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On the influence of resolution on wave modelled results in the Mediterranean Sea(*)

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Summary. — We have explored the sensitivity of the wave modelled results in the Mediterranean Sea to the grid and integration time step resolutions. The results show that in areas with a complicated coastal shape an improved grid resolution provides often substantial local differences, mostly associate to the effect of, but not necessarily close to, the coasts. Some smaller differences are associated also to the accuracy of the numerical procedure. The use of different time steps did not provide appreciable differences. We have also explored how the quality of the wind fields in the Mediterranean Sea is going to improve with the shift of the resolution of the ECMWF meteorological model from T511 (40 km) to T799 (25 km).

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1. – The reasons for the tests

The European Centre for Medium-Range Weather Forecasts (ECMWF, Reading, UK) produces operationally daily forecasts from both a global and a European wave model. The global model is fully coupled to the local meteorological model (see, *e.g.*, [1]). This implies a continuous exchange of information, in both directions, between the lower atmospheric layers and the surface wave fields, whose spectral distribution affects the values of the surface drag coefficient, hence the evolution of the atmosphere. The calculated and archived wind fields are then used to drive, in uncoupled mode, a European wave model that includes the North Atlantic, and the Baltic, Mediterranean, Black and Caspian seas.

The resolution is different in the two applications, 55 km for the global model (in both latitude and longitude directions) and 28 km for the European model.

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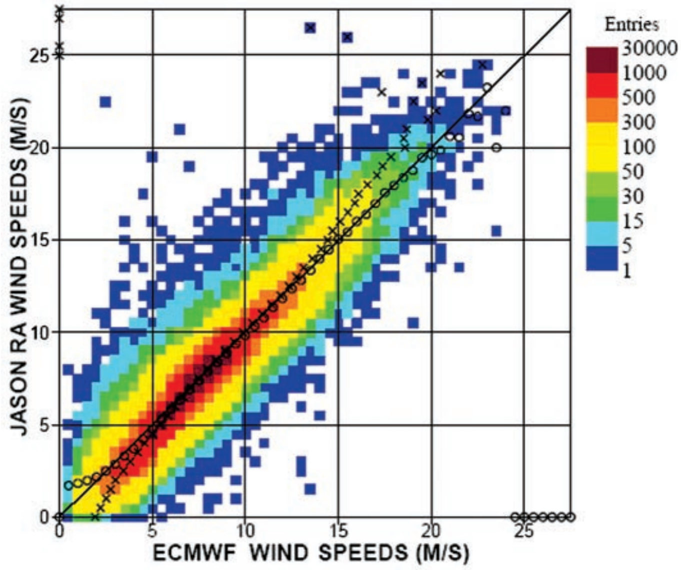

Fig. 1. – Scatter diagram between ECMWF modelled and Jason altimeter measured wind speeds on a global scale.

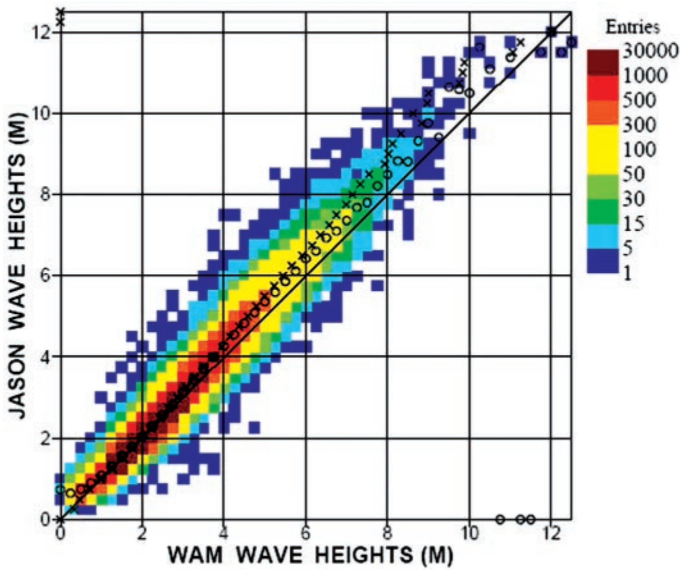

Fig. 2. – Scatter diagram between ECMWF modelled and Jason altimeter measured wave heights on a global scale.

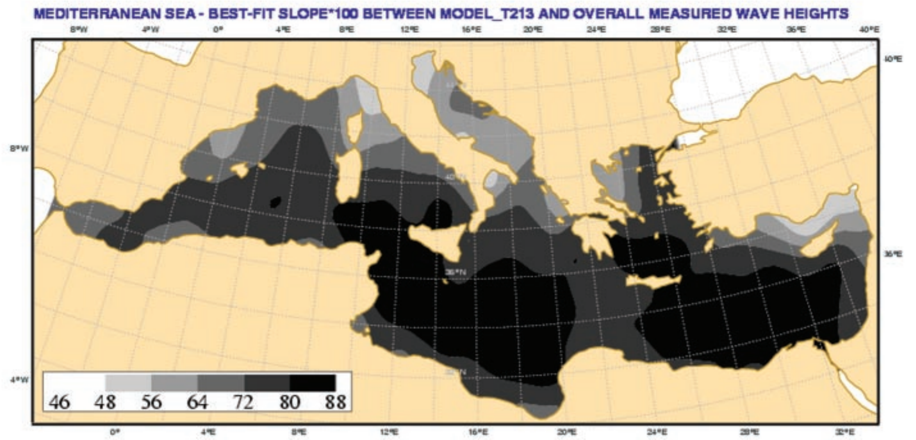

Fig. 3. – Distribution of the best-fit slopes (×100) between ECMWF modelled and altimeter measured wave heights in the Mediterranean Sea. The period considered is from July 1992 till June 2002 (after [2]).

The quality of the results for the global model is quite good, due both to the quality of the surface wind fields and to the recent improvements introduced in the locally run wave model [1]. Figures 1 and 2 provide two examples of intercomparison between modelled wind speeds and significant wave heights H_{s} *vs.* the satellite derived corresponding values. Respective best-fit slopes of 0.9971 and 1.058 and biases of $-0.14\,\mathrm{m/s}$ and $0.13\,\mathrm{m}$ on a global basis are rather reassuring results.

The situation changes substantially in the Mediterranean Sea, and more in general in the enclosed basins. Within the project Medatlas, Cavaleri and Sclavo [2] have analysed in details the performance of both the ECMWF atmospheric and wave models in the Mediterranean Sea. They have shown that in this area both the models substantially underestimate the evidence derived from measured values. Figure 3 provides a map of the distribution of the best-fit slopes between model and altimeter measured significant wave heights. The underestimate, increasing while moving from South to North, is quite evident.

While the low wind values bear an obvious responsibility in having too low wave heights, the question arises if the latter could be due also to an insufficient grid resolution. The question may look strange, because the global model (see above) has a coarser resolution, nevertheless providing very good results. The point is that the statistics is dominated by the open oceans. On the contrary in the enclosed seas the influence of the coasts becomes progressively dominant with the decreasing dimensions of the basin. This is connected both to the resolution with which we describe the coastline, hence, *e.g.*, the fetch, and to the directional distribution of energy in the wave spectra.

ECMWF has recently shifted to the T799 resolution of its meteorological model (the model is spectral-T represents the truncation level of the two-dimensional Fourier expansion with which the fields are horizontally represented). This corresponds to 25 km resolution. Parallel to this, the resolution of the global wave model has been increased to 40 km. For the European wave model no enhancement of resolution has been planned in the immediate future.

We have carried out a series of tests to determine how much the wave results in the

Mediterranean Sea would vary following an increase of its grid resolution. The tests are described in sect. **2**, and the results presented in sect. **3**. Section **4** reports the conclusions and a short discussion on the results of the tests.

2. – The tests

Our initial information is the wave height values obtained with the operational ECMWF European model in the Mediterranean Sea. They are available at 0.25 degree resolution and at six hour intervals (00, 06, 12, 18 UT).

Using as input the same analysis wind fields, we have repeated the runs using a 0.10 degree grid resolution Δx. The tests have been done for the period January-February 2005 using the same wave model WAM [3], as done at ECMWF. From the output we have then extracted the results at the same times when the ECMWF results are available, and at 0.5 degree intervals. The same has been done with the ECMWF data, this being the only grid interval at which the two grids have coincident points.

As a rule, the two grid resolutions imply also different time steps Δt in the numerical integration of the model equations, 900 s with 28 km (or 0.25 degree) resolution, and 300 s with the 0.1 degree one. It is correct to ask if this too, and not only the grid resolution, could affect the results. Therefore we have repeated the 0.25 degree run using $\Delta t = 300$ s. The other way around, *i.e.* using 900 s for the 0.1 degree grid, is not possible for the numerical stability of the procedure.

3. – Results

Expectably, the overall wave fields obtained with the 0.25 and 0.1 degree resolutions (using $\Delta t = 900$ s and 300 s, respectively) are very similar. For the purpose of the comparison, it is convenient to plot their difference (0.1−0.25) against the H_s background field. An example is given in fig. 4, showing a case of northerly flow in the Western Mediterranean (Provencal and Tyrrhenian seas), then turning to East and North-East (flow direction) in the Ionian Sea. The arrows provide the overall wave field (note the scale on the lower-left of the figure), while the isolines, at 0.10 m intervals, show the differences between the 0.1 and 0.25 degree fields (blue and thick positive, *i.e.* the 0.1 values are larger, red and thin negative. (Colours on line.)

We note several things. There are clear local differences due to the different resolutions with which the coastlines are described in the two grids. Obvious examples are at Marseille, to the left of Corsica and at Majorca. The last one is particularly noticeable because the differences are larger than 1 m, about 20% of the local significant wave height. Of the three cases the most interesting one is at Corsica, where the differences extend well off the coast. The isolines at the Algerian/Tunisian coast are associated to two small protruding peninsulas, not sufficiently represented in the 0.25 degree grid.

The more limited, but still present, differences protruding off the French/Spanish border, in the Sicily Channel and in the Ionian Sea do not have a geographical (coastal) origin, but they show the consequences of the numerical resolution on the characteristics of the fields. Note also the, albeit limited, negative values (*i.e.* larger H_s for the 0.25 degree grid) in the Ligurian Sea, between Corsica and Italy and in the Sirte gulf. Similar considerations apply also to the Adriatic Sea (to the East of Italy).

Figure 5 shows similar results, but for a different date, in the Aegean Sea. In this case most of the differences are due to the islands scattered throughout the sea, some of them represented in the 0.10 grid, but not in the 0.25 one. The positive isolines close to

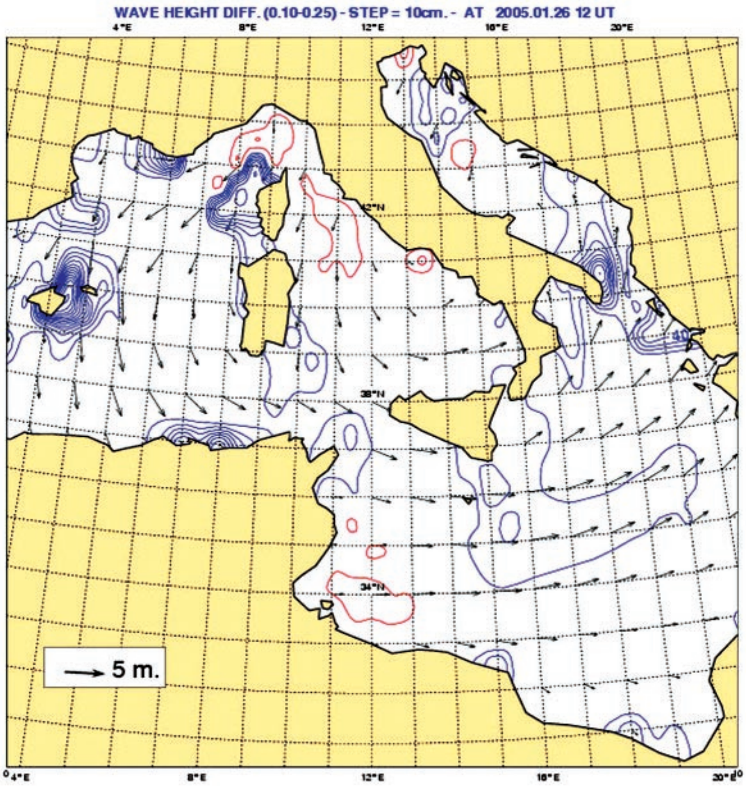

Fig. 4. – (Colours on line) The isolines, at 0.1 m intervals, show the significant wave height differences between the 0.1 and 0.25 grid resolution runs. Blue (thick) isolines = positive values, red (thin) negative. The arrows provide the background wave field. Note the scale on the lower-left of the figure.

the Peloponnesus and south-west of Crete have a clear origin in the different geometry of the coasts (note the wave direction). However, again, as in the previous figure, the differences in the northern part of the basin are associated to the characteristics of the two fields we are comparing. In other words, they carry with them the implications of the grid resolution on the numerical representation of the physical processes we want to simulate.

These two figures are typical of the differences we have found during stormy conditions. Clearly the specific locations where we find the larger values depend on the structure of the wind field, hence on the wave direction. Also, the stronger the wind, the higher the waves, and the larger the differences we can expect.

The wave conditions present in figs. 4 and 5 have been purposely chosen because of the storms present at the time and to show how far the differences can go. In general the Mediterranean exhibits long periods of calm, in which case the two resolutions lead practically to the same results. Being this the most common case, a scatter diagram (not shown) between the corresponding results from 0.25 and 0.10 degree resolutions for the whole January-February period has practically a unitary slope. However, we were interested in seeing, in case of differences, if they have a zero mean, or if there is either

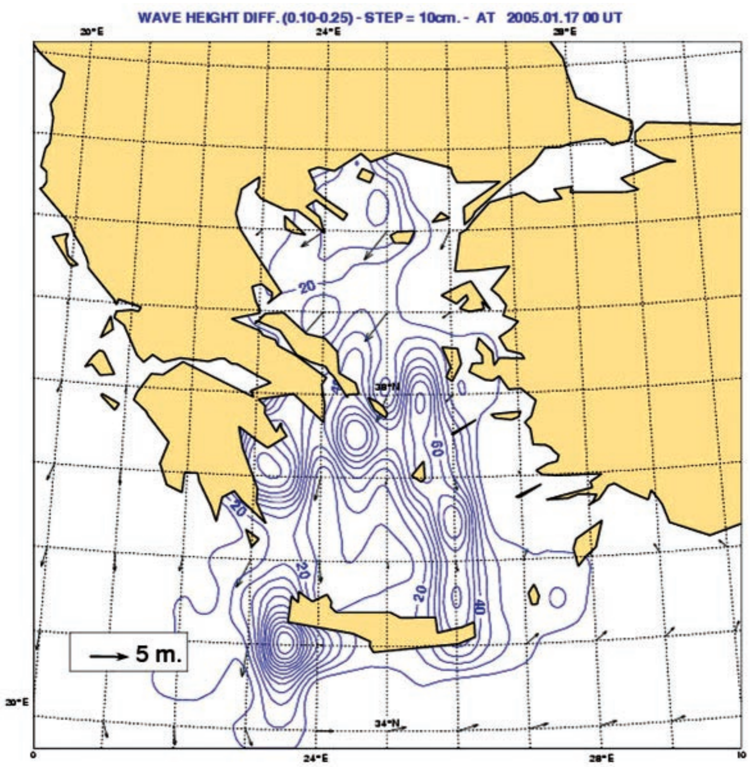

Fig. 5. – As fig. 4, but for a different date and focused on the Aegean Sea.

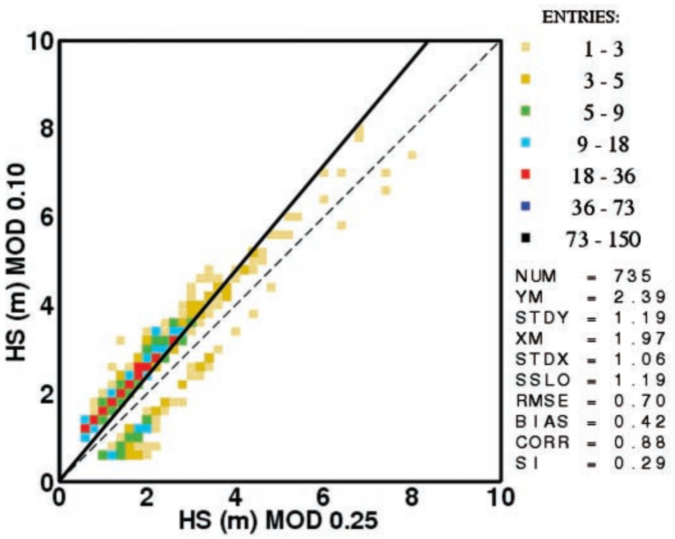

Fig. 6. – Scatter diagram between the H_s results obtained with 0.10 and 0.25 degree resolution. Only the cases when the absolute difference is larger than 0.5 m have been considered.

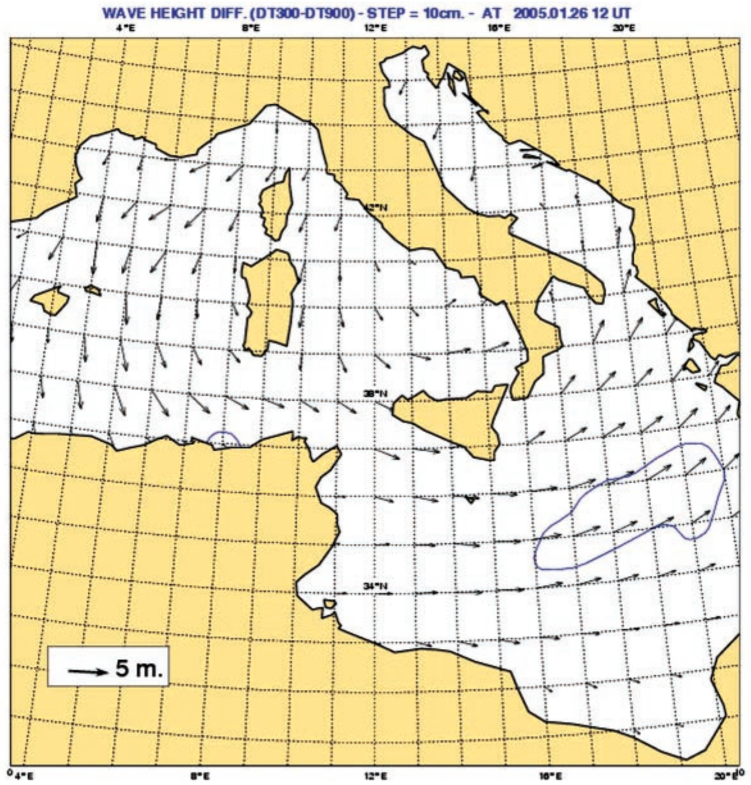

Fig. 7. – Isolines, at 0.10 m intervals, of the differences between the H_s values from the 0.25 degree resolution model run with 300 s and 900 s integration time steps. Only one isoline in the Ionian Sea is visible.

way a tendency to larger wave heights. Figure 6 shows the scatter diagram between the corresponding H_s values, having selected only the cases when the differences are larger than 0.5 m. The best-fit slope, 1.19, is a clear indication that, on the average, a difference means larger 0.10 values.

In sect. **2** we have mentioned that the two grid resolutions imply different time integration steps Δt, 900 s and 300 s for 0.25 and 0.10 degree, respectively. It is correct to ask if this is the cause of at least part of the differences we have found. Therefore we have repeated the 0.25 run using $\Delta t = 300$ s and compared the two runs. Figure 7 shows the related differences for the same storm and time of fig. 4. There is only a 0.10 m isoline in the Ionian Sea. We conclude that the differences in the previous figures are strictly associated to the different grid resolutions.

4. – Discussion and conclusions

The tests we have done have conclusively shown that a higher resolution of the WAM wave model in the Mediterranean Sea would imply, in case of a storm, appreciable differences ΔH_s, mostly positive. ΔH_s up to one metre, about 20% of the local wave height, have been found.

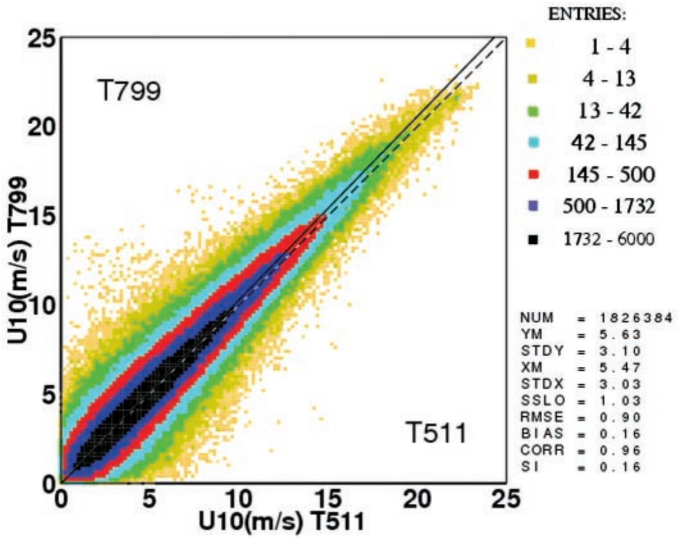

Fig. 8. – Scatter diagram between the wind speed values derived from the ECMWF meteorological model at T799 (25 km) and T511 (40 km) resolutions. The T799 winds are on the average 5% stronger.

The differences can be interpreted as basically due to two reasons. An obvious one is the resolution with which the coastline is described in the two cases. A missing promontory or island may imply higher wave heights in the otherwise shadowed zone, a fact that propagates downwards for a while before being absorbed again in the overall field. This is felt also on the side of the orographic obstacles. Examples of the first case are the differences off the west coast of Sardinia and the large ΔH_{s} between Minorca and Majorca of the Balearic Islands. In these cases a single missing (considered as land) sea point, *e.g.*, at Minorca, can, and does, lead to drastic consequences on the downward field. On the lee of an island (south-west of Sardinia) or off a coast, with the wind blowing from land toward the sea (Ligurian Sea, Northern Adriatic Sea), the differences can be either positive or negative. The sign depends on the coarser approximation of the 0.25 degree coastline, hence on the actual fetch length. A more "inner" ("outer") coastline will imply a larger (smaller) fetch, hence larger (smaller) wave heights. The second, more interesting reason is associated to the direct implications of the resolution on the accuracy with which the evolution of the wave field is physically represented in the model. Clearly, in areas characterised by rapid wave growth, early generation off the coast under strong wind, or across zones of strong wind gradients like close to a front, the different accuracy of the different resolutions leads to evident discrepancies between the two fields.

Somehow connected to this are the implications of the directional distribution of energy in the wave spectrum (the two resolutions use the same number of frequencies and number of directions). This implies that the energy flowing on the side of a coastal obstacle can propagate, so to say, sideways into the shadowed zone, somehow smoothing, but widening, the affected area. In this respect, when interpreting wave conditions like in figs. 4, 5 and 7, each arrow should be interpreted as a more or less wide distribution of energy of which the arrow shows the mean direction.

We consider the zonal differences not associated only to the coasts, like the ones in the Sicily Channel and the Ionian Sea in fig. 4, as connected to the strong local gradients of the generating wind field and therefore to areas of rapid changes of the wave spectra. In these cases a higher resolution (a smaller Δx) is clearly an advantage. The same can be said for a smaller integration time step, although in this case our tests have shown only limited differences (see the 10 cm difference in the Ionian Sea in fig. 7).

All the above tests have been done using the operational T511 meteorological model. On February 1, 2006 ECMWF moved to the T799 (25 km) resolution. Following the previous work of Cavaleri and Bertotti [4], we have explored which improvement is to be expected for the wind fields in the Mediterranean Sea. At this aim we have taken advantage of the extended trial period (several months) during which T799 was run in parallel to the operational T511 model. This has allowed a direct comparison between the corresponding wind fields. The results are summarised in the scatter diagram of fig. 8. Beside the expected scatter (scatter index = 0.24), we have found that on the average the T799 winds are 5% stronger than the T511 ones. The scatter represents also the different levels of enhancement to be found in the different areas of the Mediterranean Sea. Following Cavaleri and Sclavo [2], we expect the larger gains to be in the areas where the larger underestimates are presently found. Note that this level of enhancement is not sufficient to fill the gap between the present ECMWF model results and the measured sea truth.

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