-dominated ocean environment. In the enclosed seas, as the Mediterranean, the waves are mainly wind driven. This affects the characteristics of the wavelets, hence the reflection of the radar signal, leading to an underestimation of the surface wind speeds.

We are somehow surprised by the QuikSCAT results. Chapron and Cotton (personal communication, 2004, 2005) expect the algorithm to underestimate the wind speeds in the enclosed seas. However, as we see from Tables 1 and 2, we find the opposite. Within the limits of the dataset we have used, this result seems robust, because the quality of the high-resolution model wind fields is confirmed by the comparison of the derived wave fields against buoy data (see Section 8).

7.3. Scatter index

Looking at the scatter index SI (see Table 1), defined as the rms difference from the best-fit line divided by the mean measured value, we find that SI is larger in October, with

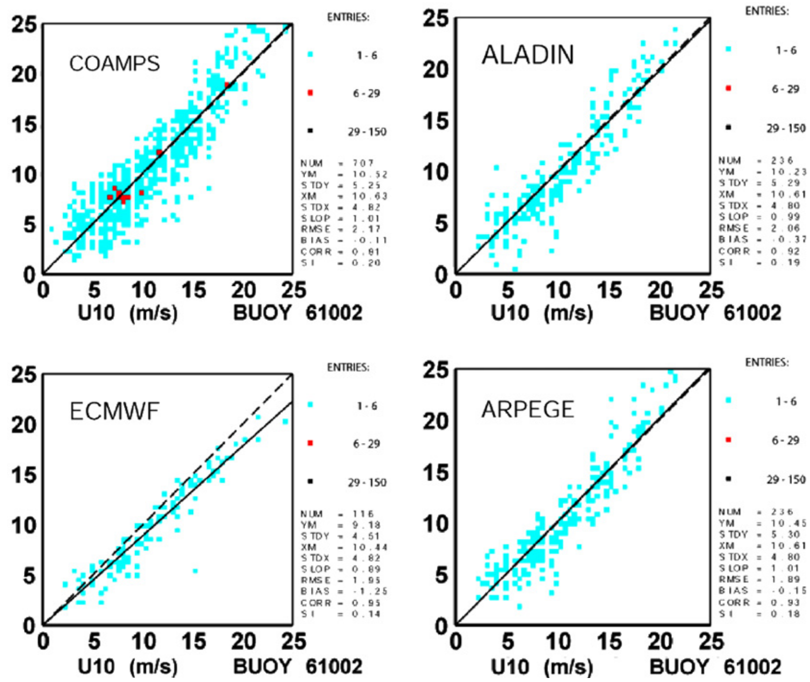

Fig. 4. Comparison of in situ and model winds for October 2002 at buoy 61002 (Gulf of Lion). The different numbers of data are due to the use of different time resolution in the wind model outputs (ECMWF: 6 h, ALADIN and ARPEGE: 3 h, COAMPS: 1 h).

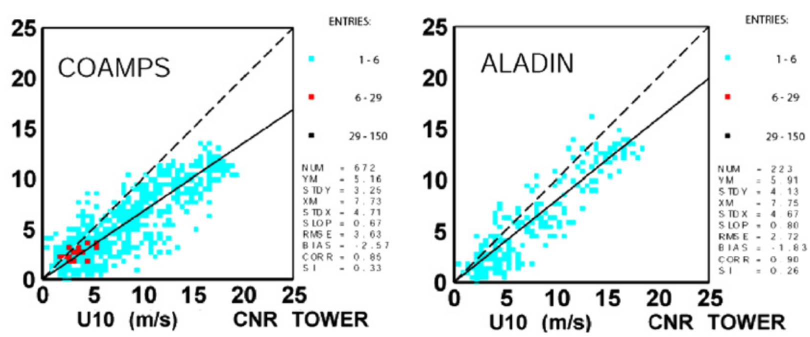

Fig. 5. Comparison of in situ and model winds for February 2003 at CNR tower.

lower wind speeds, hence a less-defined structure of the meteorological fields. This is clearly seen in the satellite data, comparing the October values with the ones from February.

Beside the large-scale errors, the scatter around the best-fit line is associated to the turbulence present in the wind fields and to how far the model spectrum extends toward high frequencies (Abdalla and Cavaleri, 2002). The higher-resolution models introduce in their fields smaller-scale features. Indeed the physics represented in the model equations may produce, in a statistical sense, the correct results (the correct oscillations). However, because of a lack of information at the small scale and of the chaotic behaviour of the atmosphere, there is no way, for the time being, to make them deterministically correct (i.e. in space and time). This introduces a further random error that increases the scatter around the correct values. If these high-frequency oscillations are not present, as in the coarser ECMWF model, the scatter decreases, being limited to the one associated to the atmospheric turbulence. Indeed in Tables 1 and 2 we see that the lowest scatter values come from the ECMWF data (note however that the 61002 wind data have been assimilated in the ECMWF analysis). Note also that the values of SI are rather uniform for the three satellites, in so doing bearing virtually no relationship with the values of the best-fit slopes. Model errors are also a source of variability, noting that the high-resolution models are short-range forecasts.

Looking at the corresponding buoy and tower data, we find a large variability of the results, that seems to depend on the position of the measurement location. The SI values are lower at the well exposed Lion 61002 buoy, and larger at Nice 61001 and at the tower. Most likely this is due to the difficulty of modelling wind fields close to relevant orographic features and to the larger level of turbulence introduced in the fields by the proximity of mountains.

There are also larger differences among the models. COAMPS has larger SI values with respect to ALADIN, and in February it displays almost always the largest values. This may be due to the rather coarse resolution (T239, or about 83 km) of NOGAPS, the global model in which COAMPS is nested, with respect to ARPEGE (20 km), from which ALADIN is the nested model, with the consequent poorer definition of the general characteristics of the fields.

It is also instructive to analyse the scatter between the corresponding fields from the four different wind sources. Table 3 shows the SI values for the different combinations of wind sources and the two test periods. As already pointed out, the values are larger in October, with weaker and less-defined wind fields. As expected, the lowest values are between ARPEGE and ALADIN, because of the father and son relationship. Conversely, the largest scatter is between the two high-resolution models, ALADIN and COAMPS. This is consistent with the previous argument about the lack of determinism in the meteorological models at the smaller scales.

Table 8, postponed because reporting also the wave results, summarizes Table 3 in single average values, evaluated excluding the ones between ARPEGE and ALADIN.

Table 3
Scatter indices between the wind speeds of the four different models

	ALADIN	COAMPS	ARPEGE	ECMWF
ALADIN		0.34	0.20	0.28
COAMPS	0.41		0.31	0.28
ARPEGE	0.21	0.38		0.25
ECMWF	0.33	0.33	0.30	

The values are given for October 2002 (lower left of the matrix) and February 2003 (upper right part).

8. Models performance: wave fields

8.1. Comparison with buoy data

As it is the case with the meteorological models, the performance of the wave models is different in the open sea and close to the coasts. As representative elements of the open sea conditions we have chosen five buoys, namely Alghero, Ponza, Mazara, Nice 61001 and Lion 61002 (see Fig. 1). As a matter of fact the first three ones are located relatively close to the coastline. However, their position is such that almost all the significant events hit the buoys from the sea. The eight chosen coastal stations are Civitavecchia, Marseille, Porquerelle, Palamos, Tarragona, Valencia, Cabo de Palos, and Malaga. Note that, to avoid any influence from the limited extent of the ALADIN winds (see Section 4), we have restrained our attention to the Western Mediterranean, i.e. to the West of the Sicily Channel between Sicily and Tunisia.

For each one of the above buoys we have evaluated the slope of the best-fit line and the value of the associated scatter index between buoy and model results. The model combinations considered are WAM run with ALADIN, COAMPS, and ECMWF winds (test on the effect of using different wind sources), and WAM, WW3 and VAG, run with ALADIN winds (test on the different wave models). The resulting statistics, separated for October and February, and given as averages over the considered buoys, are shown, respectively, in Tables 4 and 5. In each box the bold number provides the best-fit slope; the second figure provides the SI value.

A general consideration from these results is that there is no definite indication of a different performance in the open sea and at the coast. When the sea is stormy (February), the models perform better offshore. The difference is more evident when looking at the scatter index, consistently larger at the coastal stations. We

Table 4
Best-fit slopes (bold) and scatter indices of model vs buoys significant wave heights at open sea and coastal locations

WAM	October 2002			February 2003		
	ALADIN	COAMPS	ECMWF	ALADIN	COAMPS	ECMWF
Open	**0.92** 0.30	**0.86** 0.29	**0.77** 0.28	**0.97** 0.25	**1.00** 0.27	**0.79** 0.20
Coast	**0.98** 0.48	**0.94** 0.53	**0.70** 0.36	**0.93** 0.38	**0.96** 0.41	**0.70** 0.30

Average values are reported for October 2002 and February 2003. The results of WAM runs with three different wind sources are considered.

Table 5
As Table 4, but for the three wave models run with ALADIN winds

ALADIN	October 2002			February 2003		
	WAM	WW3	VAG	WAM	WW3	VAG
Open	**0.92** 0.30	**0.87** 0.30	**0.94** 0.36	**0.97** 0.25	**0.89** 0.21	**1.00** 0.26
Coast	**0.98** 0.48	**0.84** 0.43	**0.90** 0.46	**0.93** 0.38	**0.81** **0.33**	**0.85** 0.35

consider this as due to two problems. The first one is the difficulty of representing correctly the shape of the coastline in a finite grid (0.1° resolution, i.e. between 8 and 11 km). The second one is how to locate a representative grid point for the position of the buoy, taking into account the local and grid border effects. We have followed the principle of favouring a fit of the depth more than the position. As a matter of fact the errors due to shifted locations of model outputs are largely hidden by the average values shown in Tables 4 and 5. As an example, the 0.98 slope of the WAM–ALADIN combination for coastal stations is the result of a very wide range of values, from 0.53 of Cabo de Palos to 1.65 of Marseille. Clearly these values depend on the dominant pattern of the waves, coming, for instance, parallel or perpendicular to the coast. The main conclusion is that, if permanently reliable values are required at or close to the coast, a high resolution nested coastal model is required.

From Table 4 we see that the ECMWF driven wave heights are typically 10–20% lower than the corresponding ALADIN or COAMPS results. This is consistent with the 10% underestimation of the ECMWF wind speeds reported in the previous section. In a wind-generated sea the dependence of the significant wave height H_s on the wind speed U_{10} is expressed by $H_s \approx (U_{10})^{\beta}$, with β a coefficient varying between 1 (short-fetch limited conditions) and 2 (fully developed sea). In the intermediate conditions of an enclosed basin, as the Mediterranean Sea, the average value of β is about 1.5, with more extreme, larger and smaller, values depending on the actual wind speeds and the related age of the sea. Note that the difference between the ECMWF and the two high-resolution models tend to be larger at the coastal stations. We consider this a further effect of the different resolution of the meteorological models.

From Table 4 we recognize also the lower scatter associated to the use of the ECMWF winds. This is consistent with the parallel argument on the wind speeds in the previous section.

When exploring the reasons for the errors in the wave model outputs, the usual crucial question is how much is due to errors in the input winds or to the wave models themselves. An answer is given by the comparison of Tables 4 and 5. The differences between the wave model slopes appear smaller than those between different winds. This suggests that in the Western Mediterranean sea the winds are still the major source of errors for the wave model results. However, we note that in Table 4 the differences decrease substantially if we limit our attention to the two high-resolution models, ALADIN and COAMPS. Similarly in Table 5 the differences, at least in the open sea, become much smaller if we focus our attention only on WAM and VAG. This point is discussed below.

A more detailed verification of the consistency between the various models is obtained by cross-comparing the wave fields and exploring the resulting scatter. Table 6, similar to Table 3, but for H_s, shows the scatter index between the different meteorological models, both for October and February, when using the WAM model. Table 7 does the same for the output of the three wave models, when using the ALADIN winds. All these results are summarized as average values in Table 8. As done for the wind data, we have not considered in the averages the ARPEGE–ALADIN relationship.

From these results we derive several conclusions. The first one is that the wave models show a higher consistency than the one exisiting among the meteorological models. Together with the previous comparison with measured data, this suggests that, at least in the Mediterranean Sea, the errors associated to the wind fields are still larger than the one due to the wave models themselves. These errors tend to decrease in stormy conditions or, more in general, when the meteorological situation is better defined. Finally the scatter indices are lower when we intercompare third generation wave models (WAM and WW3), a likely consequence of the more sound physics they include with respect to VAG. However, it is noteworthy that this is not necessarily reflected into similar differences of the best-fit slopes. Indeed (we focus now on the performance of the wave models) from Table 5 it is clear that on average the WW3 wave heights are lower than the ones from WAM and VAG. This is true for both months, in the open sea and in coastal waters. The situation is better described by

Table 6
As Table 3, but for the WAM results (wave heights) run with different wind sources

All WAM runs	ALADIN	COAMPS	ARPEGE	ECMWF
ALADIN		0.28	0.08	0.23
COAMPS	0.34		0.28	0.26
ARPEGE	0.13	0.33		0.23
ECMWF	0.29	0.30	0.27	

Table 7
As Table 3, but for the three wave models (wave heights) run with ALADIN winds

All runs with ALADIN	WAM	WW3	VAG
WAM		0.17	0.28
WW3	0.18		0.26
VAG	0.28	0.25	

Table 8
Average values of the scatter indices SI shown in Table 3 (for wind speed), and Tables 6 and 7 for wave height

	U_{10}	WAM	ALADIN
October 2002	0.35	0.31	0.24
February 2003	0.29	0.26	0.24

The SI values between ARPEGE and ALADIN have not been considered.

Fig. 6, showing the scatter between the corresponding wave height values of WAM and WW3, and WAM and VAG. There is clearly a tendency of WW3 to an increasing underestimation while we move towards higher H_s values. This is confirmed by a similar comparison with buoy data (not shown). As a matter of fact the maximum H_s value reported during the test periods is about 12, 9 and 14 m for WAM, WW3 and VAG, respectively.

Further insight is obtained exploring the time series at the single buoys. Obviously all three models reproduce the expected time behaviour, following roughly the time evolution at the buoys. However, there is a general tendency toward an underestimation of the peaks. This is more evident for WW3. A representative example is shown in Fig. 7, comparing the significant wave height measured at Alghero (West coast of Sardinia, see Fig. 1) with the output of the three wave models during three consecutive mistral events.

This behaviour of WW3 seems to be associated with stormy events. In the low-value range the statistics of WW3 are better, by a few percents, than those of WAM. In this range Bidlot et al. (2002) have reported a tendency of WAM to overestimate the low wave heights. However, the overall performance, summarized by the statistics in Table 5, suggests, on average, too low values for WW3. Given the good performance of WW3 in the open oceans (see Tolman, 2002; and Rogers et al., 2005), the present negative bias seems to be associated to the more limited dimensions of the Mediterranean Sea. It can be corrected, probably, by a retuning of the model parameters. Further, it is likely that the use of air–sea stability dependent parameters may remove some of the bias because mistral winds are generally associated with cold winds, for which wave growth is apparently stronger (Kahma and Calkoen, 1992; Young 1998).

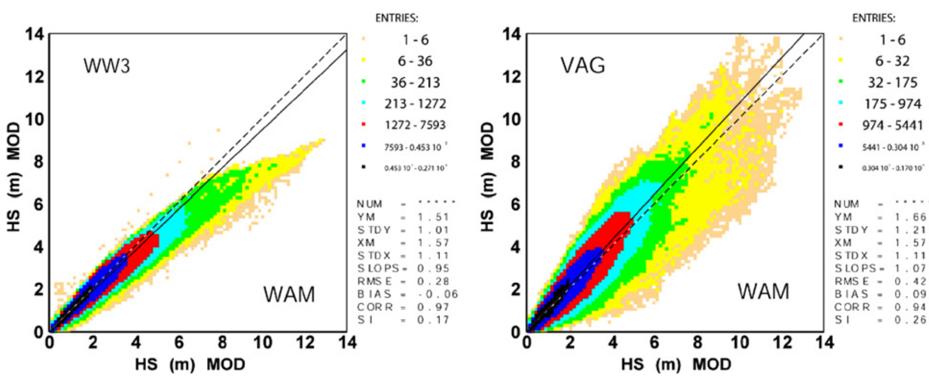

Fig. 6. Comparison of WAM and WW3, and WAM and VAG for February 2003 both using ALADIN winds.

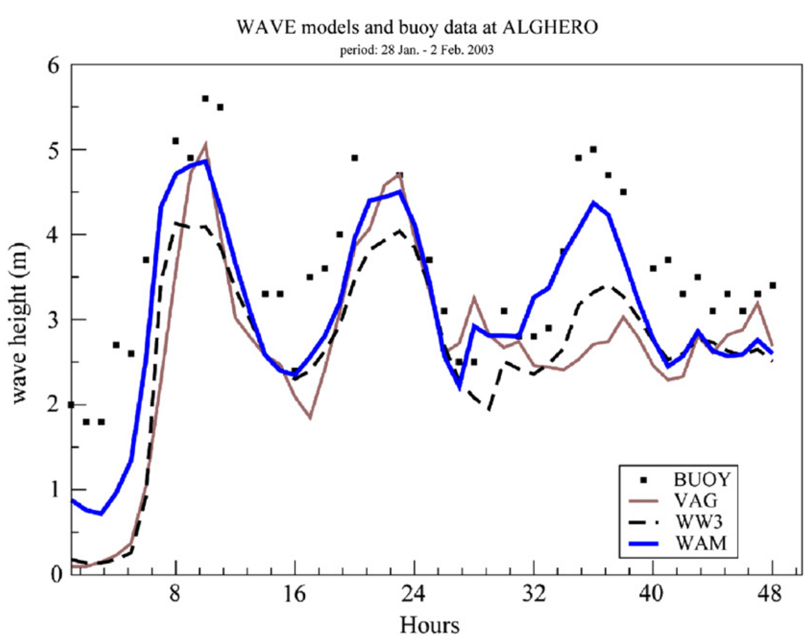

Fig. 7. Time series of the modelled wave heights (WAM, WW3, VAG), using ALADIN winds, and recorded data at Alghero during three consecutive mistral storms. This time series is typical of all the hindcast periods.

Finally, also for later use, we have analysed the statistical distribution of H_s values from both buoy and model data (at buoy positions). For models we have considered the WAM/ALADIN combination. The results are shown in Fig. 8. We note the similar distribution from the two sources, a further proof of the good behaviour of the model when driven by accurate wind fields. There is a slight overestimate by the model of the number of low wave heights, followed by an underestimation of the larger values. This is consistent with the figures in Tables 4 and 5, and with what reported by Bidlot et al. (2002).

8.2. Comparison with altimeter data

We consider the second set of measured data at disposal, namely the altimeter data from ERS-2 and Jason. Fig. 9 shows the scatter diagrams between the altimeters and the corresponding ALADIN/WAM data for February.

We note at once that the altimeter data do not approach 0, but converge to some minimum value, especially for ERS-2. The ERS-2 data do not give any value below 0.5 m, and the values up to 1 m are systematically higher then model values. That the problem lies with the altimeter is indicated by the previous comparison between model and buoy data, both at exposed and coastal locations, where no such effect is evident. Therefore, for our present purposes of evaluating the performance of the wave models, we limit our comparison to altimeter wave heights larger than 1.5 m. The Jason data show a similar problem, although at a much more limited extent. In this case we have neglected in our analysis all the altimeter data lower than 0.5 m.

The problem is not new in the literature, al least for ERS-2. It concerns the fast delivery products and was reported by Challenor and Cotton (1997), and more recently dealt with by Greenslade and Young (2004). They point out that a distribution like the one in Fig. 9, left panel, cannot be properly corrected with a single linear relationship. A more effective solution is to use two separate linear corrections, below and above a threshold to be chosen. However, having set a threshold on the data

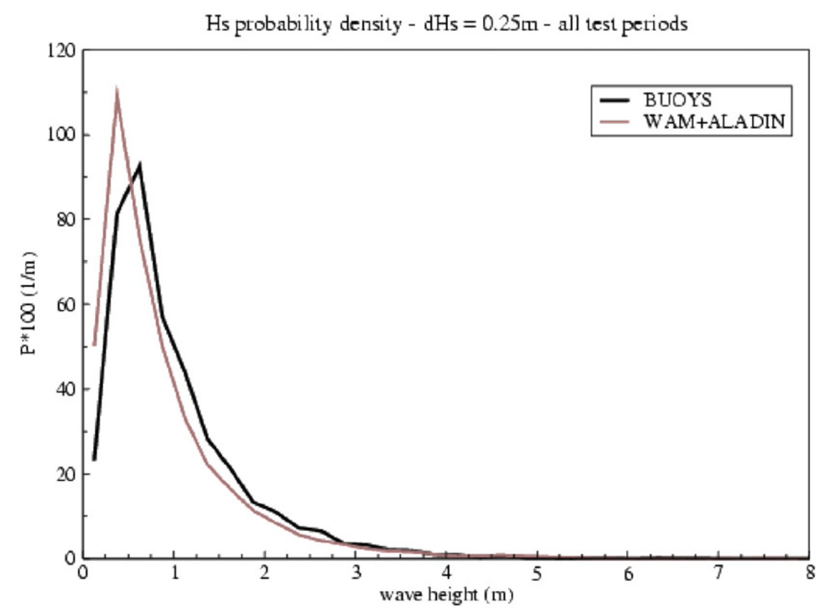

Fig. 8. Statistical distribution of the significant wave heights from buoy and model data at buoy positions.

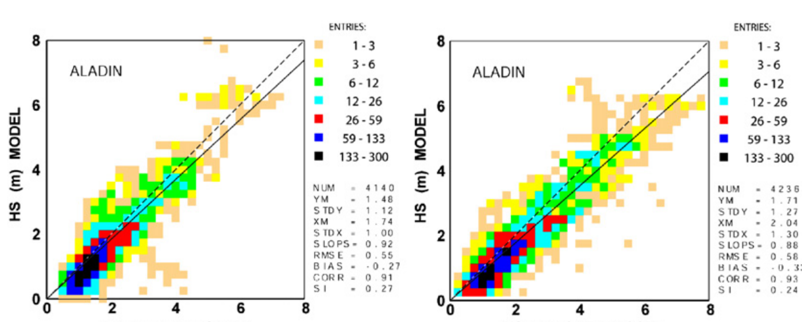

Fig. 9. Comparison of WAM results obtained with ALADIN winds for February 2003, with altimeter wave heights from ERS-2 (left) and Jason (right).

to be used, in our case we have used the data routinely available at Meteo France obtained with a single linear correction of the original altimeter data (Queffeulou, 1996)

Similarly to what was done for the buoys, we report in Table 9 the H_s statistics, best-fit slope and scatter index, of model values (WAM) with different winds against the Jason and ERS-2 ones, The results are given for the four meteorological sources, and separated for the two test periods. Table 10 provides similar results, but for the three wave models using ALADIN as input. We note the following evidence.

The ECMWF run wave results are lower by 10–15% with respect to the other wind sources. This confirms the previous findings from the comparison with buoys in Table 4.

The fits are better in February, with stronger winds and higher waves, and, implicitly, better defined meteorological situations. Also the scatter values are lower in February. The ERS-2 wave heights are consistently lower (larger fit slopes) than the Jason ones. The ERS-2 slopes are closer to the ones we have derived from the buoys. The typical difference between the two fits is the one seen in Fig. 9. This suggests that the wave heights derived from the Jason altimeter in the Mediterranean Sea are slightly too high. This is consistent with the findings of Abdalla et al. (2005).

Finally we perform the same comparison done in Section 8.1 versus the buoy data, analysing the statistical distributions, altimeters and model, of the significant wave heights. The model values are the co-located ones with the altimeter data. The results are shown in Fig. 10. Basically these figures are the integral of the panels in Fig. 9 along the x- and y-axes. Correspondingly with Fig. 9, we see that the ERS-2 distribution peaks between 1.0 and 1.25 m, with no value below 0.5 m. The corresponding WAM/ALADIN distribution is shifted towards the low H_s values, consistently with the ones at buoy positions. The different shape of the two model distributions is apparently connected to considering for altimeter data only points at least 100 km off the coast. This decreases the number of low values present when the wind is blowing offshore, hence the different model distribution with respect to Fig. 7. Note that this does not exclude the presence of low waves heights, on the contrary absent in the ERS-2 distribution.

The Jason altimeter, in Fig. 10, shows a similar, although much less pronounced, problem. Values are present till the lowest interval, 0.0–0.25 m. However, the number of data below 1 m is much less than found in the model data. The differences between the two distributions, model and altimeter, is larger than derived from the model comparison with buoys in Fig. 8. This suggests that the Jason altimeter too has a tendency, although limited, to overestimate the wave heights in the low-value range.

Table 9
Comparison between WAM wave height values, obtained with four different wind sources, and corresponding altimeter data

WAM	ALADIN		COAMPS		ARPEGE		ECMWF	
Jason	**0.79**	0.27	**0.79**	0.29	**0.79**	0.27	**0.70**	0.26
ERS-2	**0.89**	0.31	**0.83**	0.28	**0.85**	0.30	**0.72**	0.25
Jason	**0.89**	0.20	**0.87**	0.21	**0.88**	0.21	**0.76**	0.18
ERS-2	**0.95**	0.25	**0.96**	0.24	**0.91**	0.23	**0.78**	0.19

Best-fit slopes (bold) and scatter indices are provided. The upper lines show the October results, the lower ones the ones for February.

Table 10
As Table 9, but for the three wave models run with ALADIN winds

ALADIN	WAM		WW3		VAG	
Jason	**0.79**	0.27	**0.78**	0.26	**0.79**	0.30
ERS-2	**0.89**	0.31	**0.82**	0.27	**0.95**	0.33
Jason	**0.89**	0.20	**0.84**	0.18	**0.94**	0.24
ERS-2	**0.95**	0.25	**0.86**	0.21	**0.99**	0.27

8.3. Threshold analysis

For practical purposes it is of interest to know when the wave conditions will be above or below a given value H_0. More specifically, we wish to know the percentage of times, i.e. the probability PD of detection, that a model anticipates a $H_s > H_0$ event. We are also interested in the percentage of false alarms PFA, i.e. in the probability that a model anticipated event does not happen. These results are conveniently plotted in the so-called pseudo-ROC diagrams, having PFA and PD as x, y coordinates, respectively.

We have carried out this analysis separately at the open sea and coastal stations listed at the beginning of this section. As threshold values we have chosen 0.5, 1, 1.5, 2, 2.5 m for the coastal stations, extended to 1, 2, 3, 4 m for the open sea ones.

Fig. 11 shows the results of this analysis for the whole period considered (October 2002 and January–February 2003) and for the coastal buoys, using WAM run with the four different wind sources. The ideal result would be to have the representative points grouped at the upper left corner (PD = 100, i.e. all the events $H_s > H_o$ are detected; PFA = 0, no false alarm). If a model is overreacting, it will have a good (large) PD value, but also a large number of false alarms (large PFA). Conversely, a model that is usually too low will have low PD and PFA values. In Fig. 11 the latter is the case for the WAM model run with ECMWF winds. There are very few false alarms, but most of the times the model is not anticipating the $H_s > H_o$ events. Note, however, that the practically null value for the upper limit is not significant, due to the limited size of our sample and the consequent lack of a sufficient number of strong storms. In the low H_o range the other three models, ALADIN, COAMPS and ARPEGE, behave in a similar way. For low H_o PD is about 70%, with less than 20% false alarms. With increasing wave heights the quality

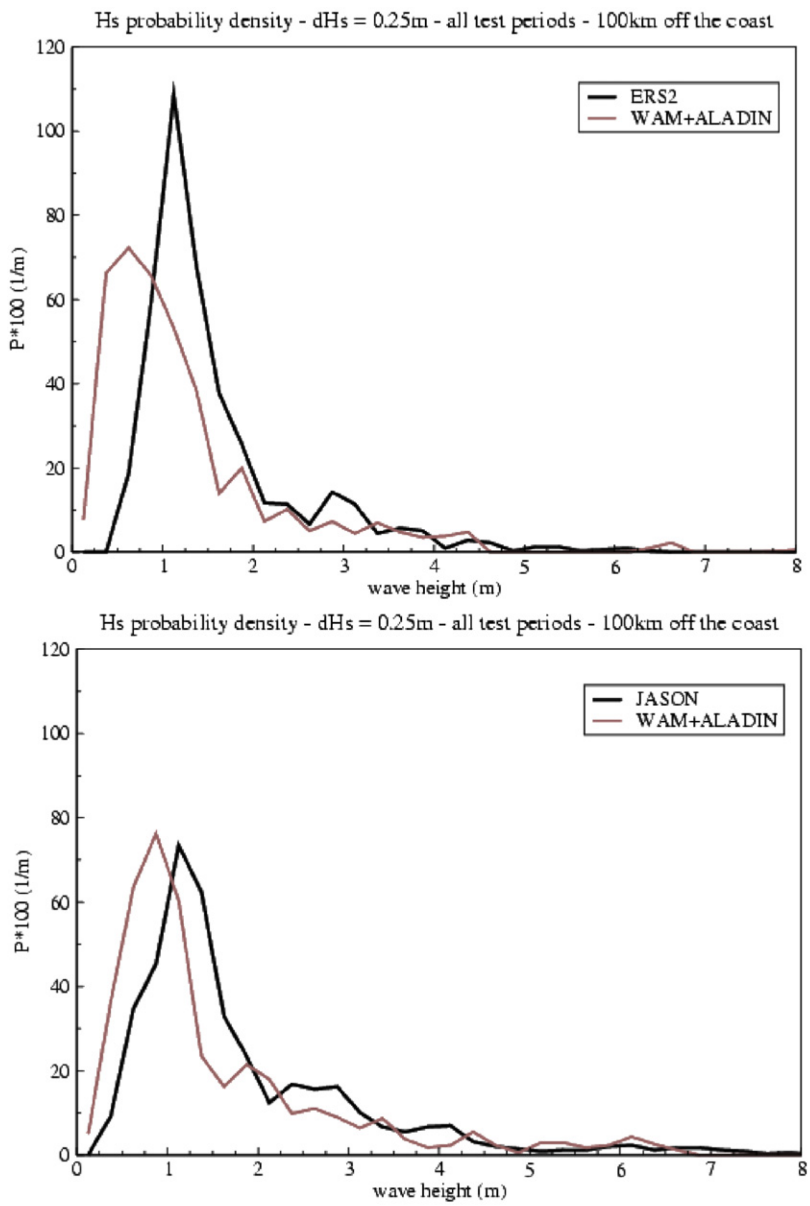

Fig. 10. Statistical distribution of the significant wave heights from altimeter and model data. The latter ones have been considered only at altimeter sampling positions. Upper panel for ERS-2, lower panel for Jason.

of the model results worsens progressively, with decreasing PD and increasing PFA values.

The conditions improve when we move to the open sea, whose results are in Fig. 12. Here the number of false alarms is very limited, at least for the lowest H_o. Most of the results are grouped between 55% and 80%. The expected exception is WAM/ECMWF, with a probability of detection below 40% for $H_o > 3$ m.

There is again a strong indication, not shown, that a critical factor for a positive result is how well the meteorological situation is defined, hence implicitly how well the meteorological models can reproduce it. For this reason, when analysed separately, we found the October results of lower quality with respect to February.

As expected, we find similar results, not shown, when plotting the results of the three wave models, all run with Aladin winds. Consistently with the previous analysis in Section 8.1, for the larger H_o values there is a growing number of misses by WW3. VAG and WAM behave very similarly with a slight tendency of VAG to overreact (larger PFA). These results are in agreement with a more active behaviour of VAG, compared to WAM, as suggested by Fig. 6.

9. Discussion and conclusions

In this intercomparison exercise we have focused more on a multi-model/instrument approach, in so doing

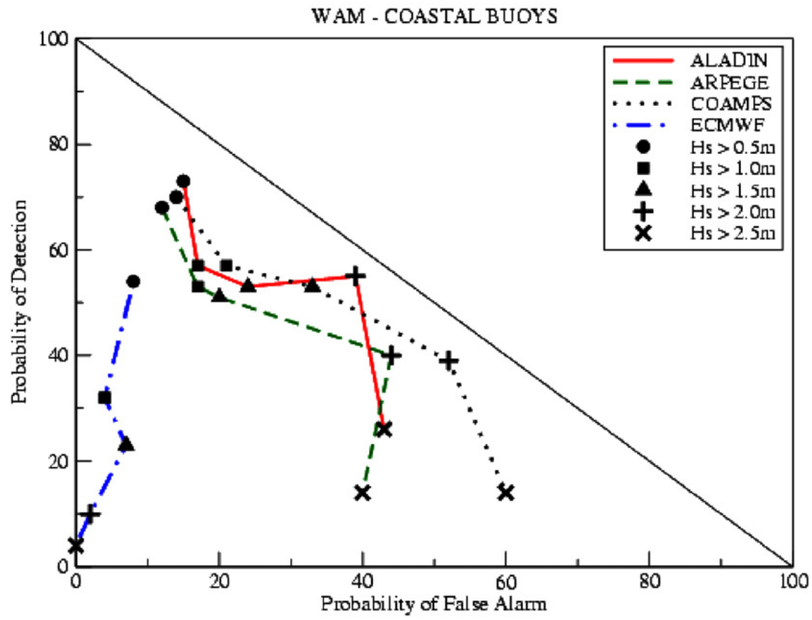

Fig. 11. Pseudo-ROC diagram of the percentage of false alarms and correct forecasts for different threshold values at coastal locations. WAM has been run with four different wind sources.

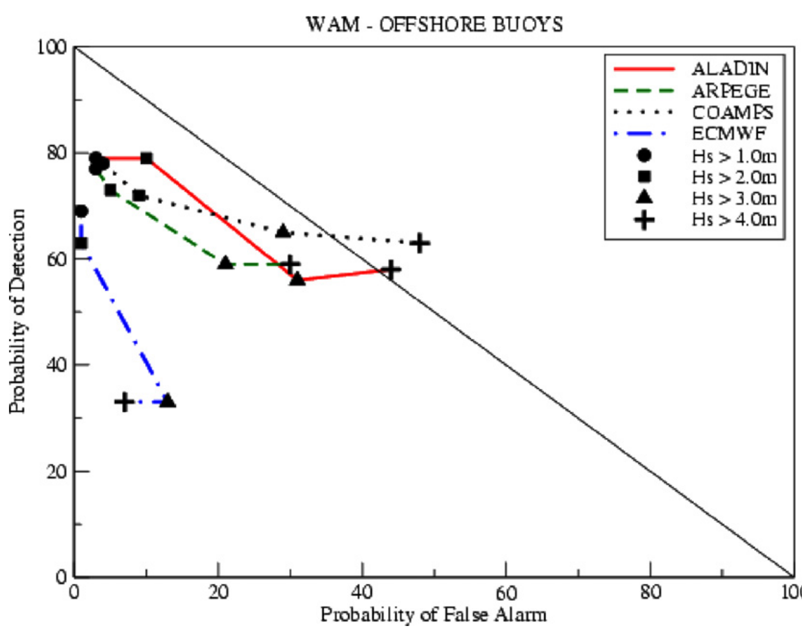

Fig. 12. As Fig. 11, but for the open sea locations.

avoiding the uncertainty derived from a single direct verification. On the other hand, the limited extent of the test period, two months, although covering a large spectrum of possible storms in the Western Mediterranean Sea, prevents us from drawing definite conclusions on the performance of the considered meteorological and wave models. However, there are strong indications of some well-defined characteristics.

The resolution of the ALADIN and COAMPS models seems sufficient to provide reliable wind fields, at least off the coasts. The comparison with the open sea buoy data is very favourable. The quality of the wind fields degrades substantially in the more coastal areas (−20% at the tower), particularly if these areas are characterized by a marked orography. For lower resolutions the quality rapidly deteriorates, both off and at the coasts. At the resolution used by ECMWF model (T799, about 25 km) the underestimation of the wind speed varies from 10% to 40%.

The comparison between model and satellite wind data shows a wider range of variability that cannot be attributed simply to sampling variability. Our data set is too limited to attempt a retuning of the retrieval algorithms. However, some general indications can be derived. We begin with the favourable results obtained comparing model and buoy data. Although with some variability, the Jason altimeter is consistent with these results. Hence we derive that its algorithm is on average correct.

This is not the case with ERS-2. Its altimeter provides, on average, lower wind speeds, typically by 10%. Taking into account also the results by Cavaleri and Sclavo (2006) on the consistency between wind and wave data in the Mediterranean Sea, we conclude that indeed the ERS-2 wind values in this basin, and more in general in the enclosed seas, are too low by about 10%. We interpret this as due to a more wind-driven wave characteristics with respect to the swell dominated ocean environment, where the altimeter algorithm has been calibrated.

The QuikSCAT data have been found larger than what suggested by the high-resolution models and the related wave model results. This contrasts with the expectations. Clearly the proper use of the scatterometer data in the inner seas deserves further attention and more thorough studies.

The accuracy of the model wind fields depends on how well the meteorological situation is defined. In stormy, well-extended areas the models are more consistent to each other. For more uncertain situations the percent errors tend to be larger. This is clearly reflected also in the scatter of the data with respect to the best-fit line. It is interesting that, when compared to measurements, the higher-resolution models show a larger scatter than the more coarse ones. This is related to the energy present in the higher part of the frequency spectrum when the resolution is increased. The associated oscillations of, e.g., wind speed are physically sound, but not deterministic. The consequence is the so-called double penalty, i.e. the addition of the pseudo-chaotic behaviour of the models at the smaller scales to the already present atmospheric turbulence, with a consequent increase of the scatter when model and measurements are compared.

Of course the scatter may be associated also to the errors in the field. We believe this is the case for COAMPS with respect to ALADIN, because of the relatively coarse resolution of the global model in which COAMPS is nested.

All the above points are reflected in the associated wave fields. For all the wave models the quality of the wave results deteriorates when approaching the coast, more so if the wind and wave directions are not perpendicular to the coastline. If a reliable wave forecast or hindcast model is required at a coastal location, we highly recommend to use a high-resolution wave model, nested in the general one, or the use of a variable grid size model.

The wave height differences due to different input wind sources are larger than those derived from the use of alternative wave models. This suggests that in the enclosed seas the input winds are still the main source of error in wave modelling. However, this must not be an excuse for wave modellers to justify wrong results. It has been customary to blame the quality of the input wind fields as the main reason for wave model errors. Our findings suggest that the high-resolution meteorological models have reached the stage when this is no longer possible, and both the models, meteorological and wave ones, need to be worked on for further improvement.

The scatter of the wave results, with respect to the buoy data, is lower than for wind. This was expected, because of the integral characteristics of the waves (in space and time) with respect to the generating wind fields, and the consequent limited sensitivity to the wind conditions at the wave measuring locations.

Comparing the performance of the three wave models, we have found that the two third-generation models, WAM and WW3, perform similarly for low wave heights. However, for growing H_s there is a progressively increasing underestimation by WW3 with respect to WAM. A more absolute statement is derived from the comparison with buoy and altimeter data. WW3 seems to underestimate substantially the largest wave heights in the Mediterranean Sea. The results of VAG are consistent with WAM, although they show a larger scatter, a likely consequence of the differences between second- and third-generation models.

For fast delivery products the altimeter derived wave heights are not reliable in the low-value range ($H_s < 1$ m). In this range they permanently overestimate the wave heights. The problem is more manifest for ERS-2.

On a more practical side we have carried out a wave height threshold analysis, i.e. we have verified at various buoy locations how frequently a wave model output is correctly anticipating an event (above the chosen threshold) or giving a false alarm. In the open sea the results are good, particularly for intermediate wave heights (2–3 m). For low H_s (<1.5 m) the uncertainty grows, particularly close to the coasts. Apart from the quality of the input wind fields, a good forecast in these areas requires a high-resolution nested model, capable of resolving in sufficient details the relevant characteristics of the coast..

10. Summary

We summarize here the main findings of our research for the Mediterranean Sea, as representative of the enclosed basins:

(1) the resolution of ALADIN and COAMPS is sufficient for reliable results in the open sea,
(2) the quality of their results degrades close to the coast, particularly if affected by orography,
(3) the ECMWF T511 winds are too low by 10% in the open sea, up to 40% in coastal unfavourable locations,
(4) the quality of the model wind fields improve for well-defined meteorological situations, e.g. for extended storms,
(5) the Jason altimeter wind speeds are on average consistent with the corresponding buoy data, although with a strong variability. The ERS-2 wind speeds are

low by about 10%. The QuikSCAT data have been found larger with respect to buoys and models,

(6) the fast delivery altimeter wave height data, particularly for ERS-2, are not reliable in the low value range (<1.0 m). These data should not be considered for a model comparison,
(7) using the high-resolution ALADIN winds, the model wave heights are only slightly underestimated, with a typical scatter index of 0.2,
(8) their scatter increases close to the coasts: a good wave forecast/hindcast requires the use of higher resolution, e.g. nested, models or other techniques such as ray-tracing or a variable grid size,
(9) there is a marked underestimation by WW3 for large wave heights in the Mediterranean Sea,
(10) if a high-resolution meteorological model is used (ALADIN or COAMPS), the H_s errors due to wind errors are comparable to the ones introduced by the wave model,
(11) a threshold analysis has shown that the wave model results are reliable in the intermediate value range (2–3 m), less so in the low-value range. For larger wave heights our results are not conclusive because of the limited sample.

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